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# Estimation of sediment sources using selected chemical tracers in the Perry lake basin, Kansas, USA

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**Abstract**

The ability to achieve meaningful decreases in sediment loads to reservoirs requires a determination of the relative importance of sediment sources within the contributing basins. In an investigation of sources of fine-grained sediment (clay and silt) within the Perry Lake Basin in northeast Kansas, representative samples of channel-bank sources, surface-soil sources (cropland and grassland), and reservoir bottom sediment were collected, chemically analyzed, and compared. The samples were sieved to isolate the <63 $\mu$m fraction and analyzed for selected nutrients (total nitrogen and total phosphorus), organic and total carbon, 25 trace elements, and the radionuclide cesium-137 ($^{137}$Cs). On the basis of substantial and consistent compositional differences among the source types, total nitrogen (TN), total phosphorus (TP), total organic carbon (TOC), and $^{137}$Cs were selected for use in the estimation of sediment sources. To further account for differences in particle-size composition between the sources and the reservoir bottom sediment, constituent ratio and clay-normalization techniques were used. Computed ratios included TOC to TN, TOC to TP, and TN to TP. Constituent concentrations (TN, TP, TOC) and activities ($^{137}$Cs) were normalized by dividing by the percentage of clay. Thus, the sediment-source estimations involved the use of seven sediment-source indicators. Within the Perry Lake Basin, the consensus of the seven indicators was that both channel-bank and surface-soil sources were important in the Atchison County Lake and Banner Creek Reservoir subbasins, whereas channel-bank sources were dominant in the Mission Lake subbasin. On the sole basis of $^{137}$Cs activity, surface-soil sources contributed the most fine-grained sediment to Atchison County Lake, and channel-bank sources contributed the most fine-grained sediment to Banner Creek Reservoir and Mission Lake. Both the seven-indicator consensus and $^{137}$Cs indicated that channel-bank sources were dominant for Perry Lake and that channel-bank sources increased in importance with distance downstream in the basin.

**Key Words:** Sediment, Source, Tracer, Perry Lake, Kansas

## 1 Introduction

Sediment is a primary concern as related to several important issues including water quality, aquatic habitat, and reservoir water-storage capacity. In the United States, billions of dollars have been spent over the past several decades to control soil and channel-bank erosion and mitigate the effects (Pimentel et al., 1995; Shields et al., 1995; Morris and Fan, 1998; Tegtmeier and Duffy, 2004). In 2005, the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) spent an estimated $30 million in Kansas for programs that either directly or indirectly addressed soil erosion (Paul Gallagher, USDA NRCS, personal communication, 2005). Examples of attempts to reduce erosion and sediment loads in streams include the implementation of best management practices (BMPs) perhaps as part of the total maximum daily load (TMDL) process (U.S. EPA, 1991), construction of small impoundments, and channel stabilization.

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Attempts to decrease sediment loads in streams continue despite the fact that a fundamental question typically is unanswered. The question is whether the sediment load originates mostly from channel or surface-soil sources within a basin. Determination of sediment sources is essential for the design of effective management strategies to achieve meaningful reductions in sediment loads and yields (Collins and Walling, 2004; Walling, 2005).

The science of sediment-source discrimination (fingerprinting) continues to evolve. Beyond what is described here, additional information on the history of the science is provided elsewhere (Collins and Walling, 2004; Walling, 2005). Previous sediment-source studies have varied considerably in several respects including: the size of the area, the sampling strategy, and the suite of constituents analyzed. Areas studied have ranged in size from basins less than 10 $km^2$ to thousands of $km^2$ (Collins et al., 1997a, 1997b; Wallbrink et al., 1998; Nagle and Ritchie, 1999; Russell et al., 2001; Collins and Walling, 2002).

Sampling strategies have varied as to the type of sediment sampled, the number of samples collected, and the depth of the sampling. Most studies to date have relied on a sampling and comparison of source materials (typically, channel banks and surface soils) and suspended sediment (Olley et al., 1993; Collins et al., 1998; Walling et al., 1999; Motha et al., 2003; Gruszowski et al., 2003). Alternatively, deposited sediments also have been used (Foster and Walling, 1994; Owens et al., 1999; Jenns et al., 2002; Miller et al., 2005). Presently, there are no guidelines for the optimum number of samples necessary to adequately characterize sediment sources (Collins and Walling, 2004). The number of samples per source type in previous studies has ranged from less than 10 (Walling et al., 1993; Nagle and Ritchie, 1999) to as many as 50 (Walling, 2005). Depth of sampling (vertically into surface soils and horizontally into channel banks), when reported, has ranged from 0.5 cm (Wallbrink et al., 1998) to 10 cm (Peart, 1993; Nagle and Ritchie, 1999) with 2 cm being the most common (Collins et al., 1997a, 1997b, 1997c; Russell et al., 2001; Walling, 2005).

The search for a single diagnostic sediment property has proven elusive, and it is now generally accepted that use of multiple sediment properties is necessary to effectively discriminate between sediment sources (Russell et al., 2001; Collins and Walling, 2002, 2004). Types of sediment properties commonly used have included geochemical, mineralogical, mineral magnetic, and radionuclide (Walling, 2005).

This paper describes an investigation of sediment-source allocation for Perry Lake, a large reservoir on the Delaware River in northeast Kansas (Fig. 1). Completed in 1969 by the U.S. Army Corps of Engineers (USCOE), the reservoir is used for flood control, water supply, recreation, fish and wildlife habitat, water-quality control, and navigation supplementation (Ken Wade, U.S. Army Corps of Engineers, personal communication, 2005). The original design life for Perry Lake was 100 years (U.S. Army Corps of Engineers, 1973). On the basis of results of a 2001 sedimentation survey, Juracek (2003) estimated that about 23% of the original conservation-pool, water-storage capacity of the lake (about 300 million $m^3$) was filled with sediment. Sedimentation in the reservoir has occurred at a rate almost twice as fast as originally projected by USCOE. Objectives of the study reported herein were to: (1) determine if the majority of the fine-grained sediment (clay and silt) deposited in Perry Lake originated from the erosion of channel banks or surface soils, and (2) assess whether or not the relative importance of the sediment sources changed with distance downstream in the basin. The use of a nested approach (involving the sampling of subbasin reservoirs) to address the second objective was believed to be unique.

## 2 Description of perry lake basin

The Perry Lake Basin, which is essentially synonymous with the Delaware River Basin (except for the 30-$km^2$ area located downstream from the dam), is an area of about 2,890 $km^2$ that drains part of northeast Kansas (Figs. 1 and 2). In addition to the Delaware River, several small tributaries contribute flow directly to the reservoir (Fig. 2).

The Delaware River Basin is located within the Dissected Till Plains of the Central Lowland physiographic province (Fenneman, 1946; Schoewe, 1949). This section is characterized by dissected deposits of glacial till that consist of silt, clay, sand, gravel, and boulders that overlie bedrock of primarily shale and limestone, with some sandstone (Jordan and Stamer, 1995). Maximum local relief is about 60 m. Slopes in the basin range from nearly level to gently sloping on the flood plains and from gently sloping to steep in the uplands. Generally, slopes are less than 10% but locally may be as steep as 25 to 40% (U.S. Department of Agriculture, Soil Conservation Service, 1960, 1977, 1979, 1982, 1984).

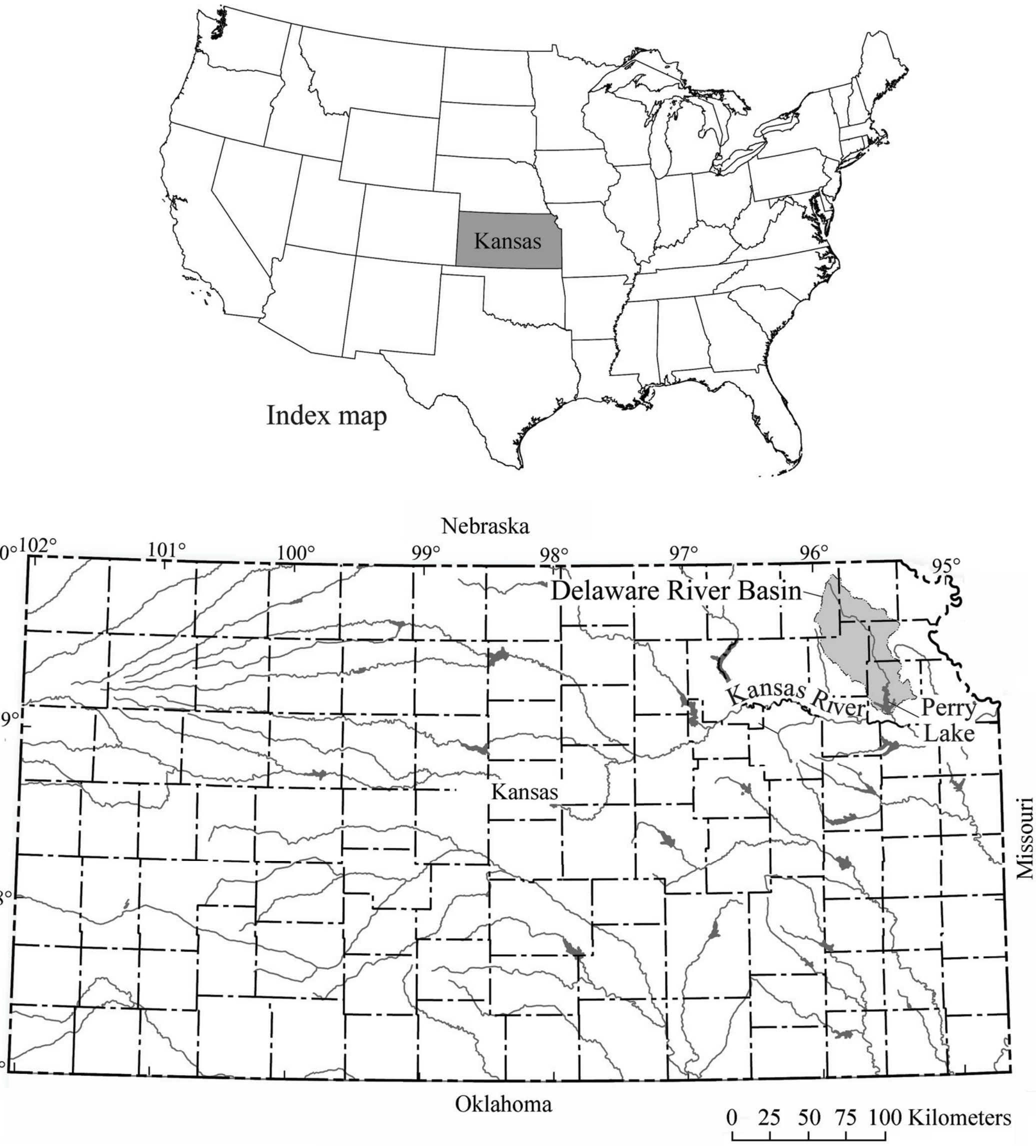


**Fig. 1** Location of Perry Lake Basin in Kansas

Soils in the basin generally are classified as mollisols (Hausenbuiller, 1985). Depth-weighted, mean soil permeability in the Delaware River Basin averages about 1.3 cm/hr. Generally, soil permeability is less in the uplands (typically 1.0 cm/hr or less) and greater in the flood plains of the principal river and streams (typically 2.8 to 3.3 cm/hr) (Juracek, 2000). Typically, there is an inverse relation between soil permeability and runoff; that is, as soil permeability decreases, the potential for runoff increases. Soil erodibility is relatively uniform throughout the basin (U.S. Department of Agriculture, 1994).

Long-term mean annual precipitation in the Delaware River Basin ranges from about 89 cm at Horton, Kansas (period of record 1900–2006), in the northern part of the basin, to about 98 cm at Oskaloosa, Kansas (period of record 1958–2006), in the south (High Plains Regional Climate Center, 2007). Most of the annual precipitation occurs during the growing season (generally April–September). Land use (1988–90) in the Delaware River Basin is mostly agricultural with grassland and cropland accounting for about 50 and 40% of the basin, respectively (Table 1) (Kansas Applied Remote Sensing Program, 1993).

## 3 Methods

Differences in the composition of the source materials, compared to the deposited sediment, can be used to estimate the relative importance (i.e., in terms of the amount of sediment contributed) of the sources in a given basin. Samples of channel banks, surface soils (cropland and grassland), and recently deposited reservoir bottom sediment were collected, chemically analyzed, and compared to estimate fine-grained sediment sources in the Perry Lake Basin. Reservoir bottom sediment provides an integrated and representative sample of the sediment originating from a basin (Smol, 2002).

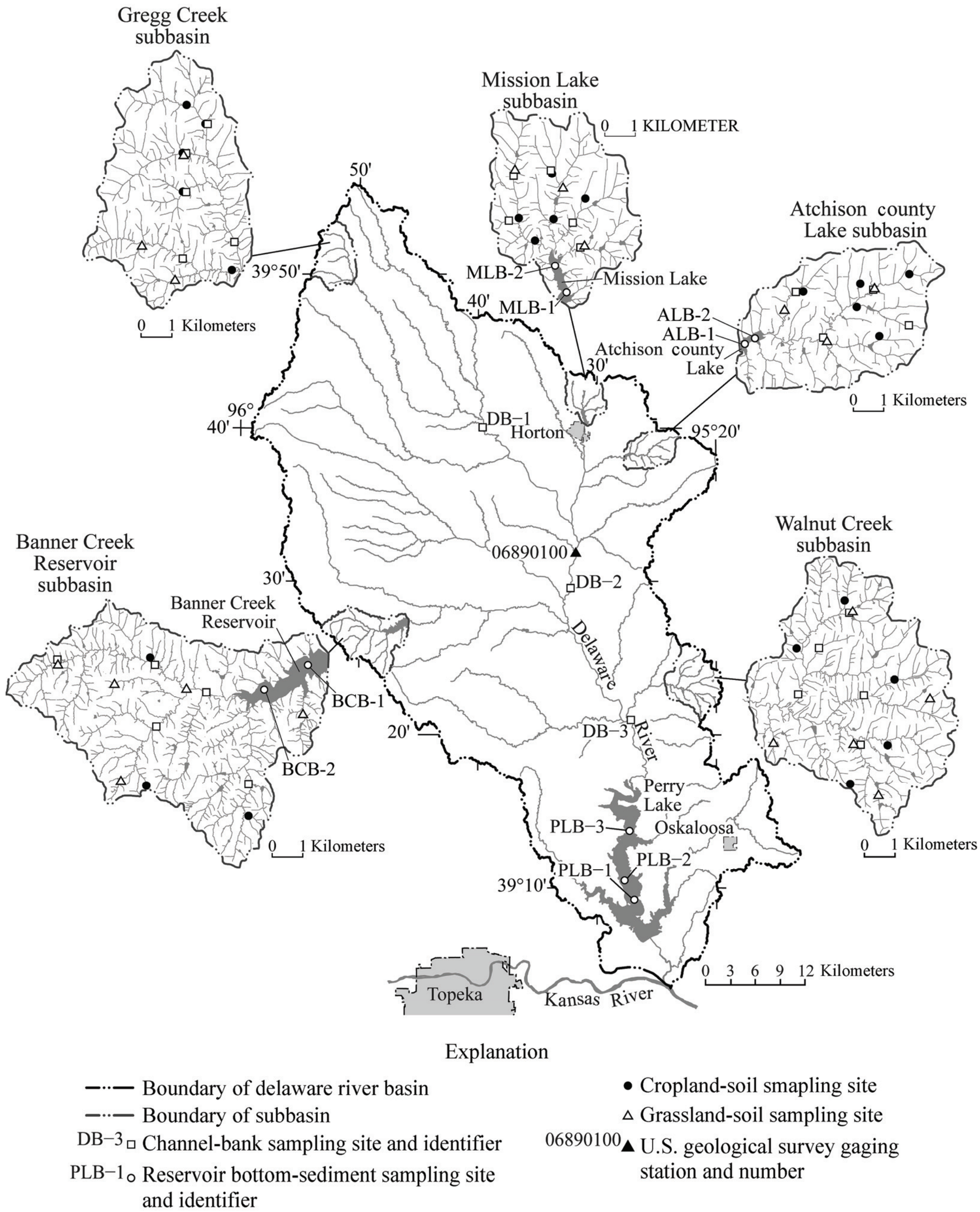


**Fig. 2** Location of sampling sites in Perry Lake Basin

3.1 Site selection

Five subbasins in the Perry Lake Basin were selected for sampling to provide a geographically representative sample of conditions in the basin and to enable an assessment of compositional differences in sediment sources among subbasins. The subbasins, which represented different land-use combinations, were Atchison County Lake, Banner Creek Reservoir, Gregg Creek, Mission Lake, and Walnut Creek (Table 1 and Fig. 2). The channel banks of the Delaware River also were sampled at three main-stem locations (Fig. 2, sites DB-1, DB-2, and DB-3).

**Table 1** Land use in the Delaware River Basin and five selected subbasins, northeast Kansas, 1988–1990 (Land-use data from Kansas Applied Remote Sensing Program, 1993)

| Basin or subbasin (Fig. 2) | Approxi- mate basin size ($km^2$) | Land use, in percentage of basin or subbasin | | | | | |
|---|---|---|---|---|---|---|---|
| | | Cropland | Grassland | Woodland | Urban | Water | Other |
| Delaware River[a] | 2,920 | 40.3 | 49.6 | 7.2 | 0.5 | 2.3 | 0.1 |
| Atchison County Lake | 24 | 75.6 | 21.9 | 1.0 | 0 | 1.4 | 0 |
| Banner Creek Reservoir | 49 | 12.5 | 75.6 | 7.4 | 0 | 4.5 | 0 |
| Gregg Creek | 31 | 69.7 | 28.0 | 2.1 | 0 | .2 | 0 |
| Mission Lake | 22 | 70.2 | 24.9 | 1.3 | .3 | 3.1 | .1 |
| Walnut Creek | 38 | 59.9 | 35.2 | 3.5 | 0 | 1.0 | .3 |

The Delaware River Basin includes the 2,890-$km^2$ Perry Lake Basin.

Within each of the five subbasins, three to five sampling sites were selected to represent each of the potential sources of sediment (Fig. 2). Specifically, the sediment sources considered were channel banks, cropland soil, and grassland soil. The small number of samples used to characterize the channel-bank and surface-soil sources in each of the subbasins is of possible concern; however, the collection of additional samples would not necessarily guarantee improved characterization. Presently, there are no guidelines for the optimum number of samples necessary to effectively characterize sediment sources (Collins and Walling, 2004).

For the cropland- and grassland-soil sampling sites, locations were selected that likely would contribute sediment to the nearby stream channel during runoff. Site selection included location in an area that sloped toward a channel and from which any runoff would drain to the channel. Typically, each sampling site was located within 15 m upslope from a conduit (i.e., a depression, drainage ditch, gully, or tile drain) that would carry flow to a channel during runoff. In addition, the grassland sampling sites were selected at locations where continuous grassland existed for at least 30 years and typically longer.

Locations for channel-bank sampling were selected that likely would contribute sediment resulting from bank erosion. Sampling sites selected typically were cutbanks characterized by steep unvegetated slopes that exhibited evidence of active erosion (e.g., exposed tree roots).

Reservoir bottom-sediment sampling sites were selected to assess upstream-to-downstream variability within each reservoir. Two sites (i.e., one in the downstream one-third and one in the upstream one-third of the reservoir) were sampled in Atchison County Lake, Banner Creek Reservoir, and Mission Lake. Three sites were sampled in Perry Lake (Fig. 2). The bottom-sediment samples were collected in relatively deep water where the sediment was least likely to be disturbed.

3.2 Sample collection

All samples were collected in the spring of 2005. Within the Perry Lake Basin, a total of 27 channel-bank, 23 cropland-soil, 19 grassland-soil, and 9 reservoir bottom-sediment samples were collected (Fig. 2). Channel-bank, cropland-soil, and grassland-soil samples were collected to a depth of about 2 cm (i.e., horizontally into the channel banks and vertically into the soils) to obtain samples of material that were likely to be eroded (Collins et al., 1997a; Collins and Walling, 2002; Walling, 2005).

Channel-bank samples were collected using an aluminum hand trowel. At each site, a vertical, unvegetated section of bank (i.e., a cutbank) was selected for sampling. The objective of the sampling was to obtain bank material that was expected to be chemically distinct from the overlying topsoil (Peart and Walling, 1986; Walling and Woodward, 1995). Generally, the middle one-third of the bank was sampled. Care was taken to avoid sampling the overlying topsoil by observing the depth of the topsoil (as frequently evidenced by a darker color and (or) the depth of the root zone). Part of the sampled interval sometimes required scraping to remove material (e.g., accumulations of loose particles or dried mud) that potentially contained topsoil and provide a clean surface for sampling. Also, the lower part of the sampled interval often had to be excavated to remove accumulated material at the base of the bank and expose a clean surface for sampling. The sample was collected along one to three vertical tracks in the bank.

Cropland-soil samples were collected using an aluminum hand trowel. Collection of the grassland-soil samples was a two-step process. First, a steel spade was used to remove the sod from an area of about 0.09 $m^2$. Then, the soil sample was separated from the roots using the aluminum hand trowel. The samples collected for both the cropland- and grassland-soil sites typically were representative of the A horizon in the soil profile. The volume of material collected at each channel-bank, cropland-soil, and grassland-soil sampling site was about 0.006 $m^3$.

The objective of the reservoir bottom-sediment sampling was to collect undisturbed surficial samples that represented the most recently deposited sediment (Foster and Walling, 1994; Zhang and Walling, 2005). These samples were collected using a box corer (Horowitz, 1991; Mudroch and Azcue, 1995). The box corer, which was lowered by rope from a boat, has a pin-activated steel jaw. When the corer encounters the lakebed, a tug of the rope releases the pin, and the steel jaw shuts thereby capturing a sample of the bottom sediment. Inside dimensions of the transparent plastic liner used in the box corer were 14 cm long by 14 cm wide by 20 cm deep. The top (most recently deposited) 2 cm of sediment was collected from each box core using a plastic spoon.

### 3.3 Sample preparation

Preparation of the individual channel-bank, cropland-soil, and grassland-soil samples for subsequent constituent analyses involved several steps. Each sample initially was placed on a clean plastic sheet for examination and removal of unwanted components (e.g., roots, sticks, grass, leaves, living organisms, and gravel). Then, the material was dried, disaggregated, and homogenized using the aluminum hand trowel. Individual channel-bank, cropland-soil, and grassland-soil samples for the Mission Lake subbasin were analyzed separately to provide an indication of the variability of the composition of the source materials. Individual channel-bank, cropland-soil, and grassland-soil samples for the remaining Perry Lake subbasins were combined and analyzed as composite channel-bank, cropland-soil, and grassland-soil samples. Channel-bank samples collected along the main-stem Delaware River also were combined into one composite sample.

The composite samples required additional preparation. Prior to compositing, the individual samples were dried, disaggregated, and homogenized. The composite sample was created by measuring an equal mass of each of the individual samples and combining the material. For example, if five cropland sites were sampled for a subbasin, then 100 g (dry weight) of soil were measured for each individual sample and combined to create a 500-g composite cropland-soil sample. The composite sample was homogenized using a plastic spoon. All reservoir bottom-sediment samples were homogenized and analyzed as individual samples.

All samples were sieved to isolate the <63 $\mu$m fraction prior to constituent analyses (Collins et al., 1997a; Nagle and Ritchie, 1999; Russell et al., 2001). This step was required to minimize potential bias in constituent concentrations that could be attributable to differences in the amount of coarse particles (e.g., sand) in the samples. The <63 $\mu$m fraction also is important because it is the most chemically active fraction of sediment (Horowitz, 1991). Samples were wet sieved at the U.S. Geological Survey (USGS) Sediment Trace Element Partitioning Laboratory in Atlanta, Georgia, according to the methods presented in Guy (1969). Additionally, the sieved samples were analyzed for clay content at the USGS Earth Surface Processes Soils Laboratory in Denver, Colorado, using a laser analyzer (Harland Goldstein, USGS, personal communication, 2006). Clay was defined as particles less than or equal to 3.9 $\mu$m in size (Wentworth, 1922).

### 3.4 Constituent analyses

Use of multiple sediment properties is necessary to effectively discriminate between sediment sources (Russell et al., 2001; Collins and Walling, 2002) and to avoid false source interpretations that may result from the use of a single property (Collins et al., 1997c). Ideally, such a composite tracer includes sediment properties from several different categories including organic constituents, trace elements, and radionuclides (Collins and Walling, 2002; Walling, 2005). A universally applicable composite tracer has not been identified and may not be possible.

In this study, all samples were analyzed for nutrients (total nitrogen and total phosphorus), organic and total carbon, 25 trace elements, and cesium-137 ($^{137}$Cs). Sediment properties included in the analysis were chosen, in part, because these properties were shown to be effective in previous sediment-source studies (discussed later). A complete list of the constituents for which analyses were performed is provided in Table 2. Constituent analyses were performed at the USGS Sediment Trace Element Partitioning Laboratory in Atlanta, Georgia. Analyses of samples for total nitrogen (TN) and carbon concentrations were performed using the methods described by Horowitz et al. (2001). Analyses for total phosphorus (TP) and trace elements were performed using the methods described by Fishman and Friedman (1989), Arbogast (1996), and Briggs and Meier (1999). Analysis of samples for $^{137}$Cs activity was performed at the USGS National Water-Quality Laboratory in Denver, Colorado, using gamma-ray spectrometry (American Society for Testing and Materials, 2004). Analytical variability, assessed through the analysis of multiple split-replicate samples, typically was less than 8% (Juracek and Ziegler, 2007).

Both $^{137}$Cs and total organic carbon (TOC) have been found to be useful as tracers to distinguish surface from channel-bank sources of fine-grained sediment (Walling and Woodward, 1995; Zhang and Walling, 2005). $^{137}$Cs is strongly sorbed to the soil particles within the top few centimeters and generally does not migrate down through the soil profile (Ritchie and McHenry, 1990). $^{137}$Cs activity in channel-bank material tends to be substantially less than in surface soils due to the often near-vertical angle of the channel banks and the depth of the banks (relative to the surface soils), which typically exceeds the depth of $^{137}$Cs penetration (He and Owens, 1995; Walling and Woodward, 1995). However, where channel banks are shallow (i.e., similar to or less than the depth of the surface soils), the $^{137}$Cs activity may be similar to surface soils.

**Table 2** Chemical analyses performed on channel-bank, cropland-soil, grassland-soil, and reservoir bottom-sediment samples from the Perry Lake Basin, northeast Kansas (number in parentheses is the method reporting limit for each constituent)

| | | | |
|---|---|---|---|
| Nutrients | | | |
| Total nitrogen (TN) (100 mg/kg) | Total phosphorus (TP) (50 mg/kg) | | |
| | | | |
| Carbon | | | |
| Carbon, total organic (TOC) (0.1%) | Carbon, total (0.1%) | | |
| | | | |
| Trace elements | | | |
| Aluminum (0.1%) | Cobalt (1.0 mg/kg) | Nickel (1.0 mg/kg) | Titanium (0.01%) |
| Antimony (0.1 mg/kg) | Copper (1.0 mg/kg) | Selenium (0.1 mg/kg) | Uranium (50 mg/kg) |
| Arsenic (0.1 mg/kg) | Iron (0.1%) | Silver (0.5 mg/kg) | Vanadium (1.0 mg/kg) |
| Barium (1.0 mg/kg) | Lead (1.0 mg/kg) | Strontium (1.0 mg/kg) | Zinc (1.0 mg/kg) |
| Beryllium (0.1 mg/kg) | Lithium (1.0 mg/kg) | Sulfur (0.1%) | |
| Cadmium (0.1 mg/kg) | Manganese (10.0 mg/kg) | Thallium (50 mg/kg) | |
| Chromium (1.0 mg/kg) | Molybdenum (1.0 mg/kg) | Tin (1.0 mg/kg) | |
| | | | |
| Radionuclide | | | |
| Cesium-137 (1.5 Bq/kg) | | | |

TOC also is typically found in concentrations that are largest at the surface and decline with depth in the soil profile and subsoil (Walling and Woodward, 1995; Jobbagy and Jackson, 2000). Therefore, surface-soil samples tend to have larger concentrations of TOC as compared to channel-bank samples. Other constituents, such as nitrogen, phosphorus, and various trace elements, also have been used for the purpose of estimating sediment sources in basins (Collins and Walling, 2002; Walling, 2005). A suite of 30 constituents was analyzed in this study to determine which were most useful for the purpose of discriminating sources of fine-grained sediment in the Perry Lake Basin.

3.5 Estimation of sediment sources

The process of sediment-source estimation involved two steps. First, constituents were selected that clearly discriminated (fingerprinted) potential sources. Second, the selected constituents were used in a comparison between the potential sources and the reservoir bottom sediment to estimate the relative importance of individual sources (Collins et al., 1997c; Collins and Walling, 2002).

To select the constituents that provided a means for discriminating between channel-bank and surface-soil (cropland and grassland) sediment sources, four criteria were used. A constituent was selected for use in the sediment-source estimations if: (1) the constituent was detected in the channel-bank and (or) surface-soil samples; (2) the differences in the mean concentrations or activities between the sources were substantial (typically at least 20% smaller or larger such that the differences could not be attributed to analytical variability) and consistent; (3) the range of concentrations or activities for each source did not overlap with another source; and (4) the concentration or activity differences between the sources were statistically significant.

Nonparametric Wilcoxon rank-sum tests (exact form) (Helsel and Hirsch, 1992) were used to determine if statistically significant differences in constituent concentrations or activities existed between the channel-bank and cropland sources, between the channel-bank and grassland sources, and between the cropland and grassland sources. Differences between two sources were considered to be statistically significant if the probability (two-sided p-value) of rejecting a correct hypothesis (in this case, no difference) was less than or equal to 0.05. This analysis was performed for the Perry Lake Basin using the composite results for the five subbasins (i.e., $N = 5$).

Selected constituents were used in a subsequent analysis to estimate whether the majority of the bottom sediment in each reservoir originated from channel-bank or surface-soil sources. Sediment-source estimations involved a comparison of the concentrations or activities for the selected constituents between the reservoir bottom sediment and the sediment sources for each reservoir. A sediment-source estimation was completed separately for Atchison County Lake, Banner Creek Reservoir, Mission Lake, and Perry Lake. Comparison of the results for the three small subbasin reservoirs to Perry Lake provided an indication of whether or not the relative importance of the sediment sources changed with distance downstream in the basin.

## 4 Results and discussion

4.1 Constituents selected for sediment-source estimations

Constituents used in the sediment-source estimations were selected on the basis of four criteria. The first required that the candidate constituents be detected in the channel-bank and (or) surface-soil samples for all basins sampled. On the basis of this criterion, silver, molybdenum, sulfur, thallium, and uranium were eliminated.

The second criterion required that the candidate constituents had original concentrations or activities that were substantially (typically smaller or larger by at least 20%) and consistently different among the sources (channel bank, cropland soil, and grassland soil). Adherence to this criterion resulted in the elimination of the remaining trace elements because the original concentrations among the three sources generally were similar or did not vary in a consistent manner (Juracek and Ziegler, 2007). Four candidate constituents satisfied the second criterion—TN, TP, TOC, and $^{137}$Cs. For all four candidates, the original channel-bank concentrations or activities typically were substantially smaller than the original cropland-soil and grassland-soil concentrations or activities for all five Perry Lake subbasins. With several exceptions, the original cropland-soil concentrations or activities typically were substantially smaller than the original grassland-soil concentrations or activities (Table 3). Relative magnitudes of the $^{137}$Cs activity measured for the channel-bank, cropland-soil, and grassland-soil sources in this study were consistent with results reported elsewhere (Ritchie and McHenry, 1990; Walling and Woodward, 1995; Zhang and Walling, 2005). Total carbon, which typically consisted mostly of organic carbon in the samples analyzed, was eliminated because it was considered to be redundant with TOC.

The third criterion required that the candidate constituents had concentration or activity ranges that did not overlap among the three sediment sources. Overlap was assessed by a comparison of the original constituent concentrations or activity for the individual channel-bank, cropland-soil, and grassland-soil sampling sites within the Mission Lake subbasin. For all four candidate constituents, the range in concentrations or activity for the channel-bank sampling sites was less than, and did not overlap with, the ranges in concentrations or activity for the cropland-soil and grassland-soil sampling sites. Conversely, for all four candidate constituents, the range in concentrations or activity for the cropland-soil and grassland-soil sampling sites generally were similar with substantial overlap (Juracek and Ziegler, 2007). Because of the overlap in the Mission Lake subbasin and potentially elsewhere, the two sources were combined into a single surface-soil sediment source. Cropland-soil and grassland-soil constituent concentrations or activity were combined for each of the five subbasins using a weighted averaging approach with land use (Table 1) as the weighting factor. Computed surface-soil concentrations or activity for the four candidate constituents are provided in Table 3.

**Table 3** Original total nitrogen, total phosphorus, and total organic carbon concentrations and cesium-137 activity for channel-bank, cropland-soil, grassland-soil, and reservoir bottom-sediment samples collected in the Perry Lake Basin, northeast Kansas, March–May 2005

| Location (Fig. 2) | Source materials | | | | Reservoir bottom sediment | | |
|---|---|---|---|---|---|---|---|
| | Channel banks[a] | Cropland soils[a] | Grassland soils[a] | Surface soils[b] | Downstream site | Middle site | Upstream site |
| Total nitrogen, mg/kg | | | | | | | |
| Atchison County Lake subbasin | 400 | 1,400 | 2,300 | 1,600 | 2,600 | -- | 2,100 |
| Banner Creek Reservoir subbasin | 600 | 1,700 | 2,600 | 2,500 | 2,300 | -- | 2,000 |
| Gregg Creek subbasin | 1,100 | 1,600 | 2,600 | 1,900 | -- | -- | -- |
| Mission Lake subbasin | 620 | 2,200 | 2,600 | 2,300 | 2,600 | -- | 1,800 |
| Walnut Creek subbasin | 500 | 1,500 | 2,800 | 2,000 | -- | -- | -- |
| | | | | | | | |
| Delaware River | 400 | -- | -- | -- | -- | -- | -- |
| Perry Lake | -- | -- | -- | -- | 1,800 | 2,000 | 1,400 |
| Total phosphorus, mg/kg | | | | | | | |
| Atchison County Lake subbasin | 370 | 440 | 790 | 520 | 1,000 | -- | 800 |
| Banner Creek Reservoir subbasin | 510 | 720 | 740 | 740 | 860 | -- | 770 |
| Gregg Creek subbasin | 390 | 540 | 610 | 560 | -- | -- | -- |
| Mission Lake subbasin | 390 | 610 | 640 | 620 | 1,100 | -- | 670 |
| Walnut Creek subbasin | 370 | 600 | 620 | 610 | -- | -- | -- |
| | | | | | | | |
| Delaware River | 510 | -- | -- | -- | -- | -- | -- |
| Perry Lake | -- | -- | -- | -- | 930 | 1,100 | 810 |
| Total organic carbon, % | | | | | | | |
| Atchison County Lake subbasin | 0.6 | 1.4 | 2.6 | 1.7 | 2.6 | -- | 2.1 |
| Banner Creek Reservoir subbasin | .6 | 1.5 | 2.0 | 1.9 | 2.0 | -- | 1.9 |
| Gregg Creek subbasin | 1.2 | 1.4 | 2.8 | 1.8 | -- | -- | -- |
| Mission Lake subbasin | .8 | 2.4 | 2.4 | 2.4 | 2.4 | -- | 1.6 |
| Walnut Creek subbasin | .7 | 1.6 | 2.9 | 2.1 | -- | -- | -- |
| | | | | | | | |
| Delaware River | .3 | -- | -- | -- | -- | -- | -- |
| Perry Lake | -- | -- | -- | -- | 1.6 | 1.8 | 1.5 |
| Cesium-137, Bq/kg | | | | | | | |
| Atchison County Lake subbasin | 1.9 | 4.8 | 6.7 | 5.2 | 9.6 | -- | 7.8 |
| Banner Creek Reservoir subbasin | 2.6 | 4.8 | 11.5 | 10.4 | 3.3 | -- | 4.1 |
| Gregg Creek subbasin | 2.2 | 3.0 | 15.9 | 6.7 | -- | -- | -- |
| Mission Lake subbasin | .7 | 7.8 | 8.5 | 8.1 | 8.1 | -- | 4.8 |
| Walnut Creek subbasin | 0 | 4.4 | 11.1 | 7.0 | -- | -- | -- |
| | | | | | | | |
| Delaware River | 0 | -- | -- | -- | -- | -- | -- |
| Perry Lake | -- | -- | -- | -- | 1.9 | 6.3 | 2.2 |

[a] Composite of three to five sites.

[b] Surface-soil constituent concentrations and activities computed as the weighted average of the cropland-soil and grassland-soil constituent concentrations and activities for each subbasin using land use as the weighting factor. Land-use information for the subbasins is provided in Table 1.

The final criterion required that the candidate constituents had concentration or activity differences between the sediment sources that were statistically significant. To test for statistical significance, nonparametric Wilcoxon rank-sum tests were performed using the composite results for the five subbasins (Table 3). Differences in mean concentrations or activity between the channel-bank and cropland sources, between the channel-bank and grassland sources, and between the channel-bank and surface-soil sources (i.e., the weighted average of the cropland and grassland sources) were significant at the 0.05 level for all four candidate constituents. Differences between the cropland and grassland sources were significant at the 0.05 level for TN, TOC, and $^{137}$Cs. Differences between the cropland and grassland sources were significant at the 0.08 level for TP.

On the basis of the four criteria, TN, TP, TOC, and $^{137}$Cs were selected for use in an analysis to estimate whether the majority of the reservoir bottom sediment originated from channel-bank or surface-soil sources within the Perry Lake Basin and the three small reservoir subbasins. $^{137}$Cs likely is the most reliable sediment-source indicator of the four selected constituents because it is known to be conservative in the environment (Ritchie and McHenry, 1990; Nagle and Ritchie, 1999; Motha et al., 2002). Restated, $^{137}$Cs is minimally affected by the processes of sediment generation and delivery and biological activity. Conservative behavior is less certain for the other three constituents. For several constituents that have been used as tracers of sediment sources, additional research is needed to verify the assumption of conservative behavior (Collins et al., 1997a; Motha et al., 2002; Walling, 2005). In this paper, the results presented are limited to the four selected constituents. Results for all 30 constituents are provided in Juracek and Ziegler (2007).

In-stream sediment usually is enriched in fine particles compared to the source materials (Walling, 1983; Walling and Woodward, 1992). Consequently, constituent concentrations and $^{137}$Cs activity associated with in-stream sediment typically are greater than in the source materials (Horowitz, 1991; He and Walling, 1996). A particle-size or specific surface-area normalization generally is required prior to sediment-source estimation and site-to-site or sample-to-sample comparisons. Sediment and source materials with differing particle-size compositions cannot be directly compared unless a normalization is used (Forstner and Wittmann, 1981; Collins et al., 1997a).

A partial particle-size normalization was done by sieving all samples to isolate the <63 $\mu$m fraction prior to chemical analyses. However, particle-size effects still were indicated by the fact that constituent concentrations for the reservoir sediment samples frequently were substantially larger than the concentrations for the source samples. Suspected particle-size differences were confirmed by additional analyses that measured a substantially larger percentage of clay-sized particles in the reservoir sediment samples. Within each reservoir, the largest clay content was measured for the downstream sample(s). This pattern was consistent with the fact that sediment tends to become finer grained with distance downstream in a reservoir (Morris and Fan, 1998). Two separate approaches were used to address the particle-size issue—one involved the use of constituent ratios and the other a particle-size normalization. Resultant ratio and particle-size normalized datasets both were used for the purpose of estimating sediment sources.

Constituent ratios are less susceptible to apparent enrichment effects and may be directly compared without the need for a particle-size normalization, provided the constituents involved behave in the same way with respect to enrichment. Thus, constituents used in a ratio both should be part of either the organic or inorganic fraction of the sediment (Walling and Kane, 1984). In this study, TOC:TN, TOC:TP, and TN:TP ratios were computed for use in the sediment-source estimations (Walling and Kane, 1984; Peart and Walling, 1986; D.E. Walling, University of Exeter, personal communication, 2006).

Particle-size normalization was achieved by dividing the constituent concentrations (TN, TP, TOC) and activity ($^{137}$Cs) by the percentage of clay for each source and sediment sample (Horowitz, 1991; Collins et al., 1998; Walling et al., 1999; Gruszowski et al., 2003). Limitations of this type of particle-size normalization include the assumptions that: (1) all, or nearly all, of the constituents of interest are contained in the size fraction of interest (in this case, the clay fraction) (Horowitz, 1991); and (2) there is a linear relation between constituent concentration or activity and particle size (Russell et al., 2001). In sum, the sediment-source estimations involved the use of seven indicators (three constituent ratios and the clay-normalized concentrations or activity for four constituents).

For a clay-normalized indicator to be valid for sediment-source estimation, it was required that the constituent concentration or activity not be solely a function of particle size. In other words, if an indicator varied only in direct relation to clay content, the indicator would not be valid for use in sediment-source estimation because actual differences in the composition of the sources do not exist. To verify the validity of the clay-normalized indicators, the coefficient of determination ($R^2$) was computed to assess the relation between percentage of clay and TN, TP, and TOC concentrations and $^{137}Cs$ activity for the combined set of Mission Lake subbasin channel-bank, cropland-soil, grassland-soil, and reservoir bottom-sediment samples. Respectively, the $R^2$ values were 0.006, 0.39, 0.0001, and 0.0004. Thus, the four selected indicators were valid.

Particle-size normalization for clay content also was applied to the trace elements. Examination of the clay-normalized trace-element concentrations again indicated that trace elements were unusable as sediment-source indicators because the concentrations among the sources generally were similar or did not vary in a consistent manner (Juracek and Ziegler, 2007).

In addition to fine particles, in-stream sediment also is usually enriched in organic matter compared to the source materials (Walling, 1983), and constituent concentrations in sediment may be affected by differences in organic matter content (Horowitz, 1991). However, a normalization for organic matter content was not performed because the relation between organic matter and constituent concentrations is complex and difficult to generalize and because enrichment in organic matter is closely related to enrichment in fine particles (Walling, 2005). Particle-size normalization likely accounts, in part, for differences in organic matter content (Russell et al., 2001).

### 4.2 Sediment sources in the Perry Lake Basin

Estimation of the relative importance of channel-bank and surface-soil sources of fine-grained sediment was based on a simple comparison of the composition of the two sources with the composition of the reservoir bottom sediment. Because the objective was to determine which of two sources was dominant, the use of a more sophisticated, multivariate sediment-mixing model (Collins et al., 1997a; Walling, 2005) was unnecessary. For studies in which the objective is to quantify the contribution of sediment from three or more sources, use of a mixing model is required. It is important to note that constituent ratios cannot be used in mixing models because they are not linearly additive.

Within the Perry Lake Basin, sediment-source estimations were completed separately for Atchison County Lake, Banner Creek Reservoir, and Mission Lake. A sediment-source estimation was completed for Perry Lake using the information from all five subbasins.

Differences in the relative contribution of fine-grained sediment from channel-bank and surface-soil sources were indicated for the three small subbasin reservoirs. For Atchison County Lake, both channel-bank and surface-soil sources contributed substantial sediment with the surface-soil sources possibly being the larger contributor (Fig. 3). $^{137}Cs$, which likely is the most reliable of the seven sediment-source indicators used, indicated that surface-soil sources were dominant in the subbasin.

For nearby Mission Lake (Fig. 2), most of the sediment originated from channel-bank sources (Fig. 4). The difference in sediment sources between Atchison County Lake and Mission Lake is apparent despite the fact that the subbasins are very similar in most respects, including basin size and land use (Table 1). In part, the difference may reflect variations in land-management practices and (or) the stability of the channel banks. For example, the amount of sediment derived from cropland will vary depending on several factors including soil type, slope, crop type, tillage practices, precipitation (timing, amount, intensity), and proximity to the stream-channel network. Likewise, the amount of sediment derived from channel banks will be affected by several factors including channel stability, channel geometry, flow properties, bank composition, and vegetation (Knighton, 1998).

Both channel-bank and surface-soil sources contributed substantial sediment to Banner Creek Reservoir (Fig. 5). $^{137}Cs$ indicated that channel-bank sources were the largest contributor, as was the case for Mission Lake. In addition to the factors previously cited, differences among the three small subbasin reservoirs may reflect the fact that a small percentage of a basin can account for a large percentage of the sediment yield (Morris and Fan, 1998; Russell et al., 2001). Importantly, the relative contribution of various sediment sources likely will change over time.

Channel banks were the dominant sediment source for Perry Lake (Fig. 6). When compared to the results for the three small subbasin reservoirs, this finding indicated that channel-bank sources increased in importance with distance downstream in the Perry Lake Basin. The tendency for channel erosion becoming more important with distance downstream in a basin has been reported elsewhere (Knighton, 1998; Lawler et al., 1999; Walling, 2005).

Some indicator values (i.e., a constituent ratio or a clay-normalized constituent concentration or activity) for the reservoir sediment were outside the range of values provided by the end member channel-bank and surface-soil sources (Figs. 3–6). Several possible explanations, in part, may account for this situation including: (1) analytical variability; (2) use of composite samples to represent sources; (3) alteration during transport and (or) by in-lake geochemical processes; and (4) unsampled sources.

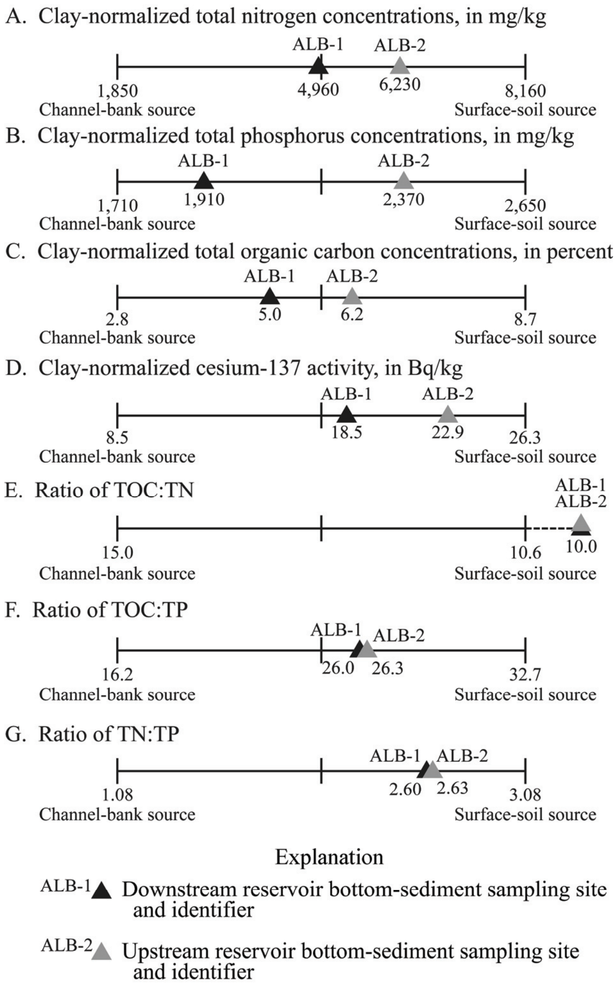


**Fig. 3** Comparison of channel-bank, surface-soil, and reservoir bottom-sediment composition for Atchison County Lake, Kansas

Within the Perry Lake Basin, the relative contribution of sediment from the erosion of channel banks in the tributary streams compared to the main-stem Delaware River was uncertain. Compositionally, a comparison of the Delaware River channel-bank material with the channel-bank material sampled for the five subbasins indicated general similarity for the four selected constituents used in the sediment-source estimations (Juracek and Ziegler, 2007).

Because channel-bank erosion inevitably mobilizes some surface soil (e.g., material at the top of a cutbank), the composition of the bank-derived sediment may vary somewhat from the composition of the channel-bank sources determined by sampling that was limited to the subsurface part of the banks. Specifically, the concentration or activity for the four selected constituents may be somewhat larger for the bank-derived sediment than was indicated by the channel-bank samples analyzed. Whether the compositional difference is significant or negligible is not known. Thus, in a given basin, the contribution of sediment from channel-bank sources may or may not be somewhat larger than what was suggested by the composition of the reservoir bottom sediment. Additional research is needed to assess the compositional effect of partial versus complete channel-bank sampling.

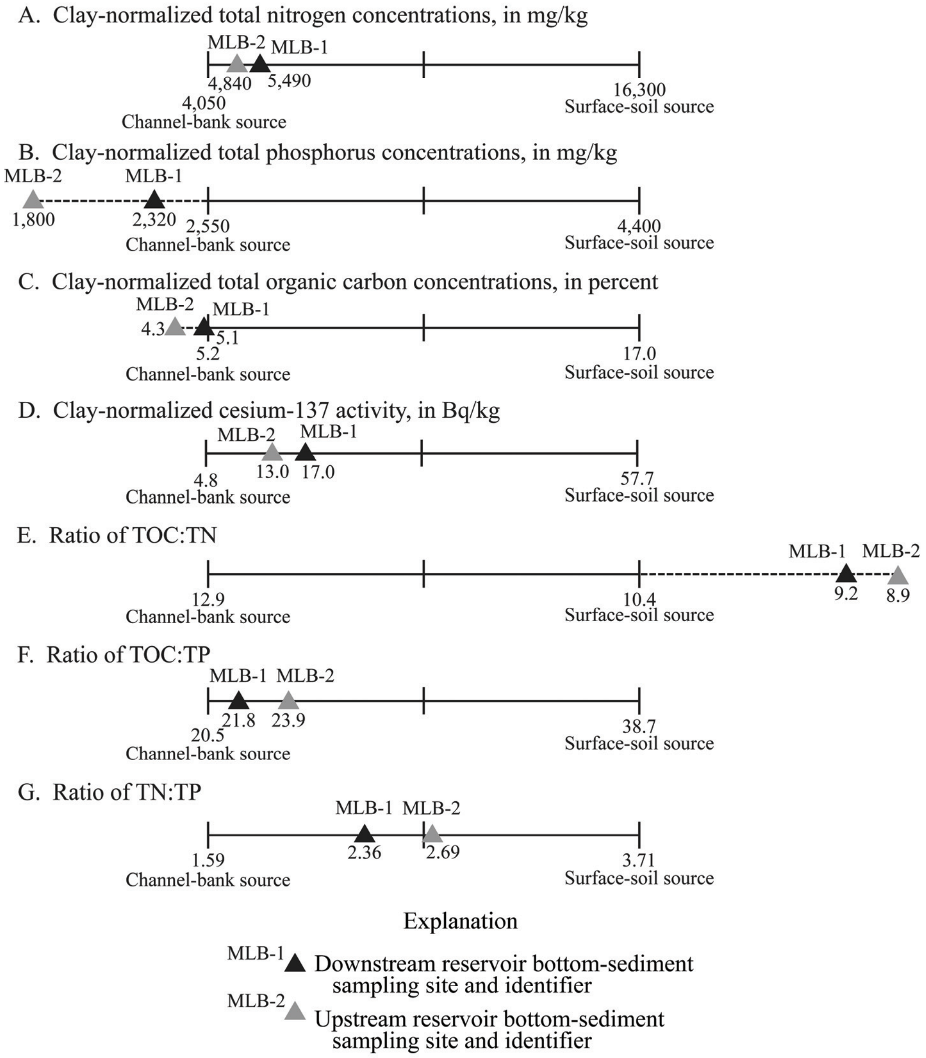


**Fig. 4** Comparison of channel-bank, surface-soil, and reservoir bottom-sediment composition for Mission Lake, Kansas

Another uncertainty is the role of channel beds as a source of fine-grained sediment. The question is whether the beds are truly a source or just a temporary storage location from which deposited sediment is subsequently remobilized and transported downstream. Pronounced bed erosion (downcutting) would be required for the beds to be a true source. This may be unlikely upstream from reservoirs because the reservoirs provide base-level control. At the gaging station on the Delaware River near Muscotah, Kansas (station 06890100, Fig. 2), stage-discharge relations indicated that the channel bed at this location has been stable (no downcutting) for at least the last 5 years. Thus, the alternate scenario of temporary storage and subsequent remobilization is more likely. In this scenario, the original source of any fine-grained sediment stored on the channel bed would be channel banks and surface soils. However, because minimal flow velocity is required to suspend and transport fine-grained particles, the bed sediment tends to consist mostly of coarser sand and gravel (as the fine particles are carried on downstream).

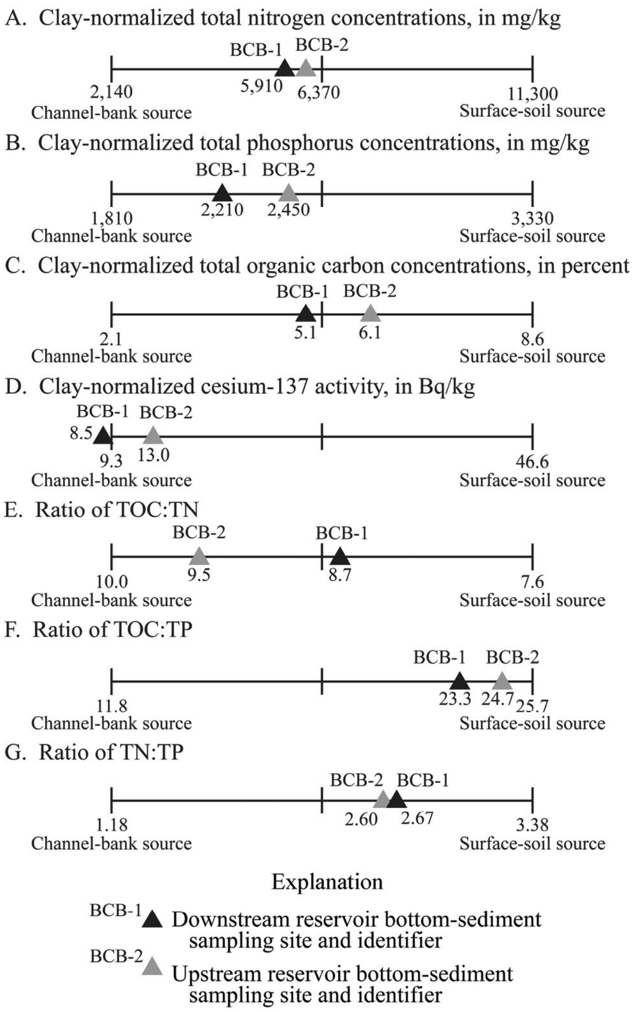


**Fig. 5** Comparison of channel-bank, surface-soil, and reservoir bottom-sediment composition for Banner Creek Reservoir, Kansas

An additional complicating factor is shoreline erosion within Perry Lake, which may have contributed sediment that is chemically similar to channel-bank sources within the upstream basin. Sampling of actively eroding shoreline in Perry Lake was not included as part of this study.

Because the relative contribution of fine-grained sediment from channel-bank and surface-soil sources was shown to vary with location in the Perry Lake Basin, it follows that the effectiveness of measures implemented to decrease erosion and in-stream sediment loads may improve if such locational differences are taken into account. For example, in the Atchison County Lake subbasin, the sediment-source estimation indicated that priority be given to surface-soil erosion. However, any sediment management strategy needs to be carefully conceived to avoid such unintentional consequences as problem transference. Case in point, channel erosion typically increases when in-stream sediment loads are small. Thus, effective erosion control on cropland may result in increased channel erosion if the runoff is not controlled as well (National Research Council, 1993). Given that the relative contribution of sediment from channel-bank and surface-soil sources can vary within and between basins and over time, basin-specific strategies for sediment management and monitoring appear to be appropriate.

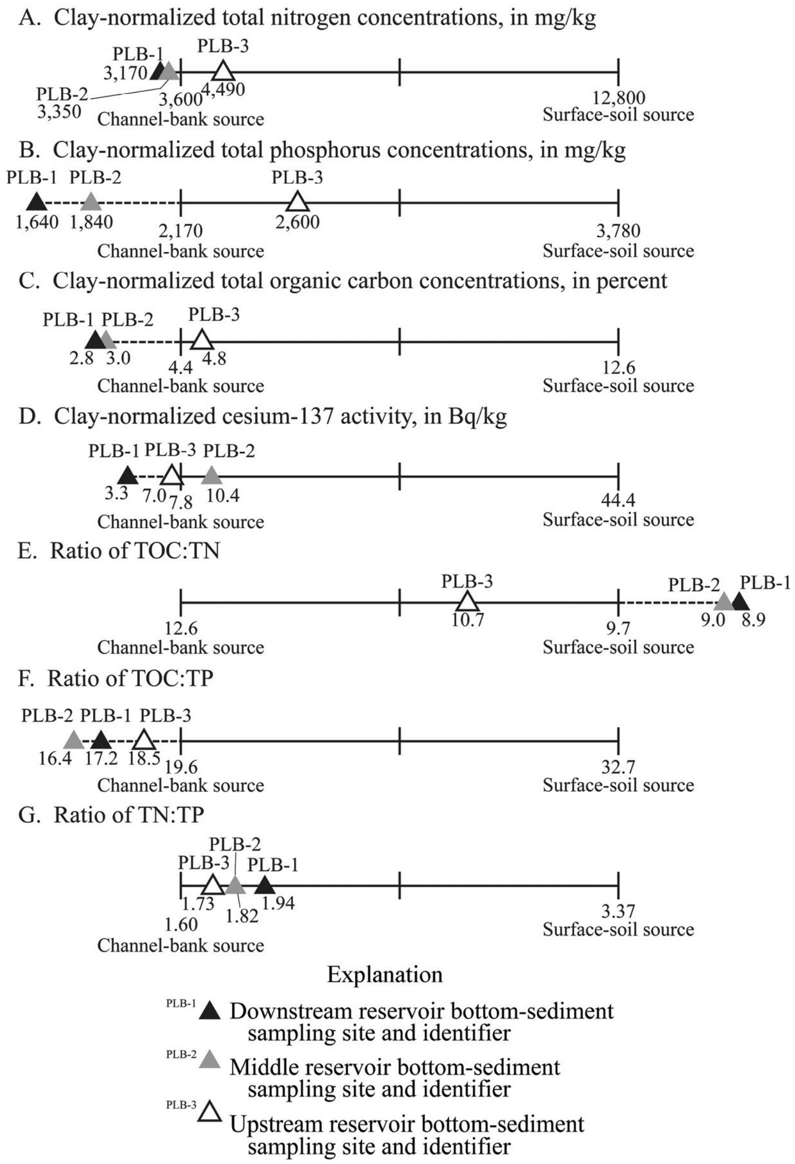


**Fig. 6** Comparison of channel-bank, surface-soil, and reservoir bottom-sediment composition for Perry Lake, Kansas

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