HYDROLOGICAL PROCESSES
Hydrol. Process. **27**, 1426–1439 (2013)
Published online 23 April 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.9284

Assessing the potential of reservoir outflow management to reduce sedimentation using continuous turbidity monitoring and reservoir modelling†

Casey Lee* and Guy Foster
US Geological Survey, Lawrence, KS, 66049, USA

Abstract:

In-stream sensors are increasingly deployed as part of ambient water quality-monitoring networks. Temporally dense data from these networks can be used to better understand the transport of constituents through streams, lakes or reservoirs. Data from existing, continuously recording in-stream flow and water quality monitoring stations were coupled with the two-dimensional hydrodynamic CE-QUAL-W2 model to assess the potential of altered reservoir outflow management to reduce sediment trapping in John Redmond Reservoir, located in east-central Kansas. Monitoring stations upstream and downstream from the reservoir were used to estimate 5.6 million metric tons of sediment transported to John Redmond Reservoir from 2007 through 2010, 88% of which was trapped within the reservoir. The two-dimensional model was used to estimate the residence time of 55 equal-volume releases from the reservoir; sediment trapping for these releases varied from 48% to 97%. Smaller trapping efficiencies were observed when the reservoir was maintained near the normal operating capacity (relative to higher flood pool levels) and when average residence times were relatively short. An idealized, alternative outflow management scenario was constructed, which minimized reservoir elevations and the length of time water was in the reservoir, while continuing to meet downstream flood control end points identified in the reservoir water control manual. The alternative scenario is projected to reduce sediment trapping in the reservoir by approximately 3%, preventing approximately 45 000 metric tons of sediment from being deposited within the reservoir annually. This article presents an approach to quantify the potential of reservoir management using existing in-stream data; actual management decisions need to consider the effects on other reservoir benefits, such as downstream flood control and aquatic life. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS suspended sediment; turbidity; sediment trapping efficiency; reservoir modelling

Received 8 August 2011; Accepted 17 February 2012

INTRODUCTION

In addition to flood control, communities are reliant on reservoir storage for drinking water, agricultural use and industrial use. In Kansas, reservoir storage is the source of drinking water for more than two thirds of the state population; studies project that a severe drought will result in water supply shortages in multiple basins (Kansas Water Office, 2008). Water supply shortages will become more likely as human populations grow and as sediment accumulation continues to decrease available reservoir storage. Solutions to maintaining reservoir storage are limited because (i) sediment is naturally transported in streams and rivers; (ii) improved erosion controls may not affect sedimentation for decades because of field, floodplain and in-stream sediment storage of previously eroded sediments (Trimble, 1999; Evans *et al*., 2000); and (iii) dredging of large reservoirs such as in Kansas has, thus far, been cost-prohibitive and disposal of sediments is difficult (Kansas Water Office, 2008).

Internationally, the effects of sediment accumulation in reservoirs have long been realized. Because of the immediacy of the problem and the expense and difficulty of dredging, decommissioning or building new reservoirs, the management of reservoir outflows has been altered to decrease or arrest sediment accumulation (Fan and Morris, 1992a, 1992b; Morris and Fan, 1998; White, 2001; Palmieri *et al*., 2003; Morris *et al*., 2008). These reservoir management strategies use the velocity of incoming flood-waters to transport incoming and previously deposited sediments through reservoirs but require varied levels of reservoir drawdown to maximize effectiveness. The feasibility of reservoir management to reduce sediment deposition varies depending on reservoir, watershed and economic considerations (White, 2001; Palmieri *et al*., 2003; Morris *et al*., 2008). Compared with reservoirs worldwide, the percentage of storage loss in large reservoirs in the United States has been limited because these reservoirs typically have large storage capacities relative to incoming inflow volumes (G. Morris, written communication, 2009).

Numerical models are improving the ability to simulate the movement of turbidity currents (Gelda and Effler, 2007; Chung *et al*., 2009) and cohesive sediment through reservoirs (Simões and Yang, 2008; Yang and Simões, 2008). However, the episodic nature of sediment transport to reservoirs and the spatial complexity of sediment within reservoirs often make it difficult to test model simulations.

*Correspondence to: Casey Lee, US Geological Survey, 4821 Quail Crest Place, Lawrence, KS, 66049, USA.
E-mail: cjlee@usgs.gov
†This article is a US Government work and is in the public domain in the USA.

Water quality sensors are increasingly being deployed continuously in streams and rivers as part of ambient water quality programs (e.g. see http://waterwatch.usgs.gov/wqwatch/). These data can accurately represent the flux of suspended sediment at fine temporal scales (Rasmussen *et al*., 2009) and when collected upstream and downstream from a lake or reservoir can be used quantify sediment trapping efficiency more accurately than through periodic sample collection (Lee *et al*., 2008). Further, when coupled with an understanding of reservoir hydrodynamics, these data can be used to characterize how short-term processes, such as how variation in reservoir outflow management affects sediment flux through reservoirs. This study coupled a CE-QUAL W2 hydrodynamic reservoir model with existing continuous turbidity data at US Geological Survey (USGS) streamgage sites upstream and downstream from John Redmond Reservoir to assess the potential of altered reservoir management to reduce reservoir sedimentation.

Study area

John Redmond Reservoir was constructed on the Neosho River from 1959 through 1964 for purposes of flood control, water supply and recreation [US Army Corps of Engineers (USACE), 1996]. Since the dam was completed in 1964, sediment deposition has reduced water storage at the normal operational level (termed the conservation pool) by 42%, which is among the largest percentage loss of reservoirs owned by the USACE in the State of Kansas (Kansas Water Office, 2010). Approximate sedimentation rates in John Redmond Reservoir from 1964 to 2006 (~910 000 m^3/year) are nearly double the expected sedimentation rate expected at the time of reservoir design (~500 000 m^3/year; Kansas Water Office, 2010). Seventy-one percent of water rights downstream from John Redmond Reservoir are allocated for cooling of the Wolf Creek Nuclear Power Plant (USACE, 2002). Most of this water is lost to evaporation after cooling (Barfield, 2010). In addition, 14% of the water rights are allocated to municipalities, 10% to irrigation and recreational uses and 5% for other industrial uses (USACE, 2002). John Redmond Reservoir typically is not thermally stratified because it is shallow (1.9 m average depth) and is easily mixed by wave action (USACE, 2002).

John Redmond Reservoir is downstream from 7810 km^2 of predominantly grass and cropland in east-central Kansas (Figure 1). The Neosho River (excluding the Cottonwood River) drains approximately 2870 km^2 of land upstream from John Redmond Reservoir and has a slope ranging from 15.8 m/km in the headwaters to 7.9 m/km near the confluence with the Cottonwood River (Carswell and Hart, 1985). The largest tributary to the Neosho River is the Cottonwood River, which runs a length of approximately 329 river kilometres, drains 4920 km^2 and has river slopes ranging from 18.5 m/km in the headwaters to 7.9 m/km near the confluence with the Neosho River (Jordan and Hart, 1985). Silty-clay loam (material with 27%–40% clay and less than 20% sand) predominates along riparian areas and in the downstream part of the basin. Silty clay (material with 40% or more clay and 40% or more silt) is the dominant soil type in the upstream part of the basin (US Department of Agriculture, 1994).

John Redmond Reservoir was completed in 1964 and had a capacity of approximately 101 million m^3 in the conservation pool, and with approximately 650 million m^3 acre-feet of capacity including the flood control pool. The deepest point of the reservoir is approximately 312.7 m above mean sea level (NGVD29; Kansas Biological Survey, 2010), and the top of the flood pool is 325.5 m above mean sea level (Figure 2). The primary outlet structure is a 170.7-m-wide ogee weir, and the crest of the spillway is located at 314.9 m above mean sea level. The outlet structure has a maximum discharge capacity of 16 400 m^3/s at maximum pool level; two additional low-flow outlet pipes exist at an elevation of 309.5 m above mean sea level with a maximum discharge capacity of 3.7 m^3/s. These pipes are typically used for improving downstream water quality during low-flow conditions (USACE, 1996) but were not incorporated into the reservoir model because specific information regarding their use was not made available and because their size relative to the larger gates precludes them from having a substantial effect on sediment flux from the reservoir. The maximum bankfull capacity of the channel downstream from the dam is 340 m^3/s; releases are typically kept below this value (USACE, 1996).

The USGS streamgages located on the Neosho River near Americus (Americus) and on the Cottonwood River near Plymouth (Plymouth) were the farthest downstream gages before stream entry to John Redmond Reservoir from February 2007 to May 2009 (Table I). These gages cover 6118 km^2 (78%) of the 7809 km^2 that drains to the reservoir (USACE, 2002). A streamgage was installed on the Neosho River at Neosho Rapids (Neosho Rapids) in August 2009, which better quantified the amount and timing of sediment transport to the reservoir (draining 7130 km^2 of the basin upstream from John Redmond Reservoir). The downstream gage is located on the Neosho River at Burlington (Burlington), approximately 5 miles downstream from John Redmond Reservoir (with 70 km^2 of unregulated drainage area). Two large USACE reservoirs regulate approximately 15% of the watershed draining to John Redmond Reservoir: Council Grove Reservoir, which has a drainage area of 637 km^2 and is located on the upper Neosho River, and Marion Reservoir, which has a drainage area of 518 km^2 and is located on the upper Cottonwood River (Figure 1).

MATERIALS AND METHODS

USGS streamgages near Americus, Plymouth, Neosho Rapids and Burlington (Table I, Figure 1) were equipped with YSI[1] 6600 continuous water quality monitors, which measured specific conductance (SC), water temperature

[1]Any use of trade, firm or product names is for descriptive purposes only and does not imply endorsement by the US Government.

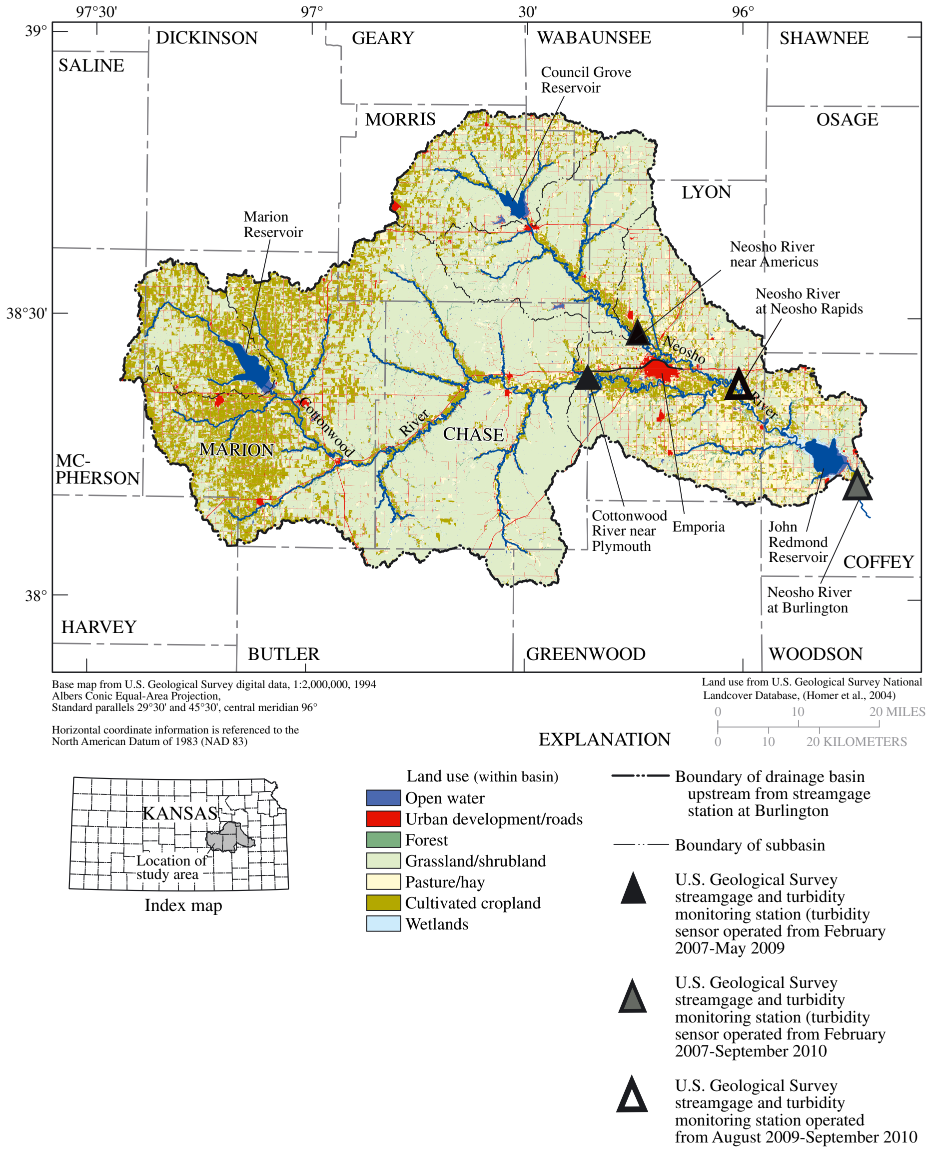

Figure 1. Sampling sites and land use upstream and downstream from John Redmond Reservoir, east-central Kansas

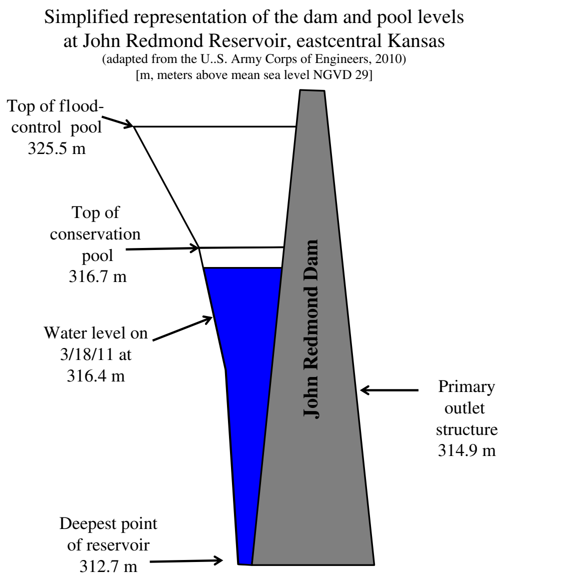

Figure 2. Simplified representation of the dam and pool levels at John Redmond Reservoir, east-central Kansas

and turbidity (model 6136), and Hach Solitax suspended-solids optical backscatter/turbidity sensors. Sensors collected values in stream and were housed in polyvinyl chloride pipes with holes drilled to allow stream water to flow through the installation. Sensors near Americus and Plymouth were installed along the bank nearest the streamgage, and sensors at Neosho Rapids and Burlington were suspended from a bridge by chain near the centre of the stream. Measurements were logged every 15 min; historical and real-time continuous data are available on the USGS Web page http://nrtwq.usgs.gov/ks. Water quality sample results are available online at http://waterdata.usgs.gov/ks/nwis/qw.

Turbidity sensor maintenance and data reporting followed the USGS procedures described by Wagner *et al.* (2006), with the exception of increased length between calibration checks (because dissolved oxygen and pH data were not collected at monitoring sites). Sensors were cleaned and calibrated approximately every 2 months; additional cleaning visits were made when real-time data

Table I. Location and contributing drainage area of sampling sites upstream and downstream from John Redmond Reservoir, east-central Kansas

USGS identification number	Site name	Total drainage area (km^2)	Unregulated drainage area (km^2)	Nearest upstream reservoir and corresponding regulated drainage area (km^2)	Latitude	Longitude	Period of streamflow and continuous turbidity operation
07179730	Neosho River near Americus, Kansas	1611	974	Council Grove Reservoir (637)	38°28′01″	96°15′01″	February 2007–May 2009
07182250	Cottonwood River near Plymouth, Kansas	4507	3989	Marion Reservoir (518)	38°23′51″	96°21′21″	February 2007–May 2009
07182390	Neosho River at Neosho Rapids, Kansas	7130	5975	Council Grove and Marion Reservoirs (1155)	38°22′03″	96°00′07″	August 2009–September 2010
07182510	Neosho River at Burlington, Kansas	7879	70	John Redmond Reservoir (7808)	38°11′40″	95°44′40″	February 2007–September 2010

indicated sensor fouling. Quality-assurance checks were made before and after sensor cleaning and calibration with an independently calibrated sensor. Because in-stream turbidity conditions occasionally exceeded the upper measurement limit of YSI 6136 turbidity sensors, Hach Solitax SC turbidity/optical backscatter sensors (Solitax) were operated at Americus, Plymouth and Neosho Rapids adjacent to YSI sensors. The Solitax sensor uses an internal algorithm to convert a ratiometric turbidity/optical backscatter signal to an estimate of suspended-solids concentration. Solitax sensors have an approximate range from 0 to 50 000 mg/l of suspended solids (Hach Company, 2005) and were installed to estimate suspended-sediment concentration (SSC) when YSI turbidity values were missing or greater than the range of the sensor (1000–1500 formazin nephelometric units).

Streamflow data were computed using the standard USGS methods (Turnipseed and Sauer, 2010). River stage was continuously measured in 15-min increments using automated methods and was cross-checked with a wire-weight gage during periodic site visits. Streamflow measurements were collected approximately every 6 weeks and during extreme flow conditions to establish and continually update a stage/discharge relation at each site, which was then used to compute a continuous, 15-min record of streamflow.

Suspended-sediment samples were collected using equal-width or equal-discharge increment methods using manual, depth-integrated sampling techniques described by Nolan *et al.* (2005). All samples were analysed for SSC, and 16 inflow samples collected during high streamflow conditions were analysed for a selected grain-size distribution (percent of sediment less than 2, 4, 8, 16, 31 and 63 μm in diameter) at the USGS Sediment Laboratory in Iowa City, Iowa, using the pipet method described by Guy (1969). Turbidity values were measured across the width of the stream during the collection of suspended-sediment samples. Median values of cross-sectional measurements were compared with in-stream sensors to assess the ability of each in-stream sensor to represent turbidity conditions across the width of the stream (for more details, see Lee *et al.*, 2008). In-stream sensors accounted for 92% to 97% of the variability across stream cross sections and had a near 1:1 relation in slope (0.90–1.11 among sites). Cross-sectional variability in turbidity was minimal at all sites, where measurements much outside of the 1:1 fit typically were during periods of rapidly changing turbidity conditions. Because consistent bias was not observed in the relation at any monitoring location, values from continuous water quality monitors are deemed representative of stream water quality across the width of the stream cross section. Turbidity records generally were rated good (error of 5%–10%) and occasionally fair (10%–15%) on the basis of the guidelines developed by Wagner *et al.* (2006).

Computation of continuous SSC

Ordinary least squares regressions were developed to compute a continuous record of SSC and suspended-sediment load using periodically collected SSC and continuous turbidity, continuous Solitax and continuous streamflow data upstream and downstream from John Redmond Reservoir (Lee *et al*., 2008). Continuous turbidity sensors were occasionally not operational or were malfunctioning during sample collection; in these instances, cross-sectional turbidity measurements were used in place of in-stream turbidity measurements in regression relations. All values were log-transformed to better approximate normality, evenly distribute regression residuals, and to avoid the prediction of negative values. Regression relations between in-stream turbidity, Solitax and SSC were applied to the continuously recorded values and multiplied by continuous streamflow data and a conversion factor (as described in Rasmussen *et al*., 2009) to obtain continuous (15-min) estimates of suspended-sediment load. After applying the regression model to log-transformed turbidity data, log-transformed SSC values were retransformed back to linear space. Because this retransformation can cause bias when adding instantaneous values of load estimates with 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). Regression methods used in this study were developed using protocols described in Rasmussen *et al*. (2009).

Occasionally, turbidity data are recorded at a sensor-specific, maximum reporting limit, typically between 1000 and 1500 formazin nephelometric units. During these periods, which were only observed at the Americus and Plymouth sampling sites, continuous Solitax-derived estimates of SSC were used when they exceeded turbidity-derived estimates. Solitax-derived estimates of SSC also were used if and when turbidity data were missing because of environmental fouling or sensor malfunction. Solitax-derived estimates of SSC during periods of sensor truncation are 3% of the total load at the Americus and Plymouth sites (which were operational through June of 2009).

Occasionally, both continuous turbidity and Solitax measurements were missing or deleted from the continuous record because of equipment malfunction, environmental fouling or both. When these data were missing during stable, low-flow conditions, SSC values were estimated by interpolating between measured data points. When turbidity and Solitax were missing during changing flow and turbidity conditions, suspended-sediment loads were estimated using continuous streamflow data as the explanatory variable (Figure 3B). These periods accounted for approximately 11% of the total sediment load transported to John Redmond Reservoir. Model standard percentage errors (Rasmussen *et al*., 2009) for turbidity-based estimates of SSC ranged from 30% to 40% at Americus to approximately 15% at Burlington.

Annual suspended-sediment loads and 95% CIs were quantified by the USGS LOADEST program (Runkel *et al*., 2004) in 2007 using both turbidity and streamflow as surrogates at Americus, Plymouth and Burlington to estimate and compare the uncertainty of annual load estimates. Turbidity-computed loads were generally less than streamflow computed loads and were more certain, ranging from approximately 20% (Americus) to 10% (Plymouth and Burlington) of annual load estimates (Figure 4). Conversely, streamflow-computed annual loads were consistently larger than turbidity-based models and were much less certain; 95% uncertainty bands were approximately 60% of the annual load at Americus, 40% of the annual load at Plymouth and 50% of the annual load at Burlington. Although 89% of incoming sediment loads were estimated using turbidity, and it can be estimated with 95% certainty that annual loads from these sites are within 10%–20%, the use of multiple data sources and the contributions of sediment from ungaged areas make it impossible to exactly quantify the uncertainty of load estimates to John Redmond Reservoir. Because the turbidity sensor was operational during practically entire period of record at Burlington, there is a 95% chance that reported annual loads from John Redmond Reservoir are within 10% of reported values.

Reservoir modelling

CE-QUAL-W2 V3.6 is a two-dimensional, hydrodynamic water quality model used in this study to simulate the average daily residence time of water leaving John Redmond Reservoir (Cole and Wells, 2008). Estimates of residence time are necessary to match flow transported from reservoir outflows to corresponding inflows to estimate sediment trapping efficiency at relatively short (days to months) time scales. Daily estimates of the average residence time of outflows were obtained by simulating the length of time a conservative tracer would remain within the reservoir (Cole and Wells, 2008). Reservoir bathymetry was represented by 26 vertical and 21 horizontal cells on the basis of an existing USACE model developed in 2007 (D. Gade, written communication, 2010) and an updated conservation pool bathymetry survey conducted in 2007 (Kansas Biological Survey, 2010) and by interpolating range lines surveyed by the USACE in 1957 for flood pool elevations (C. Gnau, written communication, 2010). The bathymetry of the flood pool upstream from available spatial data sets was initially characterized using the existing USACE model bathymetry and then adjusted on the basis of the observed differences between the USACE model and the available spatial data.

The USACE (2010) daily computed inflow and outflow data were input into the model along with daily USGS temperature, SC and continuously computed SSC values (computed as a flow-weighted average from 15-min data) collected at upstream gage sites. The USACE daily inflow data were input into the model because the USGS gage sites were upstream from the reservoir and thus would less accurately represent the timing and quantity of reservoir inflows. Before computing daily flow-weighted averages, water quality data from Americus and Plymouth were lagged by the average approximate travel times of streamflow from these sites to the Neosho Rapids site (18 and 20 h, respectively). Values were not lagged from the Neosho Rapids site because it is near where backwater

(A) Regression analysis between YSI model 6136 turbidity sensors and Hach Solitax sensors with suspended-sediment concentration, and (B) streamflow with suspended-sediment load.

[SSC, suspended-sediment concentration; Q, streamflow in cubic meters per second; Turb, Turbidity; SOL, Solitax; n, number of samples; R^2, coefficient of determination; RMSE, root mean squared error; MSPE, model standard percentage error]

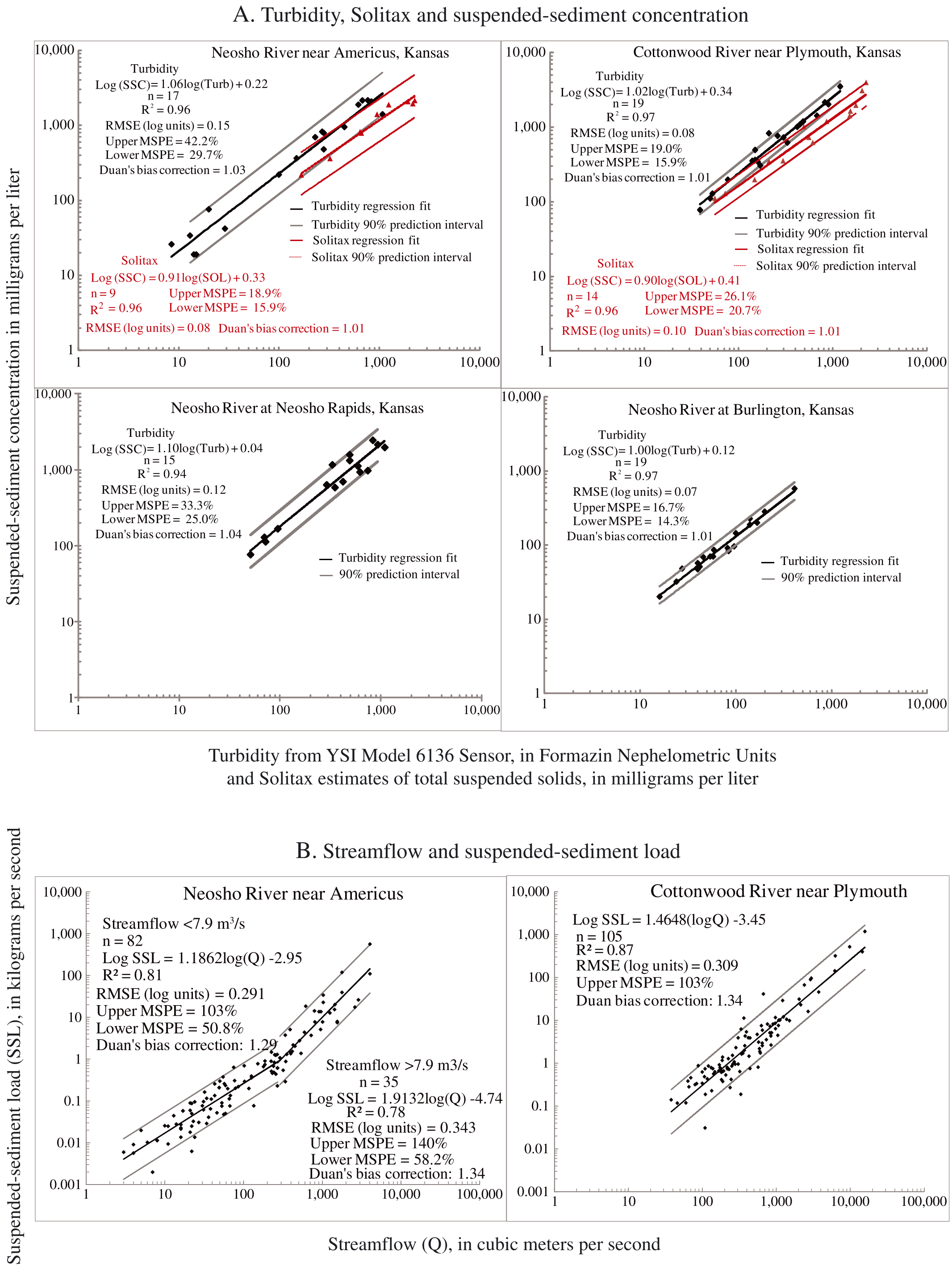

Figure 3. Regression analysis between (A) YSI model 6136 turbidity and Hach Solitax sensors with SSC and (B) streamflow with suspended-sediment load

conditions have been observed from John Redmond Reservoir during extreme flood events. In CE-QUAL-W2, it is necessary to compute incoming total dissolved solids (TDS) to simulate water density. As described by Hem (1985), TDS is linearly related to SC at a slope between 0.55 and 0.75. For this study, a value of 0.67 was used to compute daily TDS values from YSI SC values (as was performed by Sullivan *et al*., 2007).

The CE-QUAL W2 model was calibrated into the USACE reservoir elevation data from February 2007 through September 2010 (USACE, 2010), and the USGS collected temperature and SC and continuously computed

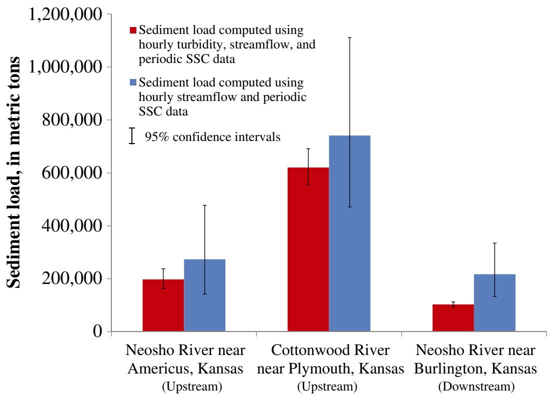

Figure 4. Comparison of continuous turbidity and streamflow-computed estimates of annual suspended-sediment loads

SSC values at the Burlington site (downstream from John Redmond Reservoir). The entire period of record was used for calibration because the model was developed exclusively to represent the residence time of water through the reservoir for the further purpose of estimating sediment trapping efficiency at temporal scales of days to weeks. Data input into the model included reservoir elevation (USACE, 2010), precipitation, air and dew point temperature, wind speed and direction and cloud cover (National Weather Service, 2010a); incoming temperature, TDS, SSC and incoming and outgoing streamflow were input into the model. Modifications to default model conditions were as follows: (i) the partitioning of incoming SSCs into four classes with different settling rates (0.001, 0.8, 1.5 and 8 m/day), which were adjusted to approximate outflow sediment concentration and load, and (ii) the adjustment of wind-sheltering coefficients to 0.80, representing that wind observed at the nearby Emporia weather station (National Weather Service, 2010a) was observed at 80% strength at the surface of John Redmond Reservoir. Although adjustments to the model were not verified to represent real-world conditions, they did result in a relatively consistent simulation of reservoir elevation relative to observed values through the study period (Figure 5A).

Simulated reservoir elevations compared well with the observed values of the USACE [root mean squared error (RMSE) of 0.10 m; Figure 5A]. Simulated outflow water temperatures also closely matched observed water temperature at Burlington (RMSE of 1.46 °C between simulated and observed values; Figure 5B). Simulated temperature profiles indicated that the reservoir was rarely stratified during the study period, which was consistent with available in-reservoir data (USACE profiles collected in 2007; D. Gade, written communication, 2010; Figure 6). Reservoir temperatures were well mixed from top to bottom during most of the spring, summer and fall of 2007 but were somewhat stratified (approximate decrease of 1 °C/m) through a 7-m water column in July of 2007.

Simulated SC from the reservoir was frequently greater than observed SC (Figure 5C), especially during periods with low flows and longer residence times. This was primarily because major ions that increase SC were not transported conservatively through the reservoir. Average SC values in inflows were 149 µS/cm greater than those in reservoir outflows. These results indicate the potential of the biomediated precipitation of calcium carbonate (typically the dominant cations/anions in temperate reservoirs; Wetzel, 2001) within the reservoir, as other studies have determined decalcification within reservoirs with similar SC values (Wetzel, 2001). Further discussion of this phenomenon is beyond the scope of this study, other than to indicate that SC was not an adequate tracer of water movement through John Redmond Reservoir, especially during longer residence times.

Although it was necessary to calibrate the model to outgoing suspended-sediment flux to represent reservoir hydrodynamics through the period of study (Figure 5D), model results were not used to evaluate the effect of reservoir management on sediment trapping. This is because no in-reservoir sediment data were collected, and thus it was impossible to represent spatial patterns of sediment deposition, or the degree to which previously deposited sediments were resuspended by waves or incoming flows. In addition, because the entire data record was used to best represent model hydrodynamics, we were not able to validate the results of sediment modelling.

Evaluation of sediment trapping efficiency using modelling output and continuous data

To evaluate the sediment-trapping efficiency of John Redmond Reservoir relative to the observed differences in reservoir management, daily values of streamflow and sediment load (computed from 15-min data) were divided into 55 individual releases, which accounted for 97% of outgoing water. Releases were delineated by first characterizing individual instances in which outflow gates were adjusted to release more or less water, and then by further dividing these periods into approximately equal-volume releases. Equal-volume releases consisted of approximately 123 million m^3 of water (approximately double the volume of the conservation pool in 2010, which was 59 million m^3), which were larger or smaller depending on the total volume of water transported from when the gates were opened and closed. The calibrated CE-QUAL-W2 model simulated the residence times for outflows at a daily time step, which were then used to match releases to corresponding inflows for the purpose of computing sediment trapping efficiency from incoming and outgoing sediment loads. Residence time–assigned inflow events were adjusted further to match more closely the volume of corresponding outflow events. Incoming flow volumes typically were within 10% of equivalent outgoing volumes—the remaining differences were because of the daily time step of streamflow and sediment loads. To account for these differences when computing sediment trapping efficiency, differences in incoming and outgoing water volumes were multiplied by the flow-weighted sediment concentration (FWSC) of the incoming event. The FWSC is defined as the total sediment load of the inflow event divided by the total water volume for a

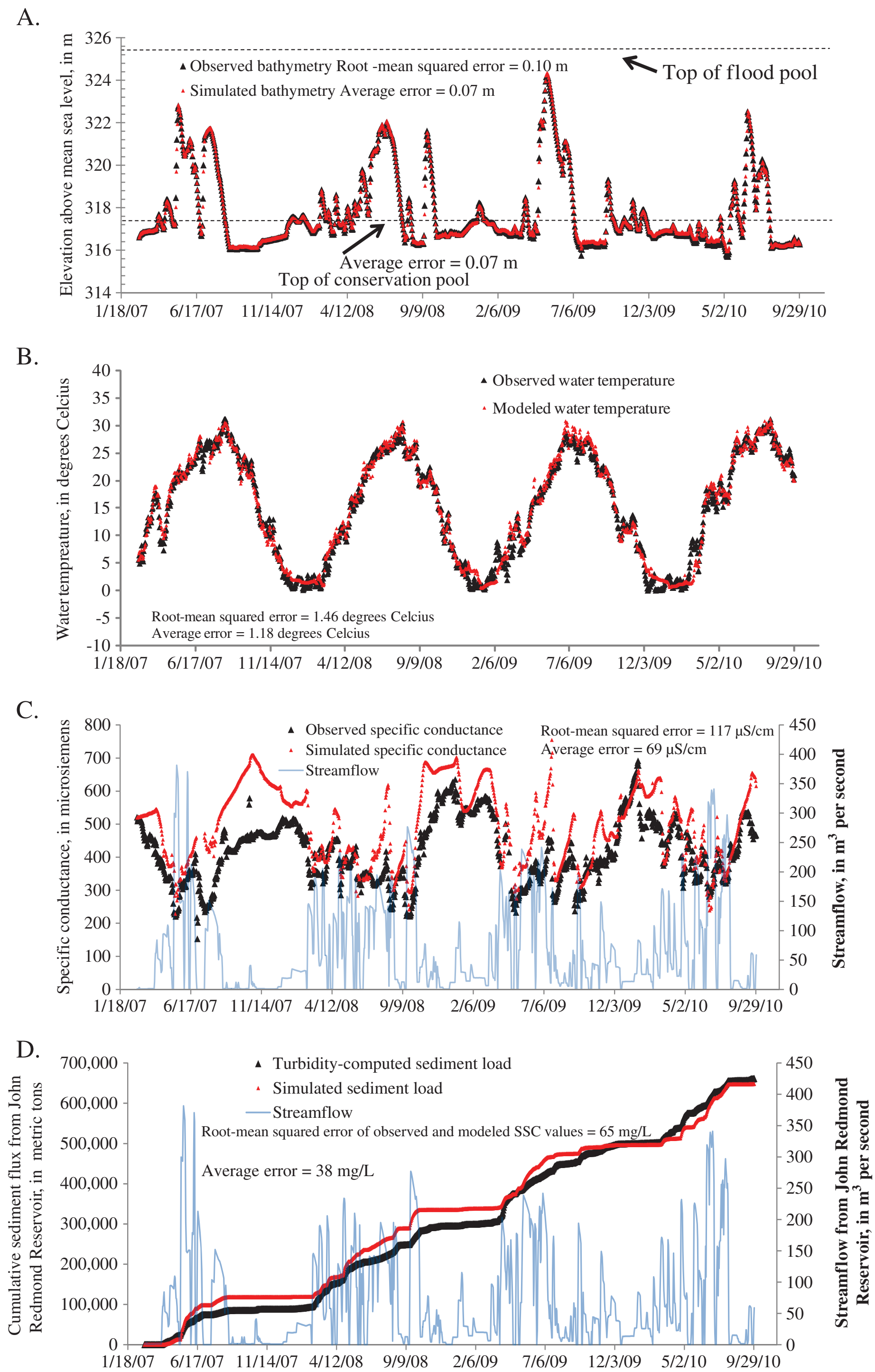

Figure 5. Comparison of simulated and observed (A) reservoir elevation, (B) outflow water temperature, (C) outflow SC and (D) outflow cumulative suspended-sediment load from February 2007 through September 2010

specified period as indicated in Equation 1:

$$FWSC_{in} = SL_{in}/WV_{in} \times 10^6 \qquad (1)$$

where $FWSC_{in}$ is the FWSC of the incoming event (mg/l), SL_{in} is the incoming sediment load of the event (metric tons) and WV_{in} is the volume of water of the incoming event (m^3). The FWSC is then multiplied by the difference in inflow/outflow volumes, and the resulting sediment load is added (or subtracted) from the original incoming sediment load as indicated in Equation 2:

$$SL_{inadj} = SL_{in} + FWSC_{in} \times (WV_{out} - WV_{in})/10^6 \qquad (2)$$

where SL_{inadj} is the adjusted incoming sediment load (metric tons) and WV_{out} is the volume of water released (m^3). Sediment trapping efficiency for each event/release pair is then defined as the percentage of the adjusted

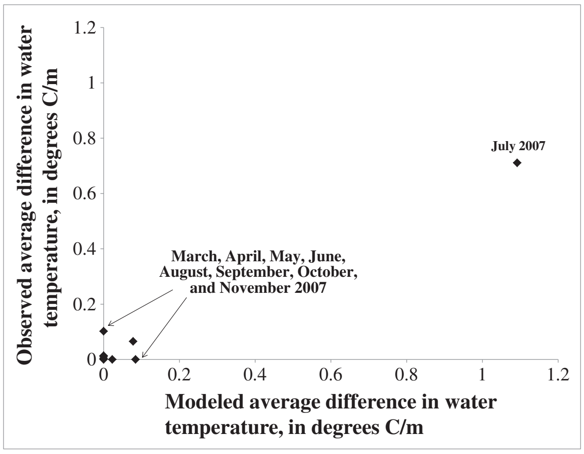

Figure 6. Modelled versus observed differences in water temperature from the surface to the bottom near John Reservoir dam, 2007

incoming sediment load trapped in the reservoir as indicated in Equation 3:

$$\mathrm{TE} = 100 \times \left(\mathrm{SL}_{\mathrm{inadj}} - \mathrm{SL}_{\mathrm{out}}\right)/\mathrm{SL}_{\mathrm{inadj}} \quad (3)$$

Equal-volume inflow events were transported between 3100 and 260 000 metric tons of suspended sediment into John Redmond Reservoir. The largest sediment loads were transported during relatively short-term rainfall/runoff events, whereas smaller loads were transported during low-flow conditions. Least squares regression was used to explore relations between the sediment trapping efficiency of event/release pairs and the measures of residence time, reservoir elevation and sediment concentration and load entering John Redmond Reservoir. Different measures of residence time and lake elevation were computed for each event/release by weighting these variables by the length of time the water (flow weighted) or sediment (sediment weighted) for a particular event/release pair was present within the reservoir (e.g. the reservoir elevation for a particular day was weighted by 0.5 if one half the water or sediment for an individual event/release pair was within the reservoir, or by 1.0 if all of the water or sediment was within the reservoir).

Only releases with incoming sediment loads greater than 37 000 metric tons were used in this analysis, as the sediment trapping efficiency of smaller events was judged to be primarily affected by background levels of sediment within the reservoir (such as from algae or wind-related resuspension of bottom sediment) or potentially from sediment suspended from the stream channel between the reservoir outflow and Burlington monitoring site. These releases are less important to predict because they represent a relatively small part of the total sediment load transported to the reservoir. Stepwise multiple linear regression was then used to characterize variables, which best estimated sediment trapping efficiency among event/release pairs without exhibiting multicollinearity.

RESULTS AND DISCUSSION

Hydrologic conditions

Precipitation upstream from John Redmond Reservoir during the study period (2007–2010) was generally greater than historical averages. The National Weather Service station at the Neosho Rapids (directly upstream from John Redmond Reservoir) recorded 81.5 in. of precipitation in 2007, 129.8 in. in 2008 and 119.6 cm. in 2009, compared with the annual average of 91.4 in. from 1950 to 2006 (National Weather Service, 2010b). Annual flows were summed from the Americus and Plymouth sites, which were 83.9 km^3 in 2007, 159.1 km^3 in 2008 and 133.2 km^3 in 2009; the median combined annual flow from these sites was 106.1 km^3 from 1964 to 2006. Rivers exceeded the 2-year (50% annual) USGS flood-frequency estimates 14 times at the Plymouth and Neosho Rapids sites (Perry *et al.*, 2004), indicating that relatively extreme storms (and corresponding high sediment loads) were frequently observed during the study period. Increased rainfall and flow during the study period indicate that sediment flux to (and likely from) the reservoir is likely larger than during a typical, 4-year study period.

Sediment transport to and from John Redmond Reservoir

The maximum computed SSC upstream from the reservoir was 7690 mg/l, whereas the maximum SSC was 1080 mg/l downstream from the reservoir. From February 2007 through September 2010, approximately 5 600 000 metric tons of sediment entered John Redmond Reservoir, 660 000 of which were transported past the Burlington site (trapping efficiency of 88%). Nearly all of the suspended sediment at upstream sampling sites consisted of silt and clay (the median sample was 96% less than 63 μm in diameter). Approximately one half of the sediments transported to John Redmond Reservoir during high-flow conditions were clays (<2 μm), the remaining sediments were distributed somewhat equally between 2 and 63 μm. Similar to inflow samples, 98% of the reservoir outflow suspended sediment sampled had diameters of less than 63 μm (full grain-size analysis was not conducted). Because suspended-sediment and reservoir-bottom samples (Juracek, 2010) indicate a lack of sand and larger-sized material and because streambed substrates at gage sites were observed to consist primarily of cobble and rock, bedload transport of sediment is not considered a substantial component of the sediment load transported to John Redmond Reservoir.

The annual volume of flow and sediment load transported into John Redmond Reservoir generally corresponded with annual patterns in precipitation (Figure 7). The trapping efficiency of the reservoir initially decreased during years with greater precipitation and streamflow in 2008 and 2009 but continued to decrease despite smaller flows and incoming sediment loads in 2010, potentially because of differences in the manner in which the reservoir was operated. An examination of inflows, outflows and reservoir levels in John Redmond Reservoir indicated that although

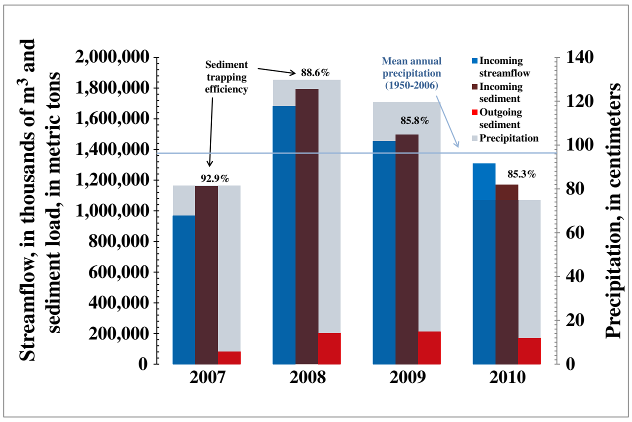

Figure 7. Annual precipitation, streamflow and sediment transport to and from John Redmond Reservoir, February 2007 to September 2010

inflows were smaller in 2010 than those in 2008 and 2009, water was released more rapidly after sediment-laden inflows in 2010, in part, because of maintenance activities that necessitated lower reservoir levels (T. Lyons, USACE, oral communication, 2010).

Sediment trapping efficiency relative to variation in reservoir management

Among the 48 event/release pairs with greater than 37 000 metric tons of incoming sediment, sediment trapping efficiency varied from 48% to 97%. Relations established between sediment trapping efficiency, flow-weighted reservoir elevation (Figure 8A) and flow-weighted residence time (Figure 8B) indicated that a larger proportion of incoming sediment is transported through John Redmond Reservoir when the reservoir is maintained at lower levels and when residence times are minimized (Table II). However, these relations were also more variable during these conditions. In addition, predicted sediment trapping efficiencies were nonlinear with respect to the primary explanatory variables (reservoir elevation, FWSCs and flow-weighted residence time); single linear regressions typically overpredicted event/release pairs with small trapping efficiencies and underpredicted event/release pairs with larger sediment trapping efficiencies. To minimize bias in predictions of sediment trapping efficiency, separate linear regressions were identified for event/release pairs above and below a reservoir elevation threshold of 318.5 m. The resulting predictions were similar to single regression equations in terms of adjusted R^2 and error, but residuals were distributed more evenly throughout the range of values.

Among event/release pairs in which reservoir elevation was maintained lower than 318.5 m, the variability in the sediment trapping efficiency was best explained by flow-weighted reservoir elevation (EL) and by the FWSC of the inflow event (Figure 8C). Among event/release pairs in which reservoir elevation was maintained higher than 318.5 m, the variability in sediment trapping efficiency

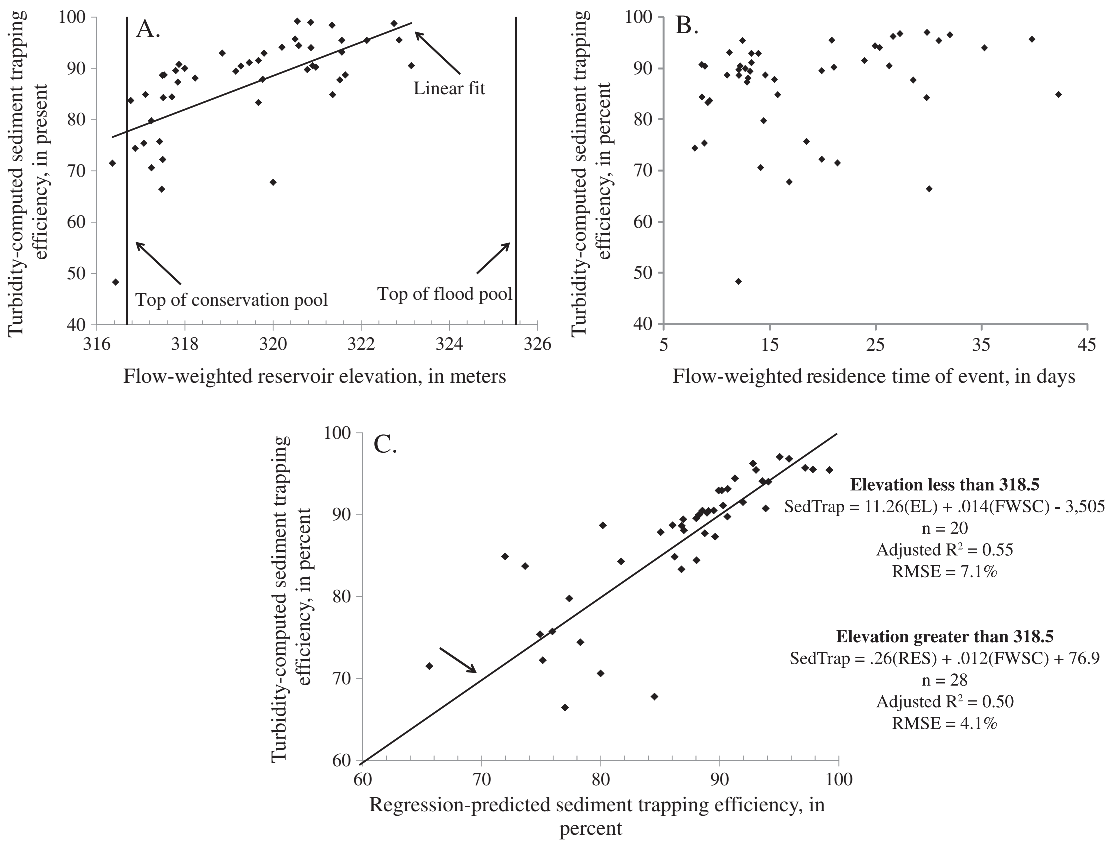

Figure 8. Regression relations between turbidity-computed sediment trapping efficiency and (A) flow-weighted reservoir elevation, (B) residence time and (C) regression-predicted estimates of sediment trapping efficiency for event/release pairs

Table II. Summary of sediment loading and reservoir characteristics during delineated inflows and releases from John Redmond Reservoir

Range of flow-weighted average reservoir elevations (ft above mean sea level)	No. event/ release pairs	Turbidity-computed load in (metric tons)	Turbidity-computed load out (metric tons)	Turbidity-computed trapping efficiency (%)	Regression-predicted sediment trapping efficiency (%)
All releases 316.1–323.4	48	5 240 000	595 000	88.6	88.7
316.1–317.3	8	708 000	179 000	74.7	74.6
317.3–317.9	10	1 101 000	159 000	85.6	86.2
317.9–319.7	8	892 000	88 000	90.1	89.2
319.7–321.0	11	1 201 000	84 000	93.0	92.5
321.0–323.4	11	1 337 000	85 000	93.6	94.5

was best explained by flow-weighted hydraulic residence time (RES) and by the FWSC of the inflow event (Figure 8C). All explanatory variables were significantly related to sediment trapping efficiency (P value < 0.05), and the regression equations chosen resulted in the largest adjusted R^2, the smallest RMSE values and the smallest prediction error sum of squares values of other potential combinations of independent variables. The variance inflation factors among independent variables were less than 1.2, indicating that multicollinearity among incoming FWSC values and flow-weighted reservoir elevations did not inflate or adversely affect regression estimates (Helsel and Hirsch, 1992). In addition to decreased sediment trapping efficiency during low reservoir levels and residence times, more sediment was trapped when incoming sediment concentrations were larger (as indicated by larger FWSC values), potentially because of increased flocculation (and thus larger effective grain size and fall velocity; Droppo and Ongley, 1994).

Although sediment trapping predictions were variable for individual event/release pairs, they were much more accurate with respect to turbidity-computed results for multiple event releases when grouped by flow-weighted reservoir elevation (Table II). Results suggest that (i) reductions in trapping efficiency consistently are observed when reservoir elevations are maintained near conservation pool levels and (ii) although regression-derived estimates of sediment trapping may be inaccurate for individual event/release pairs, this method can produce relatively accurate, long-term estimates of sediment trapping efficiency with respect to factors that can be affected by altered reservoir management.

Potential of altered reservoir management to reduce sediment trapping

The USACE water control manual for John Redmond Reservoir identifies specific flood control end points that must not be exceeded to ensure that reservoir outflows do not contribute to flood-related damages to crops and structures (Table III). Any changes to reservoir management must also meet these end points to fulfil the mission for which John Redmond Reservoir was constructed. To simulate the potential effect of changes in reservoir outflow management on sediment accumulation in John Redmond Reservoir, an idealized and altered outflow management

Table III. Maximum discharges and approximate travel times of releases to flood control points downstream from John Redmond Reservoir[†a]

Flood control end point	Approximate travel time from outflow gates (h)[†b]	Maximum discharge (m^3/s)
Neosho River at Burlington, Kansas	2	396
Neosho River at Iola, Kansas	24	510
Neosho River at Chanute, Kansas	36	510
Neosho River at Parsons, Kansas	60	481
Neosho River at Commerce, Oklahoma	84	623

[a] In addition to flood control end points, the water control manual specifies that outgoing discharges do not rise or fall by more than 56.6 m^3/s every 3 h; the manual also includes the consideration of conditions at other reservoirs in the basin (USACE, 1996).
[b] Data from USACE (1996).

scenario was constructed, which continued to meet these end points while also preserving storage for drinking water, agricultural use and industrial use (Figure 9). This scenario is 'idealized' in that it benefits from the knowledge of incoming and downstream flows, whereas, in practice, reservoir operators rely on weather forecasts and modelling to ensure consistent water supplies and to prevent downstream flooding. Because of the inability to access

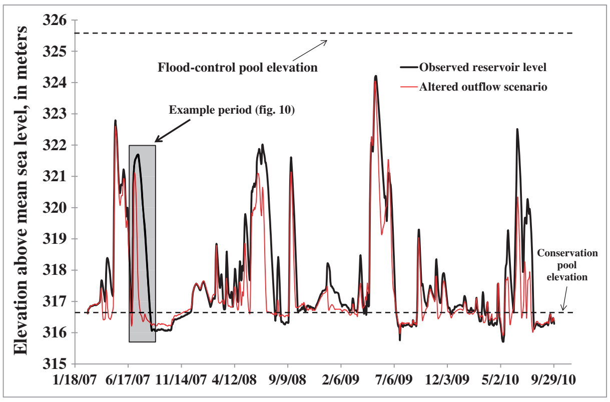

Figure 9. Observed and altered elevation at John Redmond Reservoir, February 2007 through September 2010

historical rainfall forecasts or models that predict flows to and from John Redmond Reservoir, results from this scenario are presented as the maximum potential reduction in sediment trapping that could be achieved within current operational plans.

Relative to observed reservoir management, the altered scenario purposefully minimized reservoir elevation and residence time through larger, more rapid releases of water after periods of high inflows (Figure 9). To partially compensate for uncertainties in weather forecasts and predicted streamflows, the altered management scenario was somewhat more conservative compared with water control plan restrictions in that (i) outflows were not increased by more than 85.0 m^3/s/day and (ii) outflows were never reduced by more than 56.6 m^3/s/day (other than when the reservoir was actually managed in this fashion). After the construction of the altered scenario, reservoir releases were redelineated and matched to inflows as done with observed data. Flow-weighted reservoir elevations, residence times and FWSCs for incoming events were recomputed to estimate the effect of the altered management scenario on sediment trapping efficiency (using regressions developed with observed values).

Although data and models were not available to test the uncertainty of forecasted flow conditions, an example period (Figures 9 and 10) in July 2007 is highlighted to illustrate how the consideration of sediment trapping within existing reservoir operational plans could preserve reservoir storage. During late June and early July 2007, heavy rains upstream and downstream from John Redmond Reservoir raised reservoir levels and caused flooding downstream from the reservoir (see the Neosho River at Parsons as an example; Figure 10). These flows raised reservoir levels well into the flood pool, where it was held until 16 July 2007, when John Redmond Reservoir gates began releasing more water (as indicated by the observed Burlington streamflow record; Figure 10). Historical weather forecasts from the National Weather Service for Iola, Kansas (between Burlington and Parsons; National Weather service, written communication, 2011), projected consistent (20%–50%) chances of thunderstorms throughout July. Compared with observed reservoir management, the altered outflow scenario began discharging water on 5 July 2007, while keeping downstream flows below maximum levels indicated in John Redmond Reservoir control manual (Table III). Two event/release pairs were delineated during this period; modelled residence times based on observed reservoir levels were 72 and 26 days. More rapid release of water from John Redmond Reservoir through the alternative scenario reduced these to 66 and 16 days, respectively. Sediment trapping for these periods is projected to have decreased from 97.1% to 89.3% and from 95.7% to 82.2%. Although this example illustrates that consideration of sediment trapping within reservoir operational plans can reduce sediment trapping; uncertainty of weather forecasts and rainfall runoff models will often limit the ability to preserve reservoir storage within existing operation limits.

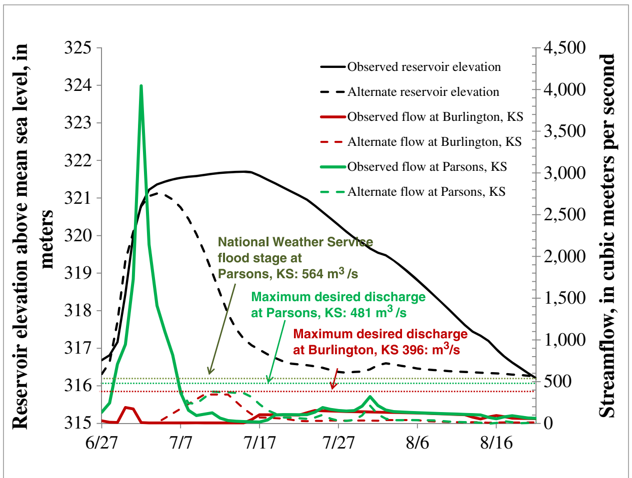

Figure 10. Comparison of observed reservoir elevations and downstream flow conditions relative to the altered reservoir management scenario, June to August 2007

From 2007 to 2010, the altered management scenario decreased the average reservoir elevation from 317.8 to 317.3 m and decreased the average daily residence times from 29.6 to 26.9 days. Forty-six releases with more than 37 000 tons of incoming sediment were delineated under the altered scenario (compared with 48 observed releases), corresponding to 5.1 million metric tons of incoming sediment (compared with 5.3 million metric tons computed with observed data; Table IV). The average reservoir elevations for event/release pairs decreased from 319.4 to 318.6 m and for residence times from 19.9 to 13.1 days. Under the altered management scenario, regression-predicted sediment trapping efficiency was reduced by 3.9%, passing approximately 180 000 additional metric tons of sediment through the reservoir. Estimates indicate that within existing operational constraints, altered reservoir management has a maximum potential of decreasing sediment trapping by approximately 45 000 metric tons per year, or approximately 3% of the annual load of 1.41 million metric tons transported during the study period.

An annual reduction of 45 000 tons of sediment from John Redmond Reservoir would preserve approximately 74 000 m^3 of storage in the reservoir per year. This rate is equivalent to 15% of the designed reservoir sedimentation rate and equivalent to 8.1% of the observed sedimentation rate in the conservation pool given the average bulk density estimates of Juracek (2010). As more reservoir storage is lost to deposited sediments, the residence time of sediment-laden inflows will continue to decrease, and reservoir management is likely to become a more effective alternative to reducing reservoir sedimentation. If existing reservoir operational plans were adapted to accommodate water supply as well as flood control uses of the reservoir, altered reservoir management might further reduce sediment accumulation.

Although continuous flow and sediment data have proven useful in determining how short-term variability in hydrology and reservoir management affect sedimentation, improved understanding of in-reservoir processes is needed

Table IV. Sediment transport to and from John Redmond Reservoir during delineated inflows and releases under the altered management scenario

Range of flow-weighted average reservoir elevations (meters above mean sea level)	No. release events	Turbidity-computed load in (metric tons)	Regression-predicted load out (metric tons)	Regression-predicted sediment trapping efficiency (%)
All releases	46	5 126 000	778 000	84.8
316.1–317.3	17	1 813 000	426 000	76.5
317.3–317.9	7	855 000	151 000	82.4
317.9–319.7	7	690 000	76 000	89.0
319.7–321.0	10	992 000	94 000	90.5
321.0–323.4	5	775 000	31 000	96.0

to better characterize how sediment moves through, is deposited within, and is resuspended from reservoirs during various hydrologic and outflow management scenarios. For example, although the maintenance of low-reservoir levels may reduce the total amount of sedimentation in the reservoir, it could change the predominant location of sediment deposition from the flood to the conservation pool, possibly decreasing storage where it is most needed. An expanded collection of turbidity data within reservoirs can improve understanding of in-reservoir processes (Effler *et al*., 2006) and could better calibrate two- or three-dimensional reservoir models. In addition, while increased sediment transport downstream from the reservoir under altered management plans would still be less than the historical pre-impoundment conditions, investigations would need to ascertain potential effects on infrastructure and aquatic life. Any potential changes to reservoir management also would need to fully evaluate the degree to which altered management plans could increase the risk of downstream flooding. However, study results indicate that despite limited in-reservoir data, the coupling of continuous streamflow and turbidity data with reservoir modelling can effectively project the degree to which changes in reservoir management can affect sedimentation in the reservoir.

CONCLUSIONS

Rapid sediment accumulation in large reservoirs will increasingly threaten communities reliant on reservoir storage for municipal, agricultural and industrial uses. Decisions will need to be made about which reservoir uses will be prioritized, such as maintenance of water supplies for nearby and downstream communities, flood control for downstream infrastructure and property owners, or recreational considerations. Study results indicate that continuous in-stream flow and turbidity monitoring can be used to quantify the potential of outflow management to reduce reservoir sedimentation. Along with the collection of hydrodynamic and sediment data within reservoirs, these data can help calibrate and validate models that better quantify spatial patterns of sediment deposition and resuspension under varying hydrologic and management scenarios. Study results indicate that depending on the specific reservoir characteristics, reservoir outflow management can help preserve water supplies, especially as sedimentation continues to usurp storage capacity. Although the approach presented can evaluate the potential of altered reservoir management to preserve storage, management decisions need to consider potential effects, changing reservoir operations on downstream flood control and aquatic ecosystems.

REFERENCES

Barfield DB. 2010. Eastern Kansas Water Supply, presentation given at the 2010 Kansas Field Conference, June 2, 2010. Available on the Web at http://www.ksda.gov/includes/document_center/dwr/Presentations/Barfield_KGSFieldTour2010.pdf.

Carswell WJ, Hart RJ. 1985. Transit losses and travel times for reservoir releases during drought conditions along the Neosho River from Council Grove Lake to Iola, east-central Kansas. U.S. Geological Survey Water-Resources Investigations Report 85–4003; 40.

Chung SW, Hipsey MR, Imberger J. 2009. Modeling the propagation of turbid density inflows into a stratified lake: Daecheong Reservoir, Korea. *Environmental Modelling and Software* **24**: 1467–1482.

Cohn TA, Gilroy EJ. 1991. Estimating loads from periodic records. U.S. Geological Survey Branch of Systems Analysis Technical Memo 91.01; 81.

Cole TM, Wells SA. 2008. CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water-quality model, 3.6, user's manual. U.S. Army Corps of Engineers Waterways Experiment Station; 125.

Droppo IG, Ongley ED. 1994. Floccuation of suspended-sediment in rivers of Southeastern Canada. *Water Research* **28**(8): 1799–1809.

Duan N. 1983. Smearing estimate—a nonparametric retransformation method. *Journal of the American Statistical Asssociation* **78**: 605–610.

Effler SW, Prestigiacomo AR, Peng F, Bulygina KB. 2006. Resolution of turbidity patterns from runoff events in a water supply reservoir, and the advantages of in situ beam attenuation measurements. *Lake and Reservoir Management* **22**(1): 79–93.

Evans JK, Gottgens JF, Gill WM, Mackey SD. 2000. Sediment yields controlled by intrabasinal storage and sediment conveyance over the interval 1842-1994: Chagrin River, Northeast Ohio, U.S.A. *Journal of Soil and Water Conservation* **55**: 264–70.

Fan J, Morris GL. 1992a. Reservoir sedimentation I: Delta and density current deposits. *Journal of Hydraulic Engineering* **118** (3): 354–69.

Fan J, Morris GL. 1992b. Reservoir sedimentation II: Reservoir desiltation and long-term storage capacity. *Journal of Hydraulic Engineering* **118** (3): 370–84.

Gelda RK, Effler SW. 2007. Modeling turbidity in a water supply reservoir: advancements and issues. *Journal of Environmental Engineering* **133**(2): 139–148.

Guy HP. 1969. Laboratory theory and methods for sediment analysis. U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. C1: 58.

Hach Company. 2005. SOLITAX sc turbidity and suspended solids user manual. Available on the Web at http://www.hach.com/fmmimghach?/CODE:DOC023.54.03232_3ED_8864|1.

Helsel DR, Hirsch RM. 1992. Statistical methods in water resources. Elsevier: New York; 522.

Hem JD. 1985. Study and interpretation of the chemical characteristics of natural water. Third Edition; U.S. Geological Survey Water-Supply Paper 2254; 263.

Homer CC, Huang L, Yang BW, Coan M. 2004. Development of a 2001 National Landcover Database for the United States. *Photogrammetric Engineering and Remote Sensing* **70** (7): 829–40.

Jordan PR, Hart RJ. 1985. Transit losses and travel times for water-supply releases from Marion Lake during drought conditions, Cottonwood River, east-central Kansas. U.S. Geological Survey Water-Resources Investigations Report 85–4263; 41.

Juracek KE. 2010. Sedimentation, sediment quality, and upstream channel stability, John Redmond Reservoir, east-central Kansas, 1964–2009. U.S. Geological Survey Scientific Investigations Report 2010–5191; 34.

Kansas Biological Survey. 2010. Bathymetry survey of John Redmond Reservoir, Coffey County, Kansas; 23.

Kansas Water Office. 2008. Sedimentation in our reservoirs: causes and solutions; 143.

Kansas Water Office. 2010. John Redmond Reservoir fact sheet, available on the Web at http://www.kwo.org/reservoirs/ReservoirFactSheets/Rpt_John_Redmond_2010.pdf

Lee CJ, Rasmussen PP, Ziegler AC. 2008. Characterization of suspended-sediment loading to and from John Redmond Reservoir, 2007-2008. U.S. Geological Survey Scientific Investigations Report 2008-5123; 25.

Morris GL, Fan J. 1998. Reservoir sedimentation handbook. McGraw Hill: New York.

Morris GL, Annandale G, Hotchkiss R. 2008. Reservoir Sedimentation. In Marcelo Garcia, ed. American Society of Civil Engineers Manual 110, Chapter 12; 579–612.

National Weather Service. 2010a. Climate-Radar Data Inventories for Emporia, KS. Available on the Web at http://www4.ncdc.noaa.gov/cgi–win/wwcgi.dll?wwDI ~ StnSrch ~ StnID ~ 20007525

National Weather Service. 2010b. Daily precipitation data from Neosho Rapids, KS. Available on the Web at http://www4.ncdc.noaa.gov/cgi–win/wwcgi.dll?wwDI ~ StnSrch ~ StnID ~ 20007533.

Nolan KM, Gray JR, Glysson DG. 2005. Introduction to suspended-sediment sampling. U.S. Geological Survey Scientific Investigations Report 2005-5077; CD-ROM.

Palmieri A, Shah F, Annandale GW, Dinar A. 2003. Reservoir conservation volume I: the RESCON approach. The World Bank; 101.

Perry CA, Wolock DM, Artman JA. 2004. Estimates of flow duration, mean flow, and peak-discharge frequency values for Kansas stream locations. U.S. Geological Survey Scientific Investigations Report 2004–5033; 219.

Rasmussen PP, Gray JR, Glysson GD, Ziegler AC. 2009. Guidelines and procedures for computing time-series suspended-sediment concentrations and loads from in-stream turbidity-sensor and streamflow data. U.S. Geological Survey Techniques and Methods, book 3, chap. C4; 57 p.

Runkel RL, Crawford CG, Cohn TA. 2004. Load estimator (LOADEST): A FORTRAN program for estimating constituent loads in streams and rivers. U.S. Geological Survey Techniques and Methods, book 4, chap. A5; 75 p.

Simões FJM, Yang CT. 2008. GSTARS computer models and their applications, part II: applications. *International Journal of Sediment Research* **23**(4): 299–315.

Sullivan AB, Rounds SA, Sobieszczyk S, Bragg HM. 2007. Modeling hydrodynamics, water temperature, and suspended sediment in Detroit Lake, Oregon. U.S. Geological Survey Scientific Investigations Report 2007–5008; 40.

Trimble SW. 1999. Decreased rates of alluvial sediment storage in the Coon Creek Basin, Wisconsin, 1975-93. *Science* **285**: 1244–1246.

Turnipseed DP, Sauer VB. 2010. Discharge measurements at gaging stations. U.S. Geological Survey Techniques and Methods, book 3, chap. A8; 87. Available at http://pubs.usgs.gov/tm/tm3-a8/.

U.S. Army Corps of Engineers. 1996. Water control manual for John Redmond Dam and Reservoir. Neosho River, Kansas. U.S. Army Corps of Engineers, Southwestern Division; Dallas, Texas; 172.

U.S. Army Corps of Engineers. 2002. Supplement to the final environmental impact statement prepared for the reallocation of water supply storage project: John Redmond Lake, Kansas. Available on the Web: http://www.kwo.org/reports_publications/Reports/rpt_JRrealloc_study_DSEIS_main_122006_kw.pdf

U.S. Army Corps of Engineers. 2010. John Redmond Lake Reservoir Data. Available on the Web: http://www.swt–wc.usace.army.mil/JOHN.lakepage.html

U.S. Department of Agriculture. 1994. State soil geographic (STATSGO) database for Kansas. Available on the Web at http://www.kansasgis.org/catalog/catalog.cfm.

Wagner RJ, Boulger RW, Jr., Oblinger CJ, Smith BA. 2006. Guidelines and standard procedures for con-tinuous water-quality monitors—Station operation, record computation, and data reporting. U.S. Geological Survey Techniques and Methods 1–D3; 51.

Wetzel RG. 2001. Limnology: Lake and river ecosystems. Academic Press: San Diego, CA.

White R. 2001. Evacuation of sediments from reservoirs. Thomas Telford Publishing: London.

Yang CT, Simões FJM. 2008. GSTARS computer models and their applications, part I: theoretical development. *International Journal of Sediment Research* **23**(3): 197–211.

