

Phosphorus Concentrations, Loads, and Sources within the Illinois River Drainage Area, Northwest Arkansas, 1997–2008

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In the Ozark Highlands and across the United States, effluent phosphorus (P) sources often have a profound impact on water column concentrations and riverine transport. This study evaluated (i) annual P loads at the Illinois River at Arkansas Highway 59 from calendar year 1997 through 2008, (ii) the relative contribution of effluent P sources to annual riverine P transport, (iii) longitudinal gradients in water column P concentrations downstream from several wastewater treatment plant effluent discharges, and (iv) changes in monthly P loads over the last decade. This study showed that annual P loads have ranged from 64,000 kg to over 426,000 kg and that P transport was positively correlated to hydrology (i.e., the amount of water delivered downstream). The relative contribution of P inputs from municipal facilities has decreased from 40% of the annual P load at the Illinois River at Arkansas Highway 59 to <15% in recent years. Elevated P concentrations during base flow conditions were traced 45 river km upstream to one municipal effluent discharge, but all effluent discharges influenced P concentrations in the receiving streams. Most important, flow-adjusted monthly P loads showed two distinct trends over time. Flow-adjusted loads significantly increased from 1997 through 2002 and significantly decreased from 2002 through 2008. The concentrations and transport of P within the Illinois River drainage area are significantly decreasing from all the watershed management changes that have occurred, and monitoring should continue to determine if this decrease continues at the same rate over the next several years.

IN THE OZARK HIGHLANDS of southern Missouri, northern Arkansas, and northeastern Oklahoma, the import of phosphorus (P) in animal feeds has resulted in substantial accumulations of this element in watersheds with high densities of confined animal feeding operations. Animal manure, particularly poultry litter, is often surface applied to pastures in this region (Sims and Wolf, 1994), and these surface applications have contributed to the buildup of P and other elements near the soil surface (Kingery et al., 1994; Sharpley et al., 2007). Several investigations have shown that runoff P concentrations and transport increase with an increase in P accumulation near the soil surface (Pote et al., 1996, 1999). Other studies have shown the influence of surface applications of animal manure on runoff P concentrations and transport (Edwards and Daniel, 1992, 1993), where the amount of water-extractable P applied in animal manure has the greatest effect on runoff P losses (DeLaune et al., 2004; Kleinman et al., 2002; Haggard et al., 2005a).

From the late 1990s to the early 2000s, the focus of watershed managers in the Ozarks was solely on diffuse sources of P, especially agricultural runoff from pastures and land application of animal manure. However, it has become apparent in this region that this shift in focus may have been premature and may have neglected the impact of point sources of P (e.g., effluent discharges from municipal wastewater treatment plants [WWTPs]). Several recent studies in this region have shown the profound influence of WWTP effluent discharge on stream P concentrations and retention (Ekka et al., 2006; Haggard et al., 2001, 2005b). The impacts of effluent P sources persist several kilometers downstream, and an internal P buffer mechanism often maintains elevated water column P concentrations when effluent P inputs are low (Haggard et al., 2005b). It also appears that effluent P sources and water column concentrations directly influence the amount of sediment P storage and the sediment–aqueous phase P equilibrium in streams (Ekka et al., 2006; Haggard et al., 2004).

The driving forces of water-quality concerns in Ozark streams are (i) the aesthetic value of the stream and (ii) the quality of downstream aquatic systems with which the stream is simply a tributary delivering P. The aesthetic value of the stream will likely be tied to its recreational use and appearance, which are influenced by the magnitude of P concentrations and associated benthic and sestonic algal growth. A positive correlation between P

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Abbreviations: AWRC, Arkansas Water Resources Center; FAL, flow-adjusted load; IRDA, Illinois River drainage area; LULC, land use land cover; SRP, soluble reactive phosphorus; TP, total phosphorus; WWTP, wastewater treatment plant.

concentrations and algal biomass in streams often exists (e.g., Biggs, 2000; Dodds et al., 1997), but this relation is highly variable because of the effects of floods, grazing, shading, catchment size, etc. (Jones et al., 1984; Lohman and Jones, 1999; Lohman et al., 1992). Nuisance production of benthic algal biomass (100–150 mg chlorophyll-*a* m⁻²) (Welch et al., 1989) represents a management issue for streams, and remedial efforts should concentrate on reducing baseflow P concentrations. However, potential eutrophic conditions of downstream reservoirs within Ozark Watersheds are water-quality concerns that should focus on seasonal and annual P export from catchments, especially stream P transport during episodic rainfall and surface runoff events.

Recent concerns over effluent P sources in several Ozark catchments have prompted widespread adoption of limits on effluent concentrations. Many municipal facilities in this region have shifted from nitrogen (N)-based management to P-based management of effluent discharge, reducing effluent total P (TP) concentrations to <1.0 mg TP L⁻¹. The purpose of this study was to examine the effect of reduced effluent P concentrations and other watershed changes on water column P concentrations and loads within the Illinois River. This study (i) presents annual P loads from calendar years 1997 through 2008, (ii) assesses the relative contribution of effluent P sources to annual riverine P transport, (iii) shows historical longitudinal gradients in water column P concentrations downstream from several WWTP effluent discharges, and (iv) evaluates changes in monthly P loads over the last decade.

Study Site Description

The focus of this study was the Illinois River Basin in the southwestern portion of the Ozark Plateaus physiographic province (Fenneman, 1938) of northwest Arkansas and northeastern Oklahoma, which is underlain with cherty limestone of the Springfield Plateau province (Adamski et al., 1995). The Illinois River Basin is about equally divided between the states of Arkansas and Oklahoma, where a small impoundment exists on this river near the state line. Several USGS streamflow and water-quality monitoring stations exist throughout the catchment in Arkansas and Oklahoma. The most notable USGS monitoring station is the Illinois River, south of Siloam Springs (Station No. 07195430) at the Highway 59 bridge crossing the stream in Benton County, Arkansas. The approximately 1500-km² drainage area upstream from this point on the Illinois River has been coined the Illinois River drainage area (IRDA) in northwest Arkansas, and the 2006 land use land cover (LULC) is 46, 41, and 13% in pasture, forest and urban, respectively. The recent land use change has been from pasture to urban or forested areas, as 1999 LULC was 56, 37, and 7% in pasture, forest, and urban, respectively.

Several municipal facilities discharge into the head waters of the IRDA, including the WWTPs at Fayetteville, Rogers, and Springdale. The City of Fayetteville's facility is a tertiary level treatment plant operating with regard to P management and regulatory effluent limits of 1 mg TP L⁻¹ since the mid-1990s. The City of Rogers' facility has tertiary treatment capacity and has been voluntarily operating under P management strategies with an effluent limit of 1 mg TP L⁻¹ since approximately

1997. The City of Springdale's facility is a tertiary system operated using N management in the 1990s and started P-based management in late 2002; the facility is upgrading and has been attempting to maintain effluent P concentrations <1 mg TP L⁻¹. These facilities receive influent from residential, industrial, and agricultural sources; the most notable agricultural source is probably poultry processing facilities. These municipal WWTPs discharge into head water tributaries of the IRDA, including Mud Creek (Fayetteville WWTP), Osage Creek (Rogers WWTP), and Spring Creek (Springdale WWTP). However, the effluent discharge into Mud Creek was eliminated in the summer of 2008, when the new Westside WWTP in Fayetteville started discharging into another Illinois River tributary, Goose Creek.

At the Illinois River, water column P concentrations and riverine P loads have been under constant evaluation by various state agencies in Arkansas and Oklahoma over the past two decades. In 1992, the U.S. Supreme Court rendered a decision that the USEPA may require upstream states to meet downstream state water-quality standards, with the potential point of regulation being the state borders (Arkansas vs. Oklahoma, 503 U.S. 91; <http://laws.findlaw.com/us/503/91.html>). Thus, the recent adoption of a TP criterion (0.037 mg L⁻¹) (OWRB, 2002) in the Illinois River and other Oklahoma scenic rivers has brought the sources of P in the IRDA under even closer scrutiny. This TP criterion will be fully implemented in 2012, where TP concentrations should not exceed the 30-d geometric mean concentration of 0.037 mg TP L⁻¹. This standard was based on the 75th percentile TP concentrations from streams draining relatively undeveloped catchments across the United States (Clark et al., 2000). The promulgation of this water-quality standard has fueled the controversy over elevated stream P concentrations between Arkansas and Oklahoma, and the Oklahoma Attorney General filed a recent lawsuit against several poultry companies based in northwest Arkansas. Several previous studies have been completed at this catchment describing P concentrations, loads, and yields at the Illinois River from 1997 through 2001 (e.g., Green and Haggard, 2001; Haggard et al., 2003b; Pickup et al., 2003).

Materials and Methods

Phosphorus Concentrations and Loads

The USGS has historical streamflow and water quality data (<http://waterdata.usgs.gov/ar/nwis/qw/>) available that have been collected at the Illinois River USGS sampling station on Arkansas Highway 59 south of Siloam Springs, Arkansas (Station No. 07195430). The Arkansas Water Resources Center (AWRC) has monitored P concentrations and estimated loads at this site on the Illinois River from calendar years 1997 through 2008. Stage was monitored by the USGS as this site, and water samples were collected using an α or kemmerer style sampler approximately every other week during base flow conditions (i.e., stage <1.5 m). Storm event samples were collected using a Sigma 900 max auto-sampler (Hach Co., Loveland, CO) configured to pull samples when the stage exceeded 1.5 m. After the autosampler was triggered, it pulled a discrete water sample after a certain volume of water (i.e., 226,500 m³) flowed past the sampling station, and storm events were

sampled in this manner as long as the stage remained elevated above 1.5 m. Each discrete sample collected during the storm events was analyzed for TP and soluble reactive P (SRP) at the AWRC-certified water quality lab during the first couple years; thereafter, the samples were composited by combining equal volumes of each sample for analysis. The samples were composited when all 24 sample bottles in the autosampler were filled or within 48 h after the collection of the first sample. Once per quarter, field blanks, sampler duplicate, and bridge replicate samples were collected for quality assurance and quality control purposes, following the USEPA-approved quality assurance project plan. All samples were analyzed using standard analytical procedures approved by the USEPA.

Annual constituent loads were calculated using the data from the collected samples and USGS stage and discharge data in 30-min intervals for base and storm flow conditions. Loads were calculated by multiplying the 30-min volume by a corresponding constituent concentration using the mid-interval approach. Corresponding concentrations were determined from grab samples collected between storm events and samples collected by the autosampler during storm events, and these concentrations were applied to the mid-point between measured concentrations. Concentrations from grab samples during base flow conditions were applied forward or backward only to where the stage remained <1.5 m. Loads (kg) were calculated by summing the 30-min loads into daily, monthly, and annual loads during the calendar year. The annual flow-weighted concentration (mg L^{-1}) was determined by dividing the total load (kg) by the annual discharge volume (m^3). The loads reported in this paper were based on data available in AWRC miscellaneous publications series.

Phosphorus loads from municipal effluent discharges within the IRDA were summarized annually from 1997 through 2006, based on concentration and discharge data provided by each facility or available through the Arkansas Department of Environmental Quality.

Water Quality Trends

Simple trend analysis of P concentrations in water samples collected by the AWRC during base flow conditions was performed using three steps (e.g., White et al., 2004). Monthly water volume (m^3) and TP loads (kg) were log transformed to account for the typical log-normal distribution of water-quality data and to minimize the effects of outliers within the data (Hirsh et al., 1991; Lettenmaier et al., 1991) (Step 1). The log-transformed TP loads were flow weighted against log-transformed monthly water volume using the LOESS two-dimensional smoothing technique (Richards and Baker, 2002; Hirsh et al., 1991) (Step 2). The LOESS two-dimensional smoothing technique uses locally weighted regression algorithms and overcomes any limitation and difficulties often associated with parametric techniques that are more sensitive to outliers in the data (Lettenmaier et al., 1991); this was performed in SigmaPlot (Systat Software Inc., San Jose, CA) using a sampling proportion of 0.5 and a first-order polynomial. The residuals from this LOESS smoothing of log-transformed data represent the flow-adjusted loads (FAL), and changes in FALs were evaluated over time using the LOESS smoothing technique (Step 3). The LOESS line through the FALs also dem-

onstrates nonlinearity of TP load changes over time, resulting from specific management actions. In this study, FALs were broken into two time periods representing before and after a major watershed management change (i.e., Springdale's municipal facility switched to P-based management strategies in late 2002). Simple linear regression was used to evaluate changes in FALs over time, and the significance of the slope was used to determine statistical trends in monthly TP loads.

Spatial Water Sampling

The spatial distribution of dissolved P concentrations was evaluated using multiple monitoring sites from the Illinois River, South of Siloam Springs (USGS Station No. 07195430) upstream to the effluent discharges in Mud Creek (a tributary to Clear Creek), Osage Creek, and Spring Creek (Fig. 1). Water samples were collected in triplicate from these sites in February, March, and April 2002, filtered through a $0.45\text{-}\mu\text{m}$ membrane, stored in a freezer, and analyzed for SRP using the automated ascorbic acid reduction method (APHA, 1998); water samples were collected from the left-center, middle (i.e., VCF), and right-center of the stream channel at each site. Soluble reactive P was determined using the modified ascorbic acid reduction method (APHA, 1998) on a Skalar San Plus Wet Chemistry Autoanalyzer (Skalar Analytical B.V., Breda, The Netherlands). Distance between sites was estimated using the GPS coordinates, digital stream hydrography, and the ESRI ArcView software program (Environmental Systems Research Institute, Redlands, CA); the sites are presented using the distance (river km) upstream from the Illinois River (USGS Station No. 07195430).

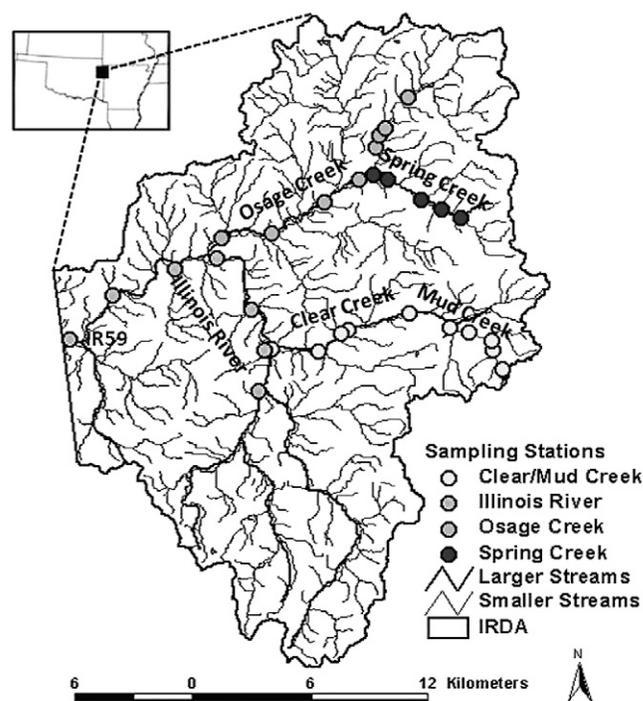


Fig. 1. The Illinois River drainage area (IRDA) in northwest Arkansas with the Illinois River at Highway 59 (IR59) identified along with the spatial distribution of sampling sites used to trace elevated phosphorus concentrations upstream to the effluent discharges at Mud Creek, Osage Creek, and Spring Creek.

Results and Discussion

Phosphorus Loads

Total P loads at the Illinois River USGS sampling station south of Siloam Springs were variable over time (from 1997 to 2008), ranging from 64,000 kg to over 426,000 kg transported annually (Table 1). The annual variation in TP loads follows the pattern in annual discharge very closely (ln-transformed data, $r = 0.90$; $P < 0.001$), suggesting that the annual transport of P from the IRDA depends heavily on precipitation and subsequently runoff amounts. The more precipitation, base flow discharge, and surface runoff during a given year, the greater the annual TP load. This strong correlation between loads and discharge shows how difficult it would be to measure P reductions after the implementation of best management practices within this relatively large watershed. Thus, monitoring programs need to be designed to adequately measure loads (e.g., annual or monthly) and to determine trends in concentrations or loads, such that changes after best management practice implementation or other management strategies may be detected within the fluvial channel.

The relation between annual loads and discharge is not surprising given that several studies have shown that P concentrations increase significantly with stream flow during surface runoff conditions (i.e., storm events) within the Illinois River (Green and Haggard, 2001; Pickup et al., 2003; Vieux and Moreda, 2003). This significant relation between P concentration and discharge has been used in log–log regressions (e.g., Green and Haggard, 2001; Pickup et al., 2003) and other synthetic approaches (e.g., Vieux and Moreda, 2003) to estimate annual P loads. Haggard et al. (2003b) showed the mean difference in annual P loads estimated using regression methods (loads based on USGS water quality data) and mid-interval approach (loads reported by Nelson et al., 1998, 1999, 2000, 2001) was <5%. This is not surprising given the observation that more than 75% of P transport occurs when the river stage exceeds 1.5 m (i.e., storm event conditions as defined in this

study). The percentage of the load transported during high flows increases with the amount of annual discharge; for example, the percent of P transported during storm events exceeded 90% in 2008, an extremely high flow year for the period of this study. A small portion of the annual P load is transported during base flow conditions, which is most influenced by contributions from WWTP effluent discharges.

The contributions from effluent discharges changed throughout the period of this study, with three distinct changes occurring from 1997 to 2009 (Fig. 2). The first change in P management within WWTPs occurred in 1997, when the Rogers municipal facility started operating under a voluntary 1 mg L⁻¹ limit on effluent P concentrations. In 2002, the Springdale municipal facility began operating using a 1 mg L⁻¹ limit on its effluent P concentrations. These changes dramatically reduced the P inputs from effluent discharges, where P inputs from WWTPs averaged approximately 91,000 kg yr⁻¹ from 1997 to 2000 and decreased to approximately 22,000 kg yr⁻¹ on average from 2004 to 2006. The municipal effluent discharges accounted for approximately 40% of the annual P load from 1997 to 2000 (assuming conservative transport) but less than 15% from 2004 to 2006. However, it is difficult to see the effects of the reduced P loads from the WWTPs when just evaluating annual transport from the IRDA because annual loads and discharge are strongly tied. For example, P loads in 2008 at the Illinois River were the greatest observed during the period of record (1997–2008) despite these important, large reductions in P inputs from the WWTPs. This observation was related to the fact that this was the wettest year recorded during the period of record; annual precipitation in 2008 was 1.5 times greater than that in 2007. The final change in WWTP management resulted when the effluent discharge at Mud Creek was stopped in summer 2008, and the new Fayetteville Westside WWTP began discharging to Goose Creek that same summer. It will be important to ascertain the effects of this change on P concentrations and transport within the Illinois River.

Table 1. Annual discharge, phosphorus loads, and flow-weighted concentrations at the Illinois River U.S. Geological Survey sampling station upstream from the Arkansas and Oklahoma border on Highway 59 bridge (IR59), 1997–2008.†

Calendar year	Annual discharge	Base flow discharge	Annual TP‡ load	Base flow TP load	Annual FWC	Base flow FWC
	10 ⁶ m ³		10 ³ kg		mg L ⁻¹	
1997	458	246	127	53.6	0.28	0.26
1998	588	378	232	41.1	0.39	0.20
1999	635	409	267	58.9	0.42	0.26
2000	536	294	283	65.8	0.53	0.27
2001	532	246	256	87.4	0.48	0.31
2002	531	230	218	86.8	0.41	0.29
2003	289	46	64.8	22.4	0.22	0.18
2004	566	291	281	30.6	0.50	0.11
2005	391	155	107	23.0	0.27	0.10
2006	257	149	96.6	19.2	0.38	0.13
2007	389	274	78.9	26.8	0.20	0.10
2008	1010	374	426	34.7	0.42	0.09
Min.	257	46	78.9	19.2	0.20	0.09
Max.	1010	409	281	87.4	0.53	0.31

† Data were obtained from the Arkansas Water Resources Center.

‡ FWC, flow-weighted concentrations; TP, total phosphorus.

Longitudinal Phosphorus Gradients

The percentage of pasture and urban areas within stream catchments shows a positive correlation to stream P concentrations in the Ozark Highlands (Haggard et al., 2003a, 2007), and this simple yet complex relation is widely observed across many streams (e.g., Ahearn et al., 2005; Brett et al., 2005; Buck et al., 2004). The relation between stream P concentrations and catchment land use within IRDA is likely similar to that observed across the Ozark Highlands, although it is specific to local hydrology, geology, and other factors influencing this interaction. However, several studies have shown that effluent discharges have a much greater impact on P concentrations during base flow conditions compared with land use and land cover, including in the Ozark Highlands (e.g., Haggard et al., 2001, 2003a, 2004, 2005b; Ekka et al., 2006). Stream P concentrations downstream from effluent discharges are often above the usual concentrations associated with a particular land use distribution.

Annual flow-weighted P concentrations ($\sim 0.4 \text{ mg L}^{-1}$; from Green and Haggard, 2001) at the Illinois River near the Arkansas and Oklahoma border from 1997 to 1999 were 2 to 20 times greater than the national and regional FWCs for undeveloped basins ($0.02\text{--}0.20 \text{ mg L}^{-1}$) (Clark et al., 2000) (i.e., at the beginning of this study period). This comparison was between the Illinois River and undeveloped basins, which drain primarily forested landscapes. However, the IRDA represents a mixed land use catchment, where pasture and urban areas comprise almost 60% of the LULC, and it should be expected to have FWCs that exceed those observed in undeveloped, forested catchments. These flow-weighted TP concentrations during base flow have generally been decreasing throughout the study period (0.31 mg L^{-1} in 2001 to 0.09 mg L^{-1} in 2008), whereas overall flow-weighted TP concentrations (based on total load and annual flow) have been more variable (from 0.20 to 0.53 mg L^{-1}) among calendar years.

In 2002, the source of these elevated P concentrations at the Illinois River near the Arkansas and Oklahoma border could be traced over 45 river km upstream to one municipal effluent discharge (i.e., Springdale's WWTP) (Fig. 3). This was based on P concentration data collected during base flow conditions during spring 2002, when dilution of the P inputs from effluent discharges should have been greatest. Soluble reactive P concentrations at the Illinois River during base flow conditions increased from 0.18 mg L^{-1} near the state border to 0.25 mg L^{-1} just downstream from its confluence with Osage Creek; SRP concentrations upstream from Osage Creek were generally $<0.05 \text{ mg L}^{-1}$ at the Illinois River. Within the Osage Creek watershed, stream SRP concentrations increased from on average 0.5 mg L^{-1} to just over 1 mg L^{-1} just downstream from its confluence with Spring Creek. Soluble reactive P concentrations continued to increase moving upstream toward the Springdale facility, measuring as great as 10 mg L^{-1} on one sampling date. The effects of all effluent discharges was easily observed with this spatial distribution of sampling sites, but the effects of one facility were most profound. Thus, a marked longitudinal gradient in stream P concentrations existed across the IRDA during these sampling dates (i.e., spring 2002). However, P concentrations at the Illinois River upstream from

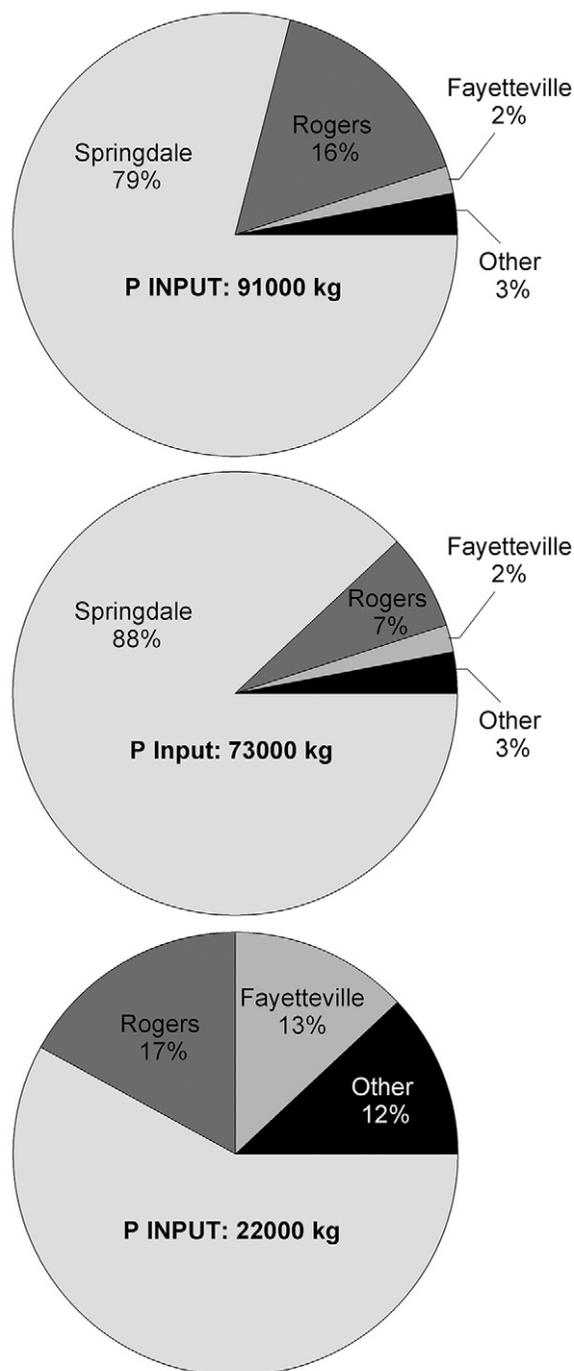


Fig. 2. Phosphorus (P) inputs from major effluent discharges during three periods from 1997 to 2000 (91,000 kg), 2001 to 2003 (73,000 kg), and 2004 to 2006 (22,000 kg), showing the percent of annual load at the Illinois River at the Highway 59 Bridge just south of Siloam Springs during each period.

Osage Creek were similar to those estimated based on land use distribution (i.e., $\sim 0.05 \text{ mg L}^{-1}$, estimated using regressions from Haggard et al., 2007).

During late 2002, the Springdale facility started operating to meet a 1 mg L^{-1} limit on effluent P concentrations. After this management change, stream P concentrations at Spring Creek decreased over time and were significantly correlated to the P concentration in the effluent discharge (Ekka et al., 2006). Phosphorus concentrations at Spring Creek often increased with distance downstream from the effluent discharge after this

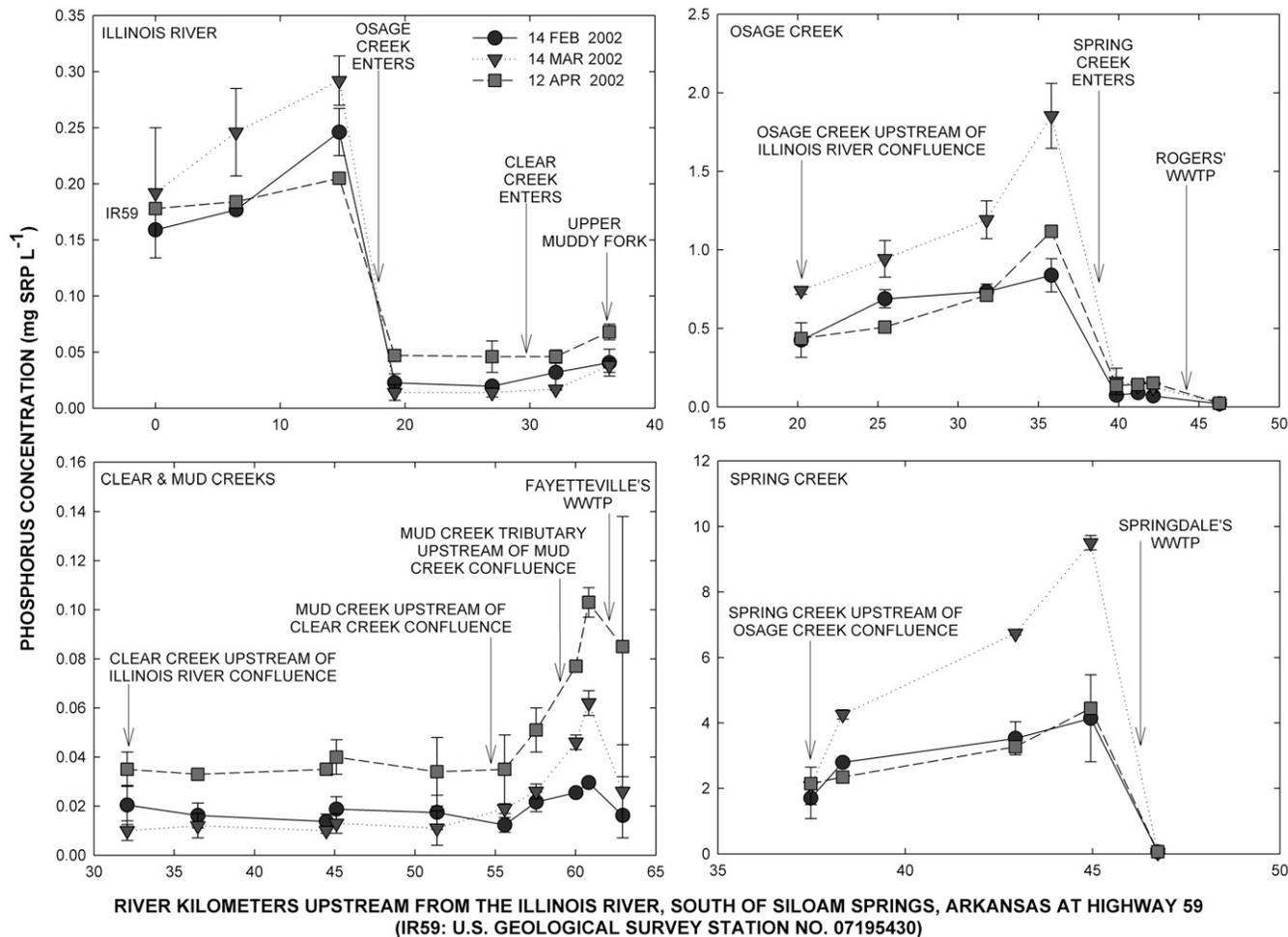


Fig. 3. Longitudinal gradient in dissolved phosphorus concentrations at the Illinois River from Arkansas Highway 59 bridge (IR59) upstream to the three major effluent discharges in Mud Creek (Fayetteville's wastewater treatment plant [WWTP]), Osage Creek (Rogers' WWTP), and Spring Creek (Springdale's WWTP), 2002. Symbols on graphs from each river or creek correspond to those sampling sites identified in Fig. 1.

management change (i.e., from October 2002 to June 2003). This observation from Ekka et al. (2006) suggests that P was being released from within the fluvial channel as the dissolved P concentration in the water column decreased below its equilibrium concentration with benthic sediments (i.e., equilibrium P concentration). Other streams have shown a net release of dissolved P downstream from effluent discharges, when concentrations resulting from P inputs decreased below some threshold concentration (Haggard et al., 2005b; Marti et al., 2004; Merseburger et al., 2005).

Phosphorus Trends

Annual P loads are closely related to the annual discharge (ln-transformed data, $r = 0.90$; $P < 0.0001$) at the Illinois River, and it should be no surprise that the two are related because, no matter what technique is used to estimate loads, it includes discharge as a factor. One of the biggest questions regarding the IRDA was how P loads have changed over time. The easiest way to answer this was to conduct trend analysis on monthly P loads normalized for changes in monthly water volume. Like annual P loads, monthly loads are strongly related to hydrology (Fig. 4), where LOESS smoothing resulted in a near linear relation. The residuals from this LOESS smoothing technique

represent the monthly loads as adjusted for changes in monthly water volume, or FALs.

Flow-adjusted loads showed a distinct pattern over time from 1997 to 2008, and, based on the LOESS smoothing technique, the FALs increased from 1997 through 2002 and then decreased from 2002 through 2008. This is consistent with the major change in watershed management that was known to have occurred during this time period, where Springdale's facility substantially reduced its effluent P concentrations and loads into Spring Creek in late 2002. Using simple least-squares regression, FALs increased significantly from 1997 through 2002 ($r^2 = 0.23$; slope = 0.010; $P < 0.0001$), and FALs decreased significantly after the implementation of P-based management at the WWTP ($r^2 = 0.20$; slope = -0.010 ; $P < 0.0001$). In this case, the least-squares regression equation is $FAL = \beta_0 + \beta_1 \times T$, where FAL represents Ln values and the slope (i.e., β_1) may be interpreted to represent the percent increase or decrease in loads as a function of time T (i.e., months). The percent change can be estimated as $(e^{\beta_1} - 1) \times 100$, where P loads are increasing at a rate of 1% per month from 1997 through 2002 and then decreasing 1% from 2002 through the end of the study period. This change may seem small, but with each month the median monthly P load decreases an estimated 1% after watershed management changes in 2002.

It appears that riverine P transport (i.e., monthly P loads) has been significantly decreasing from the IRDA after changes at Springdale's facility in 2002. However, the effects of other changes in watershed management on P transport at the Illinois River might be masked by this substantial change in WWTP management because it represented such a large percent reduction in annual inputs of P. There have been several other watershed management changes that started occurring about the same time (i.e., 2002), including the use of a P index to guide application rates of poultry litter and the transport of poultry litter outside this nutrient surplus areas (i.e., IRDA and other western and northwest Arkansas watersheds) (Goodwin et al., 2003) to the rangeland of western Oklahoma and row crops of eastern Arkansas. Litter transport has involved the services of brokers to coordinate the transport and sale of litter, especially in Arkansas and Oklahoma where federal grants had offset a portion of the hauling costs and paid the poultry farmer for the litter (Sharpley et al., 2007). The reduced litter applications that have occurred throughout the IRDA and other nutrient-surplus watersheds (i.e., from 3 to 1.5 ton acre⁻¹ yr⁻¹ between 2003 and 2008 [Sharpley et al., 2009]) also resulted in reduced P transport because land application of water-extractable P in poultry litter is an important factor in P transport from the edge of fields during episodic rainfall-runoff (DeLaune et al., 2004; Haggard et al., 2005a) as well as landscape hydrology.

Conclusions

The Illinois River and its catchment are currently the focus of a lawsuit between the Oklahoma Attorney General as the plaintiff and multiple poultry companies based in Arkansas as defendants. This lawsuit focuses on P along with other factors (including nitrogen, bacteria, trace elements, hormones, and pharmaceuticals), and it went to bench trial in late September 2009. Given the importance of this watershed, it is important to understand watershed processes and to make conclusions based on the scientific data available within the IRDA. This study concludes that (i) annual P loads have ranged from 64,000 kg to over 426,000 kg at the Illinois River on Arkansas Highway 59 and that P transport is closely tied to hydrology (i.e., the amount of water delivered downstream); (ii) the relative contribution of P inputs from municipal facilities has decreased from 40% of the annual P load at the Illinois River on Arkansas Highway 59 to approximately 15% in recent years; (iii) elevated P concentrations during base flow conditions at the IRDA were traced 45 river km upstream to one municipal effluent discharge, but all effluent discharges influence P concentrations in the receiving streams within this basin; and (iv) flow-adjusted monthly P loads have been significantly decreasing over time at the Illinois River on Arkansas Highway 59, based on data from 2002 through 2008.

The concentrations and transport of P within the Illinois River are significantly decreasing from all the watershed management changes that have occurred, and it will be interesting to see if this decrease continues at the same rate over the next several years. The reduction in P runoff from agricultural lands after implementation of P-based nutrient management planning in IRDA, which reduced the rates and extent of poultry litter application to pastures, may be masked by decreased P

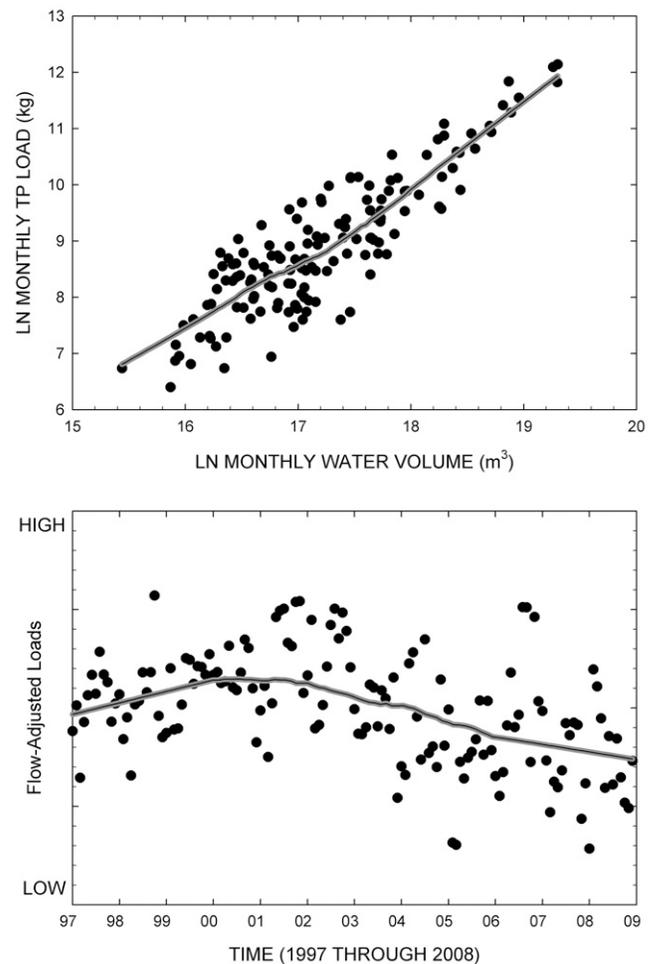


Fig. 4. Top: Locally weighted (LOESS) smoothing of monthly phosphorus loads and discharge at the Illinois River (Top). Bottom: flow-adjusted loads (i.e., the residuals from the LOESS smoothing technique) over time from 1997 through 2008. LN, natural logarithm.

inputs from municipal facilities. The volume of water transported in 2008 was the greatest over the period of this study, and this wet year might have transported legacy P stored within the fluvial channel further downstream, possibly increasing the P retention efficiency of the Illinois River relative to previous years.

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