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Effects of May through July 2015 Storm Events on Suspended Sediment Loads, Sediment Trapping Efficiency, and Storage Capacity of John Redmond Reservoir, East-Central Kansas

Scientific Investigations Report 2016–5040

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

Cover. Upper left: Flood inundated trees in park area of John Redmond Reservoir, June 22, 2015. Reservoir elevation of approximately 1,060 feet.
Upper center: Flood inundated trees in park area of John Redmond Reservoir, June 22, 2015. Reservoir elevation of approximately 1,060 feet.
Upper right: Flood inundated trees in park area of John Redmond Reservoir, June 22, 2015. Reservoir elevation of approximately 1,060 feet.
Lower center: John Redmond Reservoir Outlet, June 22, 2015. Ten thousand cubic feet per second being released.
Photographs by Lindsey R. King.

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Suggested citation:
Foster, G.M., 2016, Effects of May through July 2015 storm events on suspended sediment loads, sediment trapping efficiency, and storage capacity of John Redmond Reservoir, east-central Kansas: U.S. Geological Survey Scientific Investigations Report 2016–5040, 10 p., http://dx.doi.org/10.3133/sir20165040.

ISSN 2328-0328 (online)

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Length	
foot (ft)	3.281	meter (m)
mile (mi)	1.609	kilometer (km)
	Mass	
milligram (mg)	0.001	gram (g)
ton per year (ton/yr)	0.9072	metric ton per year

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

$$°F=(1.8×°C)+32$$

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

Effects of May through July 2015 Storm Events on Suspended Sediment Loads, Sediment Trapping Efficiency, and Storage Capacity of John Redmond Reservoir, East-Central Kansas

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Abstract

The Neosho River and its primary tributary, the Cottonwood River, are the main sources of inflow to John Redmond Reservoir in east-central Kansas. Storage loss in the reservoir resulting from sedimentation has been estimated to be 765 acre-feet per year for 1964–2014. The 1964–2014 sedimentation rate was almost 90 percent larger than the projected design sedimentation rate of 404 acre-feet per year, and resulted in a loss of about 40 percent of the original (1964) conservation (multi-purpose) pool storage capacity. To help maintain storage in the reservoir, the Kansas Water Office has implemented more than two dozen stream bank erosion control projects to reduce the annual sediment load entering the reservoir and initiated a dredging project to restore nearly 2,000 acre-feet of storage near the dam to provide additional water supply to downstream water users. Storm events during May through July 2015 caused large inflows of water and sediment into the reservoir. Initially, flood waters were held back in the reservoir in order to decrease downstream flooding in Oklahoma. Later, retained reservoir flood waters were released at high rates (up to 25,400 acre-feet per day, the maximum allowed for the reservoir) for extended periods.

The U.S. Geological Survey, in cooperation with the Kansas Water Office, computed the suspended-sediment inflows and retention in John Redmond Reservoir during May through July 2015. Computations relied upon previously published turbidity-suspended sediment relations at water-quality monitoring sites located upstream and downstream from the reservoir. During the 3-month period, approximately 872,000 tons of sediment entered the reservoir, and 57,000 tons were released through the reservoir outlet. The average monthly trapping efficiency during this period was 93 percent, and monthly averages ranged from 83 to 97 percent. During the study period, an estimated 980 acre-feet of storage was lost, over 2.4 times the design annual sedimentation rate of the reservoir. Storm inflows during the 3-month analysis period reduced reservoir storage in the conservation pool approximately 1.6 percent. This indicates that large inflows, coupled with minimal releases, can have substantial effects on reservoir storage and lifespan.

Introduction

The Upper Neosho and Cottonwood River watersheds, located in east-central Kansas, drain about 3,015 square miles (mi^2; as measured from the reservoir outlet) and are the primary inflows to John Redmond Reservoir (hereinafter referred to as the reservoir). Loss of storage due to sedimentation in the reservoir has been estimated as anywhere from 765 acre-feet per year for 1964–2014 (Kansas Water Office, 2015) to 492 acre-feet per year for 2007–2014 (Jakubauskas and others, 2014). The 1964–2014 estimated sedimentation was almost 90 percent larger than the projected design rate of 404 acre-feet per year, and resulted in a loss of about 40 percent of the conservation (multi-purpose) pool storage capacity (Kansas Water Office, 2015). To help maintain storage in the reservoir, the Kansas Water Office has implemented more than two dozen stream bank erosion control projects to reduce the annual sediment load entering the reservoir and initiated a dredging project to restore nearly 2,000 acre-feet of storage near the dam to provide additional water supply to downstream water users (Tracy Streeter, Kansas Water Office, written commun., 2016).

Rainfall in the south-central United States caused many streams and rivers in the region to reach or exceed flood stage (http://waterwatch.usgs.gov/) during the spring and summer of 2015. During May through July 2015, precipitation in the Neosho and Cottonwood watersheds delivered large quantities of runoff into the reservoir. Water was retained in the flood pool of the reservoir until late May because of downstream flooding in Oklahoma. Subsequently, water was released for the rest of the study period (June-July 2015). These changes in releases of sediment-rich water altered reservoir residence times, which directly affected reservoir sedimentation rates.

The U.S. Geological Survey (USGS), in cooperation with the Kansas Water Office, and funded in part through the

Kansas State Water Plan Fund, operates a network of streamflow and continuous water-quality monitoring sites upstream and downstream from the reservoir (fig. 1). All of the sites in this network have published turbidity-based linear regression models for the determination of suspended-sediment concentration (SSC; Lee and others, 2008; Foster, 2014). Linear regression models and data from three upstream sites and one downstream site were used to compute suspended-sediment loads (SSLs) entering and exiting the reservoir during May through July 2015. Additionally, reservoir sediment trapping efficiency and the effects of the storm events on water-storage capacity were determined.

Purpose and Scope

The purpose of this report is to summarize the results of a study to quantify SSLs entering and exiting John Redmond Reservoir during the May through July 2015 storm events and describe effects on reservoir sediment trapping efficiency and storage capacity. Streamflow and turbidity data from three upstream sites and one downstream site were used with previously published models to compute SSC, SSLs, and effects of altered residence times on reservoir storage (Lee and others, 2008; Foster, 2014).

Description of Study Area

The Upper Neosho and Cottonwood River watersheds (fig. 1), located in east-central Kansas, drain about 3,015 square miles (mi^2; as measured from the reservoir outlet) and are the primary inflows to the reservoir. The Neosho and Cottonwood Rivers have upstream reservoirs that regulate part of their drainage areas. Council Grove Lake regulates 246 mi^2 of the Neosho River headwaters, and Marion Lake regulates 200 mi^2 of the Cottonwood River headwaters (about 15 percent of the drainage area of the reservoir). Land use in the Upper Neosho River and Cottonwood River watersheds is mostly pasture and grassland (69 percent; Fry and others, 2011), but there are some areas of cultivated cropland in the upper Cottonwood River watershed and in the floodplains of both rivers and major tributaries (21 percent; Fry and others, 2011) (fig. 1).

A network of streamflow and continuous water-quality monitoring sites has been operated upstream and downstream from the reservoir since 2007 (Lee and others, 2008; Foster, 2014). Three upstream sites [Plymouth, (site ID 07182250); Burlingame Road, (site ID 07179750); and Neosho Rapids, (site ID 07182390)] and one downstream site [(Burlington, (site ID 07182510) were used to describe sediment loads entering and exiting the reservoir during May through July 2015 (fig. 1; table 1). The Neosho Rapids site is located approximately 20-river miles upstream from the reservoir inlet and the Burlington site is located approximately 5-river miles downstream from the reservoir outlet.

Methods

Continuous Water-Quality Monitoring

Continuous streamflow and turbidity data were collected at all four study sites (fig. 1) during May through July 2015. Streamflow was measured using standard USGS methods (Sauer and Turnipseed, 2010; Turnipseed and Sauer, 2010). All sites were equipped with YSI water-quality monitors that measured specific conductance, water temperature, and turbidity (YSI model 6136 at Neosho Rapids and Burlington and YSI EXO at Plymouth and Burlingame Road). Continuous water-quality monitor operation and maintenance followed standard USGS procedures (Wagner and others, 2006) and is described in Lee and others (2008) and Foster (2014). Data were recorded every 15 minutes and are available through the USGS National Water Information System (NWIS) at http://dx.doi.org/10.5066/F7P55KJN and through Water-Quality Watch http://waterwatch.usgs.gov/wqwatch/.

Validation of Linear Regression Models

Turbidity-based linear regression models used to estimate SSCs were developed for the Burlington and Plymouth sites by Lee and others (2008) and the Burlingame and Neosho Rapids sites by Foster (2014). The models and supporting documentation are available on the National Real-Time Water Quality website http://nrtwq.usgs.gov/ks/. Discrete SSC samples used for regression model validation were collected between August 2013 through August 2015 (appendix 1) following USGS equal-width-increment (EWI) methods (U.S. Geological Survey, 2006) using isokinetic samplers. All discrete SSC data are available through NWIS at http://dx.doi.org/10.5066/F7P55KJN.

Analysis of covariance (ANCOVA) was used to determine if published model form changed with the addition of newly collected samples. The ANCOVA test is used to determine if the slopes and intercepts of two or more regression lines are statistically different (Helsel and Hirsch, 2002). The F-value, also called the sample variance ratio, is calculated as a nested F-statistic comparing the variance between regression models. Significance for these analyses was set at a probability value (p-value) of less than 0.05. Validation data fit the published models and did not significantly change the model slopes (all $p > 0.18$) or intercepts (all $p > 0.47$). The previously published models, therefore, were used to estimate SSCs.

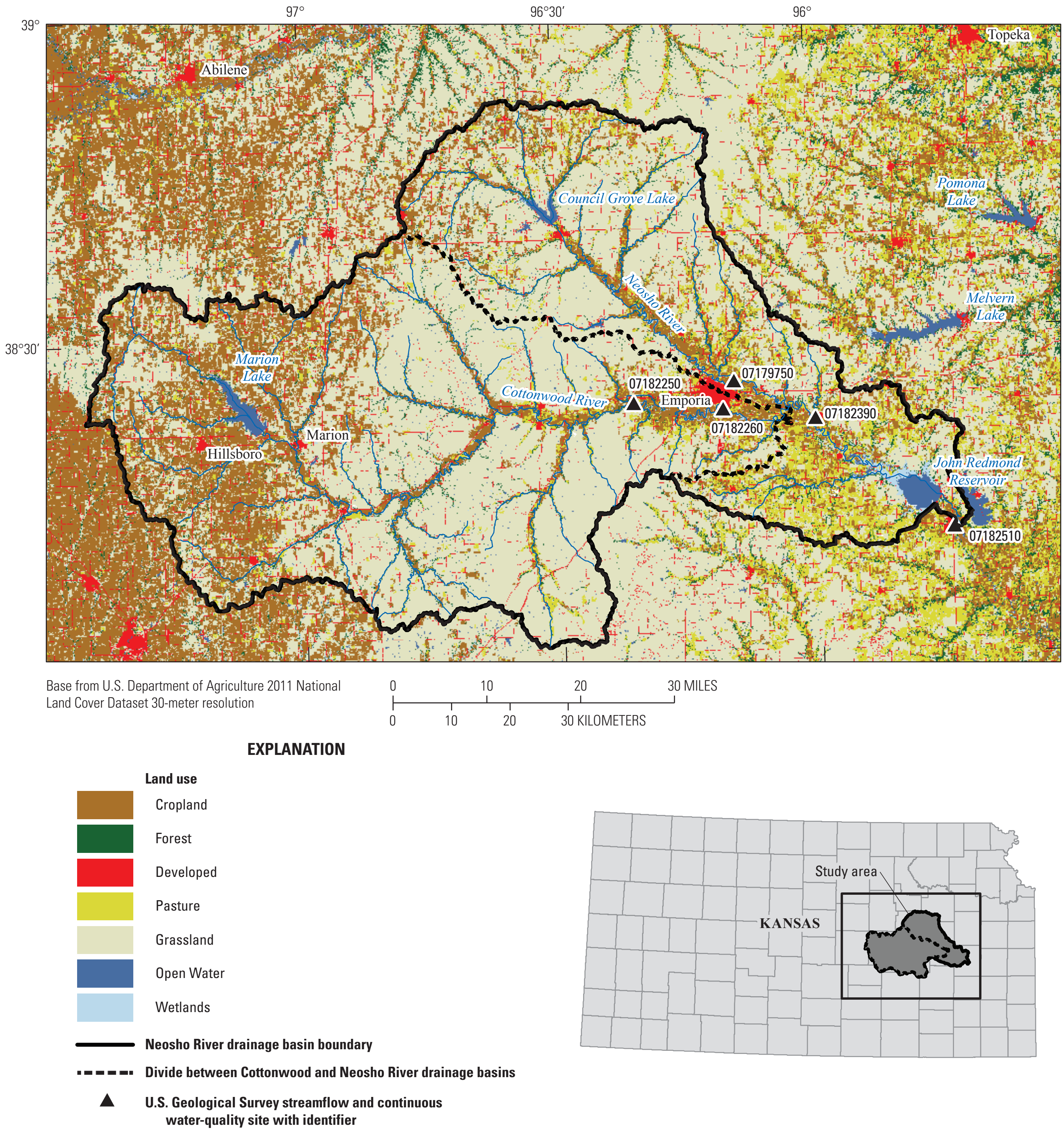

Figure 1. Location of reservoirs and U.S. Geological Survey streamflow and continuous water-quality monitoring stations in the Upper Neosho River watershed.

Table 1. Location and contributing drainage area of streamflow and continuous water quality monitoring sites.

[mi^2, square miles]

U.S. Geological Survey site identification number	Streamflow and continuous water quality monitoring site name	Short site name	Contributing drainage area (mi^2)	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)
07182250	Cottonwood River near Plymouth, Kansas	Plymouth	1,740	39°28′01″	96°15′01″
07179750	Neosho River at Burlingame Road near Emporia, Kansas	Burlingame Road	757	39°25′43″	96°09′29″
07182390	Neosho River at Neosho Rapids, Kansas	Neosho Rapids	2,753	38°22′05″	96°00′00″
07182510	Neosho River at Burlington, Kansas	Burlington	3,042	38°11′40″	95°44′06″

Computation of Streamflow During Backwater Conditions

Backwater conditions existed at Neosho Rapids during May 24 through the end of the study period as a result of high stages in John Redmond Reservoir. During backwater conditions, daily mean streamflow was estimated using the Missing Streamflow Estimation (MISTE) program, which is part of the USGS Automated Data Processing System (ADAPS; U.S. Geological Survey, 2003). The MISTE program is used to estimate daily mean streamflow for a site using stepwise regression analysis to correlate daily streamflow data from one or more index sites. The analysis produces a missing-values estimation equation for the study site. Burlingame Road (table 1; fig. 1) and the Cottonwood River at Emporia (USGS station number 07182260; fig. 1) were used as index sites to estimate daily mean streamflow at Neosho Rapids (table 1; fig. 1). Values at higher temporal resolution (every 15 minutes) were estimated in ADAPS by visually interpolating slopes of the hydrograph between mean daily streamflows. These interpolated values also were checked and corrected to seven on-site streamflow measurements taken during the study period.

Estimating Suspended-Sediment Concentration During Periods of Missing Turbidity Data

During extended periods (greater than 12 hours) of missing turbidity data, resulting from equipment malfunction or excessive fouling during storm events caused by sediment build-up in the housing pipe, discharge-SSC models were used to compute SSC as described in Foster and others (2012). During the study period, a discharge-SSC model was used at the Burlingame Road site during 7.7 days, or 8.3 percent of the time. While using a different, less accurate model introduces an unknown amount of uncertainty into the load calculations for Burlingame Road, the small amount of missing turbidity data results in small effects on the overall load computations.

Computation of Suspended-Sediment Loads and Sediment Trapping Efficiency

Previously published regression models (Lee and others, 2008; Foster, 2014) were used to calculate continuous (15-minute) SSC and SSLs at each sampling site using methods described in Rasmussen and others (2009). Sediment loads and streamflow were estimated for the ungaged drainage areas between the upstream sites (Burlingame and Plymouth) and Neosho Rapids by subtracting the sum of the Burlingame and Plymouth suspended-sediment loads and streamflow from that computed at Neosho Rapids. Suspended-sediment loads and streamflow were also estimated for the ungaged drainage area between Neosho Rapids and Burlington (which includes the drainage basin immediately surrounding the reservoir; fig. 1) by multiplying the ratio of the Burlington to Neosho Rapids drainage areas to estimate total sediment or streamflow transport through the ungaged area (Foster and others, 2012). The uncertainty associated with the ungaged record estimation is unknown. These methods do not take into account heterogeneity in natural features, precipitation, and land practices across upstream watersheds, but provide an approximation of total streamflow and sediment transport in the ungaged drainage area (Foster and others, 2012).

The trapping efficiency of the reservoir by month and study period was calculated by subtracting the total SSL transported out of the reservoir from the total SSL transported into the reservoir for the corresponding time period. This difference value was then divided by the total suspended-sediment load transported into the reservoir for the same time period, and expressed as a percentage. These values represent the suspended load only, and do not account for any bedload sediment transport entering or exiting the reservoir.

Effects of May through July 2015 Storm Events on Suspended-Sediment Loads, Sediment Trapping Efficiency, and Storage Capacity of John Redmond Reservoir

Streamflow and Suspended-Sediment Loads

Approximately 966,000 acre-feet of water entered the reservoir during May through July 2015 (fig. 2). Approximately 1.07 million acre-feet of water was released from the reservoir during the same period (fig. 2). The discrepancy between inflow and outflow totals can be explained by the uncertainties associated with estimating streamflow in the ungaged area of the watershed and other factors, such as in-lake evaporation that were not measured.

Fifty-five percent of the total inflows during the study period (535,000 acre-feet) entered the reservoir in May. During May, inflows mostly were retained in the reservoir because of downstream flooding in Oklahoma. The amount of water released from the reservoir in May was 72 percent less (150,000 acre-feet) than the amount of water that entered the reservoir. On May 28, and throughout the rest of the study period, water was released at larger rates (up to 25,400 acre-feet per day, the maximum allowed for the reservoir, U.S. Army Corps of Engineers, 1996). In June, 520,000 acre-feet were released, and 396,000 acre-feet were released in July. During June and July, only 225,000 and 206,000 acre-feet entered the reservoir, respectively.

During the 3-month study period, approximately 872,000 tons of total sediment entered the reservoir, and 57,000 tons exited the reservoir (fig. 3*A*). Based on the upstream gaging sites at Plymouth and Burlingame Road, more than twice the SSL was delivered from the Cottonwood River (413,000 tons) than from the Neosho River at Burlingame Road (186,000 tons). The sum of the computed SSLs at Plymouth and Burlingame Road fall short of the SSL computed at Neosho Rapids by 24 percent. This shortfall in SSL is estimated (fig. 3) by the difference between the SSL at Neosho Rapids and the sum of the SSL at Plymouth and Burlingame Road. The ungaged drainage area between the upstream sites and Neosho Rapids is 256 mi^2 (172 mi^2 of the Cottonwood watershed, and 84 mi^2 of the Neosho watershed, 9 percent of the total area gaged by Neosho Rapids), and likely accounts for some, but not all, of the shortfall in SSL due to sediment deposition in inundated areas or channel storage of sediment prior to the study period that was mobilized during storm events.

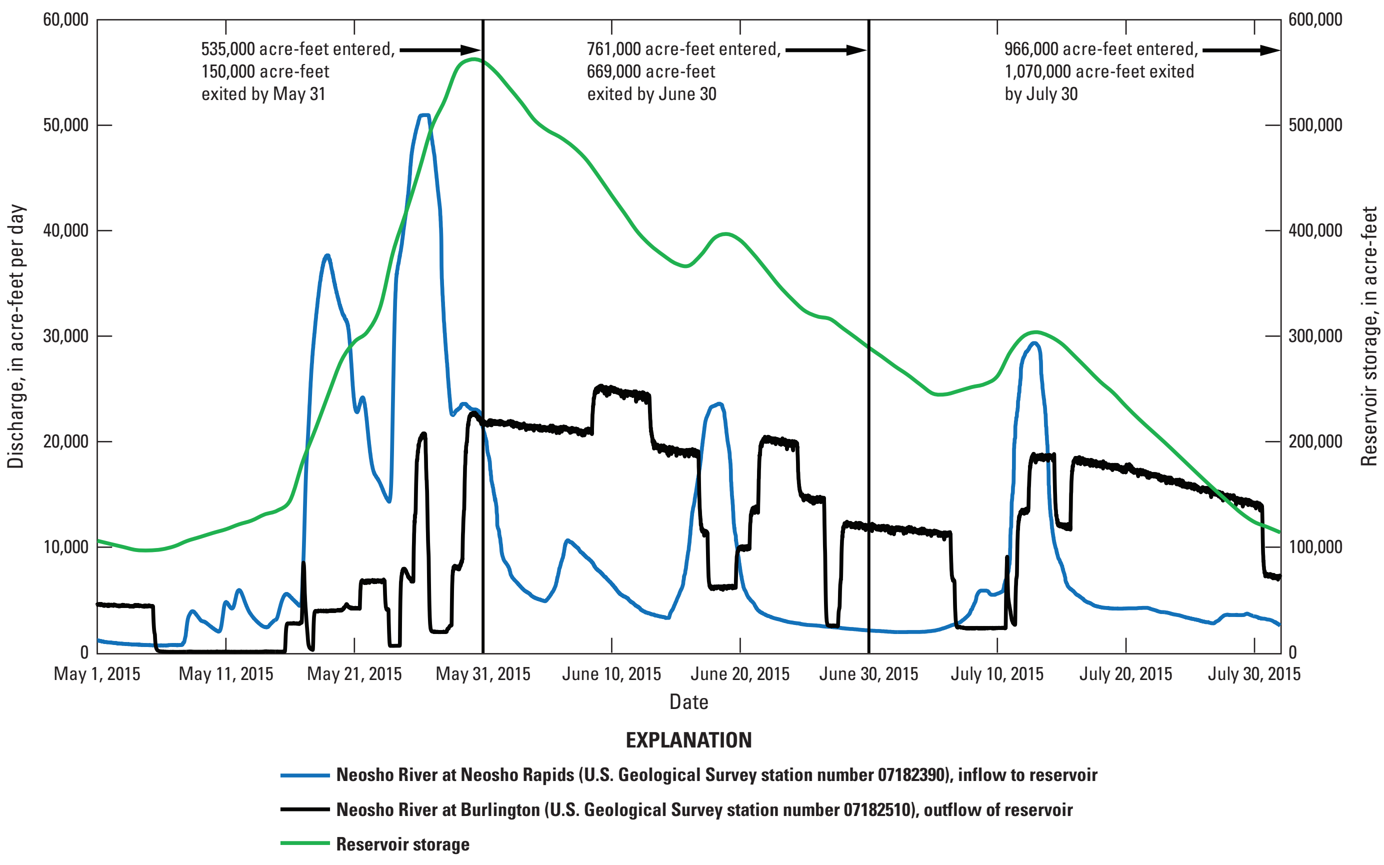

Figure 2. Streamflow hydrograph of reservoir inflows (Neosho Rapids), ouflows (Burlington), and reservoir storage during May through July 2015. Cumulative volumes may not match individual monthly values cited in text because of rounding.

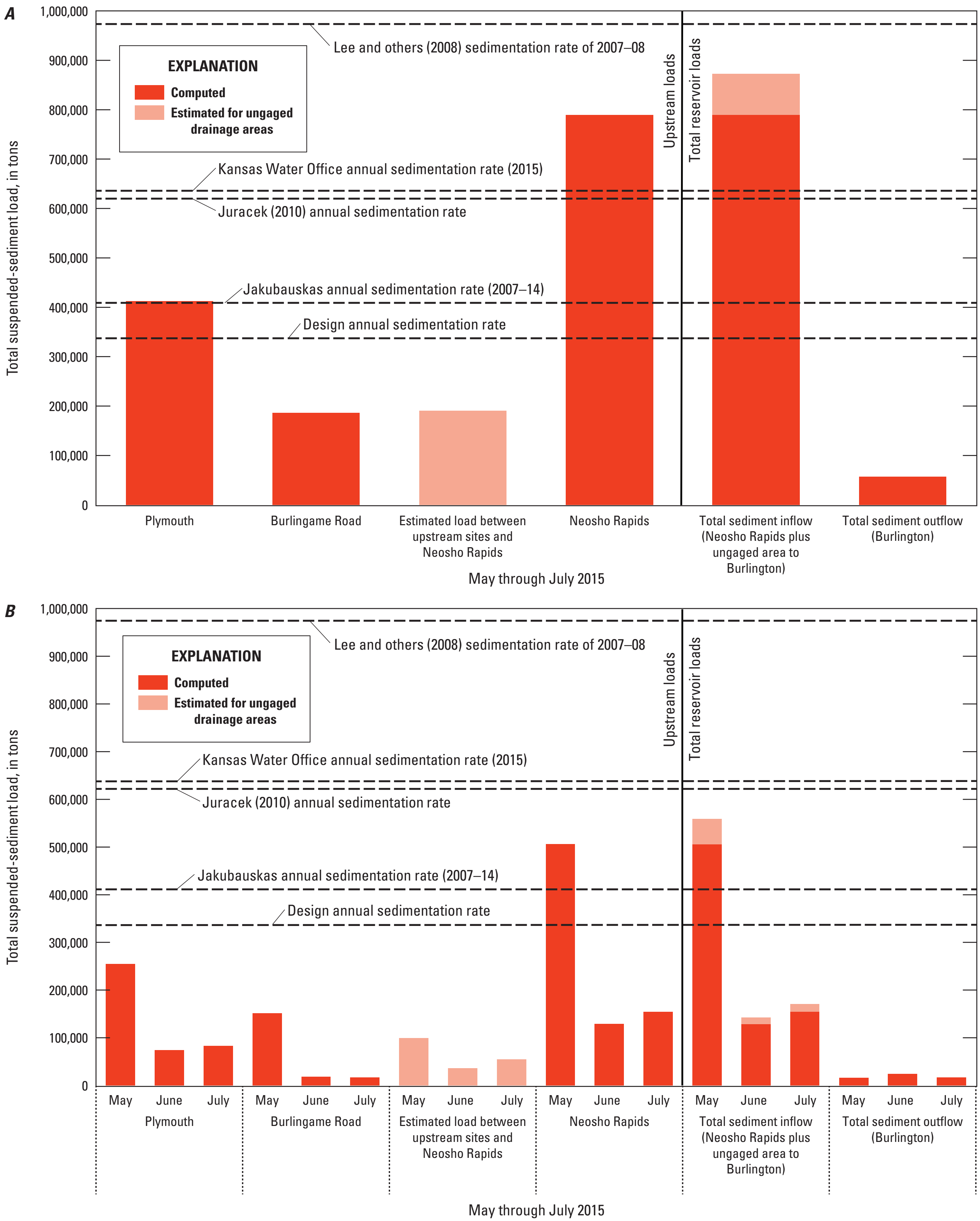

Figure 3. Computed and estimated sediment loads at gaging sites upstream and downstream from John Redmond Reservoir and published sedimentation rates: *A*, entire study period; *B*, by month.

May had almost twice the inflow SSL (559,000 tons) as June (142,000 tons) and July (171,000 tons) combined (313,000 tons) (fig. 3*B*). Conversely, about 2.5-times more sediment exited the reservoir in June (24,500 tons) and July (16,500 tons) combined (41,000 tons) than in May (16,000 tons) (fig. 3*B*). As a result of sediment trapping in the reservoir, SSLs into the reservoir were between 5 and 34-times larger than SSLs exiting the reservoir, even during the periods with the largest reservoir releases. The SSL entering the reservoir in May alone was greater than both the annual design sedimentation rate (Kansas Water Office, 2015) and estimated annual sedimentation rate from 2007 through 2014 (Jakubauskas and others, 2014).

Sediment Trapping Efficiency

The average sediment trapping efficiency of the reservoir during the study period was 93 percent, but ranged from 97 percent during May when waters were being retained in the reservoir, to 83 percent during June, the month of maximum releases (fig. 4). A similar study conducted in 2007–2008 (Lee and others, 2008) estimated trapping efficiency to be 91 percent. Changes in water residence time play a direct role in reservoir sedimentation rates and trapping efficiency (Lee and Foster, 2012). The range (83 to 97 percent) of sediment trapping efficiencies during this study was directly related to reservoir outlet operations; trapping efficiency was lowest when reservoir releases were highest. The relation between reservoir releases, water residence time, and sediment trapping efficiency may be used to manage reservoir sedimentation. Lee and Foster (2012) estimated that trapping efficiency of the reservoir could be decreased approximately 3 percent per year (equating to 56 acre-feet of storage) from current rates by altering outlet management practices specifically to reduce residence times within the reservoir.

Effect on Reservoir Storage Capacity

Utilizing a mean bulk density for the reservoir of 38.2 pounds per cubic foot (Juracek, 2010), and 815,000 tons of sediment retained over the 3-month study period, 980 acre-feet of reservoir storage was lost because of sediment deposition during May through July 2015, assuming that all sediment was deposited in the multi-purpose pool area. About 1.6 percent of the conservation-pool storage capacity of the reservoir was lost during the 3-month study period (utilizing the Jakubauskas 2014 storage tables). Slightly over 1 percent was lost during May alone. It is likely some percentage of sediment was deposited in flood- inundated areas and not the reservoir, although the amount cannot be quantified by this analysis. Storage lost during this three month period was 1.3-times larger than the estimated annual storage losses of 765 acre-feet per year for 1964–2006, 2-times larger than the 492 acre-feet per year for 2007–2014, and 2.4-times larger than the design rate of 404 acre-feet per year. These results are similar to other reservoir studies in Kansas (Foster and others, 2012; Stone and others, 2015) that indicate large volumes of sediment are delivered to reservoirs in short periods of time (hours or days). Large events, coupled with minimal releases, can have a substantial effect on reservoir storage.

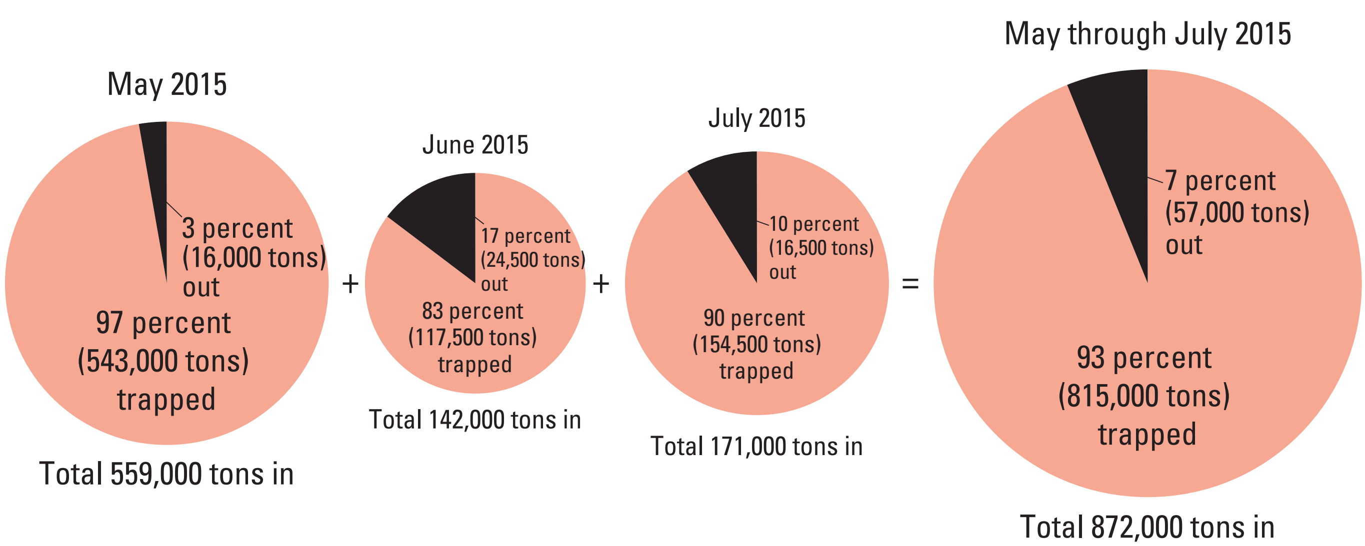

Figure 4. Sediment trapping efficiency of John Redmond Reservoir May through July, 2015.

Summary

The 1964–2014 estimated sedimentation rate in John Redmond Reservoir, located in east-central Kansas, was almost 90 percent larger than the projected design rate of 404 acre-feet per year, and resulted in a loss of about 40 percent of the conservation (multi-purpose) pool storage capacity. To help maintain storage in the reservoir, the Kansas Water Office has implemented more than two dozen stream bank erosion control projects to reduce the annual sediment load entering the reservoir and initiated a dredging project to restore nearly 2,000 acre-feet of storage near the dam to provide additional water supply to downstream water users (Tracy Streeter, Kansas Water Office, written commun., 2016). The U.S. Geological Survey, in cooperation with Kansas Water Office, and funded in part through the Kansas State Water Plan Fund, operates a network of streamflow and continuous water-quality monitoring sites upstream and downstream from the reservoir. The purpose of this report is to summarize the findings of a study conducted to quantify suspended-sediment loads entering and exiting the reservoir during May through July 2015 storm events and describe the effects on reservoir sediment trapping efficiency and storage capacity.

Three upstream streamgaging sites and one downstream site were used to describe suspended-sediment loads to and from the reservoir during May through July 2015. Previously published turbidity-based linear regression models were used to estimate suspended-sediment concentrations, which were used to calculate suspended-sediment loads and reservoir sediment trapping efficiency.

Approximately 996,000 acre-feet of water entered the reservoir during May through July 2015. Approximately 1.07 million acre-feet of water was released from the reservoir during the same period. During May, inflows mostly were retained in the reservoir because of downstream flooding; water was released at larger rates during June and July. During the 3-month study period, approximately 872,000 tons of sediment entered the reservoir and 57,000 tons exited the reservoir. May had almost twice the inflow sediment load as June and July combined. Conversely, about 2.5-times more sediment left the reservoir in June and July combined than in May. The range (83 to 97 percent) of reservoir sediment trapping efficiencies during this study was directly related to reservoir outlet operations; trapping efficiency was lowest when reservoir releases were highest.

An estimated 980 acre-feet of storage was lost in John Redmond Reservoir because of sediment deposition during May through June 2015. About 1.6 percent of the conservation-pool storage capacity of the reservoir was lost during the 3-month study period. Slightly over 1 percent was lost during May alone. These results are similar to other reservoir studies in Kansas that indicate that large volumes of sediment are delivered to reservoirs in short periods of time (hours to days). Large events, coupled with minimal releases, can have a substantial effect on reservoir storage.

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Appendix

Appendix 1. Streamflow, turbidity, and suspended sediment concentration data used to develop and validate previously published (Foster, 2014; Lee and others, 2008) linear regression models to estimate suspended sediment concentration at the Burlingame Road, Plymouth, Neosho Rapids, and Burlington study sites. Available at http://dx.doi.org/10.3133/sir20165040.

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Foster—**Effects of 2015 Storm Events on Sediment and Storage Capacity of John Redmond Reservoir, Kansas**—Scientific Investigations Report 2016–5040

ISSN 2328-0328 (online)
http://dx.doi.org/10.3133/sir20165040