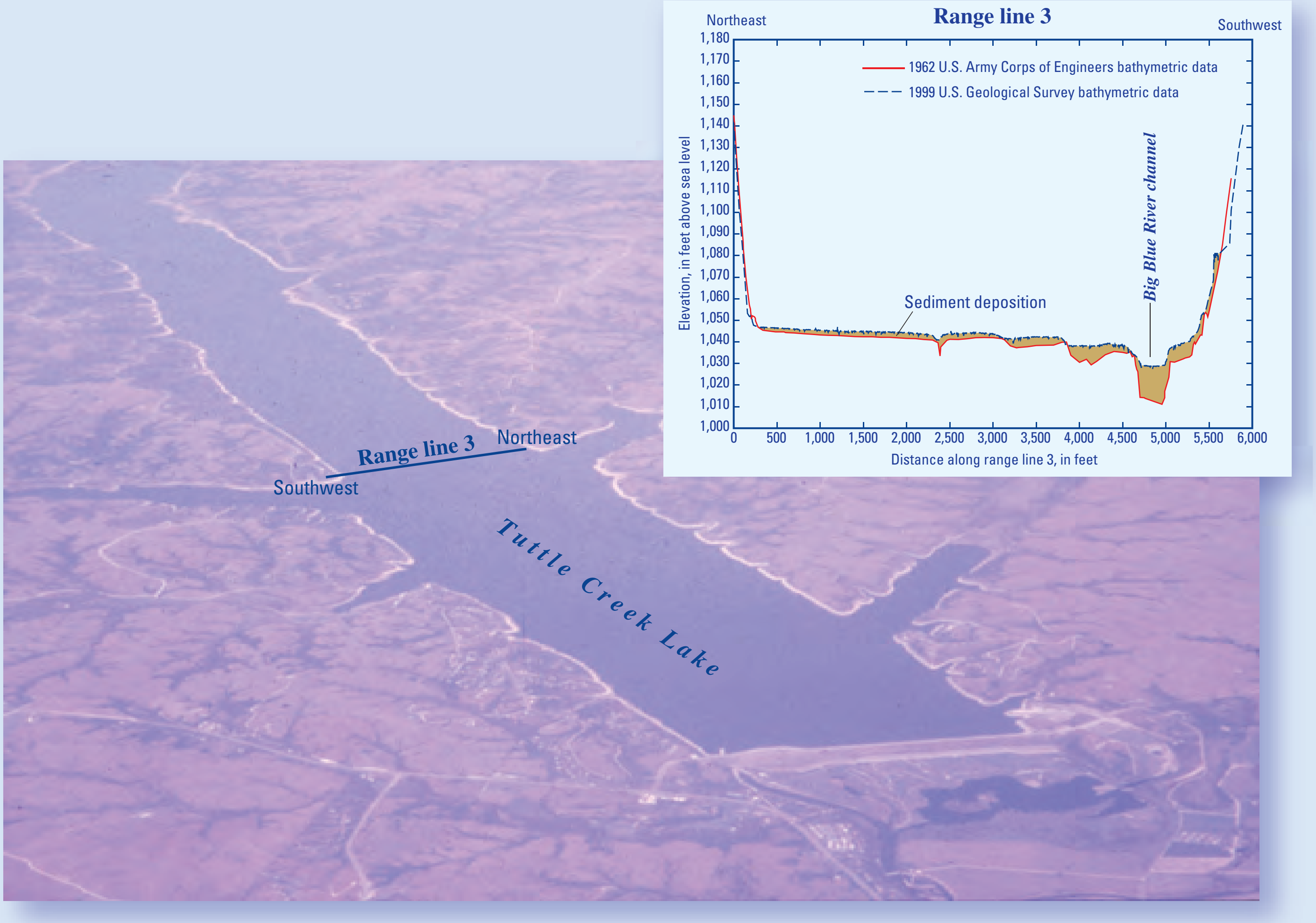
A Comparison of Approaches for Estimating Bottom-Sediment Mass in Large Reservoirs



Scientific Investigations Report 2006–5168

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

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By Kyle E. Juracek

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Conversion Factors, Abbreviations, and Datum

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Mass	
kilogram (kg)	2.205	pound (lb)
	Density	
kilogram per cubic meter (kg/m^3)	0.06243	pound per cubic foot (lb/ft^3)

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

A Comparison of Approaches for Estimating Bottom-Sediment Mass in Large Reservoirs

By Kyle E. Juracek

Abstract

Estimates of sediment and sediment-associated constituent loads and yields from drainage basins are necessary for the management of reservoir-basin systems to address important issues such as reservoir sedimentation and eutrophication. One method for the estimation of loads and yields requires a determination of the total mass of sediment deposited in a reservoir. This method involves a sediment volume-to-mass conversion using bulk-density information. A comparison of four computational approaches (partition, mean, midpoint, strategic) for using bulk-density information to estimate total bottom-sediment mass in four large reservoirs indicated that the differences among the approaches were not statistically significant. However, the lack of statistical significance may be a result of the small sample size. Compared to the partition approach, which was presumed to provide the most accurate estimates of bottom-sediment mass, the results achieved using the strategic, mean, and midpoint approaches differed by as much as ±4, ±20, and ±44 percent, respectively. It was concluded that the strategic approach may merit further investigation as a less time consuming and less costly alternative to the partition approach.

Introduction

Estimates of sediment and sediment-associated constituent loads and yields from drainage basins are important for the management of lakes and reservoirs (Morris and Fan, 1998; Umbanhowar and others, 2003). Together, sediment and constituent loads and yields provide baseline information that may be used to assess the effectiveness of implemented management practices intended to reduce sedimentation in, and improve the water quality of, a lake or reservoir. For example, such information is useful in the development, implementation, evaluation, and revision of total maximum daily loads designed to control reservoir sedimentation and eutrophication (Juracek and Stiles, 2003). For reservoirs, one method for the estimation of loads and yields involves a determination of the total mass of deposited sediment (Vanoni, 1975; Rausch and Heinemann, 1984; Annandale, 1987).

A primary factor that affects the accuracy of bottom-sediment mass determination, and associated load and yield estimates, is the spatial representativeness of available bulk-density information that is used to convert sediment volume to mass (Foster and others, 1990; Butcher and others, 1993; Verstraeten and Poesen, 2001). Sediment bulk density varies among reservoirs (Dendy and Champion, 1978; Rausch and Heinemann, 1984; Butcher and others, 1993) as well as horizontally and vertically within a reservoir (Heinemann, 1962; Lara and Pemberton, 1965; Foster and Charlesworth, 1994). For example, bulk density tends to be lowest downstream near the dam where the fine sediment is deposited and highest in the upstream part of the reservoir where the coarse delta deposits are located. This upstream-to-downstream gradation is the result of the relation between particle size, settling velocity, and flow velocity as the sediment-laden water enters and moves through a reservoir. Localized deviations from this gradation can be caused by several factors including an influx of relatively coarse-grained sediment from tributary and shore sources, and compaction (Morris and Fan, 1998). Given such spatial variability, the bulk density determined for a single site typically is not representative of the reservoir as a whole.

In this report, the results of a study to compare several approaches to using bulk-density information for the estimation of bottom-sediment mass in large reservoirs are presented. Although considerable research has addressed various aspects of reservoir sedimentation (for example, see Vanoni, 1975; Morris and Fan, 1998), a search of the literature uncovered no previous studies that provide a comparison of approaches for estimating bottom-sediment mass using reservoir surveys and bulk-density information. Because of the fundamental importance of bottom-sediment mass, an understanding of the comparability of approaches for its estimation is needed. The objective of the study described herein was to determine, for four large reservoirs, the differences in estimated bottom-sediment mass using four approaches. The approaches selected provide a set of alternatives that have been, or potentially may be, used for the purpose of estimating bottom-sediment mass. The approaches represent a range in terms of complexity and data-collection requirements.

The first two approaches, referred to as the partition and mean approaches, have been used in previous reservoir sediment studies (for example, White and others, 1997; Juracek, 1998). Optimally, both of these approaches require relatively extensive data collection to provide sufficiently detailed bulk-density information for a reservoir. In the partition approach, a reservoir is partitioned into a number of discrete in-channel and out-of-channel components. One or more bulk-density values are used to compute sediment mass for each of the individual components, which then are summed to provide an estimate of the total bottom-sediment mass for a reservoir. Because it best accounts for the variability in bulk density, the partition approach is presumed to provide the most accurate estimate of total bottom-sediment mass for a reservoir. However, this approach may not always be possible or feasible. In the mean approach, total bottom-sediment mass is computed in one step using the mean bulk-density value for a reservoir. This approach is simpler than the partition approach.

The second two approaches, referred to as the midpoint and strategic approaches, also are simpler than the partition approach and, more importantly, require less-extensive data collection. No published examples of the second two approaches were found in the literature. Given the variability of sediment deposition and bulk density within a reservoir, the appropriateness of these two approaches is questionable. Nevertheless, they are included as possible alternatives to assess their comparability to the partition approach. In the midpoint approach, total bottom-sediment mass is computed in one step using the mean bulk-density value for an area located near the middle of each reservoir. In the strategic approach, the bulk-density values determined for the upstream- and downstream-most areas of each reservoir are averaged and used to estimate total bottom-sediment mass. Both of these approaches are based on the assumption of a relatively uniform upstream-to-downstream gradation of bulk density within a reservoir. The validity of this assumption will vary among reservoirs.

In sum, the primary purpose of this report is to document whether or not less time consuming and less costly alternative approaches for estimating total bottom-sediment mass could provide results that are comparable to the partition approach. The findings presented herein could have implications for present and future reservoir and basin management, especially as related to decisions regarding data collection and the estimation of sediment and associated constituent mass, load, and yield.

Description of Study Areas

The reservoirs selected for this study were Cheney Reservoir in south-central Kansas, Hillsdale Lake in east-central Kansas, and Perry and Tuttle Creek Lakes in northeast Kansas (fig. 1). Cheney Reservoir is an impoundment on the North Fork Ninnescah River that was completed in 1964. Hillsdale Lake, completed in 1981, is an impoundment on Big Bull Creek. Perry Lake is an impoundment on the Delaware River that was completed in 1969. Tuttle Creek Lake, completed in 1962, is an impoundment on the Big Blue River. Basin sizes range from 373 km^2 for Hillsdale Lake to 24,900 km^2 for Tuttle Creek Lake. The original water-storage capacities at conservation-pool elevation ranged from 84 million m^3 for Hillsdale Lake to 524 million m^3 for Tuttle Creek Lake. The original surface areas of the reservoirs at conservation-pool elevation ranged from 18 km^2 for Hillsdale Lake to 64 km^2 for Tuttle Creek Lake (table 1). Land use in all four basins is predominantly an agricultural mix of cropland and grassland.

Methods

Available information from previously completed reservoir sediment studies of Cheney Reservoir (Pope, 1998; Mau, 2001), Hillsdale Lake (Juracek, 1997), Perry Lake (Juracek, 2003), and Tuttle Creek Lake (Juracek and Mau, 2002) was used for the purposes of this study. The information available from these studies was not collected with the present study objective in mind and, therefore, does not provide an ideal data set in terms of completeness. However, the information is believed to be representative of what is typically collected for reservoir sediment studies and is considered to be sufficiently comprehensive for the purposes of this study.

In the previously completed studies, total bottom-sediment volume for each of the reservoirs was determined by bathymetric survey. Each reservoir was resurveyed along bathymetric range lines that were established at the time of reservoir construction (figs. 2–5). Using the bathymetric range lines as boundaries (Rausch and Heinemann, 1984), the original conservation-pool surface area of each reservoir was partitioned into in-channel (that is, the pre-reservoir stream or river channel) and out-of-channel (that is, the pre-reservoir flood plain) components to improve the precision of the bottom-sediment volume estimates. For example, in Cheney Reservoir, the availability of five range lines enabled the partitioning of the reservoir into six in-channel and six out-of-channel components (fig. 2). The bottom-sediment volume for each component was computed as the total surface area multiplied by the mean thickness of the sediment. With one exception, mean sediment thickness for each component was computed as the average of the sediment thicknesses determined using the range lines that defined the component. In the case of Hillsdale Lake, the thickness of the relatively thin out-of-channel sediment deposits (generally, less than 0.3 m) was estimated using coring data. Total bottom-sediment volume for each reservoir was computed as the sum of the components.

At each reservoir, sediment cores for bulk-density determination were collected to provide a spatially representative sample of conditions upstream to downstream as well as in and out of the submerged channels. The sediment cores were collected using a gravity corer mounted on a pontoon boat. The liner used in the corer was cellulose acetate butyrate transparent tubing with a 6.67-cm inside diameter. The cores ranged in length from less than 0.5 to about 4 m. Respectively, the number of cores collected (and the approximate density of

Figure 1. Location of reservoirs in Kansas used in study.

cores per km^2 of reservoir surface area) for Cheney Reservoir, Hillsdale Lake, Perry Lake, and Tuttle Creek Lake were 10 (0.3 cores/km^2), 30 (1.7 cores/km^2), 18 (0.4 cores/km^2), and 22 (0.3 cores/km^2). The location of the coring sites for the four reservoirs is provided in figures 2 through 5.

To account for the variability of bulk density with depth in the sediment profile, the cores were divided into multiple intervals, which then were sampled for bulk-density determinations. Typically, a 2.5-cm thick sample was removed from each interval. Depending on the length of the recovered core, the number of intervals per core ranged from 1 to 17 with a typical range of 5 to 10. Bulk density was determined using standard methods (Guy, 1969; Gordon and others, 1992). The interval-specific bulk densities were averaged to determine a representative mean bulk density for each coring site.

The conversion of total sediment volume to total sediment mass was accomplished using four approaches in this report. The partition approach was presumed to provide the most accurate estimates of bottom-sediment mass as it best accounts for the spatial variability of bulk density in the bottom sediment of each reservoir. In this approach, each reservoir was partitioned into a number of in-channel and out-of-channel components to improve the precision of the sediment mass estimates. Typically, the boundaries for the components corresponded to the established bathymetric range lines (figs. 2–5). An exception was the out-of-channel area for Hillsdale Lake, which was partitioned into only three components as dictated by the limited thickness and spatial distribution of sediment (Juracek, 1997). The total number of reservoir components used ranged from 12 for Cheney Reservoir to 37 for Tuttle Creek Lake (table 2).

Sediment mass for each reservoir component was computed as the total sediment volume for the component multiplied by the representative mean bulk density for the compo-

Table 1. Year of completion, basin size, original water-storage capacity, and original surface area for selected reservoirs in Kansas.

[km^2, square kilometers; m^3, cubic meters]

Reservoir (stream or river)	Year of completion	Basin size (km^2)	Original water-storage capacity[1] (million m^3)	Original surface area[1] (km^2)
Cheney Reservoir (North Fork Ninnescah River)	1964	2,420	187	39
Hillsdale Lake (Big Bull Creek)	1981	373	84	18
Perry Lake (Delaware River)	1969	2,890	300	49
Tuttle Creek Lake (Big Blue River)	1962	24,900	524	64

[1] At conservation-pool elevation (data from the U.S. Army Corps of Engineers and the Bureau of Reclamation, written commun., various dates).

nent. As dictated by the location of the coring sites in relation to the boundaries of the reservoir components, a bulk-density value was assigned to each component using available values outright (if the component had a single coring site) or averaged (if the component had multiple coring sites) to provide what was believed to be the most representative value. In some cases, a lack of bulk-density information for a particular component necessitated the use of bulk-density information from a nearby component (that is, the nearest coring site for which a bulk-density value was available). Total sediment mass for each reservoir was computed as the sum of the masses determined for the individual reservoir components.

In the mean approach, the total sediment mass for each reservoir was computed as the total sediment volume (previously determined) multiplied by the mean bulk density for the reservoir. The mean bulk density was computed as the average of the representative mean bulk densities determined for the individual coring sites. Both the partition and mean approaches used all available bulk-density information for each reservoir.

For the midpoint approach, the total sediment mass for each reservoir was computed as the total sediment volume (previously determined) multiplied by the midpoint bulk density for the reservoir. The midpoint bulk density was computed as the average of the representative mean bulk densities determined for an in-channel and out-of-channel core collected near the middle of each reservoir. At Tuttle Creek Lake there were two out-of-channel cores collected at the selected reservoir midpoint. Thus, the average bulk density for the two sites was used as the out-of-channel value in the midpoint approach. Because Hillsdale Lake has two primary arms (fig. 3), the midpoint bulk density was computed as the average of the representative mean bulk densities determined for an in-channel and out-of-channel core collected near the middle of both arms. The coring sites used to compute the midpoint bulk density for each reservoir are identified in figures 2 through 5.

The strategic approach involved the use of bulk densities determined for two coring sites (that is, one in-channel and one out-of-channel) near both the upstream and downstream limits of each reservoir. For consistency, the in- and out-of-channel coring sites located farthest upstream and downstream were selected. The coring sites used in the strategic approach for each reservoir are identified in figures 2 through 5. Total sediment mass was computed as the total sediment volume (previously determined) multiplied by the mean bulk density for the four coring sites.

Because Hillsdale Lake has two primary arms (fig. 3), the farthest upstream and downstream coring sites for the in-channel and out-of-channel locations were included for both arms. Thus, a total of eight bulk-density values were used to compute the mean for Hillsdale Lake. It should be noted that the upstream, out-of-channel value for the Big Bull Creek arm was estimated on the basis of a regression relation ($R^2 = 0.89$) between bulk density and percent moisture content. Also, due to insufficient sediment volume, the downstream, out-of-channel values for both arms were estimated on the basis of the relation between the in- and out-of-channel values determined for upstream areas of the reservoir (Juracek, 1997).

At Tuttle Creek Lake, there were two out-of-channel coring sites located near the dam (fig. 5). Thus, the average bulk density for the two sites was used as the out-of-channel value in the strategic approach.

To determine whether or not the differences among the four approaches were statistically significant, the nonparametric Friedman two-way analysis of variance by ranks test (Siegel and Castellan, 1988) was performed. In this test, the results for each reservoir (that is, the sediment mass estimates) were ranked from smallest (rank of 1) to largest (rank of 4). Then, the sum of the ranks for each approach was used in the computation of the test statistic F_r. At the 0.05 level of significance, the critical value F_{crit} is 7.8. If $F_r > F_{crit}$, then the null hypothesis (that is, equivalence among the approaches)

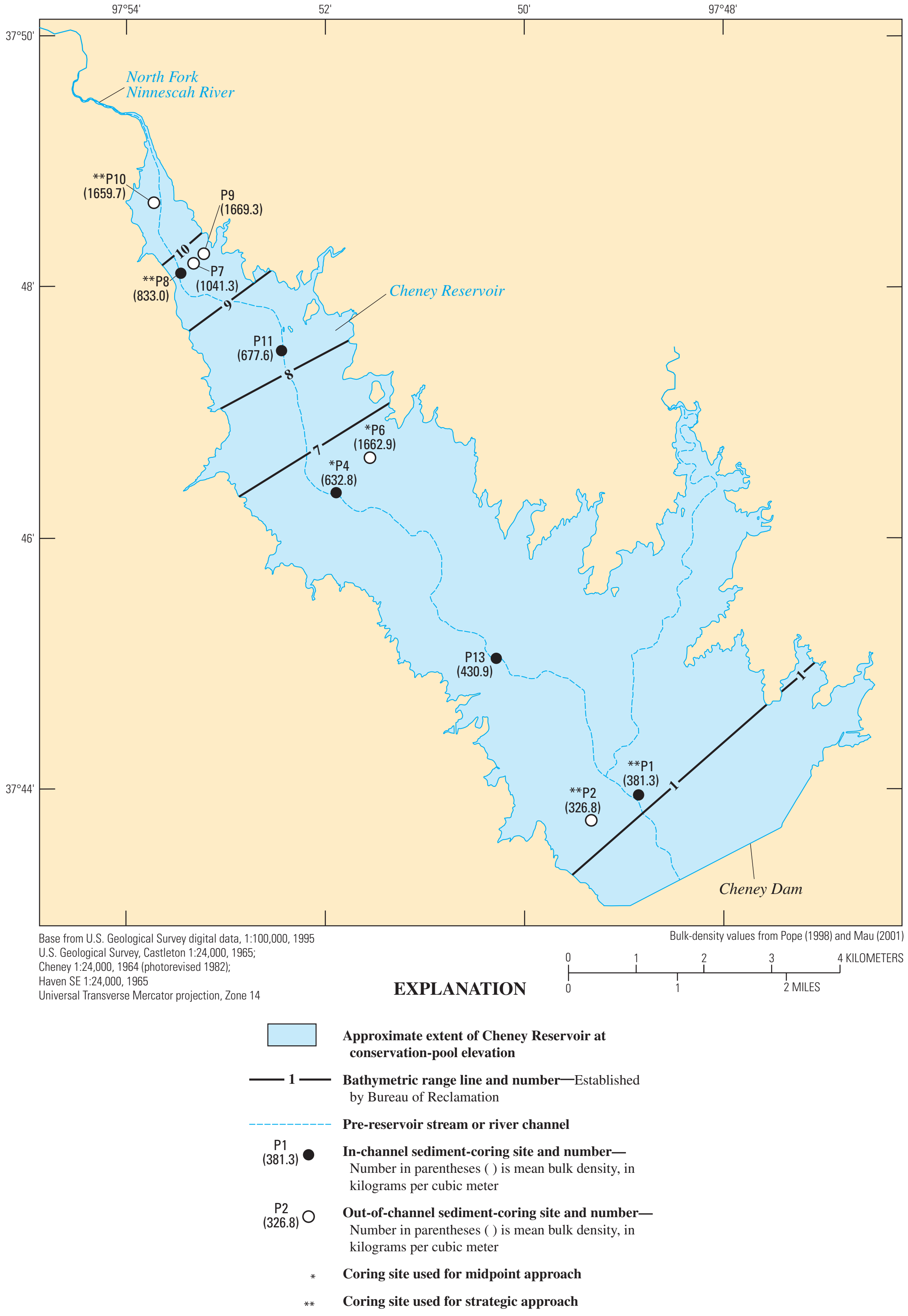


Figure 2. Location of bathymetric range lines, sediment-coring sites, estimated bulk densities, and boundaries of reservoir components for Cheney Reservoir.

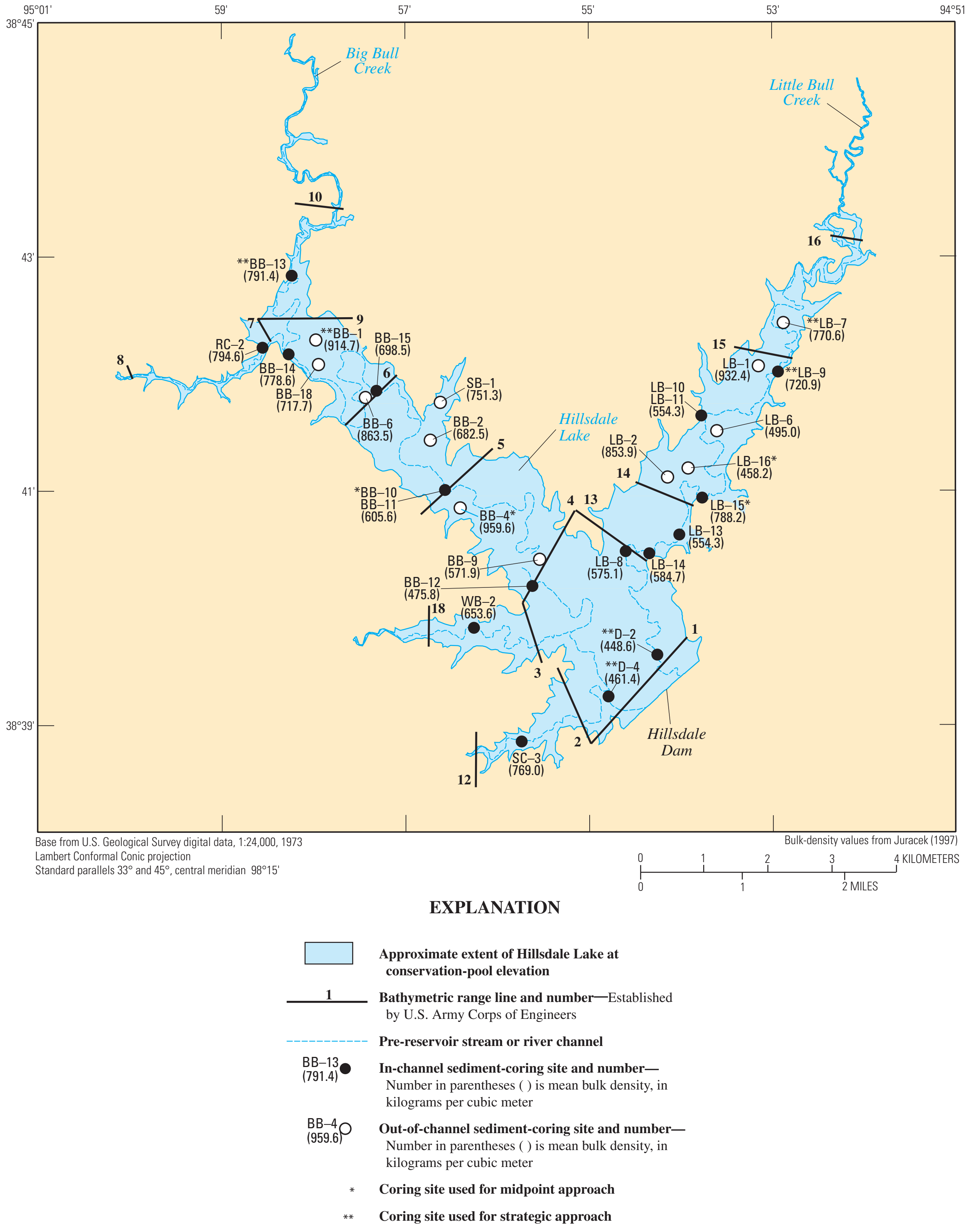
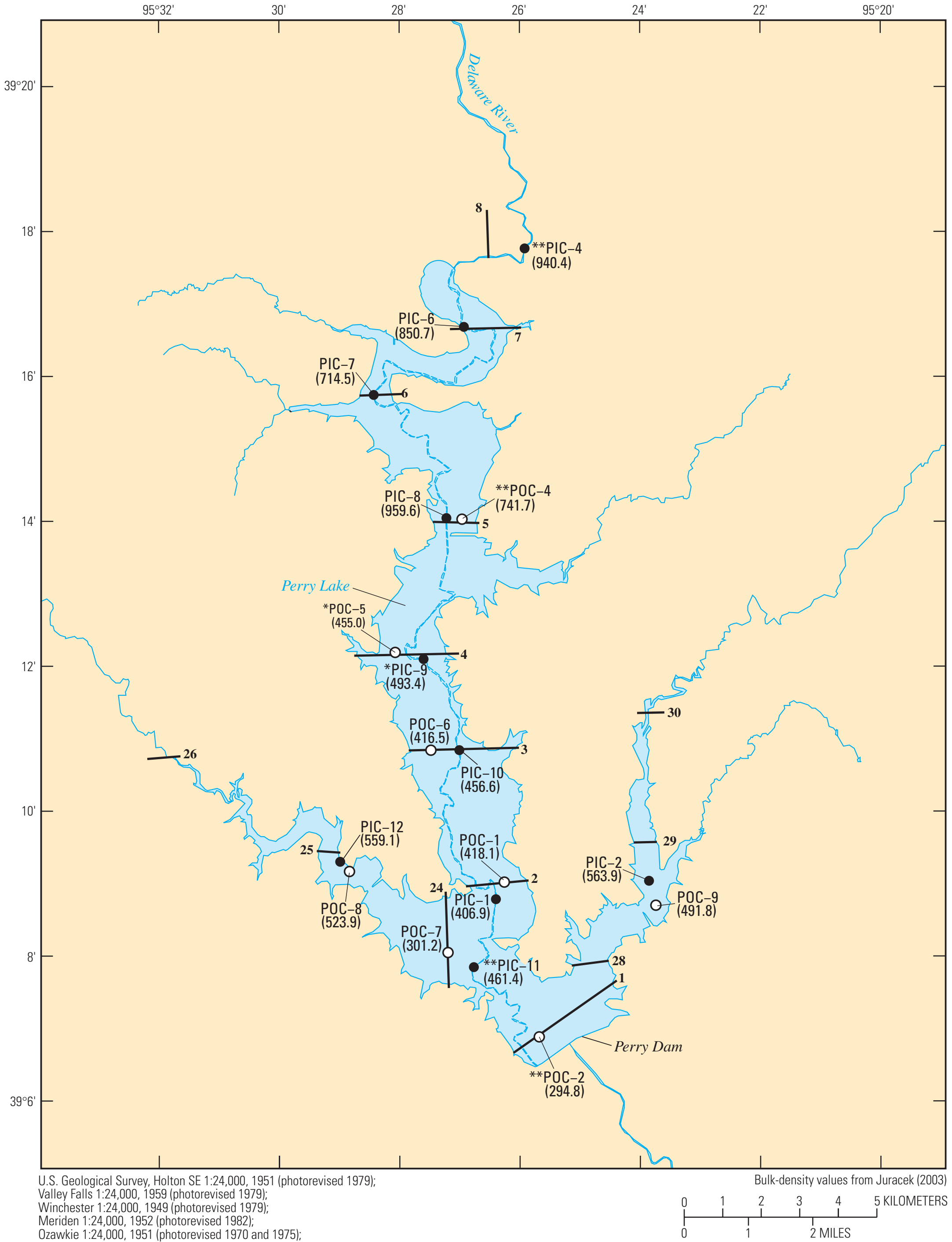


Figure 3. Location of bathymetric range lines, sediment-coring sites, estimated bulk densities, and boundaries of reservoir components for Hillsdale Lake.



U.S. Geological Survey, Holton SE 1:24,000, 1951 (photorevised 1979);
Valley Falls 1:24,000, 1959 (photorevised 1979);
Winchester 1:24,000, 1949 (photorevised 1979);
Meriden 1:24,000, 1952 (photorevised 1982);
Ozawkie 1:24,000, 1951 (photorevised 1970 and 1975);
Oskaloosa 1;24,000, 1951 (photorevised 1979);
Grantville 1:24,000, 1983;
Perry 1;24,000, 1951 (photorevised 1970 and 1975);
Williamstown 1:24,000, 1959 (photorevised 1979)

Bulk-density values from Juracek (2003)

EXPLANATION

🟦 **Approximate extent of Perry Lake at conservation-pool elevation**

1 —— **Bathymetric range line and number**—Established by U.S. Army Corps of Engineers

- - - - - **Pre-reservoir stream or river channel**

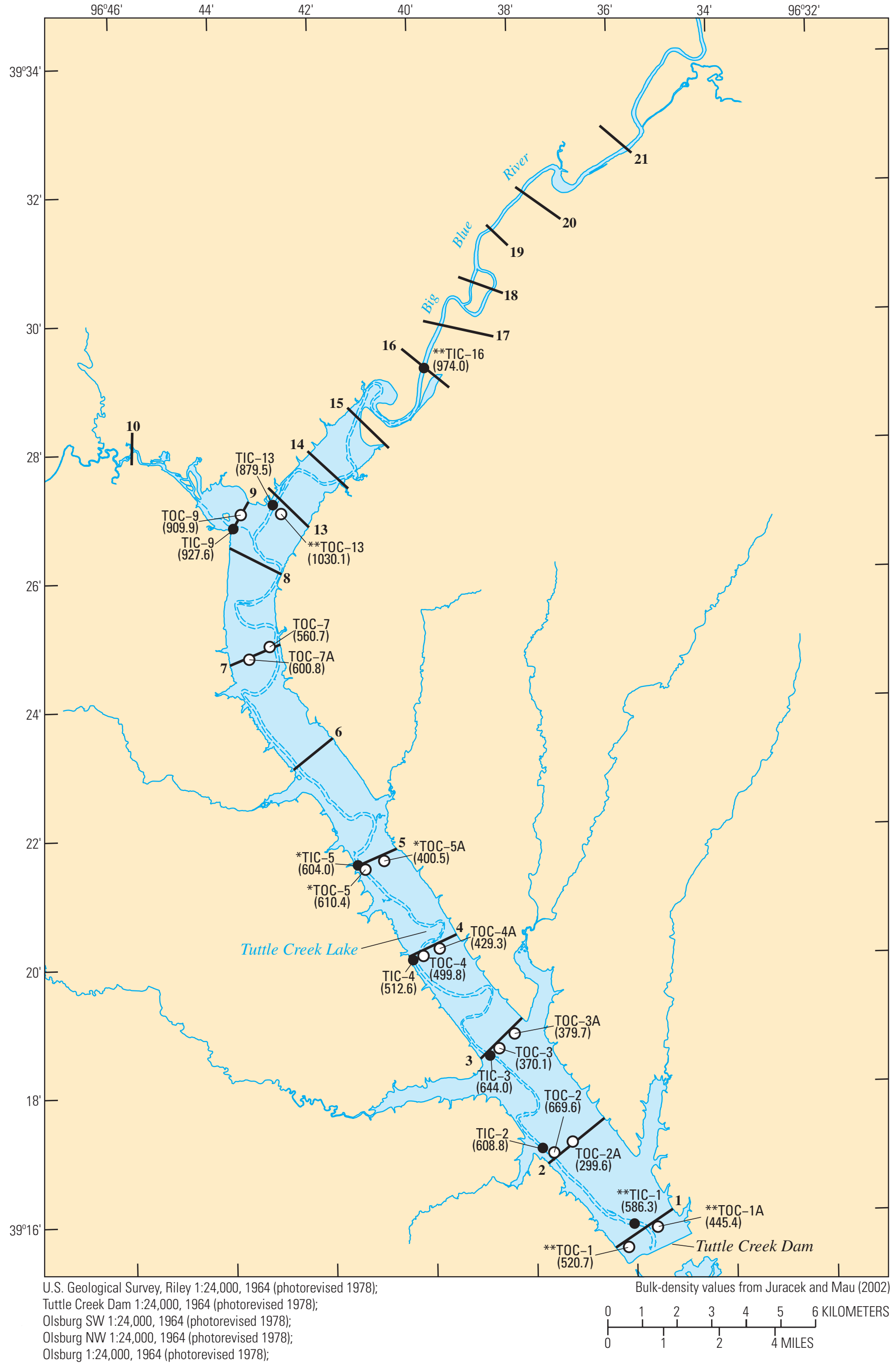
PIC–2 (563.9) ● **In-channel sediment-coring site and number**—Number in parentheses ( ) is mean bulk density, in kilograms per cubic meter

POC–1 (418.1) ○ **Out-of-channel sediment-coring site and number**—Number in parentheses ( ) is mean bulk density, in kilograms per cubic meter

* **Coring site used for midpoint approach**

** **Coring site used for strategic approach**

Figure 4. Location of bathymetric range lines, sediment-coring sites, estimated bulk densities, and boundaries of reservoir components for Perry Lake.



U.S. Geological Survey, Riley 1:24,000, 1964 (photorevised 1978);
Tuttle Creek Dam 1:24,000, 1964 (photorevised 1978);
Olsburg SW 1:24,000, 1964 (photorevised 1978);
Olsburg NW 1:24,000, 1964 (photorevised 1978);
Olsburg 1:24,000, 1964 (photorevised 1978);
Randolph 1:24,000, 1964 (photorevised 1983);
Blue Rapids SW 1:24,000, 1964 (photorevised 1983);
Blue Rapids SE 1:24,000, 1968
Universal Transverse Mercator projection, Zone 14

Bulk-density values from Juracek and Mau (2002)

EXPLANATION

▭ **Approximate extent of Tuttle Creek Lake at conservation-pool elevation**

1 — **Bathymetric range line and number**—Established by U.S. Army Corps of Engineers

- - - - **Pre-reservoir stream or river channel**

TIC–1 (586.3) ● **In-channel sediment-coring site and number**—Number in parentheses ( ) is mean bulk density, in kilograms per cubic meter

TOC–1 (520.7) ○ **Out-of-channel sediment-coring site and number**—Number in parentheses ( ) is mean bulk density, in kilograms per cubic meter

* **Coring site used for midpoint approach**

** **Coring site used for strategic approach**

Figure 5. Location of bathymetric range lines, sediment-coring sites, estimated bulk densities, and boundaries of reservoir components for Tuttle Creek Lake.

Table 2. Sediment volumes, number of reservoir components, bulk densities, and computed sediment masses for selected reservoirs in Kansas.

[m^3, cubic meters; I, in-channel; O, out-of-channel; kg/m^3, kilograms per cubic meter; kg, kilograms; %, percent]

Reservoir (fig. 1)	Sediment volume (millions of m^3)	Number of reservoir components (I,O)	Number of bulk density estimates (I,O)	Bulk density[1] (kg/m^3)				Computed sediment mass [millions of kg (percentage difference from partition approach)]			
				Minimum	Maximum	Mean	Standard deviation	Partition approach	Mean approach	Midpoint approach[2]	Strategic approach[3]
Cheney Reservoir[4]	8.75	12 (6, 6)	10 (5, 5)	326.8	1,669.3	931.6	548.1	6,990	8,150 (+16.6%)	10,000 (+43.1%)	7,000 (+0.1%)
Hillsdale Lake[5]	2.59	21 (18, 3)	30 (18, 12)	448.6	959.6	686.6	152.4	1,800	1,780 (-1.1%)	1,820 (+1.1%)	1,730 (-3.9%)
Perry Lake[6]	70.0	26 (14, 12)	18 (10, 8)	294.8	959.6	558.3	201.3	44,100	39,100 (-11.3%)	33,200 (-24.7%)	42,700 (-3.2%)
Tuttle Creek Lake[7]	175	37 (19, 18)	22 (8, 14)	299.6	1,030.1	612.0	209.3	133,000	107,000 (-19.5%)	97,100 (-27.0%)	134,000 (+0.8%)

[1] Computed using all coring sites for which representative bulk-density information was available.

[2] Mean bulk densities computed using the midpoint approach for Cheney Reservoir, Hillsdale Lake, Perry Lake, and Tuttle Creek Lake were 1,147.9, 702.9, 474.2, and 554.8 kg/m^3, respectively.

[3] Mean bulk densities computed using the strategic approach for Cheney Reservoir, Hillsdale Lake, Perry Lake, and Tuttle Creek Lake were 800.2, 668.8, 610.4, and 768.4 kg/m^3, respectively.

[4] Sources of data: Pope (1998) and Mau (2001).

[5] Source of data: Juracek (1997).

[6] Source of data: Juracek (2003).

[7] Source of data: Juracek and Mau (2002).

is rejected and the differences among the approaches may be considered statistically significant.

Comparison of Sediment Mass Estimates

Compared to the partition approach, which was presumed to provide the most accurate estimates of total bottom-sediment mass, the results achieved using the strategic, mean, and midpoint approaches differed by as much as ±4, ±20, and ±44 percent, respectively. Table 2 provides a summary of the sediment volume, bulk densities, and estimated sediment masses for each of the four reservoirs. Estimates of sediment and sediment-associated constituent loads and yields would exhibit similar differences among the four approaches.

Despite some relatively large percentage differences among the estimated sediment masses, especially between the midpoint and partition approaches (table 2), the Friedman test indicated no statistically significant differences among the four approaches at the 0.05 level of significance. The value of the test statistic F_r was 0.3. Because $F_r < F_{crit}$, the null hypothesis could not be rejected. However, the lack of statistical significance may be a result of the small sample size.

Differences between the partition approach and the three alternative approaches were expected, although it was not known in advance what to expect in terms of the magnitude of the differences. Of the three alternatives, it was anticipated that the mean approach might perform best (that is, provide sediment-mass estimates closest to the estimates obtained using the partition approach) because it used all available bulk-density information (albeit averaged), whereas the midpoint and strategic approaches used a limited subset of the available information. With the exception of Hillsdale Lake, the mean approach did perform better than the midpoint approach. However, with the exception of Hillsdale Lake, the mean approach did not perform better than the strategic approach (table 2). The excellent agreement between the partition and strategic approaches was surprising and may, in part, be a result of the small sample size (that is, four reservoirs).

The results also indicated that the differences between the partition and mean approaches may be directly related to the range in bulk density within each reservoir. That is, as the range in bulk density increases, the difference between the partition and mean approaches increases (table 2). In addition, the differences between the partition and mean approaches may be inversely related to the density of coring within the reservoirs. The difference is relatively small for Hillsdale Lake (1.7 cores/km^2), relatively moderate for Perry Lake (0.4 cores/km^2), and relatively large for Cheney Reservoir (0.3 cores/km^2) and Tuttle Creek Lake (0.3 cores/km^2). The differences between the partition and all three alternative approaches were small for Hillsdale Lake.

The sediment-mass estimates obtained represent one possible set of outcomes for each reservoir using the midpoint and strategic approaches. Because the bulk density of bottom sediment varies throughout a reservoir, the results for both approaches will vary depending on the location of the coring sites used. The available information for the four reservoirs does not allow for a comprehensive evaluation of the variability in sediment-mass estimates using the two approaches. However, a limited assessment was possible.

Tuttle Creek Lake was selected to provide an assessment of variability because the reservoir has a predominantly linear (that is, relatively simple) shape and a reasonably good number and distribution of coring sites (fig. 5). For the midpoint approach, 12 unique combinations of coring sites were used to assess variability in sediment-mass estimates (table 3). The estimates computed using the midpoint approach ranged from 79,900 to 106,000 million kg with a mean of 91,300 million kg and a standard deviation of 7,400 million kg (± 8 percent). Depending on the combination of coring sites selected for Tuttle Creek Lake, the sediment-mass estimate obtained using the midpoint approach differed from the partition-based estimate by as little as 20 percent or as much as 40 percent. The average difference was 31 percent.

Twelve unique combinations of coring sites also were used to assess variability for the strategic approach (table 4). The estimates computed using the strategic approach ranged from 110,000 to 136,000 million kg with a mean of 120,000 million kg and a standard deviation of 10,000 million kg (±9 percent). Depending on the combination of coring sites selected for Tuttle Creek Lake, the sediment-mass estimate obtained using the strategic approach differed from the partition-based estimate by as little as 1 percent or as much as 17 percent. The average difference was 10 percent. Thus, regardless of the combination of coring sites selected, the strategic approach performed better than the midpoint approach for Tuttle Creek Lake.

Additional research, using more detailed data sets, is needed to improve understanding of the spatial variability of bulk density in reservoir bottom sediment. For example, data sets are needed to determine the variability of bulk density over relatively short distances (for example, less than 0.5 km), between in-channel and out-of-channel locations, and with proximity to shore. Once assembled, such data sets can be used to better define the variability within and among approaches used to estimate total bottom-sediment mass for reservoirs. Moreover, such data sets may be used to provide guidance for determining the optimal number and location of coring sites needed to provide the representative bulk-density information required for the estimation of total bottom-sediment mass.

As evidenced in figures 2 through 5, bulk density varied substantially both upstream to downstream and laterally within the reservoirs and sometimes over relatively short distances. The expected upstream-to-downstream decrease in bulk density was generally evident for the in-channel coring sites in all four reservoirs and for the out-of-channel coring sites in Perry and Tuttle Creek Lakes. In these cases, the bulk density determined for the upstream-most coring site was always

Table 3. Coring-site combinations, mean bulk densities, and computed sediment masses using the midpoint approach for Tuttle Creek Lake, northeastern Kansas.

[kg/m^3, kilograms per cubic meter; kg, kilograms]

Combination	Coring sites used (fig. 5)	Mean bulk density[1] (kg/m^3)	Computed sediment mass (millions of kg)	Percentage difference from partition-based estimate
Original	TIC–5, TOC–5, TOC–5A	554.8	97,100	-27.0
Option A	TIC–4, TOC–4, TOC–4A	488.6	85,500	-35.7
Option B	TIC–5, TOC–4, TOC–4A	534.3	93,500	-29.7
Option C	TIC–4, TOC–5, TOC–5A	509.1	89,100	-33.0
Option D	TIC–5, TOC–5	607.2	106,000	-20.3
Option E	TIC–5, TOC–5A	502.3	87,900	-33.9
Option F	TIC–4, TOC–4	506.2	88,600	-33.4
Option G	TIC–4, TOC–4A	471.0	82,400	-38.0
Option H	TIC–5, TOC–4	551.9	96,600	-27.4
Option I	TIC–5, TOC–4A	516.7	90,400	-32.0
Option J	TIC–4, TOC–5	561.5	98,300	-26.1
Option K	TIC–4, TOC–5A	456.6	79,900	-39.9

[1] For the combinations having two out-of-channel coring sites (that is, Original, Option A, Option B, and Option C), the two sites were averaged to provide a single out-of-channel bulk-density value. Then, the out-of-channel value and the in-channel value were averaged to provide the mean bulk density used in the computation of the sediment mass.

substantially larger than the bulk density determined for the downstream-most coring site. However, the bulk densities determined for the intermediate coring sites did not necessarily grade uniformly from one endmember to the other. For Cheney Reservoir and Hillsdale Lake, a pattern of bulk-density values for the out-of-channel coring sites was not discernible. In the case of Cheney Reservoir, the absence of a discernible pattern for bulk density may be caused, in part, by limited out-of-channel sampling. The deviation of bulk density from a uniform upstream-to-downstream gradation within reservoirs can be attributed to several factors including tributary and shore inputs, and compaction. Results for the four approaches to estimating total bottom-sediment mass will vary in response to the variability of bulk density within the reservoir bottom sediment and the number and location of coring sites used for bulk-density determinations.

The absence of a discernible upstream-to-downstream gradation in the out-of-channel bulk-density values for at least one of the reservoirs (Hillsdale Lake), combined with the finding that the variability of the representative bulk densities for the out-of-channel coring sites was larger than the variability for the in-channel coring sites for three of four reservoirs (Perry Lake being the exception), indicated the possibility that the out-of-channel areas may be more important as a cause of variability in sediment-mass estimation. More spatially detailed bulk-density information is needed to confirm this observation. The implication is that out-of-channel areas of reservoirs may require more extensive sampling to provide representative bulk-density information.

Finally, on the basis of an analysis of the deviation from the mean, it was determined that the vertical (within-core) variability in bulk density typically was less than the horizontal variability in representative bulk density among the coring sites. This finding is consistent with that of Foster and Charlesworth (1994) who found that the spatial variability of bulk density for surface sediment was generally similar to, or greater than, the vertical variability for four reservoirs in England.

Summary and Conclusions

In this study, a comparison of four computational approaches (partition, mean, midpoint, strategic) for using bulk-density information to estimate total bottom-sediment mass in four large reservoirs indicated that the differences among the approaches were not statistically significant. However, the lack of statistical significance may be a result of the small sample size. Percentage-wise, some of the differences were substantial.

Table 4. Coring-site combinations, mean bulk densities, and computed sediment masses using the strategic approach for Tuttle Creek Lake, northeastern Kansas.

[kg/m^3, kilograms per cubic meter; kg, kilograms]

Combination	Coring sites used (fig. 5)	Mean bulk density[1] (kg/m^3)	Computed sediment mass (millions of kg)	Percentage difference from partition-based estimate
Original	TIC–1, TOC–1, TOC–1A, TIC–16, TOC–13	768.4	134,000	+0.8
Option A	TIC–1, TOC–1, TOC–1A, TIC–16, TOC–7	651.0	114,000	-14.3
Option B	TIC–1, TOC–1, TOC–1A, TIC–16, TOC–7A	661.1	116,000	-12.8
Option C	TIC–1, TOC–1, TOC–1A, TIC–13, TOC–13	744.8	130,000	-2.3
Option D	TIC–1, TOC–1, TOC–1A, TIC–13, TOC–7	627.4	110,000	-17.3
Option E	TIC–1, TOC–1, TOC–1A, TIC–13, TOC–7A	637.4	112,000	-15.8
Option F	TIC–2, TOC–2, TOC–2A, TIC–16, TOC–13	774.4	136,000	+2.3
Option G	TIC–2, TOC–2, TOC–2A, TIC–16, TOC–7	657.0	115,000	-13.5
Option H	TIC–2, TOC–2, TOC–2A, TIC–16, TOC–7A	667.1	117,000	-12.0
Option I	TIC–2, TOC–2, TOC–2A, TIC–13, TOC–13	750.8	131,000	-1.5
Option J	TIC–2, TOC–2, TOC–2A, TIC–13, TOC–7	633.4	111,000	-16.5
Option K	TIC–2, TOC–2, TOC–2A, TIC–13, TOC–7A	643.4	113,000	-15.0

[1] All combinations used two out-of-channel coring sites at the downstream location. The two sites were averaged to provide a single out-of-channel bulk-density value. The resultant out-of-channel value then was averaged with the other coring sites to provide the mean bulk density used in the computation of the sediment mass.

Overall, the strategic approach provided total bottom-sediment mass estimates that were the most similar to the partition approach. This result, which was unexpected given the limited amount of bulk-density information used, indicated that the strategic approach may merit further investigation as a less time consuming and less costly alternative to the partition approach. Potentially, the strategic approach may offer a viable alternative when the partition approach is not possible or feasible.

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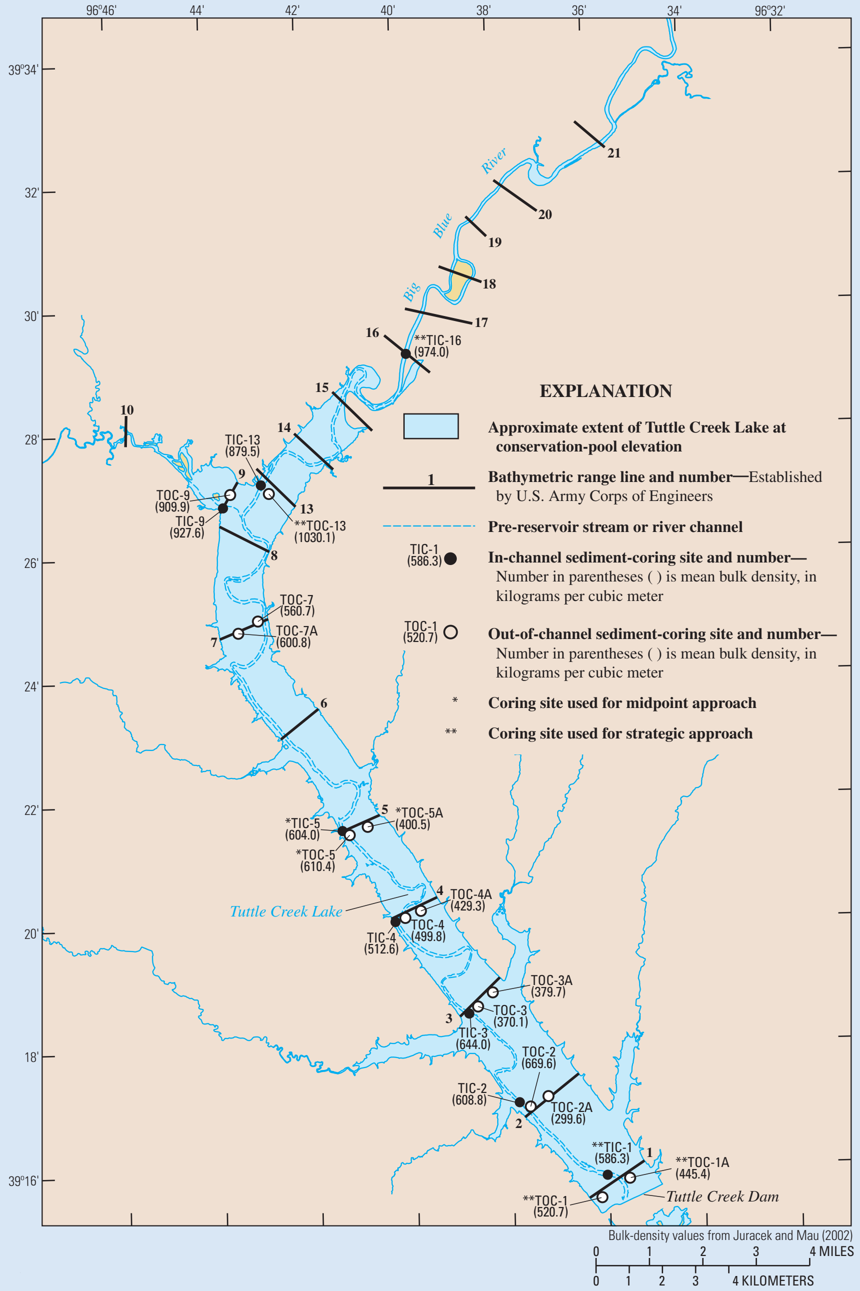

Bulk-density values from Juracek and Mau (2002)

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