U.S. Department of the Interior
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Historical Contributions of Phosphorus From Natural and Agricultural Sources and Implications for Stream Water Quality, Cheney Reservoir Watershed, South-Central Kansas

By LARRY M. POPE, CHAD R. MILLIGAN, and DAVID P. MAU

Water-Resources Investigations Report 02–4021

Prepared in cooperation with the
CITY OF WICHITA, KANSAS

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U.S. Department of the Interior

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
acre-foot (acre-ft)	1,233	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
degree Fahrenheit (°F)	([1])	degree Celsius
foot (ft)	0.3048	meter
gram per second (g/s)	0.0022	pound per second
inch (in.)	2.54	centimeter
mile (mi)	1.609	kilometer
milligram per kilogram (mg/kg)	1.6×10^{-5}	ounce per pound
milligram per liter (mg/L)	1.0	part per million
millimeter (mm)	0.03937	inch
pound (lb)	0.4536	kilogram
pound per acre (lb/acre)	1.121	kilogram per hectare
square mile (mi^2)	2.590	square kilometer

[1]Temperature can be converted to degrees Celsius (°C) or degrees Fahrenheit (°F) by the equations:

$$^{o}C = 5/9\ (^{o}F - 32)$$
$$^{o}F = 9/5\ (^{o}C) + 32.$$

Historical Contributions of Phosphorus From Natural and Agricultural Sources and Implications for Stream Water Quality, Cheney Reservoir Watershed, South-Central Kansas

By Larry M. Pope, Chad R. Milligan, *and* David P. Mau

Abstract

An examination of soil cores collected from 43 nonagricultural coring sites in the Cheney Reservoir watershed of south-central Kansas was conducted by the U.S. Geological Survey in September 1999. The cores were collected as part of an ongoing cooperative study with the city of Wichita, Kansas. The 43 sites (mostly cemeteries) were thought to have total phosphorus concentrations in the soil that are representative of natural conditions (unaffected by human activity). The purpose of this report is to present the analysis and evaluation of these soil cores, to quantify the phosphorus contributions to Cheney Reservoir from natural and agricultural sources, and to provide estimates of stream-water-quality response to natural concentrations of total phosphorus in the soil.

Analysis of soil cores from the 43 sites produced natural concentrations of total phosphorus that ranged from 74 to 539 milligrams per kilogram with a median concentration of 245 milligrams per kilogram in 2-inch soil cores and from 50 to 409 milligrams per kilogram with a median concentration of 166 milligrams per kilogram in 8-inch soil cores. Natural concentrations of total phosphorus in soil were statistically larger in samples from coring sites in the eastern half of the watershed than in samples from coring sites in the western half of the watershed. This result partly explains a previously determined west-to-east increase in total phosphorus yields in streams of the Cheney Reservoir watershed. A comparison of total phosphorus concentrations in soil under natural conditions to the historical mean total phosphorus concentration in agriculturally enriched bottom sediment in Cheney Reservoir indicated that agricultural activities within the watershed have increased total phosphorus concentrations in watershed soil that is transported in streams to about 2.9 times natural concentrations.

Retention efficiencies for phosphorus and sediment historically transported to Cheney Reservoir were calculated at 92 and 99 percent, respectively. Most of the phosphorus was retained in bottom sediment. Sediment accumulation in Cheney Reservoir was less than reservoir design-life specifications on the basis of the age of the reservoir.

Estimates of mean total phosphorus concentrations for selected streams in the Cheney Reservoir watershed under natural concentrations of total phosphorus in soil and a historic set of watershed conditions indicate that water from two of the five streamflow sampling sites would not meet the total phosphorus water-quality goal of 0.10 milligram per liter established by the Cheney Reservoir Watershed Task Force Committee. These results imply that the water-quality goal for total phosphorus in some streams of the watershed may not be met simply by reducing the amount of phosphorus applied. Instead, meeting the goal could involve a combination of approaches—for example, reducing the agricultural distribution of phosphorus and implementing

changes in watershed activities to mitigate phosphorus movement to surface water.

INTRODUCTION

Fertilizers are an important component of modern agriculture. Their use increases soil fertility and increases crop yields. Phosphorus is a macronutrient required by plants for growth and reproduction and occurs naturally in soils in varying concentrations as the result of weathering of inorganic compounds such as the mineral apatite (calcium phosphate) (Morgan, 1997); however, in soils routinely used for crop production, phosphorus may be depleted through plant uptake and subsequent harvest of the crop. Therefore, during much of the 20th century, the annual application of phosphorus-containing fertilizers to agricultural soils became a common practice.

Phosphorus often is added to agricultural soils in the form of an inorganic phosphate or in an organic form as a component of manure from confined animal-feeding operations (Smith and others, 1998) or human sewage disposal (Eberle and others, 1994). Historically, however, the routine annual application of phosphorus to agricultural soils has been in excess of crop requirements and has led to a buildup of soil phosphorus concentrations beyond that of agronomic need (Sharpley and others, 1994; Carpenter and others, 1998). This buildup of soil phosphorus has increased the potential for phosphorus transport to surface water in runoff from agricultural fields (Smith and others, 1986; Sharpley and others, 1999).

The use of phosphorus compounds as fertilizers can have detrimental effects on surface-water bodies receiving runoff from areas of application. Excess phosphorus in surface water can accelerate the natural eutrophication (nutrient enrichment) of lakes and reservoirs (Daniel and others, 1998). Eutrophication in its broadest definition is the enrichment of a water body due to an increase in nutrient loading (Horne and Goldman, 1994). Phosphorus is considered a major component of eutrophication because it is normally the nutrient in shortest supply and, thus, can be the controlling factor in biological production rates (Hem, 1985, p. 128). Accelerated phosphorus enrichment may be characterized by extensive algal growth (algal blooms) that may reduce the aesthetic and recreational value of the water, produce taste-and-odor problems in drinking water, and, in severe cases, stress or kill aquatic organisms as a result of dissolved oxygen depletion or the release of neuro- and hepatotoxins when algal blooms die (Sharpley, 1995).

The effects of eutrophication can be most pronounced on lakes and reservoirs that serve as water-quality integrators (summation of upstream constituent characteristics) for their watersheds. Cheney Reservoir, on the North Fork Ninnescah River in south-central Kansas (fig. 1), may be a reservoir with the potential for detrimental effects from nutrient enrichment and, in fact, has a history of algal blooms and taste-and-odor problems in treated drinking water (Cheney Reservoir Watershed Task Force Committee, written commun., 1996).

To address the eutrophication issues in Cheney Reservoir and nutrient (nitrogen and phosphorus species) transport from the Cheney Reservoir watershed, the U.S. Geological Survey (USGS) entered into a cooperative study with the city of Wichita in 1996. The study was designed to assess the occurrence and transport of selected water-quality constituents, including phosphorus, within the watershed and to describe their potential effect on Cheney Reservoir, a major source of public-water supply for Wichita and surrounding communities.

Results from the study will be useful to watershed managers in evaluating the sources and transport of phosphorus in the Cheney Reservoir watershed and the potential for meeting in-stream total maximum daily loads (TMDLs) for phosphorus under existing or proposed land-use and land-management practices. A TMDL is a calculation of the maximum amount of a contaminant that a water body can receive without violating State water-quality standards. Results also may have transferability to other watersheds in Kansas with similar land-use characteristics and phosphorus distribution patterns. The rather unique sampling methods used for this study could have transferability throughout the Nation where a comparison of the historical transport of water-quality constituents to natural conditions (unaffected by human activity) is required. This comparison would be particularly suited to watersheds with downstream impoundments where a record of historical transport may be contained in bottom sediment.

Setting

Cheney Reservoir is a 15-mi^2 surface area impoundment constructed in 1965 mainly for flood control. The reservoir also serves as a water-supply source for about 350,000 people in and around Wichita (Jerry Blain, city of Wichita, Kansas, Water and Sewer Department, oral commun., 2000). The reservoir has a mean depth of about 16 ft and a conservation-pool storage of 151,800 acre-ft with an additional flood-control pool capacity of 80,860 acre-ft.

The watershed of Cheney Reservoir is a 933-mi^2 contributing drainage area of the North Fork Ninnescah River used almost exclusively for crop and livestock production. Since 1965, the percentage of watershed used for major crop production (corn, sorghum, soybean, and wheat) has averaged about 52 percent annually. The remainder of the watershed is used mainly as pasture for livestock production. Annual inventories of livestock since 1965 have averaged about 64,000 cattle and calves, 18,000 hogs and pigs, and 9,400 sheep and lambs (Kansas State Board of Agriculture and U.S. Department of Agriculture, 1964–94; Kansas Department of Agriculture and U.S. Department of Agriculture, 1995–97).

Human population in the watershed is less than 4,000, much of which is associated with the approximately 1,000 farms in the watershed (Cheney Reservoir Watershed Task Force Committee, written commun., 1996). Populations of the six largest towns in the watershed range from less than 200 to slightly more than 1,200 people (Helyar, 1994).

In south-central Kansas, precipitation and temperature vary substantially throughout the year. The mean annual (1961–90) precipitation is about 27 in. but ranges in the vicinity of the Cheney Reservoir watershed from about 25.8 in. at Pratt (fig. 1) to about 29.2 in. at Hutchinson (National Oceanic and Atmospheric Administration, 1992). The mean annual temperature is 56.6 ^{o}F, with a mean monthly range of 30.7 ^{o}F in January to 81.3 ^{o}F in July (Kansas Department of Agriculture and U.S. Department of Agriculture, 1997, p. 8).

Topography in the Cheney Reservoir watershed ranges from flat to gently sloping hills. Total topographic relief is about 550 ft, with maximum local relief (within 1 mi) of about 50 ft.

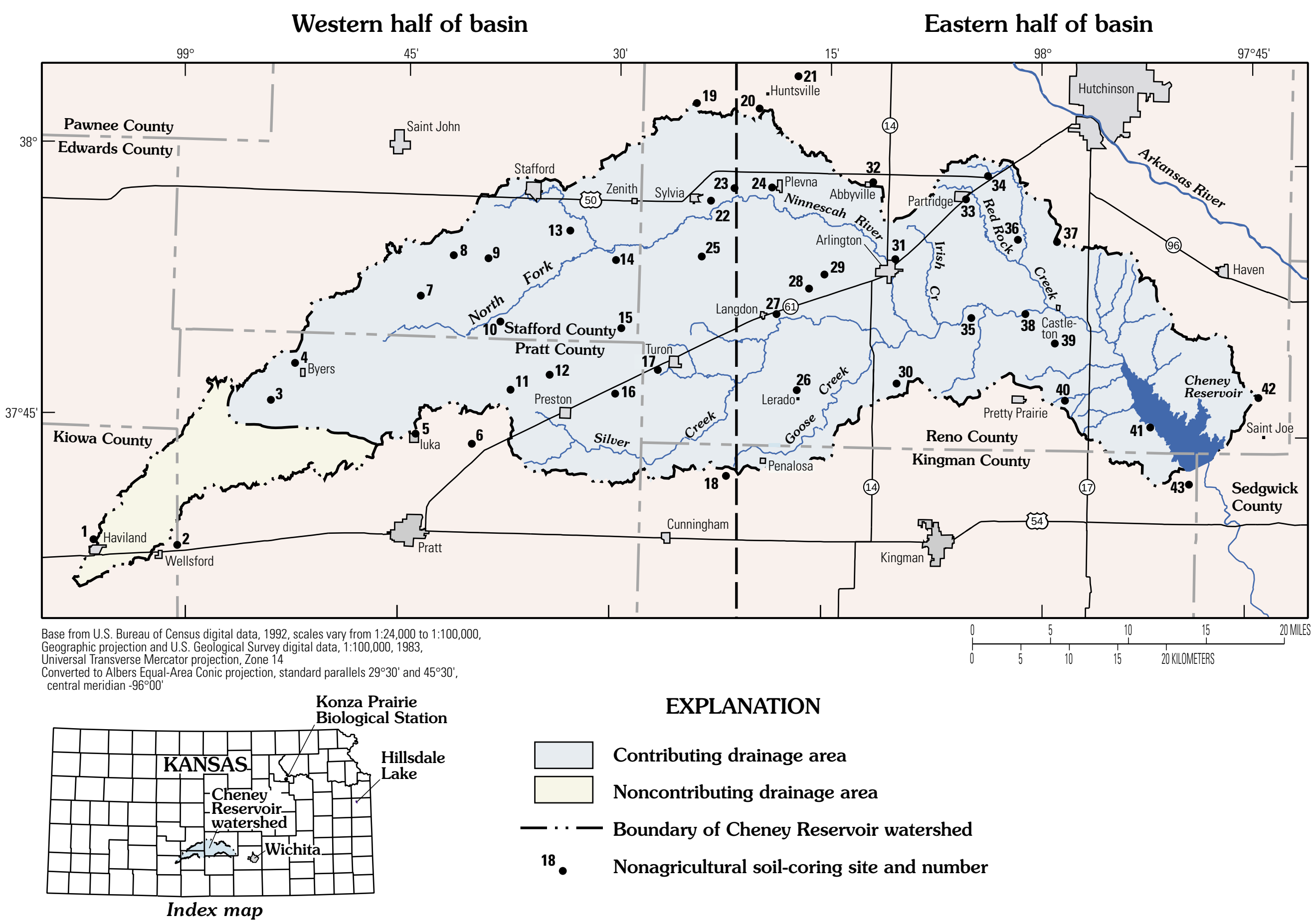

Figure 1. Location of Cheney Reservoir watershed and nonagricultural soil-coring sites, south-central Kansas.

The North Fork Ninnescah River Valley and the surrounding plains are underlain by consolidated rocks (mainly with thin layers of limestone, dolomite, siltstone, gypsum, and salt) of Permian age (230 to 280 million years old) covered by unconsolidated stream-related (mainly sand and gravel) and wind-blown (mainly silt and clay) deposits of Pleistocene age (less than 1.5 million years old) (Zeller, 1968). The unconsolidated deposits are a source of water for domestic supply, irrigation, and livestock and range in thickness from little or no saturated thickness east of Red Rock Creek (fig. 1) to more than 160 ft in the northern part of Pratt County (Hansen, 1991).

Soils in the Cheney Reservoir watershed generally are classified as clayey loam on the uplands to sand or sandy loam on low-lying areas or where slopes are less than about 3 percent. Many of the soils in the watershed are subject to erosion by wind and rainfall runoff (Rockers and others, 1966).

Previous Investigations

Previous investigations of the Cheney Reservoir watershed have described the extent of point-source discharges within the watershed (Christensen and Pope, 1997), the accumulation of phosphorus in bottom sediment of the reservoir (Pope, 1998), the transport of phosphorus (loads and yields) from selected subwatershed areas (Pope and Milligan, 2000), and historical sediment and phosphorus loading into Cheney Reservoir (Mau, 2001). These investigations have concluded (1) that point-source discharges are not a major source of nutrients in the Cheney Reservoir watershed probably because of the small human population, (2) that agricultural activities probably are the dominant source of nutrient contamination of surface water in the watershed, (3) that phosphorus transport from the watershed has been increasing over time probably because of increasing fertilizer use, (4) that phosphorus transport is not uniform across the watershed and appears to be related to water yield, soil types, and topography, and (5) that sediment deposition in Cheney Reservoir was less than reservoir design-life specifications and that historical phosphorus transport to Cheney Reservoir was more than determined previously.

Purpose and Scope

Soil phosphorus concentrations in the Cheney Reservoir watershed have been increasing at least since the construction of the reservoir (Pope, 1998). However, the extent to which these concentrations have increased relative to natural concentrations in this predominantly agricultural watershed is unknown. To determine how or if agricultural activities may need to be modified or land-management practices implemented to control phosphorus transport, it is first necessary to define the extent to which these activities have increased phosphorus transport to the reservoir. Therefore, the purposes of this report are (1) to present the results of a study that examined soil phosphorus concentrations from areas in and near Cheney Reservoir watershed believed to be representative of natural conditions, (2) to quantify the historical (1965–98) phosphorus contribution to Cheney Reservoir from natural and agricultural sources, and (3) to provide estimates of stream-water-quality response that may have occurred under natural conditions of total phosphorus in soil.

Natural concentrations of total phosphorus in soil were compared to total phosphorus concentrations previously determined (Pope, 1998) in bottom-sediment samples from Cheney Reservoir. Because of the land-use characteristics of the watershed, phosphorus concentrations in Cheney Reservoir bottom sediment are considered agriculturally enriched. Agricultural-enrichment factors were calculated and used to discuss implications for stream water quality under natural concentrations of phosphorus in soil.

METHODS

Soil-core samples were collected at 43 coring sites (fig. 1, table 1) in and near Cheney Reservoir watershed on September 1–9, 1999. The sites were selected to represent soils with natural concentrations of total phosphorus and to provide as wide a spatial distribution as possible in and near Cheney Reservoir watershed.

Soil-Core Collection, Processing, and Analysis

The North Fork Ninnescah River Basin has been in agricultural production since the middle of the 19th century. Although the widespread use of commercial

Table 1. Location of soil-coring sites in and near Cheney Reservoir watershed, south-central Kansas

Coring-site number (fig.1)	Coring-site name	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)
1	Cemetery north of Haviland, Kansas	37°37'44"	99°06'26"
2	Cemetery northeast of Wellsford, Kansas	37°37'31"	99°00'53"
3	Cemetery 2 miles southwest of Byers, Kansas	37°45'42"	98°54'11"
4	Cemetery 0.5 mile northwest of Byers, Kansas	37°47'46"	98°52'34"
5	IOOF Cemetery north of Iuka, Kansas	37°44'04"	98°43'52"
6	St. Paul Lutheran Cemetery 3 miles east of Iuka, Kansas	37°43'34"	98°39'53"
7	Rose Valley Cemetery 9 miles north of Iuka, Kansas	37°51'41"	98°43'44"
8	Cemetery 7 miles southeast of Saint John, Kansas	37°53'57"	98°41'31"
9	Cemetery 4 miles southwest of Stafford, Kansas	37°53'50"	98°39'00"
10	Cemetery 6 miles northwest of Preston, Kansas	37°50'22"	98°38'05"
11	Friendship Cemetery 3 miles northwest of Preston, Kansas	37°46'37"	98°37'12"
12	Haynesville Cemetery 2 miles north of Preston, Kansas	37°47'30"	98°34'19"
13	Cemetery 3.5 miles southeast of Stafford, Kansas	37°55'30"	98°33'16"
14	Abandoned farmstead 4 miles south of Zenith, Kansas	37°53'55"	98°29'58"
15	Old Neda Cemetery 3 miles northwest of Turon, Kansas	37°50'12"	98°29'26"
16	Pleasant Valley Geist Cemetery northeast of Preston, Kansas	37°46'34"	98°29'48"
17	Turon Cemetery near Turon, Kansas	37°47'56"	98°26'48"
18	Shelman Cemetery 4 miles northeast of Cunningham, Kansas	37°42'11"	98°21'49"
19	Hayes Township Cemetery 4 miles southwest of Huntsville, Kansas	38°02'44"	98°24'33"
20	Cemetery south of Huntsville, Kansas	38°02'35"	98°20'05"
21	Pleasant View Cemetery northeast of Huntsville, Kansas	38°04'21"	98°17'20"
22	Sylvia Cemetery east of Sylvia, Kansas	37°57'21"	98°23'21"
23	Cemetery 2 miles west of Plevna, Kansas	37°57'56"	98°21'44"
24	Plevna Cemetery west of Plevna, Kansas	37°58'10"	98°19'00"
25	Glendale Cemetery 3.5 miles south of Sylvia, Kansas	37°54'15"	98°23'54"
26	Lerado Cemetery near Lerado, Kansas	37°46'59"	98°16'56"
27	Cemetery east of Langdon, Kansas	37°51'12"	98°18'29"
28	Cemetery 3 miles northeast of Langdon, Kansas	37°52'38"	98°16'15"
29	Cemetery 3 miles west of Arlington, Kansas	37°53'26"	98°15'09"
30	Sego Cemetery 7 miles south of Arlington, Kansas	37°47'29"	98°09'51"
31	Cemetery near Arlington, Kansas	37°54'20"	98°10'08"
32	Abbyville Cemetery near Abbyville, Kansas	37°58'34"	98°11'52"
33	Partridge Cemetery near Partridge, Kansas	37°57'46"	98°05'13"
34	Cemetery northeast of Partridge, Kansas	37°59'05"	98°03'42"
35	Cemetery 6 miles southeast of Arlington, Kansas	37°51'14"	98°04'39"
36	KSU Experiment Station 4 miles southeast of Partridge, Kansas	37°55'37"	98°01'29"
37	Pleasant View Cemetery 4 miles north of Castleton, Kansas	37°55'30"	97°58'37"
38	Abandoned farmstead 2.5 miles southwest of Castleton, Kansas	37°51'31"	98°00'49"
39	St. Agnes Cemetery near Castleton, Kansas	37°49'56"	97°58'41"
40	Menonite Church cemetery near Pretty Prairie, Kansas	37°46'46"	97°57'50"
41	Old cemetery northwest of Cheney Dam, Kansas	37°45'25"	97°51'46"
42	Nichols Cemetery 3 miles north of Saint Joe, Kansas	37°47'06"	97°44'09"
43	Old cemetery south of Cheney Dam, Kansas	37°42'16"	97°48'58"

fertilizers in crop production did not become commonplace until after the Second World War, pasturing of livestock and manure applications to crop fields have provided some phosphorus input to the watershed for much of the agricultural history of the basin. This long history of supplementing natural concentrations of phosphorus in soil makes the identification of nonagriculturally affected soils difficult. However, cemeteries represent unique locations where soils have been protected from agricultural activities for extended periods.

Most of the cemeteries in and near Cheney Reservoir watershed have existed since at least the latter part of the 19th century, and therefore, soils from these locations may provide estimates of natural concentrations of soil phosphorus. These natural conditions, however, could be compromised by the addition of landscape fertilizers and by wind erosion from nearby agricultural fields.

Forty of the 43 locations selected for this study were in cemeteries (an example is shown in figure 2), two were on abandoned farmsteads, and one was on Kansas State University (KSU) land. Although several of the selected cemeteries were not located in the Cheney Reservoir watershed, it was believed that soil conditions at these nearby cemeteries would be similar to those soils within the watershed and that the positive benefits from a larger, spatially diverse data set would offset possible negative effects of dissimilar soils. Discussions with local residents and cemetery caretakers indicated that landscape fertilizers are not commonly, if ever, applied to cemetery soils in this watershed. However, to avoid sampling soils that may have been fertilized, cemeteries with unusually viable, well-maintained lawns were not selected for this study. The two abandoned farmsteads were included to increase spatial definition in the coring-site distribution. Each farmstead had been abandoned for more than 50 years, and the KSU land had no history of fertilizer applications.

Within each cemetery, sampling locations were selected in the oldest part, as indicated by headstone dates, or in areas as yet to receive burials. At each sampling location (fig. 1), soil cores of two lengths (2 and 8 in.) were collected using a 2-in. diameter soil auger. Two soil-core lengths were collected to determine vertical variability in soil phosphorus concentrations and to represent the parts of the soil profile most likely eroded and transported in runoff. The soil auger was cleaned between sampling locations in a sequence of nonphosphorus soap/water mix, tapwater rinse, and deionized-water rinse. Each soil sample was sieved through a
2-mm opening sieve (U.S. Standard No. 10) to remove plant debris, mechanically homogenized, and subsampled for analytical determinations. All soil samples were analyzed for total phosphorus at the USGS National Water-Quality Laboratory in Denver, Colorado, according to methods described in Fishman (1993). Soil particle size was determined for the percentage of sand and silt and (or) clay (percentage greater than or less than 0.062 mm in diameter, respectively) at the USGS sediment analysis laboratory in Iowa City, Iowa, according to methods described in Guy (1969).

Quality Control

Soil-core samples for analysis of total phosphorus and soil particle size were collected to determine potential within-site variability (variability among multiple sampling locations within a coring site). Information on within-site variability is useful in evaluating the representativeness of samples collected at a single location within a coring site. Large within-site variability would complicate the evaluation of spatial distribution and estimation of mean soil phosphorus concentrations in nonagricultural areas of the watershed. Additional soil-core samples were analyzed for total soil phosphorus to determine variability associated with a combination of sample collection, processing, and analytical procedures.

Figure 2. Soil-coring site 27, cemetery east of Langdon, Kansas. Location of coring site shown in figure 1.

Sequential Replicate Samples

Within-site variability was evaluated through the collection and analysis of primary and two sequential replicate soil-core samples (table 2) collected at coring sites 13, 20, 26, 27, and 40 (fig. 1). Sequential replicate soil-core samples were collected from different locations within the coring sites (cemeteries). All coring locations in cemeteries were either in the oldest developed parts or in unused areas (areas as yet to receive burials). Variation among the three resulting soil phosphorus concentrations and percentage of particle size less than 0.062 mm (silt and clay) at each coring location and depth was evaluated with a technique used by Dufour and others (1981) that expressed variation as a percentage of the mean with the equation:

$$\text{variation} = \left(\frac{s/(\sqrt{n})}{\bar{x}} \cdot 100\right), \qquad (1)$$

where

- s is the standard deviation,
- n is the number of replicate analyses, and
- $\bar{x}$ is the mean of replicate values from the analyses.

Within-site variability in soil phosphorus concentrations ranged from 2.2 percent of the mean in the 2-in. core samples from coring site 20 (fig. 1) to 31 percent of the mean in the 2-in. core samples from coring site 13. The average within-site variability was 16 percent of the mean for the 2-in. core samples and 11 percent of the mean for the 8-in. core samples from all five coring sites. The average within-site variability for both coring depths (2 and 8 in.) at all five coring sites with sequential replicate core samples (table 2) was 13 percent of the mean.

Within-site variability in percentage of soil core as silt and (or) clay (particle size less than 0.062 mm in diameter) was not as large as that for soil phosphorus concentrations. Variability in percentage of silt and (or) clay ranged from 0.2 percent of the mean in the 8 in. core samples from coring site 26 to 25 percent of the mean in the 2-in. core samples from coring site 27. The average within-site variability was 9.8 percent of the mean for the 2-in. core samples and 5.4 percent of the mean for the 8-in. core samples from all five coring sites. The average within-site variability for both coring depths at all five coring sites with sequential replicate core samples was 7.6 percent of the mean.

Evaluation of within-site variability for soil phosphorus and percentage of silt- and (or) clay-size particles produced two conclusions. First, the 2-in. core samples had greater within-site variability than the 8-in. core samples. This greater variability in the shorter core samples may be related to natural variability in organically bound phosphorus near the surface of the soil profile. This near-surface variability, in turn, probably is the result of variation in vegetative cover (organic production) within the coring site (cemetery). The greater particle-size variability in the 2-in. core samples probably is the result of preferential sorting and distribution of certain soil particles sizes that result from water and windblown processes. Closely associated with these erosional processes are variations in microenvironments that either may promote or mitigate the movement, distribution, and segregation of certain soil particle sizes within a coring site. Microenvironmental characteristics include type and percentage of vegetative cover, land slope, precipitation, orientation to prevailing wind direction, and proximity to structures, obstacles, or natural features that affect the potential for water or windblown erosion. The variability in these surface characteristics has less effect (smaller variability) on longer (8-in.) core samples because of the larger mass of these samples and their ability to dilute these near-surface effects. Second, soil phosphorus concentrations and percentage of silt- and (or) clay-size particles from the analysis of sequential replicate samples indicate that, although within-site variability may be large at some coring sites, the average soil phosphorus concentrations and percentage of silt- and (or) clay-size particles from the entire network of coring sites would be reasonably represented by single sampling locations within sampling sites.

Split Replicate Samples

Variability in total phosphorus concentrations in soil cores resulting from a combination of sample collection, processing, and analytical procedures was evaluated with split replicate core samples (table 2) collected at coring sites 9, 18, 28, 29, and 34 (fig. 1). Split replicate samples of both 2- and 8-in. soil-core samples were prepared by mechanically homogenizing each sample at the collection site and splitting the homogenized mass into two separate samples each of which was independently analyzed for total phosphorus. Variability between split replicate analyses was calculated as a percentage of the mean using equation 1.

Variability in total phosphorus concentrations in split replicate soil-core samples ranged from 0.7 percent of the mean in the 2-in. core samples from coring site 18 to 46 percent of the mean in the 2-in. core samples from coring site 9. The average variability was 14 percent of the mean for the 2-in. split replicate samples and 7.6 percent of the mean for the 8-in. split replicate samples. The average variability for all split replicate samples from both coring depths at all five coring sites was 11 percent. With the exception of the unusually large 46 percent of the mean from coring site 9, variability between all other split replicate samples was less than 17 percent of the mean. Excluding the 46 percent of the mean from the calculation of average variability reduced average variability for both coring depths at all five coring sites from 11 to 6.9 percent of the mean. Generally, therefore, results from the analyses of split replicate soil-core samples presented in table 2 indicate that sample collection, processing, and analysis of soil-core samples for total phosphorus were adequate and not a substantial source of variability.

HISTORICAL CONTRIBUTIONS OF PHOSPHORUS

Estimates of natural concentrations of total phosphorus in soil were made from the analyses of soil-core samples collected from 43 nonagricultural sites in and near Cheney Reservoir watershed. These natural concentrations were compared to total phosphorus concentrations in Cheney Reservoir bottom sediment to estimate the extent to which the agricultural distribution of phosphorus has enriched soil phosphorus concentrations in the watershed. A phosphorus-enrichment factor was calculated and used to estimate mean total phosphorus concentrations in water at selected streamflow sampling sites in the Cheney Reservoir watershed that may have occurred under conditions of natural concentrations of soil phosphorus. Before results from coring sites with quality-control samples (table 2) were used in calculations, statistical analyses, or graphical presentations, primary and replicate analyses were averaged.

Natural Soil Concentrations

Natural concentrations of total phosphorus in soil in and near Cheney Reservoir watershed were estimated from soil-core samples collected from 43 nonagricultural sites (fig. 1) and analyzed for total phosphorus (table 2). Generally, total phosphorus concentrations were larger and had a wider range in the 2-in. soil-core samples than in the 8-in. core samples (fig. 3). Total phosphorus concentrations ranged from 74 to 539 mg/kg with a median concentration of 245 mg/kg in 2-in. soil-core samples compared to a range of 50 to 409 mg/kg with a median concentration of 166 mg/kg in 8-in. soil-core samples. In contrast, there was little difference in soil particle-size composition (percentage of particle size less than 0.062 mm) in either ranges or median values between the 2-in. and 8-in. soil-core samples. Soil particle size less than 0.062 mm ranged from 0.4 to 88 percent for both 2-in. and 8-in. soil-core samples with median values of 44 and 41 percent, respectively. Some of the potential reasons for differences in total phosphorus concentrations between the 2-in. and 8-in. soil-core samples were discussed previously in the "Quality Control" section of this report.

A previous investigation of total phosphorus transport in streams of the Cheney Reservoir watershed in 1997–98 (Pope and Milligan, 2000) identified an increasing trend in total phosphorus yields in a west-to-east direction. Phosphorus yields ranged from about 0.13 lb/acre in the western part of the watershed to about 0.37 lb/acre in the eastern part. To determine if this trend is partly the result of natural variability in total phosphorus concentrations in soil, a plot of the spatial distribution of total phosphorus concentrations (fig. 4) in core samples from the 43 nonagricultural coring sites (fig. 1) sampled during the September 1999 investigation was examined. Although not definitely evident in figure 4, it appeared that the eastern part of the watershed had the larger natural concentrations of total phosphorus in soil. To verify this observation, a statistical comparison was made between coring sites located in the western half of the watershed (coring sites 1–19, 22, 23, 25, fig. 1) with those in the eastern half (coring sites 20, 21, 24, 26–43, fig. 1).

Median total phosphorus concentrations in 2-in. and 8-in core samples were 36 and 47 percent larger, respectively, in samples collected from the eastern coring sites than in samples collected from the western coring sites. These percentages were statistically significant at least at the 0.07 level of significance (p-value 0.07 or less) as determined by a Wilcoxon rank-sum test. Part of the west-to-east increase in phosphorus concentrations may be associated with a corresponding increase in the percentage

Table 2. Results of analyses of total phosphorus concentrations and particle-size determinations for selected soil cores in and near Cheney Reservoir watershed, south-central Kansas, September 1999

[mg/kg, milligrams per kilogram; mm, millimeter; --, not determined]

Coring-site number (fig. 1)	Depth of soil core (inches)	Type of sample	Total phosphorus concentration (mg/kg)	Soil particle size less than 0.062 mm (percent)
1	2	Primary	202	31.5
	8	do.	144	35.2
2	2	do.	263	49.1
	8	do.	215	50.7
3	2	do.	262	20.2
	8	do.	87.5	19.3
4	2	do.	110	28.6
	8	do.	94.7	24.7
5	2	do.	99.1	48.7
	8	do.	129	46.6
6	2	do.	157	28.4
	8	do.	105	19.5
7	2	do.	200	34.0
	8	do.	79.7	34.4
8	2	do.	167	44.8
	8	do.	134	38.0
9	2	do.	146	18.6
	8	do.	65.5	26.2
	2	Split replicate	54.6	--
	8	do.	70.0	--
10	2	Primary	219	25.6
	8	do.	158	22.4
11	2	do.	121	40.1
	8	do.	49.8	34.1
12	2	do.	341	54.2
	8	do.	205	42.7
13	2	do.	195	50.0
	8	do.	60.6	48.9
	2	Sequential replicate	75.6	53.9
	8	do.	74.0	50.0
	2	do.	93.1	57.5
	8	do.	78.6	60.6
14	2	Primary	323	21.3
	8	do.	409	2.8
15	2	do.	293	42.8
	8	do.	227	38.5
16	2	do.	355	48.0
	8	do.	243	35.5
17	2	do.	325	49.6
	8	do.	187	42.9
18	2	do.	204	52.6
	8	do.	106	.4
	2	Split replicate	207	--
	8	do.	118	--
19	2	Primary	186	13.8
	8	do.	140	17.7
20	2	do.	287	35.7
	8	do.	216	31.9
	2	Sequential replicate	266	36.1
20	8	Sequential replicate	207	35.0
	2	do.	279	45.7
	8	do.	274	31.8
21	2	Primary	325	48.8
	8	do.	282	50.1
22	2	do.	395	65.8
	8	do.	322	59.8
23	2	do.	326	71.2
	8	do.	271	73.9
24	2	do.	199	28.9
	8	do.	103	29.0
25	2	do.	111	18.0
	8	do.	114	14.4
26	2	do.	302	39.4
	8	do.	132	31.5
	2	Sequential replicate	213	30.2
	8	do.	99.0	31.3
	2	do.	115	28.4
	8	do.	141	31.3
27	2	Primary	268	47.4
	8	do.	214	46.4
	2	Sequential replicate	163	82.3
	8	do.	226	43.9
	2	do.	231	36.7
	8	do.	202	40.4
28	2	Primary	263	38.4
	8	do.	226	41.1
	2	Split replicate	242	--
	8	do.	183	--
29	2	Primary	211	35.1
	8	do.	145	34.1
	2	Split replicate	202	--
	8	do.	167	--
30	2	Primary	472	56.2
	8	do.	360	54.2
31	2	do.	344	44.4
	8	do.	186	46.5
32	2	do.	539	50.6
	8	do.	129	66.8
33	2	do.	359	54.7
	8	do.	137	55.2
34	2	do.	86.8	39.8
	8	do.	71.4	40.8
	2	Split replicate	61.9	--
	8	do.	90.4	38.2
35	2	Primary	294	55.3
	8	do.	201	51.0

Table 2. Results of analyses of total phosphorus concentrations and particle-size determinations for selected soil cores in and near Cheney Reservoir watershed, south-central Kansas, September 1999—Continued

Coring-site number (fig. 1)	Depth of soil core (inches)	Type of sample	Total phosphorus concentration (mg/kg)	Soil particle size less than 0.062 mm (percent)
36	2	Primary	373	74.9
	8	do.	339	71.1
37	2	do.	245	29.9
	8	do.	250	27.8
38	2	do.	241	7.9
	8	do.	166	26.9
39	2	do.	218	53.3
	8	do.	253	49.7
40	2	do.	257	48.6
	8	do.	94.0	31.6
	2	Sequential replicate	288	50.0
	8	do.	223	47.1
	2	do.	304	47.5
	8	do.	239	48.6
41	2	Primary	277	65.5
	8	do.	255	66.4
42	2	do.	394	87.6
	8	do.	317	87.6
43	2	do.	145	.4
	8	do.	160	53.0

of silt- and (or) clay-size particles (particles less than 0.062 mm in diameter) in samples from the eastern coring sites (fig. 5). Median percentages of silt- and (or) clay-size particles were 17 and 34 percent larger in 2-in. and 8-in. soil-core samples, respectively, from the eastern coring sites than in samples from the western coring sites. The determination that soils are sandier in the western part of the watershed is substantiated by Rockers and others (1966), Horsch and others (1968), and Dodge and others (1978). Although the west-to-east variability in natural soil phosphorus concentrations in the Cheney Reservoir watershed has a part in explaining the previously determined west-to-east trend in total phosphorus yield, other factors such as variability in land-use and land-management characteristics, precipitation and water yield, and topography may contribute substantially more to the 185-percent increase in total phosphorus yields from west to east in the Cheney Reservoir watershed.

Agricultural Enrichment

To evaluate the effects of agriculture on soil phosphorus concentrations in the Cheney Reservoir watershed, concentrations of total phosphorus in soils from nonagricultural areas were compared to total phosphorus concentrations in Cheney Reservoir bottom sediment. A previous examination (Pope, 1998) of Cheney Reservoir bottom sediment indicated that phosphorus transport from the watershed has been increasing since at least construction of the reservoir, probably as a result of agricultural activities, as evident in bottom-sediment cores from Cheney Reservoir (fig. 6) and that a direct relationship exists between total phosphorus concentrations and percentage of silt- and (or) clay-size particles in bottom sediment (fig. 7). This relation of particle size to total phosphorus also has been identified by other researchers (Keulder, 1982; Dong and others, 1983; Viner, 1984). Therefore, variability in total phosphorus concentrations among samples of soil or sediment with varying particle-size composition may reflect only the variability with particle size and not that associated with agriculture. To make comparisons of this type, all samples first must be normalized relative to particle-size composition. This normalization process also compensates for the preferential transport of silt- and (or) clay-size particles in runoff from agricultural fields (Rhoton and others, 1979; Dean, 1983). The preferential transport of silt and clay particles with their potentially larger phosphorus concentrations relative to the source soil naturally would tend to enrich deposited material in Cheney Reservoir.

Particle-Size Weighted Concentrations

Soil samples collected from nonagricultural locations (fig. 1) for this study and previously collected bottom sediment from Cheney Reservoir (Pope, 1998) were normalized (weighted) relative to the percentage of the silt and (or) clay fraction of the particle-size composition. Particle-size weighted (hereinafter referred to as weighted) mean total phosphorus concentrations for both the 2-in. and 8-in. soil-core samples from nonagricultural locations in the Cheney Reservoir watershed were calculated with the equation:

$$\text{weighted mean total phosphorus concentration} = \frac{\sum_{1}^{43} C \cdot P}{\sum_{1}^{43} P}, \quad (2)$$

where

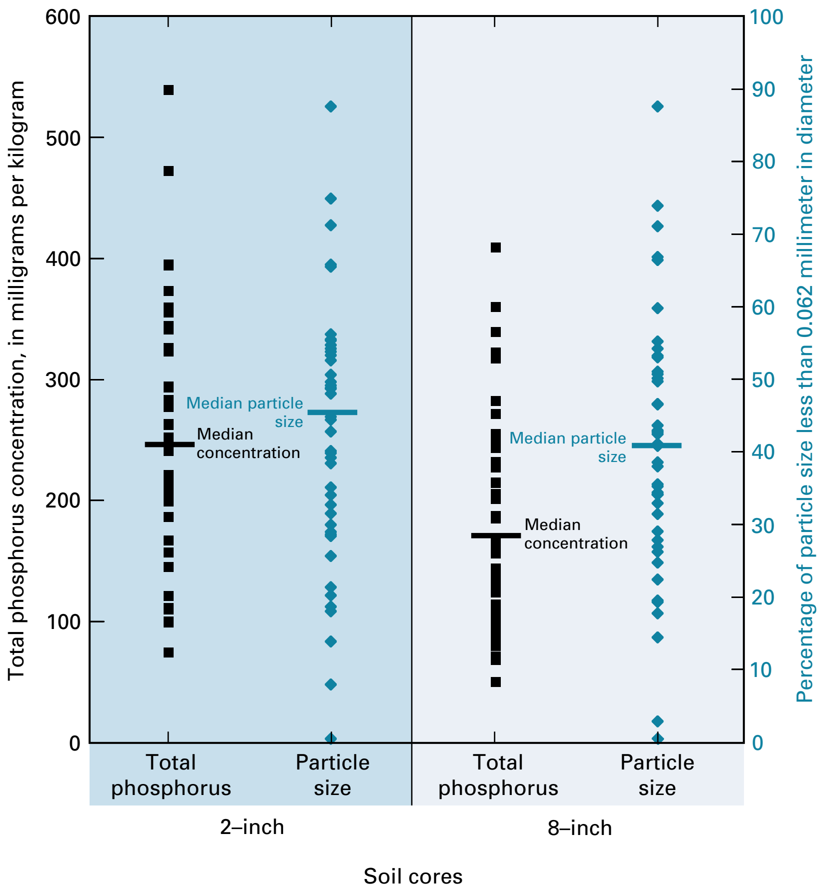

Figure 3. Comparison of total phosphorus concentrations and particle sizes less than 0.062 millimeter in diameter between 2-inch and 8-inch soil-core samples collected from 43 nonagricultural sites in and near Cheney Reservoir watershed, September 1999.

C is the concentration of total phosphorus in 2- or 8-in. soil-core samples, and

P is the percentage of the silt and (or) clay particle-size fraction in 2- or 8-in. soil-core samples.

A similar technique was used to calculate weighted mean total phosphorus concentrations in Cheney Reservoir sediment from results of bottom-sediment core analysis as presented in Pope (1998).

The weighted mean total phosphorus concentration in Cheney Reservoir bottom sediment was substantially larger than weighted mean total phosphorus concentrations in either the 2-in. (1.8 times larger) or 8-in. (2.6 times larger) soil-core samples from nonagricultural areas in and near Cheney Reservoir watershed (fig. 8). The sediment in Cheney Reservoir was derived almost exclusively from lands used for agricultural purposes (crops and livestock); therefore, the agricultural enrichment of phosphorus in this sediment as evident from figure 8 is probably the result of agricultural use of commercial phosphorus fertilizers and the surface application of livestock manure.

The differences between weighted mean total phosphorus concentrations in the two soil-core depths (fig. 8) probably reflect a natural buildup near the surface of the core profile of organic phosphorus from plant or microbial origins or possibly windblown deposits from nearby agricultural land. Because of a much smaller sample mass associated with the shorter soil core, this buildup would have a greater effect on mean total phosphorus concentrations (produce a larger mean concentration) in a short (2-in.) core sample than it would on the larger mass in a longer (8-in.) core sample.

Wind-transport processes also might be a reason for the larger weighted mean total phosphorus concentration in the shorter soil cores. Nearly all coring sites shown in figure 1 are surrounded by or in close proximity to agricultural lands where phosphorus fertilizers are used. South-central Kansas is subject to strong winds during times when cropland is relatively bare of vegetation. These winds have the potential for erosion of cropland with chemical transport to and deposition on nonagricultural areas. If phosphorus enrichment resulting from wind transport is substantial, then the differences between Cheney Reservoir bottom sediment and the nonagricultural soil samples could be even greater than that indicated in figure 8. Unfortunately, the extent, if any, of phosphorus enrichment resulting from wind transport is not known and probably cannot be quantified.

The 2.6 enrichment factor calculated using 8-in. soil-core samples collected at the 43 nonagricultural sites probably is the more representative factor for the Cheney Reservoir watershed because (1) results from 8-in. soil cores would minimize the effects (relative to results from 2-in. soil cores) of phosphorus enrichment by wind transport from nearby agricultural fields, and (2) results from 8-in. soil cores probably are more indicative of total phosphorus availability from land tilled for crop production, which is a substantial land use in the Cheney Reservoir water-

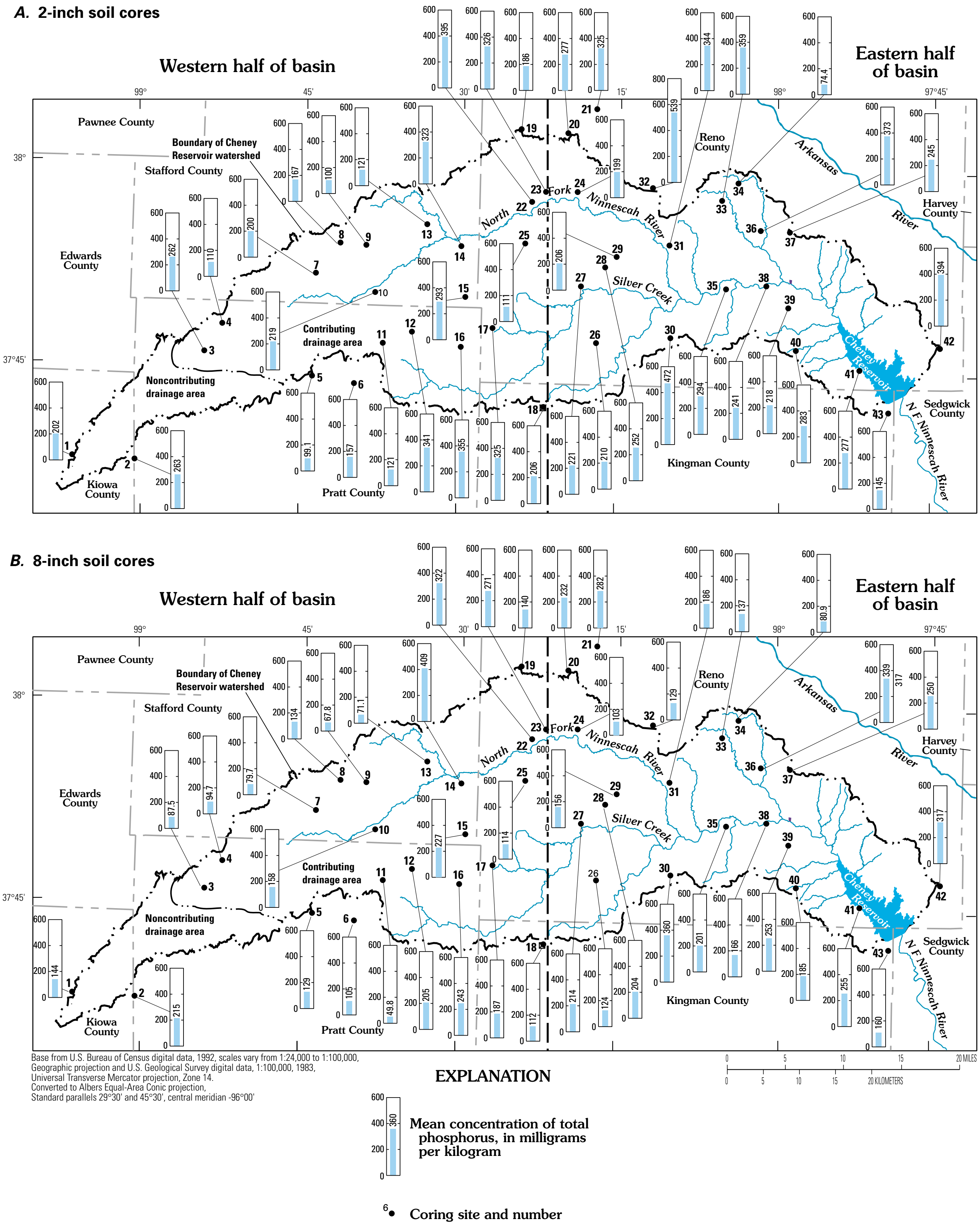

Figure 4. Distribution of total phosphorus concentrations in *(A)* 2-inch and *(B)* 8-inch soil-core samples at 43 nonagricultural coring sites in and near Cheney Reservoir watershed, September 1999.

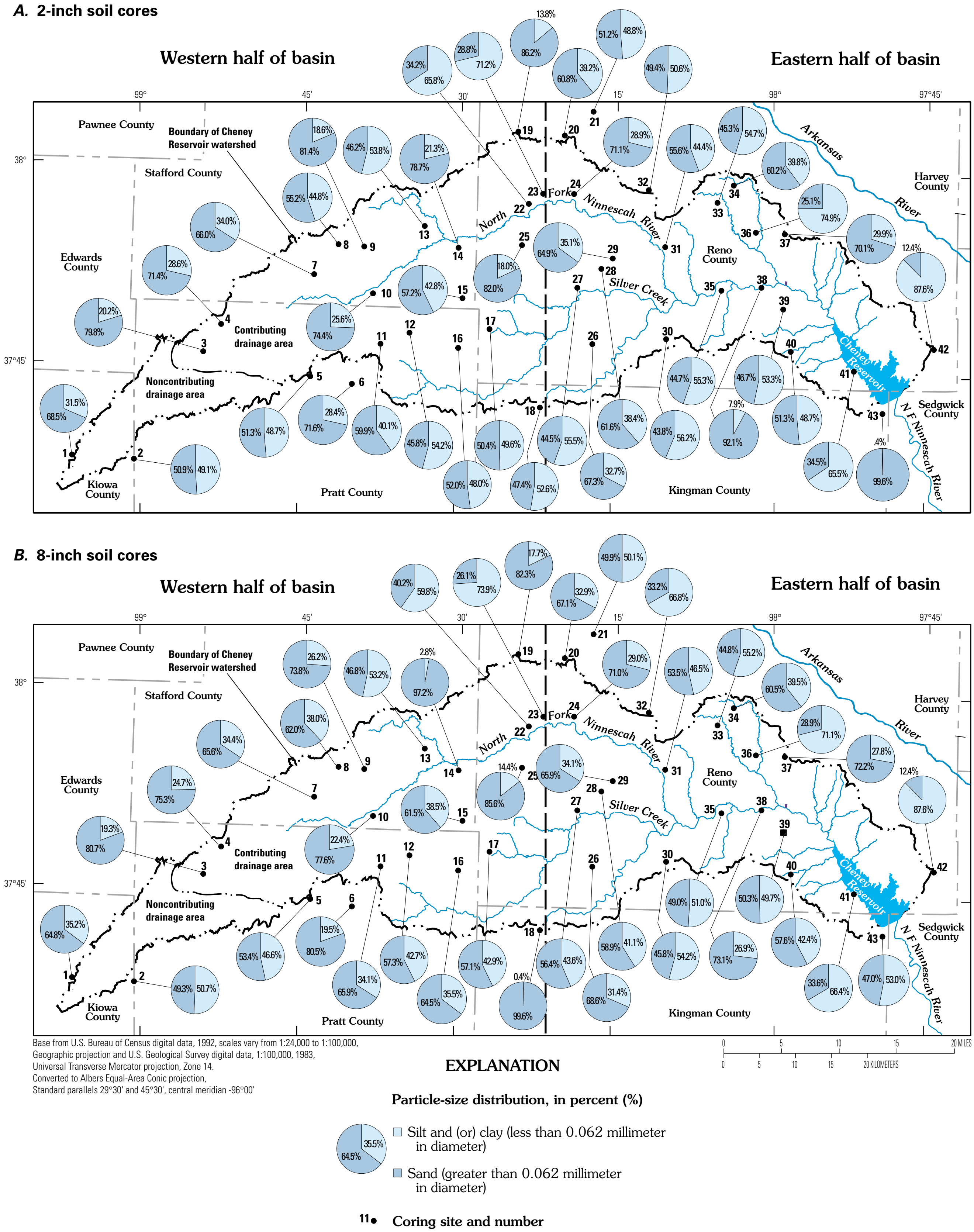

Figure 5. Distribution of soil particle size in *(A)* 2-inch and *(B)* 8-inch soil-core samples at 43 nonagricultural coring sites in and near Cheney Reservoir watershed, September 1999.

shed. Most tilled (plowed or cultivated) land probably is worked to at least an 8-in. depth and is the land most susceptible to erosion and transport of phosphorus.

Phosphorus Mass

The calculation of an agricultural-enrichment factor for total phosphorus can have water-quality implications when that factor is used to quantify historical contributions of phosphorus from natural and agricultural sources and to estimate the attainability of stream-water-quality goals under natural concentrations of total phosphorus in soil. Therefore, the validity of the calculated enrichment factor is critical. To verify the 2.6 agricultural-enrichment factor for total phosphorus previously determined, the factor also was calculated on the basis of information presented in a recently published report quantifying sedimentation and phosphorus loading in Cheney Reservoir (Mau, 2001).

Mau (2001) estimated the total mass of sediment (15.4 billion lb) and mass of phosphorus (7.7 million lb) associated with that sediment in Cheney Reservoir. These masses were estimated on the basis of bathymetric surveys of the reservoir conducted in 1964 and 1998 and on sediment density and phosphorus concentrations determined in bottom-sediment samples collected (1997–98) from a network of 23 sediment-coring sites within the reservoir. For the purpose of this report, these two masses were used to calculate a mean total phosphorus concentration (500 mg/kg) in Cheney Reservoir bottom sediment; Mau

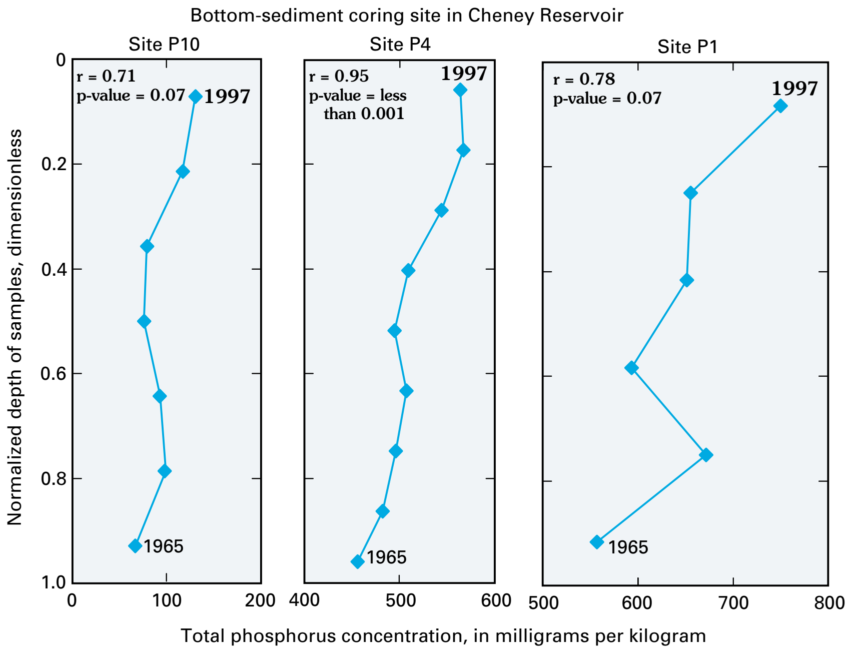

Figure 6. Relation between total phosphorus concentrations in bottom-sediment core samples and normalized depth of samples from selected coring sites in Cheney Reservoir, 1965–97 (modified from Pope, 1998, fig. 10; r is correlation coefficient). Sediment cores were collected August 1997.

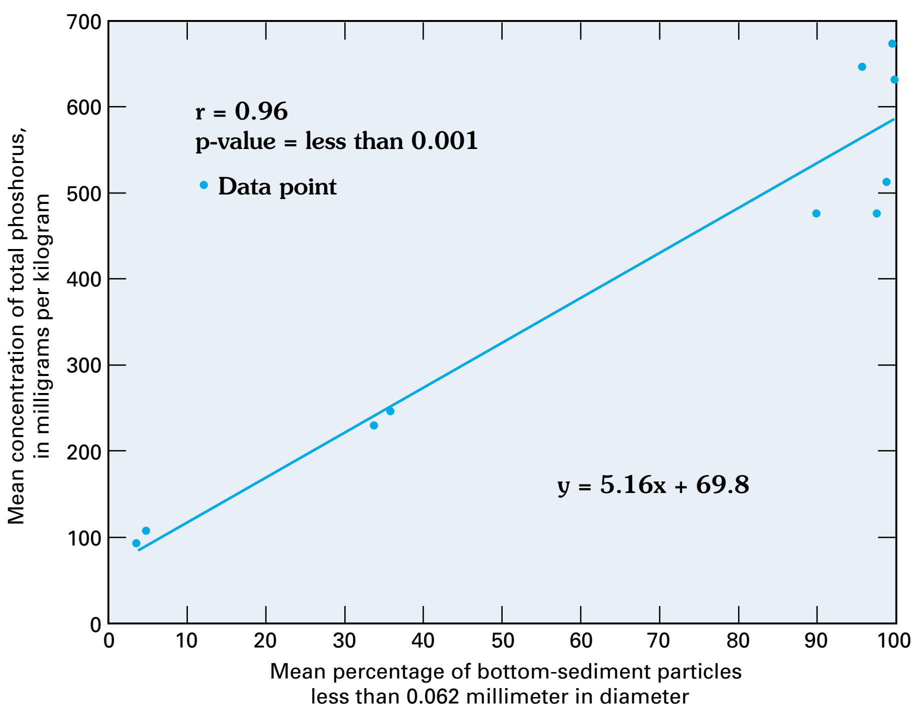

Figure 7. Relation between mean percentage of bottom-sediment particles less than 0.062 millimeter in diameter (silt and clay) and mean concentrations of total phosphorus in bottom-sediment samples from 10 coring sites in Cheney Reservoir, August 1997 (modified from Pope, 1998).

(2001) reported a sediment-volume weighted mean phosphorus concentration of 498 mg/kg. Because the 500 mg/kg mean concentration was calculated from the ratio of total phosphorus mass to total sediment mass in the reservoir, variability in particle size (as previously discussed) was not an issue. A direct comparison between mean total phosphorus concentration in reservoir bottom sediment and mean concentration in nonagricultural soils could be made.

An agricultural-enrichment factor for total phosphorus was calculated using the mean total phosphorus concentration in Cheney Reservoir bottom sediment (500 mg/kg) and the mean total phosphorus concentration (184 mg/kg) in 8-in. soil-core samples collected from 43 nonagricultural coring sites (fig. 1, table 1) used in the study described in this report. The mean total phosphorus concentration in 8-in. soil-core samples was calculated from data presented in table 2 after first averaging, by coring site, results of primary and replicate sample analyses. The agricultural-enrichment factor for total phosphorus in the Cheney Reservoir watershed was calculated by dividing the mean concentration in Cheney Reservoir bottom sediment (500 mg/kg) by the mean concentration (184 mg/kg) in 8-in. soil-core samples. The result of this calculation (2.7) produced an agricultural-enrichment factor for total phosphorus that was essentially the same as the 2.6 factor calculated from the results of the study described in this report. In summary, the information presented by Mau (2001) and the agricultural-enrichment factor calculated from that information provide supporting evidence for the validity of the particle-size weighted approach and methodology used in the study described in this report.

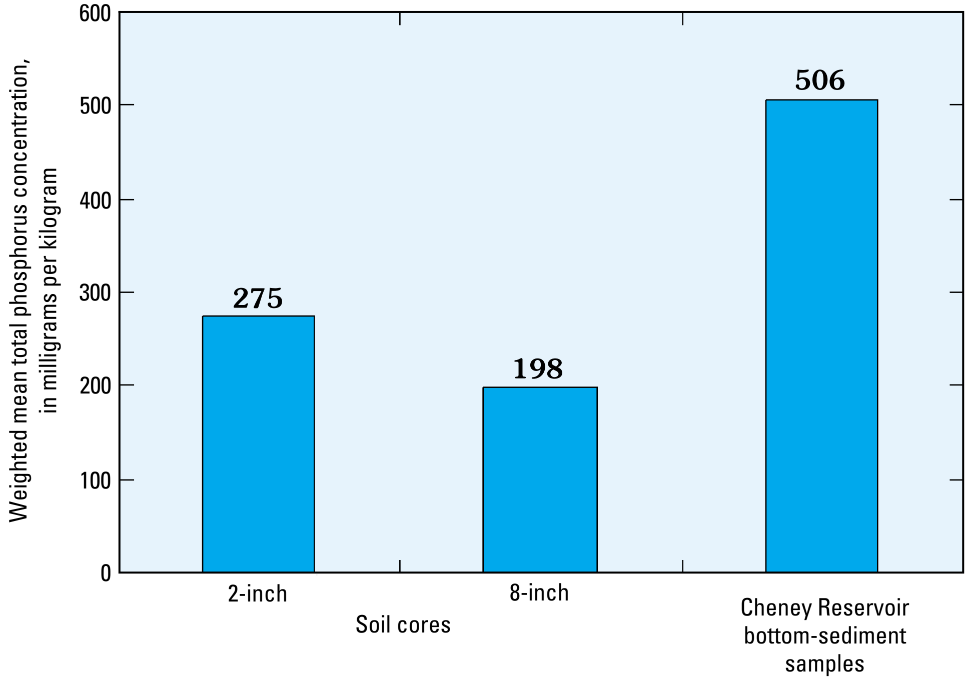

Figure 8. Comparison of particle-size weighted mean total phosphorus concentrations in soil-core samples from 43 nonagricultural sites in and near Cheney Reservoir watershed, September 1999, and in bottom-sediment samples from Cheney Reservoir, August 1997.

Both the 2.6 and 2.7 calculated enrichment factors for total phosphorus are conservative estimates of the effect of agricultural inputs of phosphorus in the Cheney Reservoir watershed because the factors do not account for (1) the phosphorus mass dissolved or suspended in the water at the time of collection of bottom-sediment samples, and (2) the mass of phosphorus historically discharged from the reservoir. These masses, however, can be estimated, added to the total mass of phosphorus in bottom sediment in Cheney Reservoir as determined by Mau (2001), and subsequently, used in the calculation of a historical mean agricultural-enrichment factor.

The phosphorus mass (in pounds) dissolved or suspended in the water at the time of collection of bottom-sediment samples (1997–98) was estimated from a calculation of the storage capacity of Cheney Reservoir at the conservation-pool elevation in 1998, 154,000 acre-ft (Putnam and others, 2000; Mau, 2001), multiplied by the mean concentration of total phosphorus, 0.10 mg/L (Milligan and Pope, 2001), of water in storage and by a unit conversion factor (2.720). The mean concentration of total phosphorus in water in storage was estimated as the mean concentration in water discharged from Cheney Reservoir during the course of the Cheney Reservoir watershed study (1997–2000). Estimated total phosphorus mass in Cheney Reservoir water at the time of collection of bottom-sediment samples was 42,000 lb.

The phosphorus mass historically discharged from Cheney Reservoir was estimated as a combination of mass actually discharged (into the North Fork Ninnescah River) and mass as part of the volume of water withdrawn by the city of Wichita for municipal supply. The phosphorus mass (in pounds) actually discharged from the reservoir was estimated from a calculation of volume of water discharged from the reservoir October 1, 1965, through September 30, 1998 (2.96 million acre-ft; Mau, 2001), multiplied by an estimated historical mean concentration of total phosphorus (0.07 mg/L) and by a unit conversion factor (2.720). The historical mean concentration of total phosphorus was estimated on the basis of the fact that the mean concentration of total phosphorus in reservoir discharge during the course of the Cheney Reservoir watershed study (1997–2000) was 0.10 mg/L (Milligan and Pope, 2001) and that total phosphorus transport from the watershed has been increasing with time (Pope, 1998; Mau, 2001). Therefore, the 0.10-mg/L mean concentration calculated for reservoir discharge (1997–2000) probably reflects a historical maximum mean concentration. No comprehensive historical (1965–98) database exists for concentrations of total phosphorus in water discharged or withdrawn from Cheney Reservoir. Consequently, the estimated 0.07-mg/L concentration of total phosphorus represents a compromise between what is believed to be an upper limit (0.10 mg/L) in mean total phosphorus concentration and an estimated lower limit (0.05 mg/L) determined on the basis of best professional judgement. Estimated total phosphorus mass actually discharged from Cheney Reservoir (1965–98) was calculated at 564,000 lb.

The phosphorus mass (in pounds) as part of the volume of water withdrawn by the city of Wichita for municipal supply was estimated from a calculation of volume of water withdrawn from the reservoir October 1, 1965, through September 30, 1998 (694,000 acre-ft; Mau, 2001), multiplied by an estimated historical mean concentration of total phosphorus (0.07 mg/L) and by a unit conversion factor (2.720). Estimated total phosphorus mass as part of the volume of water withdrawn for municipal supply was calculated at 132,000 lb.

Mau (2001) calculated the total mass of phosphorus in bottom sediment of Cheney Reservoir at 7.7 million lb. The total mass of phosphorus historically transported into Cheney Reservoir from the watershed is a summation of phosphorus mass in bottom sediment (7.7 million lb), in the reservoir water at the time of bottom-sediment sample collection (42,000 lb), in water discharged from the reservoir (564,000 lb), and in water withdrawn from the reservoir (132,000 lb). Total phosphorus mass historically transported (1965–98) into Cheney Reservoir was 8.4 million lb.

A historical mean agricultural-enrichment factor for total phosphorus can be calculated as the ratio of the historical phosphorus mass, expressed as a mean concentration of total phosphorus in sediment transported into Cheney Reservoir, to (divided by) the mean concentration of total phosphorus in soils from nonagricultural areas of the Cheney Reservoir watershed. The historical mean total phosphorus concentration in sediment transported into Cheney Reservoir (542 mg/kg) was calculated as total phosphorus mass divided by total sediment mass. Total phosphorus mass (8.4 million lb) was previously calculated. Mau (2001) calculated the total sediment mass deposited in Cheney Reservoir during 1965–98 (15.4 billion lb); however, this mass did not include an estimate for sediment discharged from the reservoir.

Sediment mass discharged from the reservoir (actually discharged and withdrawn) was calculated using the same method and water volumes as used in the calculation of phosphorus mass except a historical mean concentration of sediment in water discharged from Cheney Reservoir was estimated on the basis of a mean concentration of total suspended solids in water (9.8 mg/L) discharged from the reservoir during 1997–2000 (Milligan and Pope, 2001). Total sediment mass discharged from the reservoir during 1965–98 was calculated at 97.0 million lb. Total sediment in reservoir water at the time of bottom-sediment sample collection (1998) was believed to be insignificant and was not calculated. Therefore, total sediment mass historically (1965–98) transported into Cheney Reservoir was 15.5 billion lb, and the historical mean agricultural-enrichment factor was 2.9 (542 mg/kg divided by 184 mg/kg).

It should be emphasized that the 2.9 enrichment factor is a historical mean and that a current (2001) enrichment factor may be greater because of an apparent increasing trend in phosphorus transport from the watershed (fig. 6). In summary, agricultural activities during 1965–98 have increased the transport of phosphorus into Cheney Reservoir 2.9 times greater than that expected under natural concentrations of phosphorus in watershed soil.

Natural and Agricultural Sources

Historical contributions of phosphorus to Cheney Reservoir from natural and agricultural sources could not be measured directly, but instead, were estimated from the previously calculated 2.9 historical mean agricultural-enrichment factor for total phosphorus. The enrichment factor, in effect, indicates that the mass of phosphorus historically transported into Cheney Reservoir is 2.9 times greater than the mass expected under conditions where the watershed soil contains an average natural concentration of soil phosphorus. In other words, the total mass of phosphorus historically transported into Cheney Reservoir (8.4 million lb) is about 2.9 times the mass from natural sources; thus, the mass from natural sources is about 8.4 million lb divided by 2.9, or 2.9 million lb (35 percent of the total mass historically transported). The percentage of this total mass of phosphorus transported into Cheney Reservoir that originated from agricultural sources, therefore, was about 65 percent (5.5 million lb) (fig. 9).

The percentages shown in figure 9 represent historical averages and may not accurately describe current (2001) conditions. However, these percentages do indicate that, because of the large percentage of phosphorus from agricultural sources, changes to agricultural or land-management practices that would mitigate the movement of sediment and associated phosphorus or changes in phosphorus application and distribution in the watershed have a large potential for reducing the mass of phosphorus transported to Cheney Reservoir.

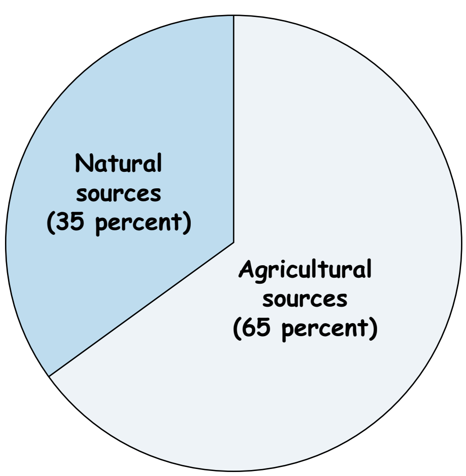

Figure 9. Comparison of phosphorus transported to Cheney Reservoir from natural and agricultural sources, 1965–98.

PHOSPHORUS AND SEDIMENT RETENTION EFFICIENCIES OF CHENEY RESERVOIR

The masses of phosphorus and sediment transported to and retained in Cheney Reservoir can be used to calculate the retention efficiency of the reservoir for these constituents. Retention efficiency, expressed as a percentage, was calculated by dividing the mass deposited as or in association with reservoir bottom sediment by the total mass transported into the reservoir, and multiplying the quotient by 100. The historical retention efficiency for phosphorus was 92 percent (7.7 million lb divided by 8.4 million lb, times 100). The historical retention efficiency for sediment was 99 percent (15.4 billion lb divided by 15.5 billion lb, times 100). These results indicate that Cheney Reservoir is a sink for much of the mass of those water-quality constituents transported from the watershed.

A previous investigation of Cheney Reservoir (Pope and Milligan, 2000) calculated a retention efficiency of 62 percent for total phosphorus. This relatively small retention efficiency, however, was calculated on the basis of phosphorus loads transported in streamflow into and discharged from Cheney Reservoir, and it is probable that the 2 years (1997–98) for that investigation was not representative of historical average phosphorus transport conditions because of the absence of substantial runoff or flooding conditions during 1997–98 (Putnam and others, 1998–99).

The potential for surface-water bodies to retain phosphorus varies, but many studies have documented large retention efficiencies. For example, phosphorus retention efficiencies for wetland and swamp areas in Florida were calculated at 72 percent (Moustafa and others, 1998) and 82 percent (Moustafa, 1999), respectively; an agriculturally affected lake in southwest Finland had a retention efficiency of greater than 80 percent (Ekholm and others, 1997); and a multi-pond system in southeastern China had a retention efficiency of about 98 percent (Weijin and others, 1998). More locally, Juracek (1998) calculated a historical phosphorus budget for Hillsdale Lake in northeast Kansas (fig. 1) that produced a phosphorus retention efficiency of 89 percent. The 92-percent phosphorus retention efficiency calculated for Cheney Reservoir, therefore, seems reasonable.

In a process similar to that for phosphorus, reservoirs also have the potential to retain large percentages of the inflow sediment load. Jansson and Erlingsson (2000) calculated a sediment retention efficiency of about 80 percent for Cachi Reservoir in Costa Rica. Tobin and Hollowed (1991) calculated a sediment retention efficiency for Kenney Reservoir in northwestern Colorado that ranged from 91 to about 98 percent; the latter percentage corresponds well to the 99-percent sediment retention efficiency calculated for Cheney Reservoir in the study described in this report.

Large retention efficiencies of water-quality constituents such as phosphorus or sediment may have water-quality implications for, and may reduce the useful life of, a reservoir. Phosphorus accumulation in reservoir bottom sediment may provide a source of internal loading of phosphorus (release of bioavailable phosphorus from sediment) (Morris and Fan, 1998), particularly under anaerobic (absence of oxygen) conditions at the sediment-water interface (Alaoui Mhamdi and others, 1994; Istranovics, 1994). This released bioavailable phosphorus may increase the rate of algal production (Horne and Goldman, 1994) and, subsequently, the occurrence of taste-and-odor problems in treated drinking water (Juttner, 1984; Hoson, 1992). However, under aerobic (oxygenated) conditions at the sediment-water interface, phosphorus release from sediment may be greatly suppressed (Erickson and Auer, 1998).

On the basis of limited depth profiling of dissolved oxygen concentrations collected during the Cheney Reservoir watershed study (1997–2000), anaerobic conditions in Cheney Reservoir have not occurred. Additionally, Gibson (1997) provided evidence that indicated there is a phosphorus-concentration threshold at approximately 1,000 mg/kg dry sediment below which sediment tended not to release phosphorus back into the water column. Phosphorus concentrations in Cheney Reservoir bottom sediment did not exceed this threshold (Pope, 1998; Mau, 2001).

Although Cheney Reservoir has a large retention efficiency for phosphorus (92 percent), other factors such as well-oxygenated water and relatively small concentrations of phosphorus in bottom sediment (less than 1,000 mg/kg) may limit algal proliferation and subsequent occurrences of taste-and-odor problems in treated drinking water from the reservoir by inhibiting the internal loading of phosphorus. In fact, taste-and-odor problems in treated drinking water occurred during several summers in the early 1990s (Cheney Reservoir Watershed Task Force Committee, written commun., 1996) but were not observed and reported during the Cheney Reservoir watershed water-quality study (1996–2001) until the summer of 2001.

One of the principal concerns with the transport of sediment into Cheney Reservoir is a loss of reservoir storage capacity (Cheney Reservoir Watershed Task Force Committee, written commun., 1996). Decreases in reservoir storage capacity can affect reservoir allocations used for flood control, drinking-water supplies, recreation, and wildlife habitat. The part of a reservoir designed for sediment storage is called the inactive conservation storage pool and commonly is designed to provide storage for 100 years of sediment deposition (Morris and Fan, 1998). As of 1998, 34 years of sediment deposition had occurred in Cheney Reservoir, which equates to 34 percent of the design life of the reservoir. A previous investigation of Cheney Reservoir (Mau, 2001) determined that during the first 34 years in the design life of Cheney Reservoir, 27 percent of the allocated sediment storage capacity had been used. Although the sediment retention efficiency at Cheney Reservoir was large (99 percent), the design life of the reservoir is being met provided that the common design-life specifications were used in the design of the reservoir.

IMPLICATIONS FOR STREAM WATER QUALITY

Information on natural concentrations of total phosphorus in soil of the Cheney Reservoir watershed relative to total phosphorus transported from the watershed can provide insight into the attainability of stream-water-quality goals. The U.S. Environmental Protection Agency (1986) has recommended a goal of 0.10 mg/L of total phosphorus in flowing surface water. Additionally, the Cheney Reservoir Watershed Task Force Committee (written commun., 1996) has recommended the same long-term mean water-quality goal of 0.10 mg/L for streams in the Cheney Reservoir watershed.

In 1996, the USGS entered into a cooperative study with the city of Wichita to assess the occurrence and transport of selected water-quality constituents, including phosphorus, within the Cheney Reservoir watershed. As part of that study, six streamflow sampling sites were established in the watershed (fig. 10, table 3). Streamflow sampling sites 1–5 were located on the main stem of the North Fork Ninnescah River or its tributary streams. Sampling site 6 was located at the outflow of Cheney Reservoir. A continuous record of streamflow was collected at all six sampling sites.

Samples of streamflow were collected during base flow (low-flow conditions) and during runoff (high-flow conditions) (table 4).

Automatic samplers were installed at streamflow sampling sites 1–5. The analysis of samples collected from these automatic samplers (automatic samples) and additional manually collected samples (manual samples) comprised the water-quality database for the Cheney Reservoir watershed assessment. Most runoff samples were collected with automatic samplers. Manual samples were collected to provide depth- and width-integrated composite samples representative of the average chemical composition of the stream's cross-sectional area. Automatic samples were collected from a single point in the stream cross-sectional area and, therefore, may not be representative of the average chemical composition of the stream's cross-sectional area at the time of sample collection. Samples were collected from January 1997 through December 2000. Samples were analyzed for total phosphorus concentrations at the city of Wichita laboratory using U.S. Environmental Protection Agency method 365.2 (U.S. Environmental Protection Agency, 1999).

Concentrations of total phosphorus determined from automatically collected point samples were adjusted to approximate the average cross-sectional phosphorus concentration provided by depth- and width-integrated manually collected samples. This approximation was accomplished through the development and application of sampling-site-specific linear-regression relations between total phosphorus concentrations determined for pairs of concurrently collected automatic and manual samples from streamflow sampling sites 1–5 (fig. 10). Details of this adjustment procedure are presented in Milligan and Pope (2001).

More samples of streamflow for analysis of total phosphorus were collected during runoff than during base flow (table 4) because the majority of phosphorus from the Cheney Reservoir watershed is transported during runoff conditions. For example, at sampling site 4 (fig. 10), the main inflow site to Cheney Reservoir, it was estimated that 72 percent of the phosphorus in streamflow at this site (1997–2000) was transported during runoff. This percentage mirrors the percentage of samples collected during runoff at sampling site 4 (73 percent, table 4).

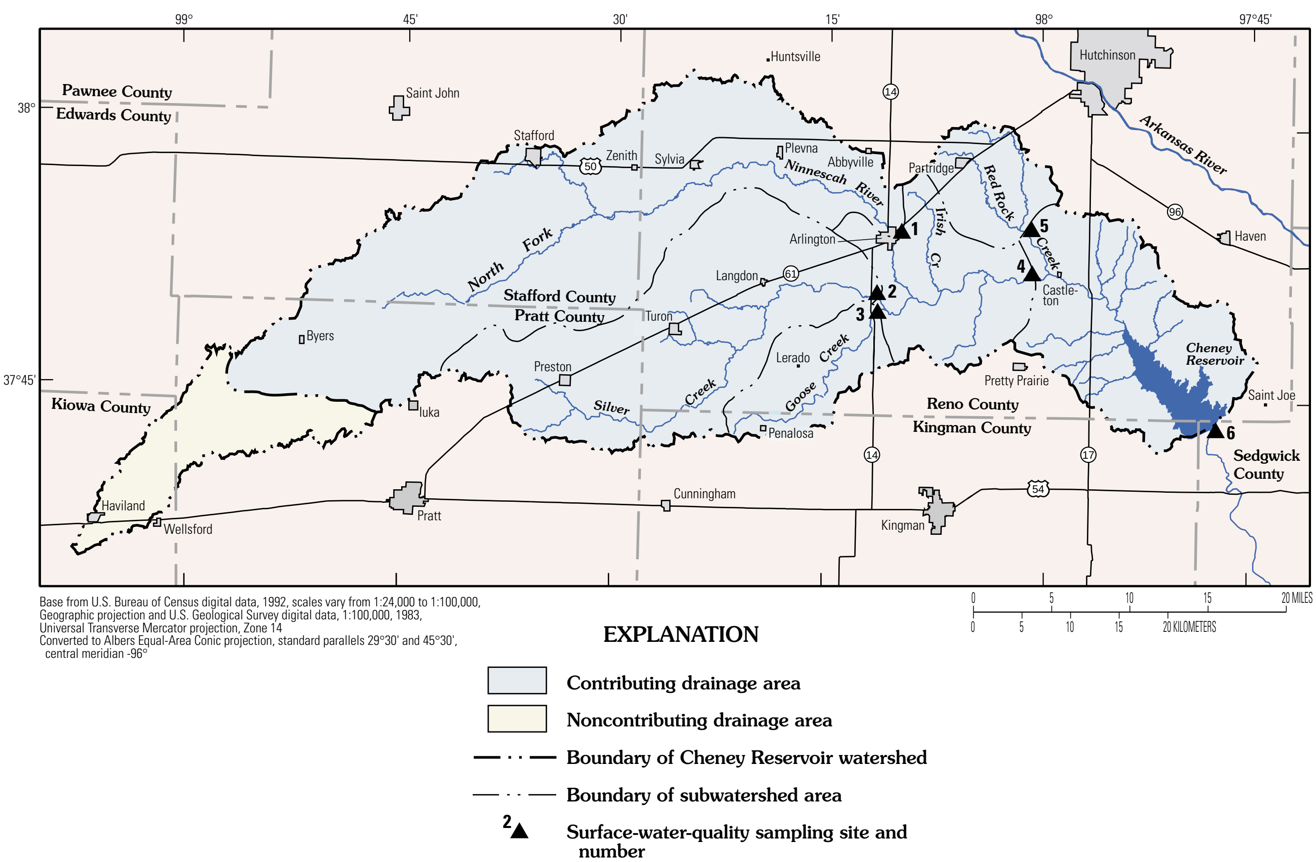

Figure 10. Location of streamflow sampling sites in Cheney Reservoir watershed.

Table 3. Description of streamflow sampling sites in Cheney Reservoir watershed, south-central Kansas

Sampling-site map index number (fig. 10)	U.S. Geological Survey site identification number	Sampling-site name	Contributing drainage area (square miles)
1	07144601	North Fork Ninnescah River at Arlington, Kansas	403
2	07144660	Silver Creek near Arlington, Kansas	193
3	07144680	Goose Creek near Arlington, Kansas	51.8
4	07144780	North Fork Ninnescah River near Pretty Prairie, Kansas	734
5	07144730	Red Rock Creek near Pretty Prairie, Kansas	53.2
6	07144795	North Fork Ninnescah River at Cheney Dam, Kansas	933

Table 4. Number of samples analyzed and mean concentrations of total phosphorus in streamflow during base-flow, runoff, and long-term streamflow conditions at sampling sites 1–5 in Cheney Reservoir watershed, south-central Kansas, 1997–2000

[N, number of samples analyzed; mg/L, milligrams per liter]

Sampling-site map index number (fig. 10)	Base flow[1]		Runoff[1]		Long term[1] (1997–2000)	
	N	Mean concentration (mg/L)	N	Mean concentration (mg/L)	N	Mean concentration[2] (mg/L)
1	36	0.13	92	0.29	128	0.25
2	38	.14	78	.28	116	.23
3	40	.11	78	.48	118	.36
4	32	.10	85	.38	117	.30
5	37	.14	106	.62	143	.50

[1]Data from Milligan and Pope (2001).
[2]Calculated using all available base-flow and runoff analyses.

The 72-percent transport estimate for phosphorus during runoff was calculated using a regression equation that related phosphorus load (PL, dependent variable), in grams per second, to streamflow (Q, independent variable), in cubic feet per second. This equation [$PL = 0.00063Q^{1.423}$; R^2 (coefficient of determination) equals 0.84, p-value of less than 0.0001] was an updated version of an equation used in a previous investigation of phosphorus transport in the Cheney Reservoir watershed during 1997–98 (Pope and Milligan, 2000). It was updated to include total phosphorus and streamflow data through 2000. Daily mean streamflow (Putnam and others, 1998–2001) for periods of base flow and runoff were used as input variables for the regression equation. Daily loads and, ultimately, percentage transport for base flow and runoff were calculated.

On average, total phosphorus concentration in samples of streamflow collected during runoff were about 2.0 (sampling site 2) to 4.4 (sampling sites 3 and 5) times larger than concentrations in samples of streamflow collected during base flow (table 4). Mean concentrations of total phosphorus in samples of streamflow also were calculated as a long-term (1997–2000) average (table 4) using all available (base-flow and runoff) adjusted automatic and manual sample concentrations (fig. 11).

One of the purposes of determining natural concentrations of total phosphorus in soil is the estimation of the potential to achieve stream-water-quality goals under natural conditions, all other watershed factors being historically constant. This information may have substantial watershed-management implications.

Mean total phosphorus concentrations at streamflow sampling sites 1–5 that have occurred under natural concentrations of total phosphorus in soil were estimated by dividing the previously determined mean total phosphorus concentrations calculated from streamflow samples (1997–2000) by an agricultural-enrichment factor of 2.9. A comparison of measured

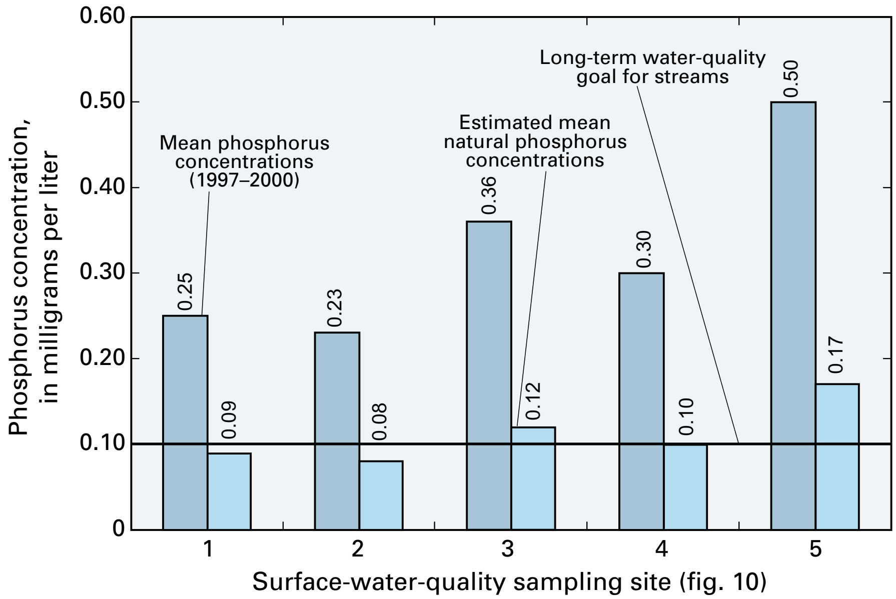

Figure 11. Comparison of measured (1997–2000) mean total phosphorus concentrations in water samples from five streamflow sampling sites in Cheney Reservoir watershed and mean concentrations estimated on basis of agricultural-enrichment factor of 2.9. Long-term stream-water-quality goal established by Cheney Reservoir Watershed Task Force Committee (written commun., 1996).

mean and estimated mean total phosphorus concentrations (on the basis of a historical mean agricultural-enrichment factor of 2.9) in water from streamflow sampling sites 1–5 is presented in figure 11. An examination of results presented in figure 11 indicates that under natural concentrations of total phosphorus in soil, mean total phosphorus concentrations in water from two of the five streamflow sampling sites upstream from Cheney Reservoir (sampling sites 3 and 5) would not meet the water-quality goal of 0.10 mg/L established by the Cheney Reservoir Watershed Task Force Committee. The conclusion, therefore, is that even if soils in the Cheney Reservoir watershed were maintained with natural concentrations of total phosphorus, some streams or stream segments would not meet water-quality goals assuming all the other historical watershed conditions remained the same.

The implication of the information presented in figure 11 is that the water-quality goal for total phosphorus in some streams in the Cheney Reservoir watershed may not be met simply by reducing phosphorus concentrations in soil (reducing the amount of phosphorus applied). Instead, meeting the goal could involve a combination of approaches—for example, reducing the agricultural distribution of phosphorus and implementing changes in land-use, land-management, and agricultural practices that reduce the loss of phosphorus from soil to water or the movement of phosphorus-laden soil in runoff (Devlin and others, 1998). Previous investigations have shown a direct relation between phosphorus concentrations and percentages of the fine silt- and (or) clay-size (less than 0.062 mm) particles (Galeone, 1996; Pope, 1998). Therefore, changes in the watershed that would mitigate the transport of these fine particles also would reduce the movement of phosphorus to surface water and, potentially, the eutrophication of Cheney Reservoir.

The possibility of substantial reductions in estimated long-term mean concentrations of total phosphorus in water from several sampling sites (for example, sites 1, 2, and 4; figs. 10 and 11) probably is not great. An analysis of total phosphorus concentrations in water from Kings Creek (USGS gaging station 06879650) located on the Konza Prairie Biological Station (KPBS) (fig. 1) in northeast Kansas was conducted to compare results from the agriculturally dominated Cheney Reservoir watershed to a “natural” (predevelopment) prairie-grass environment. The KPBS is representative of an eastern Kansas native tallgrass prairie ecosystem (Kansas State University, 2001).

Between 1980 and 1996, the USGS collected and analyzed 76 samples of streamflow from Kings Creek for total phosphorus. The mean concentration of total phosphorus in these samples was 0.06 mg/L (data on file at USGS office in Lawrence, Kansas), not too dissimilar to the estimated long-term mean concentrations determined under natural soil phosphorus conditions at sampling sites 1, 2, and 4 in the Cheney Reservoir watershed (fig. 11). This 0.06-mg/L concentration may provide insight as to a lower threshold limit of total phosphorus in eastern Kansas, tallgrass prairie streams under “natural” conditions. Therefore, it is probably unrealistic to expect that a long-term mean concentration of total phosphorus in water from a managed agricultural watershed would be less than 0.06 mg/L regardless of whether the soil phosphorus concentrations in the watershed were natural concentrations or not. However, this supposition is qualified with the fact that in 1987 the KPBS had a permanent herd of bison established in the Kings Creek watershed and that in 1992 an experimental herd of cattle was introduced (Kansas State University, 2001). It is unknown to what extent these animal populations have affected the long-term mean concentration of total phosphorus in water from Kings Creek. The available data set is not adequate for that type of analysis.

SUMMARY AND CONCLUSIONS

Phosphorus has been added routinely to agricultural soils to increase crop production. Historically, however, applications have been in excess of crop requirements and have led to a buildup of phosphorus concentrations in soil beyond agronomic need. This buildup of soil phosphorus has increased the potential for phosphorus transport to surface water in runoff from agricultural lands.

Excess phosphorus in surface water can accelerate eutrophication (nutrient enrichment) particularly in lakes and reservoirs. Cheney Reservoir in south-central Kansas may be a reservoir with the potential for detrimental effects from eutrophication and, in fact, has a history of algal blooms and taste-and-odor problems in treated drinking water.

To address the eutrophication issues in Cheney Reservoir and nutrient transport from the Cheney Reservoir watershed, the U.S. Geological Survey, in 1996, entered into a cooperative study with the city of Wichita, Kansas. Results from this study will be useful to watershed managers in evaluating the sources and transport of phosphorus in the Cheney Reservoir watershed and the potential for meeting in-stream total maximum daily loads for phosphorus under existing or proposed land-use and land-management practices.

Concentrations of soil phosphorus transported to Cheney Reservoir have been increasing at least since the construction of the reservoir as indicated by bottom-sediment cores collected in 1997. However, the extent to which these concentrations have increased compared to natural concentrations is unknown. To help determine if agricultural activities need to be modified or land-management practices implemented to control phosphorus transport, it was first necessary to define the extent to which these activities have increased phosphorus transport to the reservoir. Therefore, soil-core samples were collected at 43 nonagricultural coring sites (mostly cemeteries) in and near Cheney Reservoir watershed in September 1999. These sites were selected to represent soils with natural concentrations of total phosphorus. Analyses of soil-core samples from these 43 nonagricultural sites resulted in natural concentrations of total phosphorus that ranged from 74 to 539 mg/kg with a median concentration of 245 mg/kg in 2-in. soil-core samples and from 50 to 409 mg/kg with a median concentration of 166 mg/kg in 8-in. soil-core samples. Natural concentrations of total phosphorus in soil were statistically larger in coring-site samples from the eastern half of the watershed than in coring-site samples from the western half of the watershed. This determination partly explains a previously determined west-to-east increase in total phosphorus yields in streams of the Cheney Reservoir watershed.

A comparison of soil phosphorus concentrations from 43 nonagricultural sites in and near Cheney Reservoir watershed to the historical mean total phosphorus concentration in agriculturally enriched bottom sediment of Cheney Reservoir was made. Results of this comparison indicated that agricultural activities within the watershed have increased total phosphorus concentrations in soil to about 2.9 times natural concentrations.

Retention efficiencies for the mass of phosphorus and sediment historically transported to Cheney Reservoir were calculated at 92 and 99 percent, respectively. Most of the phosphorus was retained in the bottom sediment. These large retention efficiencies raise concerns about potential water-quality issues and loss of reservoir storage. However, reservoir factors such as well-oxygenated water and total phosphorus concentrations in bottom sediment less than a threshold concentration of 1,000 mg/kg, believed to release phosphorus back into the water column, may limit problems associated with phosphorus in sediment. Sediment accumulation in Cheney Reservoir was less than reservoir design-life specifications on the basis of the age of the reservoir.

Information on agricultural enrichment of total phosphorus concentrations in soil was used to estimate mean total phosphorus concentrations in selected streams of the Cheney Reservoir watershed that may have occurred under natural total phosphorus conditions in soil. These estimates were made by dividing the mean total phosphorus concentrations calculated from water samples collected at five streamflow sampling sites during 1997–2000 by an agricultural-enrichment factor of 2.9. Results of these estimates indicated that, under natural phosphorus conditions in soil and a historic set of watershed conditions, mean total phosphorus concentrations in water from two of the five streamflow sampling sites in the Cheney Reservoir watershed would not meet a water-quality goal of 0.10 mg/L established by the Cheney Reservoir Watershed Task Force Committee. The implication of these results is that the water-quality goal for total phosphorus in some streams of the Cheney Reservoir watershed may not be met simply by reducing the amount of phosphorus applied. Instead, meeting the goal could involve a combination of approaches—for example, reducing the agricultural distribution of phosphorus and implementing changes in watershed activities to mitigate phosphorus movement to surface water.

Agricultural activities have had an effect on phosphorus input to Cheney Reservoir and may have contributed to past reservoir algal blooms and taste-and-odor problems in treated drinking water and may reduce the aesthetic and recreational value of the reservoir. Information concerning the extent of phosphorus enrichment in soil of the Cheney Reservoir watershed will assist watershed managers in formulating plans and evaluating options to mitigate phosphorus distribution, its transport, and, ultimately, its role in eutrophication of Cheney Reservoir.

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