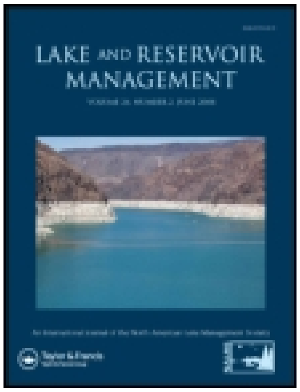

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Eutrophication of Tenkiller Reservoir, Oklahoma, from nonpoint agricultural runoff

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Abstract

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Tenkiller Ferry Reservoir, a large (51.6 km^2) US midcontinent reservoir in Oklahoma, switched from oligo-mesotrophic prior to 1975 to eutrophic by 1986, evidenced by changes in phytoplankton taxa, chlorophyll (Chl), total phosphorus (TP), transparency, and areal hypolimnetic oxygen deficit. External TP loading increased 2.5-fold between 1974 and 2004, mainly as nonpoint loading from disposal of an annual (2001–2004) average 406,818 metric tons (mt) of untreated poultry litter on watershed pastures, which added an annual (2001–2006) average 4120 mt of TP. Phosphorus runoff from litter, estimated as 5 % of applied, was 63 % of external loading to the Illinois River from 2001– 2004, 71 % after the 2004 waste water treatment plant upgrade. The 9 % load decrease from the upgrade did not affect Chl. Sediment TP release, seldom determined for reservoirs, accounted for 16 % of annual external plus internal TP load. Trophic state graded from riverine to lacustrine zone. In wet summers with low residence times, the lacustrine zone was eutrophic; in dry summers it was mesotrophic. Transition and riverine zones were always eutrophic or hypereutrophic. Trophic state assessment ideally requires multiple sampling years in all reservoir zones. A similar Oklahoma reference reservoir, Broken Bow, with modest watershed poultry activities and low inflow TP concentrations, was oligo-mesotrophic. Rehabilitation of Tenkiller Reservoir requires large reductions of TP loading by ceasing watershed litter disposal, changes in watershed management practices, and application of in-reservoir procedures.
[Supplemental materials are available for this article. Go to the publisher's online edition of Lake and Reservoir Management *to view the supplemental file.]*

Key words: eutrophication, nonpoint loading, oxygen deficits, phosphorus loading, phytoplankton, poultry litter, reservoir management, Tenkiller Reservoir

The trophic state of midcontinent reservoirs is largely a function of location in the landscape, which determines watershed size and hydrologic residence time, and depth (dam height), which determines volume. A third factor, land cover in the watershed, is potentially variable over time and determines nutrient loading. In the rural US Midwest, most nutrient loading is from nonpoint agricultural sources (Carpenter et al. 1998), and reservoir trophic state metrics increase with percent agriculture and decrease with forest cover (Knoll et al. 2003, Carney 2009, Jones et al. 2009). Reservoirs with low and moderate production are usually located in deep wooded valleys with modest agriculture (Jones et al. 2004, 2008; those with relatively undisturbed watersheds display trophic states near regional reference conditions (Carney 2009). Age is not significant in explaining reservoir trophic state. Newly constructed reservoirs and those decades older fit within the same cross-system pattern (Carney 2009, Jones et al. 2009). Temporal variation in individual reservoirs is a response to climate and the timing of inflows relative to stratification (Knowlton and Jones 2006).

Many midcontinent reservoirs are relatively new additions to the landscape and were constructed after historic vegetation was altered for intensive agriculture. Growth of the animal industry is the largest regional change during this period, and large confined feeding operations clustered in rural areas are increasingly common (Carpenter et al. 1998). Often

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feed for livestock comes from outside the watershed, followed by local land application of manure. Manure disposal to pastures and cropland is a source of nonpoint nutrient loading to streams (Carpenter et al. 1998), and application rates can exceed pasture and cropland needs leading to soil nutrient build-up and greater nonpoint loss from the landscape (Sharpley et al. 2003, Carpenter 2005).

Tenkiller Ferry Reservoir (Tenkiller) and its major inflow, the Illinois River (IR), were among Oklahoma's most outstanding water resources (1953–1957), with clear water of exceptional quality (Brill 1957). Tenkiller has since undergone eutrophication and is now identified as eutrophic (OWRB 1995, Tortorelli and Pickup 2006). This change in trophic state coincides with rapid poultry industry growth and disposal of untreated litter on watershed pastures.

Changes in Tenkiller provide a regional case study of a reservoir undergoing eutrophication over a time frame of decades in response to intensified agriculture. Our purpose is to determine trophic state characteristics in riverine, transition, and lacustrine zones of Tenkiller between 1960 and 2008 and to quantitatively describe external point and nonpoint, as well as internal total phosphorus (TP) loading. There have been few studies of trophic state changes in reservoir zones over extended periods, and computations of internal P release are rare. Our quantitative estimation of nonpoint TP loading, compared to point loading, seems to be unique. Our analysis was enhanced by the use of a reference, Broken Bow Reservoir, Oklahoma, which is physically similar but with less intensive agriculture and a TP loading closely matching early levels in Tenkiller. These data provide the basis for recommendations for rehabilitation of Tenkiller.

Site descriptions

Illinois River Watershed (IRW)

The IRW, located on the Arkansas–Oklahoma border (2 counties in Arkansas, 3 in Oklahoma; area = 4331 km^2), is in the Ozark Highlands ecoregion 39b Dissected Springfield Hills-Elk River Basin. This subecoregion has narrow ridges (elevations to 430 m), steep valleys, carbonate rocks, and associated mantled karst with fractures and faults. Soils are low fertility ultisols, subject to runoff in eastern (mainly Arkansas) and infiltration in western (mainly Oklahoma) portions. Shallow groundwater, susceptible to contamination via fractures and infiltration, enters the IR (Woods et al. 2005). Prior to deforestation and growth of the poultry industry, TP concentrations in the IR were estimated at 16–20 μg/L (McDowell and Omernik 1979). In 2001, primary land uses in the IRW were forest (43 %), pasture (42 %), developed (9 %), and row crop agriculture (0.14 %; National Land Cover Data Set 2001). The IRW human population (2000 census) was 280,383, a 3-fold increase since 1950.

Table 1.-Comparisons of Tenkiller Reservoir (TK) and Broken Bow Reservoir (BB).

	BB	TK
Mean depth, m	19.7	15.5
Area, km^2	56.8	51.6
Hypolimnion % total volume	43.5	40
Water residence time, half years	3.5	1.1
Watershed:reservoir area ratio	34	80
Lacustrine area >6 m - %	88	86
Forest % of watershed	79	43
Pasture % of watershed	12	45
Developed % of watershed	4	9
Agricultural crop land %	<1	<1
WWTP, % of P load	<1	9
Active poultry houses (2006)	248	1917
Broiler density (2002)	17×10^6	140×10^6
Mean TP inflow, μg/L May - September (years)	29 (3)	171 (9)
EPA Map expected TP, μg/L*	16–20	16–20
True color, PC units**	11	14
TP-Chl relation for 143 MO reservoirs***	conforms	conforms

*McDowell and Omernik 1979 (stream map class 3)
** Oklahoma Water Resources Board 2007 BUMP Report
***Jones and Knowlton (2005); Figure 4 this report

Poultry production dominates IRW agriculture. In 2002 (last year of data with direct comparison to Broken Bow), broiler sales (~90 % of total poultry) were 140×10^6 birds from 1917 active poultry houses. The swine and cattle population was about 100,000 animals (Appendix A; this and other appendices are available in the Journal's online version). Pastures were used for poultry litter disposal.

Tenkiller Ferry Reservoir

Tenkiller's dam was closed in 1953, impounding the IR and tributaries (Baron Fork, Caney Creek). The US Army Corps of Engineers (USCOE) operates the reservoir for flood control, hydropower, and recreation (see reservoir characteristics in Table 1).

Broken Bow Reservoir

Broken Bow, a USCOE project, was filled in 1970 by damming the Mountain Fork River for flood control, hydropower, water supply, and recreation. It is in subecoregion 36b, Central Mountain Ranges (near Ozark Highlands), characterized by steep terrain (to 700 m) with springs and waterfalls. Soils are low fertility ultisols, and stream TP concentrations are expected near 16–20 μg/L (McDowell and Omernik 1979, Woods et al. 2005). The watershed is 79 % forested, consistent with low stream TP concentrations (Jones et al. 2004). In 2002, broiler sales from 248 houses were 17 × 10^6 birds (similar to the IRW in 1953; Appendix A).

Broken Bow was the reference reservoir because it is oligo-mesotrophic (OWRB 2004–2007), in a highly similar, adjacent ecoregion to Tenkiller, and has small poultry operations and pasture areas relative to forested area. As in Tenkiller, earlier trophic state data were from multiple reservoir stations, and there were extensive fish data (Welch et al. 2011). Other Oklahoma reservoirs, few with similar data, are in southern and western cropland areas with higher stream TP concentrations and eutrophic conditions (Woods et al. 2005, OWRB BUMP 2007). Watershed and reservoir characteristics are in Table 1.

Methods

External TP loading for 1974–1975 and 1991–1993 were from the US Environmental Protection Agency (USEPA 1977), Oklahoma Water Resource Board (OWRB 1995), and Gade (1998). External TP loading was calculated separately for baseflow and runoff conditions for 1997–2004 by the US Geological Survey (USGS; Pickup et al. 2003, Tortorelli and Pickup 2006). USGS averaged 2-year periods for 7 years to reduce variation, producing 6 loading estimates. We averaged the 6 estimates to produce loading for 1997–2004. We increased the load from the IR and Baron Fork by 3.7 % to include the third tributary, Caney Creek, entering midway through the riverine zone (Fig. 1). The correction factor is based on spring–summer (May–Sep) loads in 2006 when Caney Creek was monitored, and TP loads from the IR were similar to those during 2000–2004 (Tortorelli and Pickup 2006).

Volume-weighted, spring–summer 2005–2006 inflow TP concentrations were determined from USGS flow data at Tahlequah and the Baron Fork, from monthly USGS TP determinations, and from twice-monthly TP data collected by Camp Dresser McKee (CDM) at Tahlequah, Baron Fork (at Eldon, OK), and Caney Creek. The mean annual and summer volume-weighted inflow concentrations were obtained by dividing load (kilograms per time) by average inflow volume, corrected for Caney Creek. Tahlequah spring–summer inflow concentrations were extrapolated to all 3 inflows by dividing by the ratio of flow-weighted concentration in the 3 inflows to that at Tahlequah alone (0.79) during 2006. Volume-weighted inflow concentrations to Broken Bow for 2005 and 2007 were from monthly (Apr–Aug) OWRB data ($n = 11$) and from the USGS gauge at Smithville, Oklahoma, on the Mountain Fork River.

Riverine zone (LK04) net sediment TP release (internal loading) was calculated from biweekly concentration differences between inflow and riverine, multiplied by riverine volume (22.75 × 10^6 m^3), divided by mean riverine zone residence time (10 days). Gross transition zone (LK03) internal TP release was assumed equal to net rate per unit area in LK04 multiplied by transition zone area. Lacustrine zone (LK02, LK01) sediment TP release was calculated by change in hypolimnetic TP concentrations (mg/m^2 per day) multiplied by respective hypolimnetic areas.

Tenkiller was sampled by CDM during June–September 2005–2008 at 3 reservoir zones (riverine, LK04; transition, LK03; and lacustrine, LK02 and LK01; Fig. 1), using GPS to locate the sites corresponding to those used by OWRB (1995) and USCOE studies. Sampling frequencies per zone were 9 in 2005 and 2006, 3 in 2007, and 4 in 2008.

Broken Bow was sampled twice by CDM in August 2007 at riverine, transition, and lacustrine stations (BB08, BB06, BB03; Fig. 2) for all variables. Data for 1995, 1997, 2004, and 2006 were from one-time summer samples by the OWRB Beneficial Use Monitoring Program (BUMP).

Trophic state for recent and older agency studies was determined from June-September samples using epilimnetic means for TP and chlorophyll (Chl), and station means for Secchi disk (SD) transparency. Trophic state boundaries were assigned according to Nürnberg (1996) (see Figs. 3 and 6 in present article). In 2005–2008, concentrations at 0, 3, and 6 m were averaged. Whole-reservoir epilimnion means were volume-weighted, correcting for reservoir volume changes. Transparency was area-weighted (all data, with standard errors, in Appendices B, C, and D). Hypolimnetic TP accumulation rate was determined from 3 to 4 vertical TP profiles of concentration with depth per summer. Historical summer trophic state data (Jun–Sep) were from agency documents and literature (cited throughout text).

Reservoir P concentration is due in part to water residence time (τ). Trophic state analysis is based on summer months, so half-year (Apr–Sep) residence time was calculated (reservoir volume/outflow per half-year) using USGS data. Half-year was used because much inflow in late fall and winter would have passed through Tenkiller, given the short average τ (0.7 years), and not affected reservoir constituents in summer. The short τ indicates summer TP was mostly from April through summer inflows, plus sediment release.

TP concentrations for 2005–2008 were determined by Aquatic Research Inc. (Seattle, WA; Method 4500 PF; Eaton et al. 2005) and reported as TP. Other fractions were not determined. Nine blind standards were shipped, and results were within method control limits. Field QA/QC involved distilled water rinses of samplers and field duplication.

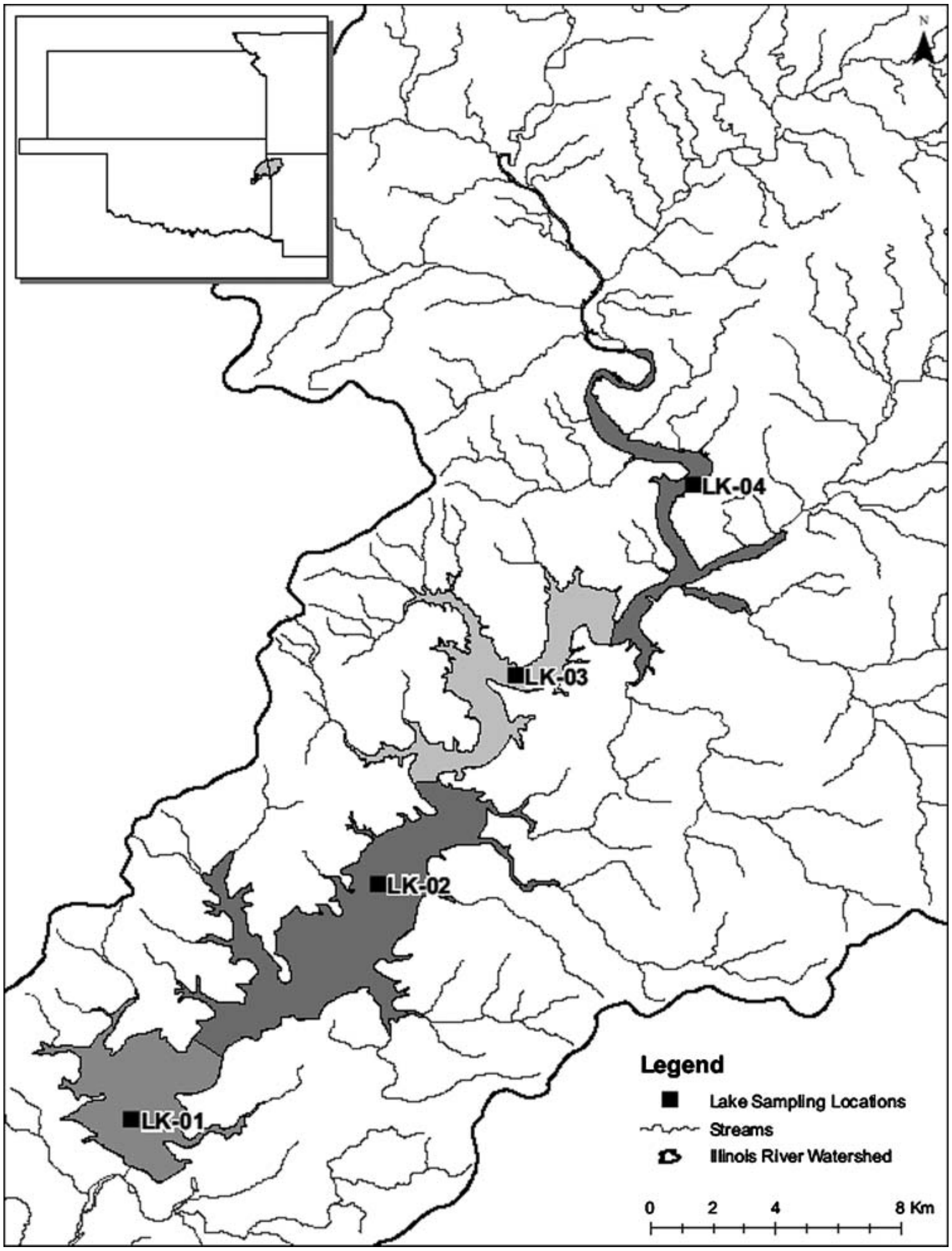

Figure 1.-Tenkiller Ferry Reservoir, showing sampling locations and the Illlinois River. Inset: Illinois River Watershed in Arkansas and Oklahoma.

USCOE TP data for 2001–2004, based on test kits, are not reported here.

Chlorophyll samples were handled as directed in OWRB (2001) and analyzed by Aquatec Biological Sciences (Williston, VT). Chlorophyll for 1986, 1992–1993, 2001–2004, and 2005–2008 was determined with method 10200 H (Eaton et al. 2005 and earlier editions); Chl data for 1986 and 2001–2004 were from USCOE. Integrated epilimnetic samples at LK01, LK02, LK03, and LK04 were obtained in June and August 1974 (USEPA 1977), but we omitted the June sample because massive rainfall before sampling (36 cm in one day) replaced 51 % of reservoir volume, which turned the reservoir into a river, washing out its phytoplankton and loading it with nutrients, silt, and river water (USGS 07196500, gauge near Tahlequah, OK; USEPA 1977). The June 1974 samples were not relevant because they did not involve reservoir autotrophic processes; therefore, August 1974 Chl data were used. Inflow

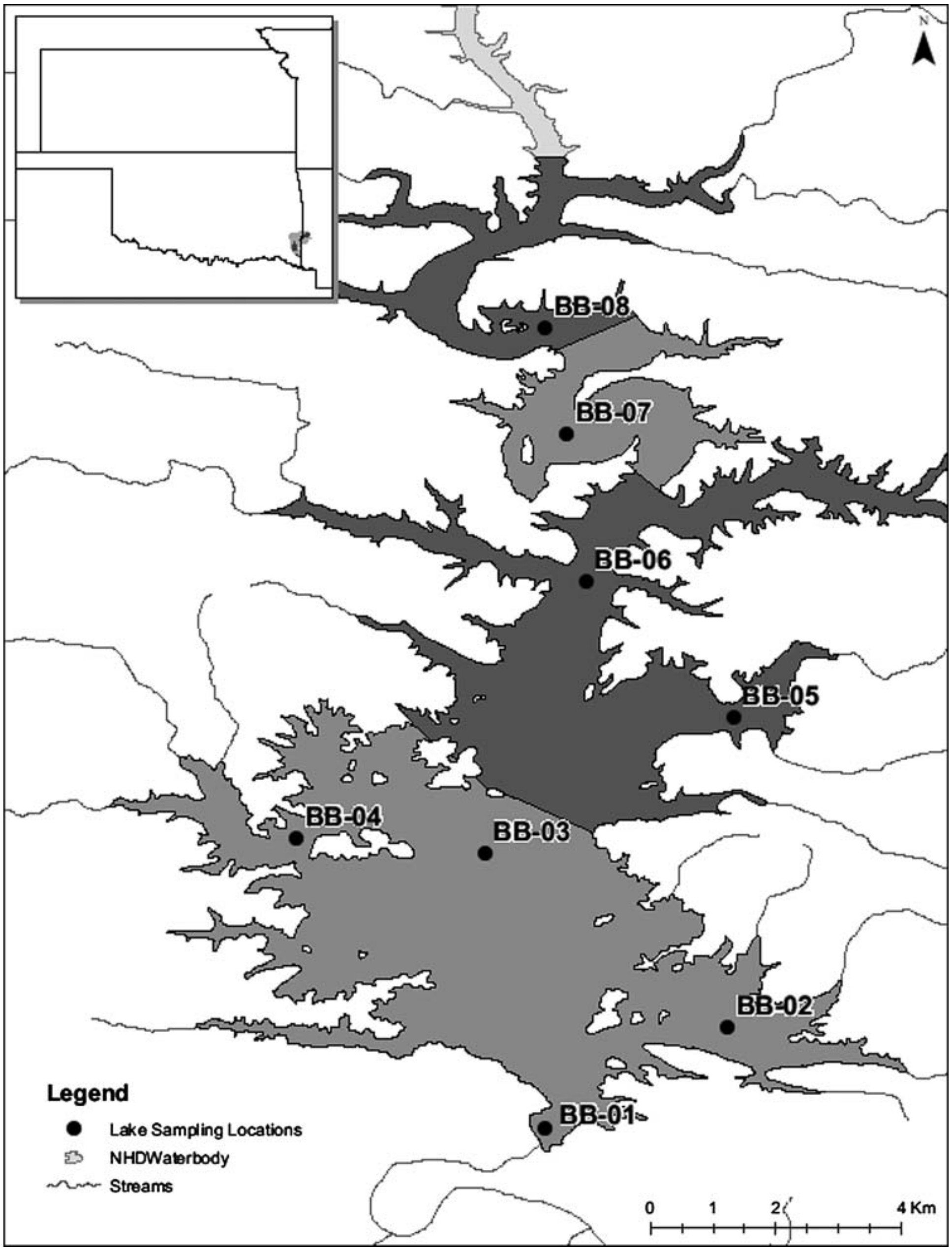

Figure 2.-Broken Bow Reservoir, showing sampling locations and the Mountain Fork River. Inset: Mountain Fork Watershed, southeastern Oklahoma.

and TP concentration data for 1974 were used to estimate 1974–1975 loading (USEPA 1977).

Transparency was determined with a 20 cm diameter Secchi disk, deployed on the boat's shaded side.

Phytoplankton taxa for 2006 and 2007, as well as in agency reports, were identified and enumerated (Ütermohl Method) from whole-water surface samples preserved in Lugol's. Biovolumes were calculated from at least 20 individual cells, filaments, or colonies and geometrical formulae approximating cell shapes, at 560X (Janik 2009). Phytoplankton taxa and biovolumes for 2001–2002 were from T. Clyde (Tulsa office, USCOE).

A Hydrolab datasonde was used to determine dissolved oxygen (DO), temperature, and oxidation-reduction potential (ORP) for 2005–2008 at 1 m intervals with depth at cross-sectional midpoints in the 4 zones. DO air calibration was checked with Winkler titrations. DO profile data from the lacustrine of Broken Bow (BBL03) were collected

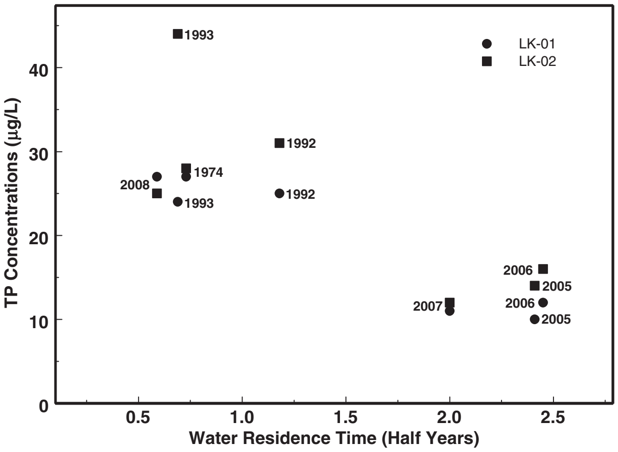

Figure 3.-Relationship between water residence time (half-years) and TP concentration (μg/L) in the surface water at lacustrine stations LK01 and LK02 in Tenkiller Reservoir.

by OWRB during the stratified period in 2001 and 2004 and used to determine areal hypolimnetic oxygen deficits (AHODs). DO data collected by USEPA for 1974, USCOE for 1986 and 2001–2004, and OWRB for 1992–1993 were used for Tenkiller AHODs. AHODs were calculated from 2 volume-weighted DO concentrations, separated as widely as possible during the stratified period, with the later value prior to minimum DO reaching 1 mg/L. For 1960, concentrations were interpolated from hand-drawn DO profiles for July, August, and September (Summers 1961). Volume weighting of DO concentrations for AHODs was for depths below 12 m, and volumes were adjusted as reservoir level changed.

Results

P loading

The primary source of new P to the IRW each year was poultry feed. In 2002 (last year of available data), 4224 metric tons (mt) of P were imported as feed (76 % of all imports). Swine and cattle feed, and fertilizer (lawns, row-crops), were 17 %. The percent of P imported for poultry increased rapidly from 1959 to 1969 and then remained constant at 75 % of annual imports through 2002 (Appendix E).

The IRW 2006 broiler density (about 90 % of all poultry) was 164 × 10^6, increasing greatly from 1954 to present times. The 2007 density in Broken Bow's watershed was about 20 × 10^6, similar to the IRW's in 1954 (Appendix F). Poultry densities for the watersheds in 2002 (Table 1) are the last year of comparable data.

The annual average poultry litter production in the IRW (2001–2006) was 406,818 mt (s.e. = 9540), containing on average 4120 mt of P (s.e. = 96; Appendix G). Data are not available for Broken Bow's watershed, but proportionally (to IRW), the 20 × 10^6 broilers there (2007) would have produced about 50,000 mt of litter and 500 mt of P.

About 90 % of litter was disposed of on pastures within 20 km of IRW poultry houses (80 % within 6 km), and about 64 % was applied during the February–June rainy seasons (Agricultural Environmental Management Services, Oklahoma Department of Agriculture, Food and Forestry, Oklahoma City, OK). The 20 km distance suggests some was transported from the IRW, so 80 % was used in calculations. Runoff from litter was confirmed in the IR from a gene specific to a bacterium found in poultry litter that appeared in all stream samples near poultry houses and in the IR but not in uncontaminated IRW waters away from poultry (Weidhaas et al. 2010, 2011).

Phosphorus losses from poultry litter-amended pastures range from 2–11 % of applied, and about 80–90 % is dissolved reactive P (Edwards and Daniel 1993, Sauer et al. 1999, 2000, Schroeder et al. 2004, Willett et al. 2006). A conservative value of 5 % for P loss to surface water from litter-amended soils was chosen to estimate P lost to water in the IRW. If 80 % of litter was disposed on IRW pastures, also a conservative estimate, about 165 mt of P (4120 mt × 0.80 × 0.05) entered the IR annually from litter disposal, via nonpoint runoff, whereas about 25 mt could enter the Mountain Fork River to Broken Bow. Groundwater contributions to TP loading are unknown.

High soil test P (STP; Mehlich 3) occurred throughout the IRW. Mean STP in Arkansas (2005–2007) was 201 mg/kg (n = 6558 samples) and was 51 mg/kg in Oklahoma counties (n = 4216 samples). IRW pastures not receiving poultry litter had an STP of 14–19 mg/kg. In Arkansas, 90 % of samples, and in Oklahoma 78 % of samples, exceeded 33 mg/kg (Oklahoma and Arkansas Cooperative Extension reports). An STP of 33 mg/kg provides maximum agronomic benefit (Sharpley et al. 2003).

Soil and litter P leaving IRW pastures was stored in stream and reservoir sediments because only 1.5 % of annual P imports were lost annually from the watershed, mainly as outflow through the dam, deer harvest, and crops exported (Dr. B. Engel, Purdue University, 2008, pers. comm.). Reservoir sediment-stored P was partly recycled to the water column as internal P load.

TP loading to the reservoir surface was 2.1 g/m^2 per yr for 1974–1975 (USEPA 1977). It was 3.93 g/m^2 per yr for 1976–1985, based on average mass input of 195,772 kg/yr (Harton 1989). Loading estimated in 1991–1993 was

4.57 g/m^2 per yr (OWRB 1995, Gade 1998). Recent annual (1997–2004) external loading to Tenkiller calculated by us from Pickup et al. (2003) and Tortorelli and Pickup (2006) averaged 260 × 10^3 kg/yr (s.e. = 34), or 5.04 g/m^2 per yr.

Average annual inflow TP concentrations would have been 88, 163, and 190 μg/L, for 1974–1975, 1976–1985, and 1992–1993, respectively, assuming direct relations between concentration and flow as during 1997–2004 (Tortorelli and Pickup 2006). Inflow concentration after dam closure would have been about 20 μg/L (Omernik 1977, McDowell and Omernik 1979, Clark et al. 2000). The average volume-weighted inflow TP concentration to Tenkiller for 1997–2006 was 210 μg/L. May–September average volume-weighted inflow concentration was 171 μg/L (s.e. = 51). Average volume-weighted 2005–2007 spring-summer inflow TP concentration to Broken Bow was 29 μg/L (s.e. = 3; OWRB E. B. Welch, 2008, pers. comm.; Table 1). For comparison, volume-weighted spring-summer inflow concentration to Tenkiller for the 2005–2006 low-flow years averaged 99 μg/L (s.e. = 8; no 2007 data).

Point source TP loading to Tenkiller from the watershed's 9 waste water treatment plants (WWTPs) averaged 64,000 kg/yr during 1998–2003, about 25 % of external loading (National Pollution Discharge Elimination Permit data provided to R. Jarmin, 2008, pers. comm.; Appendix H). About 40 % of P was removed from waste water by 2003 and 2004 plant upgrades, leaving an average of 37,000 kg/yr during 2004–2007 and a new reservoir P load of 233,000 kg (233 meteric tons (mt)) per year, representing about 9 % P removal (Appendix H).

Nonpoint P runoff dominated external P load. The average annual P load from poultry litter surface runoff was estimated as 165 mt (5 % P loss from 80 % of litter applied). The annual P load (1997–2004) was 260 mt; after WWTP upgrade it was estimated as 233 mt. Therefore nonpoint runoff from all sources to Tenkiller before upgrade was 63 % (165 mt/260 mt), and 71 % (165 mt/233 mt) of the total annual TP load after the upgrade.

Riverine (LK04) TP averaged 106 ± 25 μg/L for the 6 summers (1992–1993, 2005–2008) and was partly due to internal loading, as indicated by twice-monthly riverine TP concentrations averaging 1.8 times higher (by 54.3 μg/L) than inflow concentrations during summers 2005 and 2006 (Table 2). Net internal P loading for 120 days (Jun–Sep) at LK04 was estimated as 14,800 kg, or 18.2 mg/m^2 per day (2.18 g/m^2 per summer; Table 3).

Table 2.-Flow-weighted inflow with the Illinois River and Baron Fork vs. riverine TP concentrations in μg/L for Tenkiller Reservoir.

	2 inflows flow wt mean	Riverine LK04	Riverine - Inflow
28 Jun 2005	67.6	no data	
11 Jul 2005	54.8	no data	
25 Jul 2005	68.8	176	107.2
8 Aug 2005	61.1	99	37.9
24 Aug 2005	83.9	143	59.1
6 Sept 2005	69.2	104	34.8
19 Sept 2005	73.5	119	45.5
31 May 2006	59.4	106	46.6
13 Jun 2006	60.8	199	138.2
26 Jun 2006	68.5	187	118.5
12 Jul 2006	65.3	97	31.7
24 Jul 2006	68.3	116	47.7
10 Aug 2006	81.9	128	46.1
21 Aug 2006	76.2	157	80.8
13 Sept 2006	77.2	102	24.8
25 Sept 2006	222.4	163	−59.4

Ratio of LK04:inflow concentration averaged 1.83
Mean difference: LK04 – inflow = 54.3 μg/L

Transition zone TP was lower than riverine inflow concentrations due to flow decrease and deposition. Nevertheless, gross internal load probably occurred in this unstratified zone; therefore, the net rate observed in the riverine zone was probably an underestimate of the transition zone's gross rate. Using the riverine zone net rate, unstratified transition zone sediments (LK03) released about 9100 kg (Table 3), giving a total of about 24,000 kg for the upper one-third of the reservoir (LK04 + LK03) during 120 days of summer.

Internal loading occurred in the anoxic hypolimnion. Average 2005–2006 TP release rates were 2.7 and 22.9 mg/m^2 per day at LK01 and LK02, respectively. Those rates, multiplied by respective hypolimnetic areas, were 1900 and 25,100 kg for the 90-day period of increase (Table 3). The higher re-

Table 3.-Internal loading rates of P estimated for Tenkiller Reservoir during 2005 and 2006. Totals were rounded to nearest 100 kg.

Zone	Area (10^6 m^2)	Int. load rate mg/m^2 per day	Time days	Total int. load (kg)
Lacustrine	(>16m)			
LK01	7.82	2.7[1]	90	1900
LK02	12.24	22.9[1]	90	25,100
Riverine	(surface)			
LK04	6.758	18.2[2]	120	14,800
Transition	(>2 m)			
LK03	4.184	18.2[3]	120	9100
				50, 900

[1] Means for 2005 and 2006.

[2] $\frac{\text{Riverinevolume}(22.75\times10^{6}\ \text{m})\times54.3^{4}\ \text{mg/m TP (ave.LK04}-\text{inflow)}}{\text{Averageresidencetimeof 10 days}}$.

[3] Assume same rate as Riverine (see text for explanation).

[4] From Table 2

Table 4.-Mean of means summer TP concentrations (μg/L) in Tenkiller Reservoir riverine (LK04), transition (LK03), and lacustrine (LK01 + LK02) zones and τ. O = oligotrophic, M = mesotrophic, E = eutrophic, and HE = hypereutrophic. O/M, M/E, E/HE = borderline trophic states.

	LK01 + LK02	**LK03**	**LK04**	**Whole Reservoir**
Long τ summers (2005–2007), mean $\tau = 2.3$ half years	12.5 μg/L (O/M) n = 38 samples	29.1 (M/E) n = 19	117.3 (HE) n = 19	23.7 (M) n = 76
Short τ summers (1992–1993, 2008), mean $\tau = 0.82$ years	29.3 μg /L (M/E) n = 32 samples	42.7 (E) n = 16	94.3 (E/HE) n = 16	37.7 (E) n = 64

lease rate at LK02 was associated with a longer period of anoxia (i.e., DO reached <1.0 mg/L a month or more earlier) and lower ORP (−240 mv) than at LK01. The higher release rate at LK02 in 2005 than in 2006 corresponded with a longer period of negative ORP.

The sum of estimated internal TP loading in all zones was 50,900 kg, or about 1.0 g/m^2 per summer (Table 3), for the whole reservoir (51.6 km^2). Internal load was therefore an additional 16 % of external load plus internal load annually. Riverine and transition zone internal loading was 8 % annually but about one-third during June–September.

Reservoir phosphorus concentrations

Water residence time was an important determinant of TP concentrations (Fig. 3). Whole-reservoir volume-weighted mean summer epilimnetic TP concentration (35 collections per zone, 6 summers) was 31 μg/L (meso-eutrophic border). In dry summers (2005–2007) with longer residence times, whole-reservoir volume-weighted mean TP was 24 μg/L (mesotrophic); in wet summers with shorter residence times (1992–1993, 2008), it was 38 μg/L (eutrophic; Fig. 3; Table 4). Based on TP, the lacustrine zone (LK01, LK02) was borderline oligo-mesotrophic in dry summers (mean = 13 μg/L) and meso-eutrophic (mean = 29 μg/L) in wet summers. The riverine zone (LK04) was eutrophic (45 % of samples > 30 μg/L) or hypereutrophic (55 % of samples > 100 μg/L) in each summer, in part from sediment P release (Table 4), and the transition zone was eutrophic.

In Broken Bow, whole-reservoir volume-weighted summer (2001, 2004, 2006–2007) epilimnetic mean of means TP concentration was borderline oligotrophic at 10.5 μg/L (range = 9–12 μg/L, all stations from riverine to dam).

Trends in phytoplankton taxa

Phytoplankton in Tenkiller in 1960, 1974, and 1975 indicated oligo-mesotrophic conditions, with little cyanobacteria presence (Summers 1961, Oklahoma Department of Health 1976–1977, Hern et al. 1979). There were no samples between 1975 and 1985. A qualitative survey in 1985–1986 (Nolen et al. 1989, USCOE 1988) found blooms of the dinoflagellate *Peridiniopsis polonicus* in coves and at LK01, plus mats of unidentified algae. In 1992–1993 (OWRB 1995), spring blooms were dominated by diatoms and the summer phytoplankton (based on cell density, not biovolume) by cyanobacteria (*Anabaena*, *Lyngbya*, *Oscillatoria* (now *Planktothrix*), and *Microcystis*). The dominant genera in 2001–2004 (USCOE unpublished) and 2006–2007 were cyanobacteria, with *Cylindrospermopsis raciborskii* dominant in 2006–2007. Cyanobacteria comprised 70–80 % of biovolume, except in summer 2006 (longest τ) when percentages fell to 25–35 %, and lacustrine zone TP concentrations fell to oligo-mesotrophic levels (Table 5 and 6). After 1975 the phytoplankton were dominated by species characteristic of eutrophy.

Lacustrine, transition, and riverine zones of Broken Bow in 2007 were 85 % (by biovolume) *Aphanizomenon ovalisporum* and *Planktolyngbya limnetica* (cyanobacteria). Biovolume was less than half of Tenkiller's in riverine and transition zones and 7 % in the lacustrine zone on the same dates, indicating oligo-mesotrophic conditions.

Algal biomass (Chl)

Mean whole-reservoir Chl and TP for Tenkiller and Broken Bow, and means for Tenkiller reservoir zones, fit within the distribution of these variables in 143 nearby Missouri reservoirs (Jones and Knowlton 2005; Fig. 4). Chl in both reservoirs bear the general regional relation to TP, and factors increasing reservoir TP would produce corresponding larger Chl levels.

Epilimnetic Chl in August 1974 was 6.6, 5.7, 6.6, and 12.0 μg/L from LK01 through LK04, respectively, with a mean of 7.7 μg/L (USEPA 1977). Excepting the eutrophic levels at LK04, Chl was on the oligo-mesotrophic border in 1974.

Whole-reservoir epilimnetic, volume-weighted mean Chl in Tenkiller was in the eutrophic category every summer (Appendix C), though at the mesotrophic border in 2002–2003 and 2006 (Fig. 5); however, whole-reservoir mean of means (n = 11 summers) volume-weighted Chl was 13.5 μg/L, or

Table 5.-Dominant summer phytoplankton taxa in 4 reservoir zones in Tenkiller Reservoir.

Summer	LK01	LK02	LK03	LK04
1960[1]	*Melosira*	*Melosira*	*Melosira*	*Melosira*
1974[2]	*Achnanthes*	ND	ND	ND
2001[3]	*Lyngbya*	*Microcystis*	*Microcystis*	*Anacystis*
2002[3]	*Microcystis*	*Microcystis*	*Cylindrospermopsis*	*Merismopedia*
2003[3]	*Ceratium*	*Lyngbya*	*Lyngbya*	ND
2004[3]	*Anacystis*	*Anacystis*	*Anacystis*	ND
2006[4]	*C. raciborskii*	*Mougeotia*	*C. raciborskii*	*Pseudanabaena*
2007[4]	*C. raciborskii*	*C. raciborskii*	*C. raciborskii*	*Pseudanabaena*

[1] Summers (1961)
[2] Hern et al. (1979)
[3] US Army Corps of Engineers, Tulsa, Oklahoma Office (Tony Clyde)
[4] Camp Dresser McKee 2006–2007 samples, this study
ND = no data

mid-eutrophic (Fig. 6). Transition and riverine zones (LK03, LK04) were eutrophic to hypereutrophic in the 11 summers sampled between 1986 and 2008, with LK04 hypereutrophic in 5 summers and nearly hypereutrophic in the other 6 summers (Fig. 5). The lacustrine zone (LK02, LK01) was eutrophic in 5 summers (1986, 1992–1993, 2005, and 2008), mesotrophic in 2002–2003 and 2006–2007. In 2001 and 2004, LK01 was mesotrophic, while LK02 was eutrophic.

The 2003–2004 WWTP upgrade reduced external P loading by about 9 % (Appendix H) but was too small to affect Chl at LK04 or LK03, which were direct recipients of TP-rich inflows. Mean pre-WWTP upgrade Chl concentrations at LK03 and LK04 in 1986–2002 (n = 5 summers) were 14.6 and 27.5 μg/L respectively, while mean concentrations in 2004–2008 (n = 5 summers) were 15.6 and 26.0 μg/L respectively.

Mean whole-reservoir and reservoir zone (riverine, transition, lacustrine) Chl varied from year to year (Fig. 5). As examples, in 2008 every zone and the whole-reservoir mean were eutrophic or hypereutrophic. In 2006 the lacustrine zone was borderline oligotrophic while the transition and riverine zones were eutrophic.

Table 6.-Percent cyanobacteria of mean summer (Jun–Sep) surface (0–6 m) phytoplankton biovolumes in Tenkiller Reservoir in1960, 1974, 2001–2002, and 2006–2007.

Station	1960[1]	1974[2]	2001[3]	2002[3]	2006[4]	2007[4]
LK01	0	<15	65	82	26	79
LK02	0	ND	79	79	32	67
LK03	0	ND	88	68	35	50
LK04	0	ND	81	70	25	72

ND = no data
[1] Summers (1961)
[2] USEPA (1977)
[3] US Army Corps of Engineers, Tulsa, Oklahoma Office (Tony Clyde)
[4] Camp Dresser McKee 2006–2007 samples, this study

Chlorophyll in Broken Bow indicated oligo- mesotrophic conditions from riverine to lacustrine. Mean volume-weighted whole-reservoir Chl was 1.9 μg/L (oligotrophic) in 2004 and 4.0 μg/L (borderline mesotrophic) in 2007, the only summers with data. Lacustrine Chl averaged 3.0 and the riverine zone averaged 4.8 μg/L for those summers.

Secchi disk (SD) transparency

SD transparency (Appendix D) at LK04 indicated hypereutrophy, and LK03 was always eutrophic (63 observa-

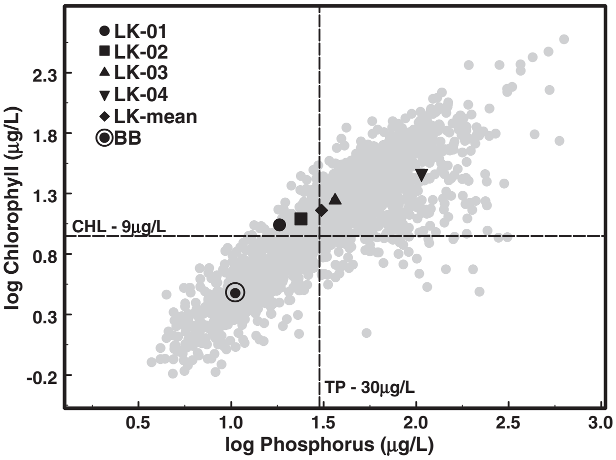

Figure 4.-Relationship between summer volume-weighted surface (0–6 m) mean TP and Chl concentrations at 4 stations and whole lake during 1992–1993 and 2005–2008 in Tenkiller and whole-lake means in Broken Bow Reservoirs, compared with those from 143 Missouri reservoirs (Jones and Knowlton 2005). Dotted lines denote Nürnberg (1996) boundaries between mesotrophic and eutrophic conditions for Chl and TP.

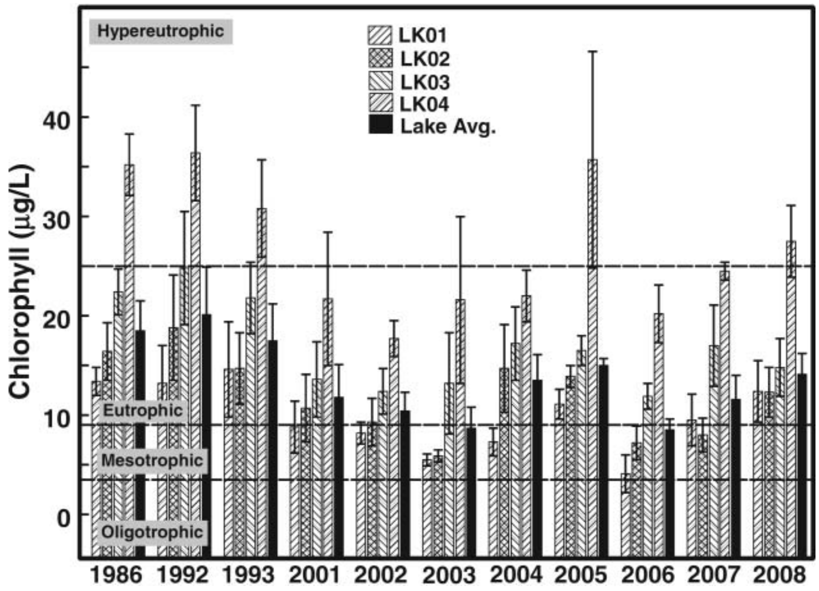

Figure 5.-Summer (Jun–Sep) mean, volume-weighted surface (0–6 m) Chl concentrations in Tenkiller Reservoir, using 1975 data from USEPA (1977); 1986, 2001–2004 from USArmy Corps Engineers; 1992–1993 from OWRB (1995); and 2005–2008 from Camp Dresser McKee sampling program. Standard errors of means are shown on bars. Trophic state boundaries are from Nürnberg (1996).

tions per zone, 11 summers between 1986 and 2008). LK01 was eutrophic in 1992–1993, 2002–2003, and 2007–2008, and meso-eutrophic in 1986 and 2004–2006. The whole-reservoir area-weighted SD for the 11 summers was 1.53 m (eutrophic; Fig. 6), but the LK01 summer mean was often in the mesotrophic category (2.2 m). In 2006, the longest τ summer, LK01 SD averaged 3.4 m, but returned to eutrophy in 2007 and 2008.

The trophic state of Tenkiller is summarized as mean of means for TP, Chl, and SD for 1992–1993, 2005–2008, indicating response variables (Chl, SD) were at eutrophic-hypereutrophic conditions in all zones and the whole reservoir (Fig. 6). TP was in the mesotrophic category at LK01 and LK02, and borderline eutrophic for the whole reservoir.

Areal hypolimnetic oxygen deficit (AHOD)

Estimated AHOD in 1960 averaged 610 mg/m^2 per day at LK01 (Summers 1961), less than half the 1986–2008 mean of 1456 ± 390 mg/m^2 per day ($n = 12$; Fig. 7). In 1974 the rate was 1093 mg/m^2 per day. Walker (1987) determined lower rates with 1974 and 1986 data, probably due to using the whole lacustrine zone (LK01 + LK02). The LK02 average for 1986–2008 was 20 % less than for LK01.

AHOD rates for 2001 and 2004 in Broken Bow's deep lacustrine site (BBL03) averaged 492 mg/m^2 per day (Fig. 7). Rates at the up-reservoir lacustrine site (BBL06) averaged 571 mg/m^2 per day.

Discussion

Long-term data from Tenkiller Reservoir, Oklahoma, show 3 findings about eutrophication of large midcontinent US reservoirs. First, we described the eutrophication history of the reservoir, starting in 1960, 7 years after dam closure when Tenkiller was oligo-mesotrophic, and ending in 1986–2008 when Tenkiller was eutrophic to hypereutrophic. The reservoir changed rapidly from one of Oklahoma's high quality water resources (Brill 1957) to a eutrophic-hypereutrophic water body. Second, we examined trophic states of reservoir zones (riverine, transition, lacustrine) from 1986 through 2008, finding that trophic states varied longitudinally and temporally, even as volume-weighted whole-reservoir trophic state was eutrophic. Water residence time was an important cause of that variation. Finally, we quantitatively determined that a nonpoint nutrient source, runoff from poultry litter disposed on watershed pastures, was the dominant (71 %) source of TP. Recycled P (16 % of external plus internal loads), rarely determined for reservoirs, was also important.

Tenkiller is eutrophic based on standard trophic state metrics. Mean whole-reservoir epilimnetic TP over 11 summers was 31 μg/L and Chl was 13 μg/L (Fig. 6), meso-eutrophic and eutrophic by Nürnberg (1996) boundaries. More conservative criteria (e.g., 25 μg/L for TP and 7 μg/L for Chl for eutrophic boundaries; Forsberg and Ryding 1980, Carlson 2007) further demonstrate Tenkiller's eutrophic conditions. Regardless of criteria, the causal (TP) and response variables (Chl) indicated a eutrophic epilimnion.

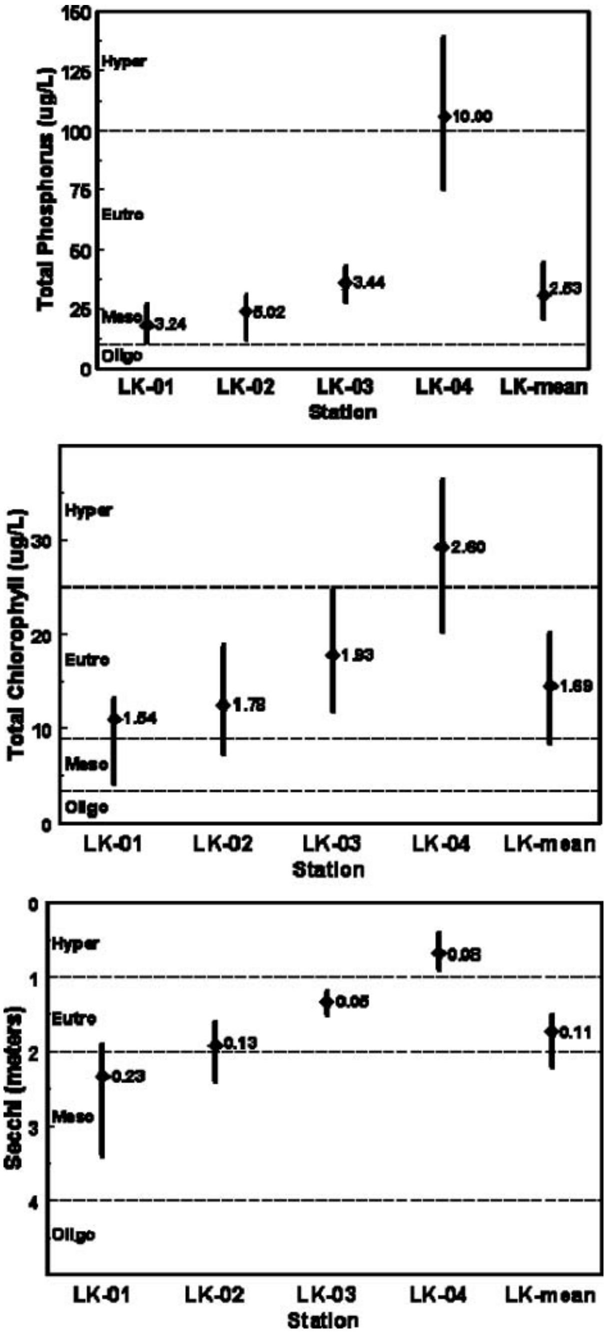

Figure 6.-Means of surface (0–6 m) volume-weighted summer means of TP and Chl concentrations (μg/L) and transparency (m) for lacustrine (LK01 and LK02), transition (LK03), and riverine (LK04) zones of Tenkiller Reservoir for 1992–1993 and 2005–2008. Vertical bar is range and number is standard error. Trophic state boundaries are from Nürnberg (1996).

In August 1960, there were oxic conditions below the epilimnion (Summers1961), but AHOD has more than doubled since then, resulting in annual anoxia for part of the summer. AHOD depends on TP (Cornett and Rigler 1980, Walker 1979, Welch and Perkins 1979, Nürnberg 1996), and TP is strongly related to algal biomass in Tenkiller and Broken Bow. AHOD is also related to reservoir hydrology and sedimentation (Thornton et al. 1990). A large algal biomass, produced in the P-rich riverine and transition zones, coupled with allochthonous organic matter, moved by sedimentation and density-driven interflows to the middepth water column where aphotic conditions and respiration led to rapid DO depletion in the meta- and hypolinmnia (Welch et al. 2011). AHODs at the deep lacustrine site (mean 1986–2008 of 1456 mg/m^2 per day) were within eutrophic boundaries (Nürnberg 1996). This rate was more than twice that of the 1960s and greater than the 1974 rate of 1093 mg/m^2 per day. Modern Broken Bow rates were the same as Tenkiller's in 1960, corresponding to an oligo-mesotrophic state at that time.

Tenkiller trophic state metrics varied in response to hydrology (Fig. 3). In wet summers (1992–1993, 2008), TP-rich inflows moved farther down the reservoir, sedimentation in riverine and transition zones was less (Thornton et al. 1990), and lacustrine zone TP and Chl were at eutrophic levels. The lacustrine zone was protected by sedimentation and interflows, particularly in the dry summers, and led in those summers to a lacustrine zone with mesotrophic levels of TP, Chl (Fig. 5), and transparency (Appendices B, C, D).

Phytoplankton taxa switched with eutrophication. Collections from 1960 and 1974 were dominated by diatoms (Table 5 and 6), and subsequent collections had progressive changes, first to dinoflagellate blooms (1985–1986), then to cyanobacteria (1992–2004), and more recently (2007–2008) to the exotic cyanobacterium *Cylindrospermopsis raciborskii*. (Table 6). Dominance by large cyanobacteria is expected with eutrophication (Downing et al. 2001). Algal biomass supports this conclusion. Chl concentrations in August 1974 were on the oligo-mesotrophic border near the dam and eutrophic in the riverine zone. By 1986, Chl values were eutrophic throughout the reservoir, which persisted through 2008 (Fig. 5).

Temporal variation is expected and is a second-order effect of hydrology and TP concentrations in midcontinent reservoirs (Jones et al. 2008). It is common for seasonal mean concentrations to vary 2- to 3-fold over time, and reservoirs seem to be particularly responsive to variation in inflows. This means that long-term data, 6–8 summers of sampling in all reservoir zones, are needed to accurately estimate trophic state (Knowlton and Jones 2006). Historic and recent Tenkiller data matched or exceeded this goal, providing confidence about our trophic state assessments. We found that determination of trophic state from lacustrine samples alone, or from one or a few summers of sampling, could lead to assessments that differ from the overall average. For example, Tenkiller was meso-eutrophic and nearly

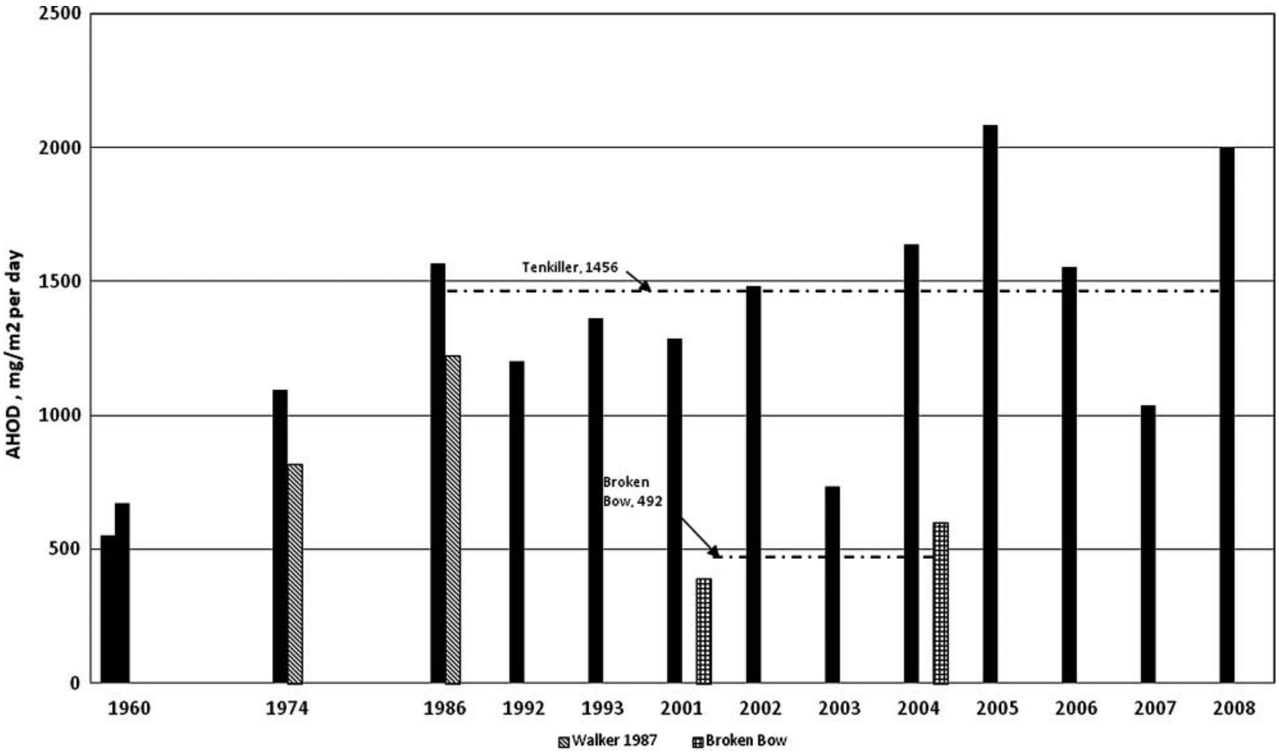

Figure 7.-Areal hypolimnetic oxygen deficit rates (AHOD) in the lacustrine zone (LK01) of Tenkiller Reservoir, using 1974 data from USEPA (1977); 1986 and 2001–2004 from US Army Corps Engineers; 1992–1993 from OWRB (1995); 2005–2008 from this study, and 1960 values for 2 periods (Jul–Aug = 548, Jul–Sep = 673 mg/m^2 per day) from Summers (1961), and in the lacustrine zone (BBL03) of Broken Bow Reservoir using data from OWRB for 2001 and 2004. Walker (1987) rates are for whole lacustrine zone.

oligotrophic at LK01 in 2006, a dry summer, but eutrophic at LK03 and LK04. It was eutrophic in all zones in 2008, a wet summer (Fig. 5). Sampling of all reservoir zones over multiple years seems to be necessary for accurate trophic state assessements.

Changes in Tenkiller's trophic state were from increased nutrient loading from intensified animal agriculture. The reservoir responded as expected, based on central concepts of applied limnology (Cooke et al. 2005). This cultural eutrophication occurred rapidly as the poultry industry grew and was not from "natural aging." Phosphorus loading increased from 2.1 g/m^2 per year (1974–1975), to 3.93 g/m^2 per year (1976–1985), to the recent rate of 5.04 g/m^2 per year. Annual TP additions of the IRW as poultry feed increased from 2018 mt to 4224 mt over this period.

Most of the TP load to Tenkiller was nonpoint and came from poultry litter disposal on pastures at an average annual rate of 4120 mt TP (2001–2006, Appendix G). The annual pasture load was equivalent to P in domestic waste from about 8 million people (Vieux and Moreda 2003). The influence of agriculture on water quality occurs broadly across a wide geographic range, and regionally in the Midwest (Knoll et al. 2003, Jones et al. 2004, 2009, Carney 2009), but there are few documented case studies until now that show quantitatively how nonpoint activities on a landscape produced reservoir trophic state change.

Sediment P release is rarely determined in reservoirs, largely because external loads on average are twice those of lakes (Thornton et al. 1981) and it could be assumed internal TP loading is small relative to external loading. In one of the few quantitative analyses in reservoirs (Kennedy et al. 1986), it was important. Riverine and transition zone sediment TP release in Tenkiller added about 24,000 kg TP beyond the annual external load during summer, an additional cause of hypereutrophic levels of Chl in these zones and the associated DO depletion in the lacustrine zone. Summer TP release from Tenkiller hypolimnetic sediments was extensive but may not have reached the epilimnion in this sharply stratified reservoir (Welch and Cooke 1995, Mataraza and Cooke 1997, Welch and Jacoby 2004).

Evidence that poultry litter was the primary TP source to the IR is inferential and direct. Poultry feed is the dominant new source of TP to the watershed and is disposed of as litter on pastures, mainly during rainy seasons. High STP, a well-known P source to streams (Sharpley et al. 2003) occurs in the IRW. Runoff and infiltration to groundwater are characteristics of the ecoregion (Woods et al. 2005) allowing the inference that runoff from litter contaminated the IR. There is also direct evidence. About 5 % of P experimentally applied to land as litter runs off each year (Sauer et al. 2000, Haggard et al. 2003, Schroeder et al. 2004, Willett et al. 2006), accounting for about 71 % of Tenkiller's annual loading. Most of the P in the IR comes from litter disposal and subsequent runoff. Appearance in IRW streams and the IR of a bacterium specific to poultry litter is also direct evidence that litter runoff contaminated the water (Weidhass et al. 2010, 2011).

The contrast in trophic state between Broken Bow and Tenkiller is striking. Had TP concentrations in the IR remained near ecoregional background levels, Tenkiller would have remained oligo-mesotrophic. Broken Bow remained oligo-mesotrophic because inflow TP remained low, likely due to low poultry densities, little pasture area, a small human population, and a high percentage of forest in the watershed (Jones et al. 2009). The use of a reference reservoir was instructive in identifying causes of eutrophication.

Animal waste pollution of soil and water through manure disposal or its excessive use as fertilizer is significant in the United States, where there is a net soil accumulation rate of 22 kg P/ha per year (Carpenter et al. 1998). In IRW pastures receiving poultry litter, STP was above the upper agronomic benefit level. TP in pasture runoff is strongly correlated with STP ($r^2 = 0.88$; Sharpley et al. 2003), supporting our conclusion of IR contamination from litter disposal. Runoff from manure-amended soils may continue for decades after cessation of disposal (Sauer et al. 2000, Carpenter 2005), maintaining Tenkiller's eutrophic state. Eutrophic conditions can be highly stable (Scheffer 1990). Polluted soil will be difficult to treat, but options include soil removal from sites of high concentration, and soil treatment with alum (Moore et al. 2000). Development of riparian buffer zones may impede some P export if properly constructed and sufficiently wide, but they take years to develop, must be maintained, and remove land from other uses (Cooke et al. 2005). Unlike runoff from row crops, confined animal nutrient sources are a point source (e.g., poultry houses) made into a nonpoint source (land surface disposal). The most direct solution to pollution of the IR, and to pollution from manure runoff throughout the United States, is litter retention at the source, followed by specific treatments such as transport to waste treatment facilities.

Early in their history, IR and Tenkiller had exceptional water quality; this is not the case now. Current eutrophic conditions were caused primarily by nonpoint TP runoff from pastures amended annually with thousands of tons of poultry wastes and from internal TP release from sediments deposited from the watershed. Multiple-year and all reservoir zone sampling, and the use of a reference reservoir, provide great confidence in our trophic state designation. Rehabilitation of Tenkiller Reservoir requires severe curtailment or cessation of pasture runoff, followed by in-reservoir treatments that could include aeration (fish habitat rehabilitation; Welch et al. 2011) and sediment alum treatment.

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