Water Air Soil Pollut
DOI 10.1007/s11270-006-9214-y

Sediment Phosphorus Release at Beaver Reservoir, Northwest Arkansas, USA, 2002–2003: A Preliminary Investigation

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Received: 22 February 2006 / Accepted: 14 June 2006

Abstract Phosphorus (P) release from bottom sediments can be a significant source to the overlying water column, potentially maintaining and enhancing algal growth and eutrophic conditions in lakes and reservoirs. Thus, the objectives of this study were to: (1) measure P flux under aerobic and anaerobic conditions from intact sediment cores collected at Beaver Reservoir, northwest Arkansas, (2) evaluate the spatial variability in measured sediment P flux under aerobic and anaerobic conditions along the reservoir, and (3) compare external and internal P loads to Beaver Reservoir. Six intact sediment cores were collected at three sites representing the lacustrine, transitional, and riverine zones during June 2003, September 2003 and February 2004 and incubated for 21 days in the dark at ~22°C. Three cores from each site were incubated under aerobic conditions and anaerobic conditions. Water samples were collected from the overlying water column in each core daily for the first five days and every other day thereafter and analyzed for soluble reactive phosphorus (SRP). Water removed from the core was replaced with filtered lake water, maintaining a constant overlying water volume of 1 l. Sediment P flux under anaerobic conditions (<0.01–1.77 mg m^{-2} day^{-1}) was generally greater than that measured under aerobic conditions (<0.01– 0.89 mg m^{-2} day^{-1}). Some spatial variability existed in sediment P flux where P flux was generally greatest at the sites in the riverine and transitional zones. Maximum sediment P flux was observed under anaerobic conditions in cores collected from the transitional zone during September 2003. Average sediment P flux under aerobic conditions (0.09 mg m^{-2} day^{-1}) and anaerobic conditions (0.31 mg m^{-2} day^{-1}) was greater than the external P flux (0.05 mg m^{-2} day^{-1}) estimated from the Beaver Reservoir tributaries. Results showed that the annual internal P load (7 Mg $year^{-1}$) from bottom sediments in Beaver Reservoir was less than 10% of the annual external P

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load (~81 Mg P year^{-1}). The internal P load was significant, but it would not currently be cost effective to manage this P source given the large surface area of Beaver Reservoir.

Keywords phosphorus · bottom sediments · internal sources · aerobic and anaerobic conditions

1 Introduction

Sediments play an important role in the accumulation and release of phosphorus (P) in lakes and reservoirs. In particular, P release from lake and reservoir bottom sediments has been studied for several decades (Andersen & Jensen, 1992; Cooke, McComas, Waller, & Kennedy, 1977; Gächter, Meyer, & Mares, 1988; Haggard, Moore, & DeLaune, 2005; Mortimer, 1941, 1942; Riley & Prepas, 1984). In many eutrophic lakes and reservoirs, historical external P loading has often resulted in a significant amount of P accumulation in bottom sediments. The subsequent release of P from bottom sediments may be sufficient to maintain and enhance anthropogenic eutrophication. Lakes and reservoirs often failed to respond to reduced external P load because of this internal sediment P source (Larson, Van Sickle, Malueg, & Smith, 1979; Ryding, 1981). Therefore, it is critical to quantify the P loads from external and internal sources to lakes and reservoirs in order to develop sound management plans and achieve or maintain long term water quality goals.

Sediment P flux has been evaluated under aerobic and anaerobic conditions using intact sediment cores in several studies (e.g., see Anderson, 1975; Haggard et al., 2005; Moore & Reddy, 1994; Moore, Reddy, & Fisher, 1998). Mortimer (1941, 1942) concluded that P flux from lake bottom sediments was greater under anaerobic conditions due to reduction of manganese (Mn) and iron (Fe) minerals. Microbial activity in the hypolimnion and bottom sediments of lakes and reservoirs often consume dissolved oxygen (DO), resulting in anoxic and reducing conditions. Under reducing conditions, Mn (IV) and Fe (III) in bottom sediments reduce to more soluble forms, Mn (II) and Fe (II), thereby releasing P associated with these minerals (Kamp-Nielsen, 1974; Moore & Reddy, 1994).

Several studies have demonstrated direct and indirect effects of different physical and chemical factors on P release and solubility near the sediment-water interface. Lake water temperature has been reported as an important factor (Boström, Andersen, Fleisher, & Jansson, 1988; Boström, Jansson, & Forsberg, 1982), where increased temperature of the water column above bottom sediments stimulates microbial mineralization of organic matter potentially releasing dissolved P into the overlying water. Several other studies have reported that mineral solubility may also control sediment P release, e.g., P solubility was controlled by presence of Fe minerals under aerobic conditions and by calcium (Ca) minerals under anaerobic conditions (Moore & Reddy, 1994; Moore et al., 1998). Jensen and Anderson (1992) observed that the molar ratio between Fe and P of the sediments had direct effect on the magnitude of sediment P release, where greater P release occurred in sediments with lower molar ratios. In contrast, internal P cycling in calcareous lake sediments was related to the fraction of carbonate minerals (calcite and dolomite) in sediments and was less dependent on the presence of Mn and Fe minerals and the redox status of the overlying water (Moore, Reddy, & Graetz, 1991).

Recently, the Beaver Water District in northwest Arkansas has become concerned with episodic taste and odor problems in the finished drinking water produced from Beaver Reservoir. These concerns and other scientific interests have prompted several investigations into Beaver Reservoir, and the overall purpose of this study was to evaluate the ability of bottom sediments to release P in this reservoir. Specifically, the objectives of this study were to: (1) measure P flux under aerobic and anaerobic conditions using intact bottom-sediment cores, (2) evaluate the spatial variability in measured sediment P flux under aerobic and anaerobic conditions, and (3) compare external and internal P loads at Beaver Reservoir.

2 Materials and Methods

2.1 Site description

Beaver Reservoir is a multi-purpose impoundment constructed in 1963 on the White River in northwest Arkansas with a surface area of 103 km^2. It is operated by the US Army Corps of Engineers for the purposes of hydroelectric power generation, flood control, and recreational activities; the reservoir is the main drinking water supply for more than 300,000 customers of Beaver Water District in the northwest Arkansas area. The depth of the reservoir at the dam is about 60 m, the average depth throughout the reservoir is 18 m, and the average hydraulic retention time of the reservoir is about 1.5 years. The catchment area of Beaver Reservoir encompasses approximately 310,000 ha with a major land use distribution of forest (69%), agriculture and pasture (26%), water (4%) and urban (1%). The primary inflows to Beaver Reservoir include the White River, Richland Creek, Brush Creek, and War Eagle Creek; several other smaller tributaries also form inflows to the reservoir. Between 1993 and 1995, average total P (TP) load into Beaver Reservoir was 75 Mg $year^{-1}$ from the 4,300 km^2 watershed, and the White River contributed ~62% to the overall load (Haggard, Moore, Chaubey, & Stanley, 2003). Approximately 65% of the TP entering the reservoir was in the soluble-reactive form (Haggard et al., 2003), which is considered to be bioavailable.

Beaver Reservoir is a long, relatively narrow impoundment with a prominent trophic gradient, where the riverine zone is generally eutrophic and shifts to mesotrophic and oligotrophic conditions down reservoir near the dam (Haggard, Moore, Daniel, & Edwards, 1999; Galloway & Green, 2006). The Beaver Water District's water intake structure is in the transitional zone of the reservoir where conditions are generally mesotrophic to eutrophic. Increased concerns over anthropogenic eutrophication in Beaver Reservoir have recently accelerated many investigations within this reservoir and its catchment; these concerns are primarily focused on increasing urbanization and historical agricultural production from poultry and other animal industries within the watershed. To study P release from sediments, three locations at Beaver Reservoir were selected as sampling sites (Figure 1). One sampling site was selected in the lacustrine zone (36°19.64′N, 94°00.77′W) near the US Highway 12 Bridge crossing the reservoir. The second sampling site was selected in the transitional zone (36°15.56′N, 94°03.89′W), and the third site was selected in the riverine zone (36°13.95′N, 94°00.08′W) at the confluence of the White River and War Eagle Creek branches of the reservoir. Reservoir water and intact sediment cores were collected from the three sites in June 2003, September 2003, and February 2004.

2.2 Field and laboratory procedures

Six intact sediment cores were collected at each sediment sampling location and date in acrylic Plexiglas tubes (6.35 cm i.d. and 100 cm long) by skilled scuba divers. The tubes were inserted into the bottom sediments to a depth of 10 to 50 cm, as allowed by the amount of deposited sediment at each site. The intact sediment cores were gently removed from the bottom sediments and sealed at each end under water with no. 13 rubber stoppers. A properly collected core had relatively undisturbed sediment at the surface and with depth, and the overlying water in the core was not turbid from sediment disturbance but relatively clear. Following sediment core collection, approximately 50 l of lake water was collected at US Highway 12 Bridge near the headwater of the lacustrine zone.

Upon return to the laboratory, the collected lake water was filtered through a 0.45 μm membrane and stored in the laboratory for maintenance of overlying water levels in the cores during incubation. Next, the water overlying the sediments in each core was adjusted to a volume of 1 l, and then the intact sediment cores were wrapped with aluminum (Al) foil to avoid exposure to light. In order to bring all the cores to the same base conditions, air was bubbled through the overlying water of each intact sediment cores using an aquarium pump and Tygon tubing for the first 24 h. Dissolved oxygen (DO) was then measured using a YSI 55 DO Meter (YSI Environmental, Yellow Springs, OH) in the overlying water column of each sediment cores.

After baseline DO conditions were achieved (≥5 mg DO l^{-1}), three of the six intact sediment cores were incubated at 22°C under anaerobic conditions by bubbling the overlying water column with N_2 gas with 330 ppm CO_2, whereas the remaining three sediment cores were incubated at 22°C under aerobic conditions by bubbling air (as in the first 24 h) through the water column. Water samples (~60 ml) were collected at one to three day intervals for approximately three weeks. Out of each ~60 ml aliquot removed, ~20 ml was filtered through a 0.45 μm membrane filter, acidified to pH 2 with HCl, and analyzed for SRP using the automated ascorbic acid method (APHA, 1992). The remaining 40-ml aliquot was not filtered and was used to measure pH and electrical conductivity (EC). The amount of water removed from the overlying water column was replaced by filtered lake water of known

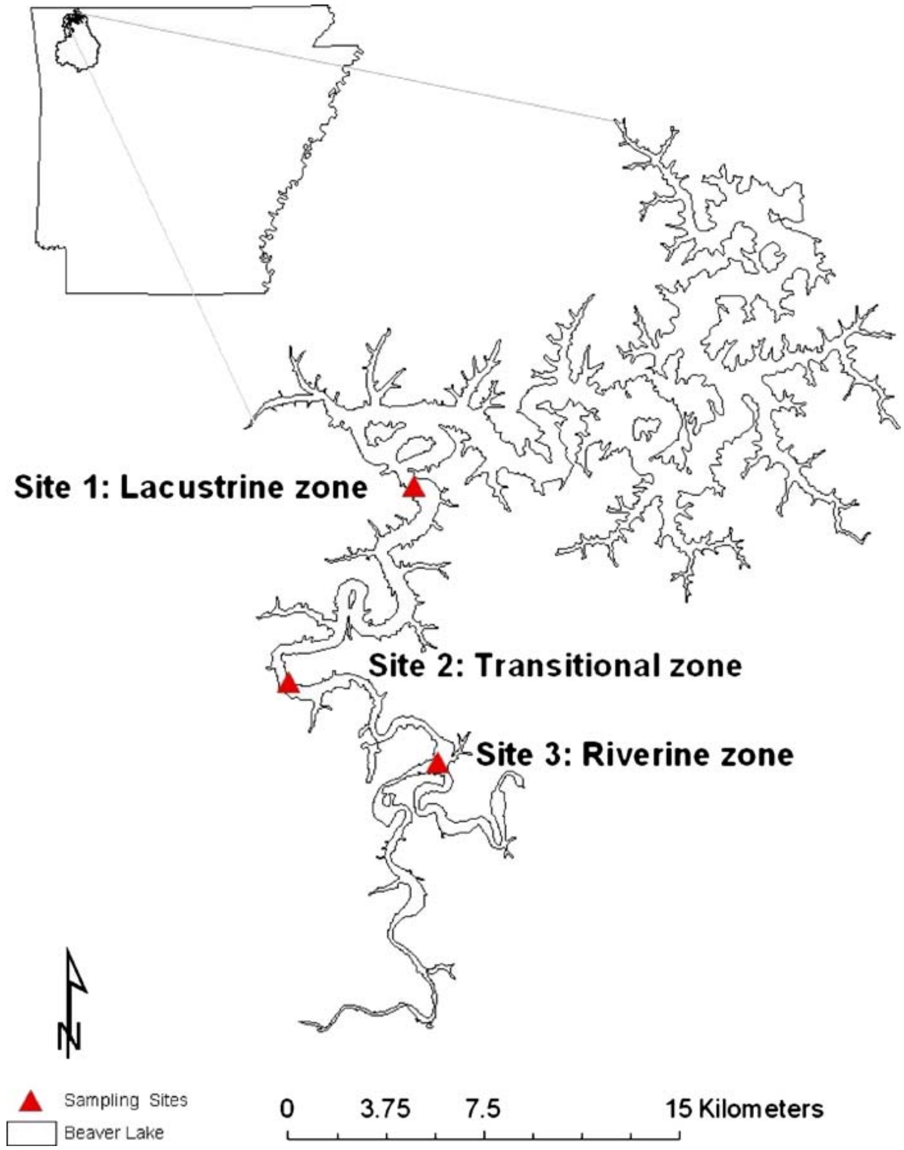

Figure 1 Sampling sites in the lacustrine, transitional and riverine zones at Beaver Reservoir, northwest Arkansas, where intact sediment cores were collected in June 2003, September 2003, and February 2004.

SRP to maintain 1 l of water overlying the sediments in each core.

Flux calculations used the change in SRP mass in the overlying water of the intact sediment cores incubated under aerobic and anaerobic conditions over time. Sediment P flux (mg m^{-2} day^{-1}) was calculated as the linear change (mg day^{-1}) in SRP mass (after corrections for the 60-ml water removal and replacement) as a function of time divided by the core area (0.0032 m^2). Simple linear regression was used to determine the slope of the relationship between adjusted SRP mass and time. The slope was used to estimate sediment P release rates even when the slope was not statistically different than zero; the slope value provides an estimate representing natural conditions better than using a zero value. Furthermore, the slopes were generally very small values and resulted in low estimates of sediment P flux.

2.3 External load estimation

Daily mean stream discharge (1999–2002) and available P concentration data (2001–2002) were obtained from the US Geological Survey (USGS) National Water Information System (NWIS) database for War Eagle Creek (USGS Station No. 07049000), Richland Creek (USGS Station No. 07048800) and the White River (USGS Station No. 07048600; http://waterdata.usgs.gov/ar/nwis/sw/). Concentration data were available for orthophosphate-P (PO_4-P), dissolved P (DP), and TP (Total P) from the USGS NWIS database (http://waterdata.usgs.gov/ar/nwis/qw/). The coefficients for external P loading were calculated by log-linear regression of load (L) and concentration (C), daily mean discharge (Q) and time (T) using the LOADEST software program (Runkel, Crawford, & Cohn, 2004). This software program uses a minimum variance unbiased estimator (MVUE) to transform results from ln values into daily loads (Cohn, DeLong, Gilroy, Hirsh, & Wells, 1989) because simple transformation from ln space to real space often underestimates P loads (Ferguson, 1986). The following equations were used to estimate daily concentration and load:

$$\ln(C) = \beta_1 + \beta_2 \ln(Q) + \beta_3 T + \beta_4 \sin(2\pi T) + \beta_5 \cos(2\pi T) \quad (1)$$

$$\ln(L) = \beta_1 + \beta_2 \ln(Q) + \beta_3 T + \beta_4 \sin(2\pi T) + \beta_5 \cos(2\pi T) \quad (2)$$

where L is load in kg day^{-1}, C is concentration in mg l^{-1}, T is time in Julian days, Q is mean daily discharge in cubic feet per second, and b_1 is the regression constant and $\beta_{2,3,4,5}$ are the regression coefficients. The sine and cosine factors are used to account for temporal variability in P loads that may occur in the streams draining these catchments.

Daily loads, estimated using this regression technique, were then summed to quantify annual loads for each of the P constituents available from the USGS database.

2.4 Data analysis

Simple linear regression and sediment P flux calculations were conducted using Microsoft Excel (Microsoft Inc., 2003). Additionally, JMP software (version 5.2, SAS Institute, Cary, NC) was used to compare slopes of adjusted SRP mass with time under aerobic and anaerobic conditions at a site on a given sampling date using a significance level (α) of 0.10; an α of 0.10 was used because of the inherent variability in natural conditions and the historical data (Haggard, 1997; B.E. Haggard, unpublished data) from the hypolimnion suggested SRP concentrations were relatively low during most of the year. These slope comparisons were also used to evaluate spatial variability in sediment P flux at Beaver Reservoir.

3 Results

3.1 Sediment phosphorus – June 2003

Average SRP concentration of the filtered replacement water was <0.01 mg l^{-1} during the June 2003 experiment. Initial SRP concentrations after the initiation of incubation in the water overlying the sediment cores were generally <0.03 mg l^{-1}, except under anaerobic conditions at the transitional site (0.06 mg l^{-1}). After the 18 day incubation, final SRP concentrations were within the range of initial concentrations under aerobic conditions, whereas final SRP concentrations were variable under anaerobic conditions (0.02–0.20 mg l^{-1}). Under anaerobic conditions, SRP concentrations in the overlying water generally increased with time during incubation, except at the lacustrine site (Figure 2). The slope describing the change in adjusted SRP mass with time was significantly different from zero only at the transitional and riverine sites under anaerobic conditions (Table I).

The changes in adjusted SRP mass with time produced significantly different estimates of sediment P flux under aerobic and anaerobic conditions at the transitional and riverine sites (Table I), whereas sediment P flux at lacustrine zone was similar under both conditions. Sediment P flux was greater under anaerobic conditions compared to aerobic conditions when significant differences were noted (Table II). Although many slopes were not significantly different than zero, these values were used to estimate sediment P flux under aerobic conditions (0.04–0.15 mg m^{-2} day^{-1}). The range in sediment P flux under anaerobic conditions was from <0.01 to 1.77 mg m^{-2} day^{-1}, with the greatest flux occurring in intact sediment cores collected from the transitional zone. Spatial variability was only observed under anaerobic conditions where all three sites had different estimates of sediment P flux (transitional zone > riverine zone > lacustrine zone; slope comparison; $p < 0.10$). Average sediment P flux across the sites on this sampling date was 0.11 mg m^{-2} day^{-1} under aerobic conditions and 0.83 mg m^{-2} day^{-1} under anaerobic conditions.

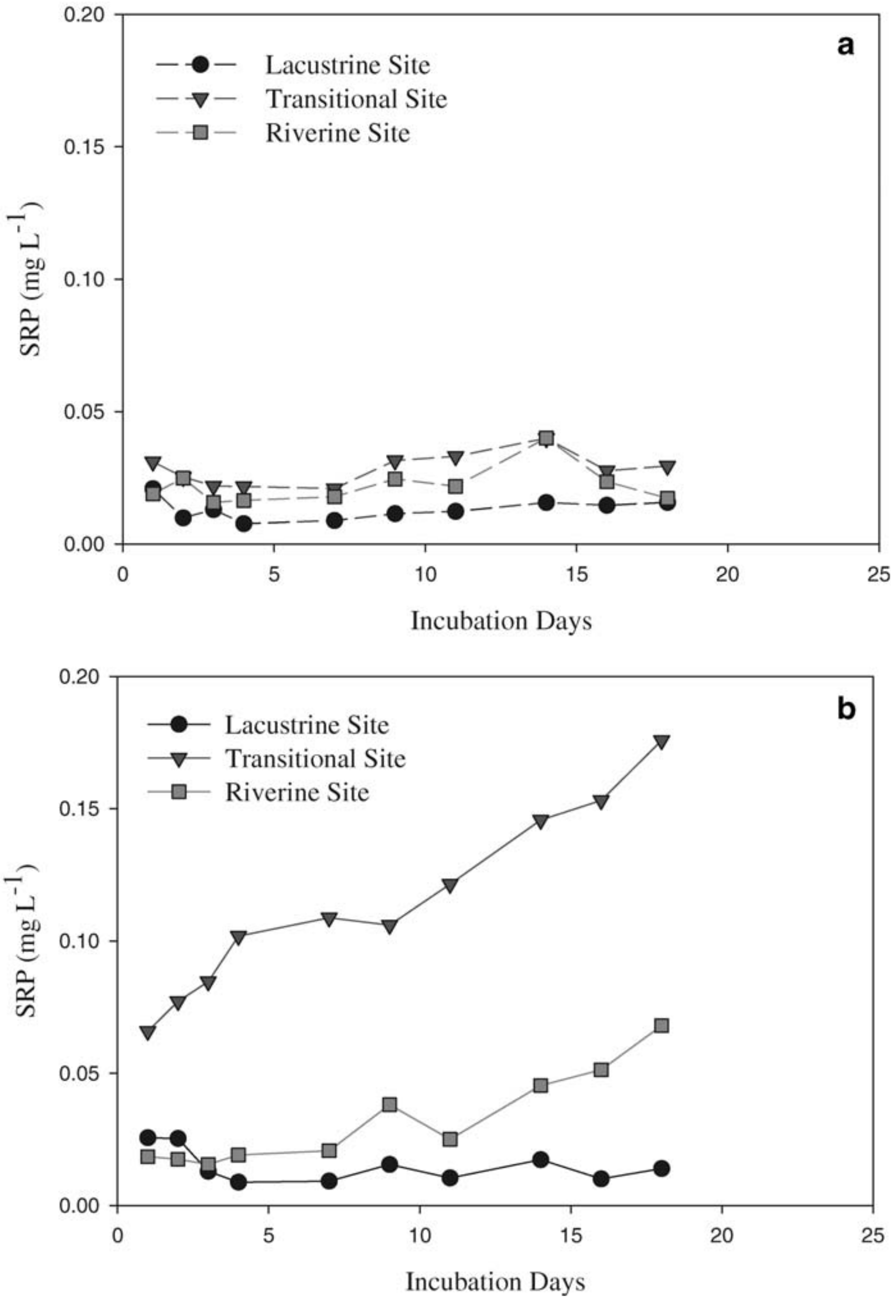

Figure 2 Soluble reactive phosphorus (SRP) concentrations in the overlying water under aerobic conditions (a) and under anaerobic conditions (b) of intact sediment cores collected from three sites at Beaver Reservoir during June 2003. (Symbols represent the average of the three cores incubated under aerobic and anaerobic conditions from each site).

3.2 Sediment phosphorus flux – September 2003

Average SRP concentration of the filtered replacement water was <0.01 mg l^{-1} during the September 2003 experiment. Initial SRP concentrations after the initiation of incubation in the water overlying the sediment cores were generally <0.05 mg l^{-1}. Similar to the June 2003 sampling after the 21 day incubation, final SRP concentrations were within the range of the initial conditions under aerobic treatment, but SRP concentrations were somewhat variable during the aerobic incubation. The final SRP concentrations in the overlying water under anaerobic conditions were generally higher compared to the initial conditions (0.06 – 0.08 mg l^{-1}). Under anaerobic conditions, SRP concentrations in the overlying water increased during

Table I Linear relationship between time and adjusted soluble reactive phosphorus (SRP) mass released into the overlying water to the intact sediment cores from three sites in Beaver Reservoir under aerobic and anaerobic conditions during June 2003, September 2003, and February 2004

Date	Site	Aerobic				Anaerobic			
		b_0^*	b_1	R^2	(P-value)	b_0^*	b_1	R^2	(P-value)
June 2003	L	0.012	<0.001	0.04	(0.57)	0.018	<0.001	0.18	(0.22)
	T	0.024	<0.001	0.29	(0.11)	0.065	0.006	0.95	(<0.01)
	R	0.019	<0.001	0.12	(0.33)	0.009	0.003	0.86	(<0.01)
September 2003	L	0.018	<0.001	<0.01	(0.96)	0.017	0.002	0.31	(0.08)
	T	0.014	0.003	0.27	(0.10)	<0.001	0.005	0.63	(<0.01)
	R	0.026	0.003	0.35	(0.05)	0.030	0.002	0.15	(0.23)
February 2004	L	0.022	<0.001	<0.01	(0.95)	0.018	<0.001	<0.01	(0.84)
	T	0.019	<0.001	<0.01	(0.84)	0.014	0.001	0.16	(0.20)
	R	0.023	<0.001	<0.01	(0.84)	0.018	0.001	0.20	(0.15)

L denotes lacustrine zone site 1; *T* denotes transitional zone site 2; *R* denotes riverine zone site 3; b_0 is the *y*-intercept of linear model between adjusted SRP mass released and time; and b_1 is the slope of linear model between adjusted SRP mass released and time.

the incubation, similar to that observed in June 2003. The slope describing the linear relation between adjusted SRP mass and time was significant at the riverine site under aerobic conditions and at the lacustrine site and transitional site under anaerobic conditions (Table I).

Table II Comparison of aerobic and anaerobic sediment P flux from intact sediment cores from three sites in Beaver Reservoir under aerobic and anaerobic conditions during June 2003, September 2003, and February 2004 (statistical comparisons were made between the slopes of the linear relations used to estimate sediment P flux under aerobic and anaerobic conditions)

Sampling Dates	Site	Aerobic Sediment P Flux (mg m^{-2} day^{-1})	Anaerobic Sediment P Flux (mg m^{-2} day^{-1})	H$_o$: Slopes (b_1) equal / H$_a$: Slopes (b_1) not equal	
				F	P
June 2003	L	0.04	<0.01	2.10	0.17
	T	0.15	1.77	53.20	<0.01
	R	0.13	0.85	14.02	<0.01
September 2003	L	0.02	0.55	2.27	0.15
	T	0.89	1.59	2.04	0.17
	R	0.81	0.53	0.02	0.90
February 2004	L	<0.01	<0.01	0.04	0.85
	T	0.02	0.21	0.76	0.39
	R	<0.01	0.27	1.14	0.30

L denotes lacustrine zone site 1; *T* denotes transitional zone site 2; *R* denotes riverine zone site 3; and b_1 is the slope of linear model between adjusted SRP mass released and time.

The slope of the linear relation was used to provide a numerical estimate of the sediment P flux, even when the slope was not significantly different from zero. Estimated sediment P flux was from 0.02 to 0.89 mg m^{-2} day^{-1} under aerobic conditions, whereas sediment P flux was from 0.53 to 1.59 mg m^{-2} day^{-1} under anaerobic conditions (Table II). Some spatial variability was observed in sediment P flux under aerobic and anaerobic conditions, but the variability in measured SRP concentrations with time limited the observed differences. Sediment P flux under aerobic conditions was generally greater at the riverine and transitional zone compared to that observed at the lacustrine zone (slope comparison, $p < 0.10$). Sediment P flux under anaerobic conditions at the transitional zone was also greater than that observed at the lacustrine zone (slope comparison, $p < 0.10$). Average sediment P flux on this sampling date was 0.57 mg m^{-2} day^{-1} under aerobic conditions and 0.89 mg m^{-2} day^{-1} under anaerobic conditions.

3.3 Sediment phosphorus flux – February 2004

Average SRP concentration of the filtered replacement water was <0.01 mg l^{-1} during the February 2004 experiment, as observed in the proceeding experiments. Initial SRP concentrations in the overlying water of the sediment cores were <0.02 mg l^{-1}. After the 21-day incubation, final SRP concentrations were within the range of the initial conditions under aerobic and anaerobic treatment. The changes in adjusted SRP

Table III Estimated average sediment P flux and internal P load from the lacustrine, transitional and riverine zones at Beaver Reservoir under aerobic and anaerobic conditions where it was assumed that the hypolimnion of the impoundment is stratified and anoxic for four months out of the year in the lacustrine zone and six months out of the year in the transitional and riverine zones based on Galloway and Green (2006)

Sediment Sampling Site	Area (km^2)	Sediment P flux (mg m^{-2} day^{-1})		Internal P load (Mg $year^{-1}$)	
		Aerobic	Anaerobic	Aerobic	Anaerobic
L	80	0.02	0.18	0.4	1.2
T	14	0.35	1.19	0.9	3.0
R	9	0.31	0.55	0.5	0.9
Total	103	0.09	0.35	1.8	5.1

L denotes lacustrine zone site 1; *T* denotes transitional zone site 2; *R* denotes riverine zone site 3.

mass with time did not differ under aerobic and anaerobic conditions (Table I). Sediment P flux estimates ranged from <0.01 to 0.02 mg m^{-2} day^{-1} under aerobic conditions and from <0.01 to 0.27 mg m^{-2} day^{-1} under anaerobic conditions (Table II). Average sediment P flux on this sampling date was <0.01 mg m^{-2} day^{-1} under aerobic conditions and 0.15 mg m^{-2} day^{-1} under anaerobic conditions. Sediment P flux measured under aerobic and anaerobic condition did not vary spatially during this experiment and was less during this experiment than that observed during the other two sampling events (June 2003 and September 2003).

3.4 Internal phosphorus loads

The average sediment P flux from the lacustrine, transitional and riverine zones at Beaver Reservoir under aerobic conditions was 0.02, 0.35 and 0.31 mg m^{-2} day^{-1}, whereas the sediment P flux under anaerobic conditions was 0.18, 1.19 and 0.55 mg m^{-2} day^{-1}, respectively (Table III). The area-weighted sediment P flux for Beaver Reservoir was 0.09 and 0.35 mg m^{-2} day^{-1} under aerobic and anaerobic conditions; however, these values should be interpreted cautiously and used as an estimate of the sediment P release rates at Beaver Reservoir. The internal P loads estimated at Beaver Reservoir were 1.8 and 5.1 Mg P $year^{-1}$ under aerobic and anaerobic conditions, respectively, assuming the hypolimnion was stratified and anoxic near the sediment-water interface for four months a year in the lacustrine zone and six months out of the year in the transitional and riverine zones. The length of stratification was determined from Galloway and Green (2006) and their analysis of ambient limnology and water quality at Beaver Reservoir. This study only used three sites within a rather large and long impoundment to provide preliminary data on internal P loads.

3.5 External phosphorus loads using USGS data

The linear relation between the natural logarithm of P concentration data [$\ln(C_{PO4\text{-}P}$, C_{DP} and $C_{TP})$] obtained from the USGS and mean daily discharge [$\ln(Q_d)$] or instantaneous discharge [$\ln(Q_i)$] were variable and were not consistently significant ($p < 0.10$) at the White River, War Eagle Creek and Richland Creek. Using the LOADEST software program, the average annual TP load from 2001 and 2002 at the

Table IV Estimated average annual total phosphorus (TP) loading during 2001 and 2002 using US Geological Survey concentration data and mean daily discharge from the White River, War Eagle Creek and Richland Creek which flow into Beaver Reservoir

Sampling Site (USGS Site No.)	Catchment Area (km^2)	TP flux (mg m^{-2} day^{-1})	TP load (Mg $year^{-1}$)
White River (07048600)	1,900	0.09	64.6
War Eagle (07049000)	1,400	0.02	9.9
Richland Creek (07048800)	900	0.01	4.1
Tributary Sum	4,200	0.05	78.7
WWTP		–	2.4
Total		0.05	81.0

White River, War Eagle Creek, and Richland Creek was 64.6, 9.9 and 4.1 Mg year^{-1}, respectively. The resulting average annual TP load entering Beaver Reservoir was 78.7 Mg year^{-1} from these three main tributaries, and the average annual TP load including the city of Fayetteville's WWTP effluent discharge (2.4 Mg TP year^{-1}) was approximately 81 Mg year^{-1} (Table IV). These data were similar to external load estimations provided by Haggard et al. (2003).

4 Discussion

Hypolimnetic P concentrations are dependent upon many factors, including mineral solubility, sediment P buffering capacity, microbial uptake and mineralization, and microbial-mediated Fe and Mn reduction near the bottom sediment-water interface. These processes often result in a P concentration gradient in the hypolimnion where concentrations increase with depth reaching a maximum near the bottom sediments, as observed in Beaver Reservoir (Haggard, 1997; Galloway & Green, 2006). Hypolimnetic P concentrations were also strongly correlated to dissolved Fe and Mn concentrations at Beaver Reservoir (Haggard, 1997), suggesting the reduction of Fe and Mn minerals in the bottom sediments released dissolved P into the water column. At site number 2 in the transitional zone, dissolved P concentrations near the sediment–water interface before fall turnover (0.12–0.20 mg SRP l^{-1}; B.E. Haggard, unpublished data) were similar to that measured under anaerobic conditions in the overlying water of the intact sediment cores collected June 2003 and incubated almost 21 days (0.15 mg SRP l^{-1}). At Beaver Reservoir, Galloway and Green (2006) observed similar dissolved P concentrations near the sediment-water interface in the hypolimnion of the transitional zone.

This study showed that sediment P flux was generally greater under anaerobic conditions compared to aerobic conditions, as has been observed in many studies (e.g., see Cooke et al., 1977; James, Barko, & Eakin, 1995; Haggard et al., 2005; Moore & Reddy, 1994; Moore et al., 1991). Sediment P release rates reported in this study are on the lower end of the range typically observed in eutrophic lakes and reservoirs under either aerobic conditions (−4.5 to 5.71 mg m^{-2} day^{-1}) or anaerobic conditions (2.0–32.0 mg m^{-2} day^{-1}) across North America (Cooke et al., 1977; Haggard et al., 2005; Holdren & Armstrong, 1980; James et al., 1995, 2000; Malecki, White, & Reddy, 2004; Moore & Reddy, 1994; Moore et al., 1991, 1998; Theis & McCabe, 1978). Specifically, sediment P flux at Beaver Reservoir under anaerobic conditions (0.18 –1.19 mg m^{-2} day^{-1}) was comparable to aerobic release rates (1.03 mg m^{-2} day^{-1}) at a nearby Ozark impoundment, Lake Eucha (Haggard et al., 2005). The intact cores collected at these sites and on these sampling dates do not suggest that sediment P release rates are extremely high at Beaver Reservoir, especially when compared to other regional impoundments that have been classified as eutrophic.

This study intended to provide some preliminary estimates of bottom sediment P flux at Beaver Reservoir and was limited to three sampling sites where intact sediment cores were collected. This study showed that sediment P release rates were spatially variable and were typically greater in the transitional and riverine zones of the impoundment. These reservoir zones, particularly the transitional zone, are typically the areas of sediment and other material deposition (James, Kennedy, Montogomery, & Nix, 1987; Thornton, Kimmel, & Payne, 1990). Thornton et al. (1990) also suggested that bottom sediment P release rates are influenced by the longitudinal gradient of physical and chemical conditions in reservoirs.

The internal cycling of P represents an important mechanism that maintains and even increases the rate of anthropogenic eutrophication in some eutrophic lakes and reservoirs, where not considering sediments as a potential P source would likely delay lake or reservoir recovery (Larson et al., 1979; Ryding, 1981). Several previous investigations have reported on chemical remediation techniques that have been used to reduce or eliminate the release of P from bottom sediments (Kennedy, Barko, James, Taylor, & Godshalk, 1987; Kennedy & Cooke, 1982; Welch & Schrieve, 1994); the most commonly studied chemical used is aluminum sulfate [$Al_3(SO_4)_2$; commonly referred to as alum]. The aforementioned studies have also observed reductions in P concentrations, chlorophyll *a* concentrations, and the abundance of nuisance algae following alum treatment of bottom sediments and general improvements in water quality. This technique has been investigated using intact sediment cores from Lake Eucha in the Ozarks, and alum treatment significantly reduced sediment P flux

(Haggard et al., 2005). However, alum treatment of Beaver Reservoir may not be an economically viable option, given the large surface area of the impoundment and that internal P load was estimated to be only 6.9 Mg P year^{-1} or less than 10% of the external P load from the three main tributaries. Sen (2005) showed that alum treatment of intact sediment cores collected from Beaver Lake generally resulted in reduced estimates of sediment P release under aerobic and anaerobic conditions.

The limitations of our study stem from the limited number of sediment sampling stations across this large reservoir. Recent investigations into Beaver Reservoir have used a global positioning system (GPS) and echo sounding radars to identify areas of sediment deposition in the transitional and riverine zones upstream from our site number 2 (Boss, 2004). Future investigations into sediment P flux should concentrate on these identified areas of sediment deposition, and intact sediment cores should be collected and incubated as described in this study. If sediment P release rates are significant from these deposition areas, then targeted alum treatment might be a possible option in reservoir management strategies. James, Barko, Eakin, and Helsel (2000) suggested that alum treatment would be most effective in areas of sediment accumulation at lakes and reservoirs, where sediment P flux was significant.

Acknowledgments This study was funded by the Arkansas Soil and Water Conservation Commission and the US Environmental Protection Agency 319 Nonpoint Source Program (Grant No. 02-1200:SGA 029), the University of Arkansas Division of Agriculture and the US Department of Agriculture Agricultural Research Service Poultry Production and Product Safety Research Unit. We greatly appreciate the assistance of Stephanie Williamson, Ray Avery and Anna Erickson at the USDA ARS Poultry Production and Product Safety Research Unit, Poultry Waste and Water Quality Laboratory, Fayetteville, AR, during field and laboratory work.

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