Phosphorus Transport Pathways to Streams in Tile-Drained Agricultural Watersheds

L. E. Gentry,* M. B. David, T. V. Royer, C. A. Mitchell, and K. M. Starks

ABSTRACT

Agriculture is a major nonpoint source of phosphorus (P) in the Midwest, but how surface runoff and tile drainage interact to affect temporal concentrations and fluxes of both dissolved and particulate P remains unclear. Our objective was to determine the dominant form of P in streams (dissolved or particulate) and identify the mode of transport of this P from fields to streams in tile-drained agricultural watersheds. We measured dissolved reactive P (DRP) and total P (TP) concentrations and loads in stream and tile water in the upper reaches of three watersheds in east-central Illinois (Embarras River, Lake Fork of the Kaskaskia River, and Big Ditch of the Sangamon River). For all 16 water year by watershed combinations examined, annual flow-weighted mean TP concentrations were >0.1 mg L^{-1}, and seven water year by watershed combinations exceeded 0.2 mg L^{-1}. Concentrations of DRP and particulate P (PP) increased with stream discharge; however, particulate P was the dominant form during overland runoff events, which greatly affected annual TP loads. Concentrations of DRP and PP in tiles increased with discharge, indicating tiles were a source of P to streams. Across watersheds, the greatest DRP concentrations (as high as 1.25 mg L^{-1}) were associated with a precipitation event that followed widespread application of P fertilizer on frozen soils. Although eliminating this practice would reduce the potential for overland runoff of P, soil erosion and tile drainage would continue to be important transport pathways of P to streams in east-central Illinois.

PHOSPHORUS (P) concentrations in surface waters are considered elevated above background concentrations throughout much of the United States due to anthropogenic sources. During the past several decades, P inputs from point sources have been reduced through the NPDES permit system, required monitoring of wastewater discharges, and general regulatory action. In addition, P removal from soap and laundry detergents has reduced P inputs from waste water treatment plants (Litke, 1999). Although sewage effluent from metropolitan areas is still an important P source, the USEPA has identified agriculture as the major nonpoint source of P to surface waters, and the greatest impediment to achieving water quality goals stated in the Clean Water Act (Parry, 1998; USEPA, 1998).

In many areas of the Midwest, corn and soybean production relies on commercial fertilizer, rather than animal manure, to enhance soil fertility. In regions of the Midwest where livestock production has decreased over the past 50 yr, nonpoint source pollution of P remains a pervasive and difficult water quality problem. As agriculture has become the focal point for P contribution to surface waters, there has been a proliferation of monitoring research that has been summarized in several review papers (Carpenter et al., 1998; Sims et al., 1998; McDowell et al., 2001; Hart et al., 2004).

Numerous studies have documented the importance of overland runoff in dissolved and particulate P transport from agricultural fields to streams (Schuman et al., 1973; Kronvang, 1992; Sharpley et al., 1994; Svendsen et al., 1995; Sharpley et al., 1999). The transport of P can be reduced through various cultural and erosion management practices, such as regular soil testing, variable rate fertilizer application, form and timing of P fertilizer application, incorporation of P fertilizer, tillage practice, contour farming, grassed waterways, and riparian buffer strips (Daniels and Gilliam, 1996; Sharpley et al., 2000; Bundy et al., 2001; McDowell and Wilcock, 2004). In general, overland flow is the dominant P transport mechanism from agricultural fields to offsite locations (Sharpley et al., 1994); however, P transport in artificial drainage (subterranean pipes called tiles) is also an important transport pathway (Sims et al., 1998; Stamm et al., 1998; Xue et al., 1998; Dils and Heathwaite, 1999; Heathwaite and Dils, 2000; Chapman et al., 2001). Although P transport has been widely studied, there is a lack of long-term intensive data needed to provide a complete understanding of P transport from fields to streams (and resulting forms, concentrations, and loads) under a range of flow conditions (and controlling weather patterns) in heavily tile-drained agricultural watersheds.

Our overall objective was to determine the dominant P form (dissolved or particulate) and to identify the primary P transport pathways in tile-drained agricultural watersheds using intensive long-term data. Select stream and tile flow events were closely examined to investigate the source of P in ditches and streams. Due to the lack of animal production or significant municipal wastewater discharges, watersheds in east-central Illinois are well-suited for investigating the transport of P from agricultural sources to streams.

MATERIALS AND METHODS

Study Site Description

Sampling stations were established to investigate P concentrations and loads of three streams in east-central Illinois, USA: the Embarras River (EMC), Lake Fork of the Kaskaskia River (LFK), and Big Ditch of the Sangamon River (BDO).

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Published in J. Environ. Qual. 36:408–415 (2007).
Technical Reports: Surface Water Quality
doi:10.2134/jeq2006.0098

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Abbreviations: BDO, Big Ditch of the Sangamon River; DAP, diammonium phosphate; DRP, dissolved reactive phosphorus; EMC, Embarras River; LFK, Lake Fork of the Kaskaskia River; P, phosphorus; PP, particulate phosphorus; TP, total phosphorus.

Stream discharge was available at the U.S. Geological Survey (USGS, 2006) National Water Information System for EMC (USGS site no. 03343400) and LFK (USGS site no. 05590800). Stream discharge for BDO was available from the Illinois State Water Survey (station 106). Annual stream discharge is based on a water year (the period from October through September, designated by the calendar year in which it ends). We sampled eight additional locations in central Illinois that were used to investigate water quality before and during a rain-on-snow event in 2001. These sites included: Black Slough and the East Branch of the Embarras River upstream of EMC; an unnamed tributary upstream of BDO; and Big Creek, Long Creek, South Branch of Salt Creek, North Fork of Salt Creek, and the main stem of Salt Creek (Fig. 1).

Due to the relatively flat, low gradient landscape throughout east-central Illinois, most soils are poorly or very poorly drained Mollisols. The dominant topographic features are glacial moraines, which define watershed boundaries and provide recharge to streams. In the late 1800s, drainage districts were established, headwater channels were dredged, and artificial drainage was extensively installed throughout the area (David et al., 1997). Enhanced drainage created fertile, arable soils, and increased crop production continues today from improved drainage. However, agricultural drainage modifications have greatly altered the hydrologic cycle, and water is quickly moved from agricultural fields through tiles into channelized headwater drainage ditches and streams.

Land use in the three watersheds is predominantly row crop agriculture with nearly an equal amount of corn (*Zea mays* L.) and soybean (*Glycine max* L.) production during the study period (Table 1). Soils in this area consist of approximately 0.5 m of loess and contain 4 to 5% organic matter. Phosphorus deficiency in crops can occur without addition of fertilizers and it is recommended to maintain Bray-P1 values above 50 kg ha^{-1} in this region of Illinois (University of Illinois Extension Service, 2003). To accomplish this producers commonly apply P fertilizer as di-ammonium phosphate (DAP) every other year following harvest of fields planted to soybean.

Precipitation Estimates

Annual precipitation for each watershed (water year basis) was estimated by averaging available data from various weather stations operated by the National Climate Data Center–National Oceanic and Atmospheric Administration within or near each watershed (National Climate Data Center–National Oceanic and Atmospheric Administration, 2006). For the Embarras River watershed, precipitation was estimated using stations at Urbana, Sidell, and Tuscola. For the Lake Fork watershed, precipitation was estimated using stations at Tuscola, Hammond, and Cerro Gordo. Precipitation data for Cerro Gordo began in 1997. For the Big Ditch watershed, Rantoul was the only source of precipitation data for 1994–1998. Fisher began collecting data in 1999. Data was collected at Mahomet from January 2000 through April 2001.

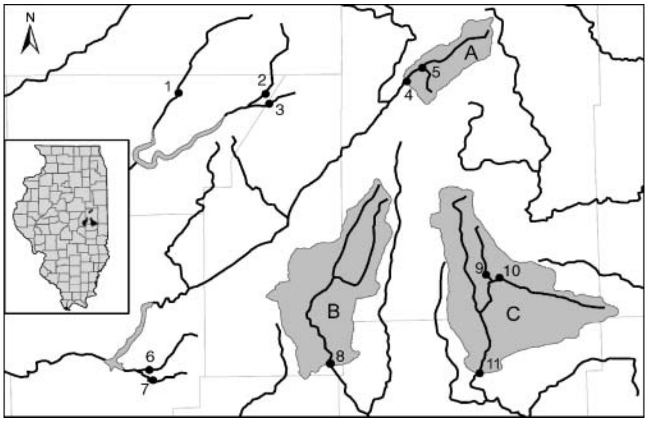

Fig. 1. Map of east-central Illinois indicating three agricultural watersheds and sampling sites used in the study. Watersheds include: (A) Big Ditch, (B) Lake Fork, and (C) Embarras River; and sites are (1) North Fork of Salt Creek, (2) main stem of Salt Creek, (3) South Branch of Salt Creek, (4) Big Ditch (BDO), (5) unnamed tributary of Big Ditch, (6) Long Creek, (7) Big Creek, (8) Lake Fork (LFK), (9) Black Slough, (10) East Branch of the Embarras River, and (11) Embarras River (EMC).

Water Sampling and Analysis

Water samples for nutrient analysis were collected weekly or more frequently during storm events by manual grab sampling into flowing water. To supplement grab samples at LFK and BDO, an automated water sampler (model 2900, Isco, Lincoln, NE) was used to collect discrete samples every 6 h during high flow events in the winter and spring. During the period of record for each site, we collected 515, 389, and 245 water samples at EMC, LFK, and BDO, respectively.

Four tiles (A, B, C, and D) in the Embarras River watershed were monitored during the 1995–1996 water years using a weir structure, pressure transducer, and an automated water sampler (Xue et al., 1998). Three tiles (1, 2, and 3) in the Big Ditch watershed were monitored during the 2001–2002 water years using a Sigma 900 MAX area velocity sampler (Hach Company, Loveland, CO). All tiles were sampled on a flow proportional basis with sampling intervals from 40 000 to 120 000 L depending on the maximum discharge of each tile.

All water samples were placed in a cooler in the field and were filtered and preserved on returning to the laboratory, generally within 4 h of collection. During the past 10 yr, our laboratory methods for sample preservation and P analysis have changed. Water samples analyzed for dissolved reactive phosphorus (DRP) and ammonium (NH_4–N) were filtered through Whatman GF/C glass fiber filters (pore size 1.2 μm) until March 1999, after which they were filtered through Fisherbrand cellulose acetate/cellulose nitrate filters (pore size 0.45 μm). Tests were conducted to compare effect of filter pore size and no significant differences in DRP or NH_4–N concentrations were detected.

Dissolved reactive P concentration was measured manually using the ascorbic acid reduction method with colorimetric analyses until November 2002 after which a Lachat QuikChem 8000 Flow Injection Analysis system (Hach Company, Loveland, CO) was used. Before November 2002, unfiltered aliquots for total P (TP) were preserved by freezing; after that time unfiltered aliquots were acidified with H_2SO_4 to pH < 2 and stored at 4°C. Unfiltered water samples were digested using ammonium persulfate and H_2SO_4 and then analyzed for TP as described earlier for each period (APHA, 1998). Particulate P (PP) was estimated as TP minus DRP. Ammonium concentration was measured using the automated phenate method on a Technicon segmented flow auto analyzer until November 2002. Thereafter, samples were analyzed for NH_4–N using an automated sodium salicylate method on the Lachat QuikChem 8000 system. We used a full QA/QC program, including external quality control samples, to ensure high quality data throughout the study.

Load Calculations and Data Analysis

Daily stream P loads were determined by multiplying mean daily discharge by nutrient concentration. Linear interpolation

Table 1. Abbreviations, coordinates, and watershed descriptors for each stream used in the study. Watersheds are located in east-central Illinois, USA.

Watershed	Site	Coordinates	Watershed area	Row-crop agriculture	Period of record
			km^2	% land cover	water years
Embarras River	**EMC**	**39°47′29″ N; 88°11′08″ W**	**481**	**91**	**1994–2003**
Lake Fork	**LFK**	**39°50′09″ N; 88°29′18″ W**	**365**	**91**	**1998–2003**
Big Ditch	**BDO**	**40°16′06″ N; 88°19′35″ W**	**101**	**86**	**2001–2003**

in SAS was used to estimate P concentrations between sampling dates (SAS Institute, 1990). Annual P loads were determined by summing the daily loads for each watershed for each water year during the period of record. Tile P loads were estimated by multiplying discharge by the P concentration, assuming the concentration was constant from a time halfway between the previous sample and the present sample to a time halfway between the present sample and the subsequent sample (Gentry et al., 2000).

Cumulative error in the measurement of stream and tile discharge, sample handling, and sample analysis contribute to overall uncertainty in load estimates (Harmel et al., 2006). Given the quality of the discharge data, our intensive sampling regime and focused sampling during periods of changing discharge, and our QA/QC program, we believe the uncertainty in our load estimates to be <10% based on the analysis of Harmel et al. (2006).

RESULTS AND DISCUSSION

Precipitation and Discharge

Average annual precipitation for the 1994–2003 water years was 97, 96, and 92 cm for the Embarras River, Lake Fork, and Big Ditch watersheds, respectively (Table 2). Based on (±) 5 cm from the average annual precipitation, water years 1994, 1996, 1998, and 2002 had above average precipitation and 2000, 2001, and 2003 were below average. The interaction of precipitation, infiltration, runoff, and evapotranspiration (ET) created a seasonal pattern of low discharge during the summer and fall and multiple high flow events during the winter and spring months (Fig. 2, 3, and 4). Annual discharge ranged from 52 to 290, 31 to 187, and 8 to 38 million m^3 at EMC, LFK, and BDO, respectively, during the 10-yr period (Table 2). Average annual discharge represented 33, 31, and 28% of the annual precipitation at EMC, LFK, and BDO.

Table 2. Total precipitation and discharge for three tile-drained agricultural watersheds in central Illinois for water years 1994–2003. See text for description of precipitation estimates.

	Precipitation			Discharge		
Water year	Embarras River	Lake Fork	Big Ditch	Embarras River	Lake Fork	Big Ditch
	cm			10^6 m^3		
1994	**101**	**103**	**93**	**235**	**177**	**38**
1995	**94**	**92**	**96**	**125**	**118**	**29**
1996	**107**	**111**	**82**	**186**	**122**	**31**
1997	**95**	**96**	**97**	**137**	**80**	**35**
1998	**111**	**107**	**114**	**228**	**179**	**36**
1999	**95**	**88**	**85**	**132**	**96**	**19**
2000	**81**	**84**	**77**	**52**	**46**	**8**
2001	**80**	**86**	**78**	**92**	**100**	**19**
2002	**119**	**115**	**105**	**290**	**187**	**34**
2003	**87**	**80**	**99**	**53**	**31**	**16**
Average	**97**	**96**	**92**	**153**	**114**	**26**

Dissolved Reactive Phosphorus and Total Phosphorus Stream Loads

The range of annual TP loads was wider than the range of annual stream discharges at EMC and LFK suggesting wet years exported disproportionately more P than dry years. Annual TP loads ranged from 7.6 to 102.5 and 3.5 to 38.8 Mg at EMC and LFK, respectively (Table 3). For both streams, DRP loads were approximately 50 to 73% of the TP loads except during the 2002 water year when DRP loads were 35% of the TP loads. At BDO, annual DRP and TP loads ranged from 1.4 to 4.1 Mg and 3.1 to 7.7 Mg, respectively, and DRP loads were 41 to 61% of the TP loads. The annual DRP/TP load ratios for the three streams were similar to other streams in agriculturally dominated watersheds of the Corn Belt (Goolsby et al., 1999).

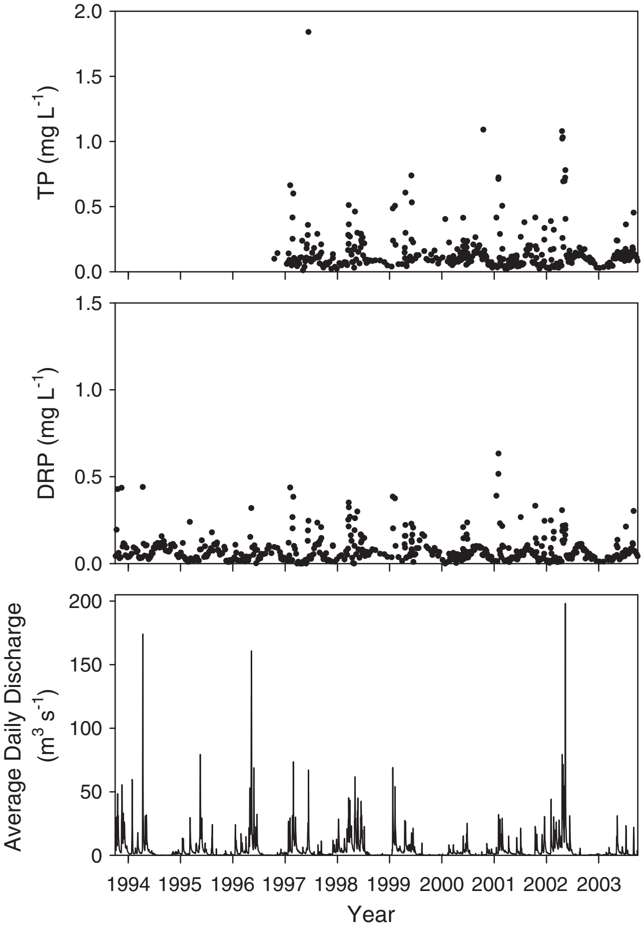

Fig. 2. Stream hydrograph and P concentrations for Embarras River site (EMC) during the 1994 through 2003 water years. TP, total phosphorus; DRP, dissolved reactive phosphorus.

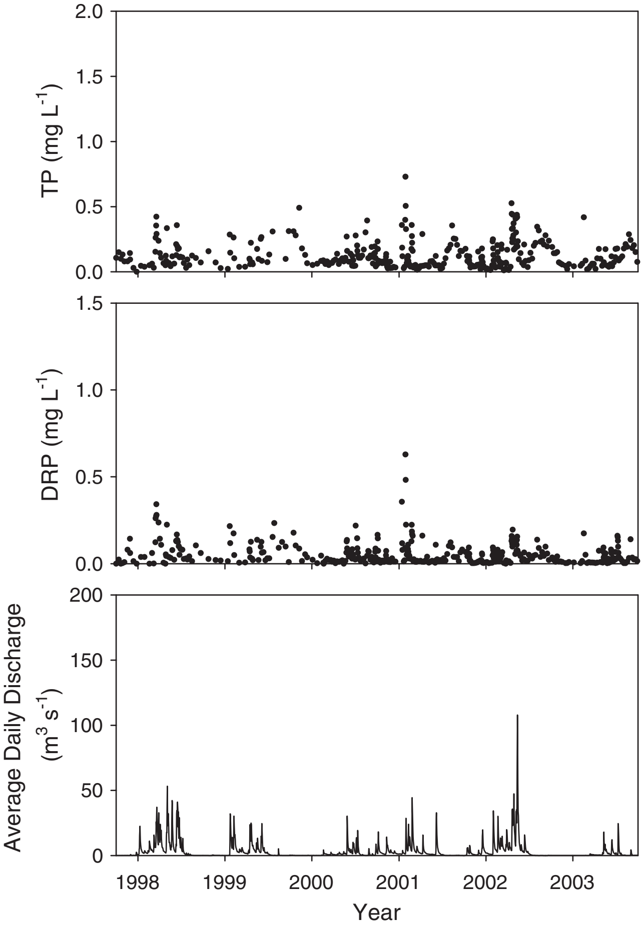

Fig. 3. Stream hydrograph and P concentrations for Lake Fork site (LFK) during the 1998 through 2003 water years. TP, total phosphorus; DRP, dissolved reactive phosphorus.

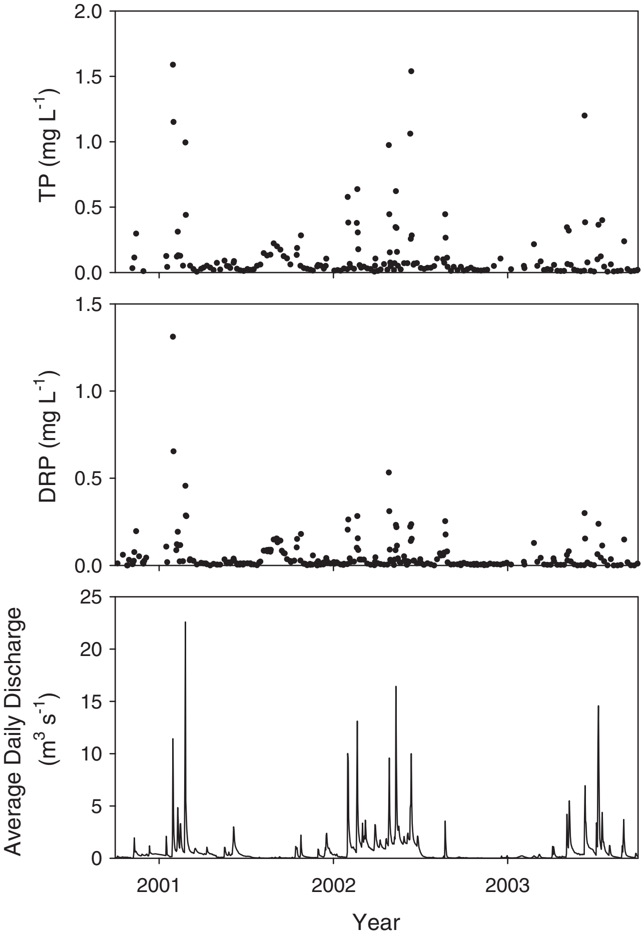

Fig. 4. Stream hydrograph and P concentrations for Big Ditch site (BDO) during the 2001 through 2003 water years. TP, total phosphorus; DRP, dissolved reactive phosphorus.

On an areal basis, average annual stream export of TP was 0.75, 0.46, and 0.58 kg ha^{-1} at EMC, LFK, and BDO, respectively. However, there was great variability from year to year and during years with the least discharge, TP yield was only 0.09 to 0.16 kg ha^{-1}. In contrast, the year with the greatest discharge during the 10-yr period had TP yields of 2.12 and 1.01 kg ha^{-1} at EMC and LFK, respectively. Although these values represent a large loss of terrestrial P from these watersheds, they are similar to other intensively farmed areas of the Midwest. For example, Baker and Richards (2002) showed that TP yields were often >1.5 kg ha^{-1} yr^{-1} in two agriculturally dominated watersheds in northwestern Ohio. Overall, our findings are similar to those of Goolsby et al. (1999), who estimated TP export of 0.42 kg ha^{-1} yr^{-1} from the entire Mississippi River Basin and concluded that TP export was greatest from interior watersheds consisting of either dense human population or intensive row crop agriculture.

Dissolved Reactive Phosphorus and Total Phosphorus Stream Concentrations

Annual flow-weighted mean DRP and TP concentrations showed less year-to-year variability compared with annual P loads, but generally corresponded with annual precipitation (Tables 2 and 3). For example, the smallest annual flow-weighted mean DRP and TP concentrations for each watershed occurred during the year with the smallest P loads (EMC in 2000; LFK and BDO in 2003). In contrast, years with above average annual precipitation did not always produce flow-weighted mean concentrations greater than those occurring in years with average precipitation. Furthermore, for the two wettest years (1998 and 2002) LFK had similar water yields but quite different flow-weighted mean concentrations. The difference in discharge patterns between these 2 yr greatly affected loads and flow-weighted mean P concentrations at EMC and LFK (Fig. 2 and 3).

Similar to other studies, we found DRP and TP concentrations in streams were elevated (>0.2 mg L^{-1}) during storm events and reduced (<0.05 mg L^{-1}) during base flow in the summer and fall (Schuman et al., 1973; Sharpley et al., 1993; Sharpley et al., 1999; Borah et al., 2003). Total P concentrations occasionally exceeded 0.5 mg L^{-1} during storm events at each site (Fig. 2, 3, and 4). McDowell and Wilcock (2004) showed that TP concentrations >0.2 mg L^{-1} were associated with intense rainfall events that could result in higher flows with increased sediment transport capacity. For example in the spring of 2002, approximately 10 cm of rain fell on

Table 3. Annual phosphorus loads and flow-weighted mean concentrations for three tile-drained agricultural watersheds in central Illinois.

Water year	P Load		Flow-weighted concentration	
	DRP†	TP	DRP	TP
	Mg		mg L^{-1}	
Embarras River				
1994	43.4	–	0.173	–
1995	10.7	–	0.091	–
1996	24.2	–	0.140	–
1997	21.4	39.5	0.145	0.289
1998	30.7	45.6	0.142	0.200
1999	20.5	30.2	0.156	0.230
2000	4.3	7.6	0.084	0.147
2001	12.1	16.5	0.132	0.180
2002	35.4	102.5	0.122	0.356
2003	5.1	9.4	0.096	0.179
Lake Fork				
1998	21.3	29.2	0.119	0.164
1999	8.7	14.3	0.090	0.150
2000	3.4	6.4	0.073	0.139
2001	9.6	13.7	0.096	0.137
2002	13.7	38.8	0.073	0.208
2003	1.8	3.5	0.058	0.111
Big Ditch				
2001	4.1	6.7	0.231	0.378
2002	3.2	7.7	0.094	0.225
2003	1.4	3.1	0.087	0.190

† DRP, dissolved reactive phosphorus; TP, total phosphorus.

saturated soils in the Embarras River and Lake Fork watersheds and produced the largest discharge events during the 10-yr period at EMC and LFK (Fig. 2 and 3). During this event, PP concentrations at EMC and LFK were two to five times greater than DRP concentrations which resulted in annual flow-weighted TP concentrations that were threefold greater than the annual flow-weighted DRP concentrations (Table 3). Although large discharge events exacerbate bank erosion and potentially entrain benthic sediments, the 2002 event at EMC and LFK likely transported large amounts of eroded soil from fields to streams. Other studies have shown a similar pattern in PP and attributed it to overland runoff with a heavy silt load (House and Warwick, 1998; Bowes et al., 2005). In general, extreme discharge events that originate from overland runoff appear to play a disproportionately large role in P export, particularly in the Corn Belt region of the Midwest (Borah et al., 2003; Royer et al., 2006).

Water years without extreme discharge events had annual flow-weighted mean DRP concentrations that were 50 to 73% of the corresponding TP concentrations. More evenly distributed precipitation such as during 1998 created numerous moderate flow events with similar DRP and PP concentrations at peak discharge. When precipitation rates did not exceed infiltration rates and surface runoff was minimal, DRP concentrations were greater than PP concentrations at peak discharge. Therefore, in dry years without overland runoff (e.g., 2000 and 2003) tile drainage was assumed to be the dominant transport pathway of P to ditches and streams (both DRP and TP). Although entrainment of benthic sediments and bank erosion may have contributed to P loads in all years, we believe these mechanisms to be relatively minor compared with tile drainage during dry years.

Watershed Comparisons

Annual flow-weighted mean DRP and TP concentrations were less at LFK than at EMC or BDO (Table 3). All three watersheds are dominated by conventional row crop agriculture, suggesting the differences in flow-weighted mean P concentrations were likely due to other watershed or stream channel characteristics. Although all three streams are highly modified to enhance drainage, Lake Fork appears to be entirely channelized. Dredge spoils along channelized streams in central Illinois often create a barrier to direct inputs of overland runoff, except during extreme events. With its extensively channelized stream network, Lake Fork watershed may generate less overland runoff, soil erosion, and river sediment load. This hypothesis is supported by the observation that high flows resulted in elevated concentrations of PP at EMC and BDO, but to a lesser extent at LFK (Fig. 5).

Unique at EMC was an annual pattern of elevated P during the late summer and fall months (Fig. 2). Approximately 10 km above the monitoring station at EMC is the wastewater treatment plant for Villa Grove, Illinois (population of 2500). We assume that as stream flow declined throughout the summer the sewage effluent represented a greater percentage of river flow and resulted in increased P concentrations. Effluent monitoring by the treatment plant indicates that 0.21 to

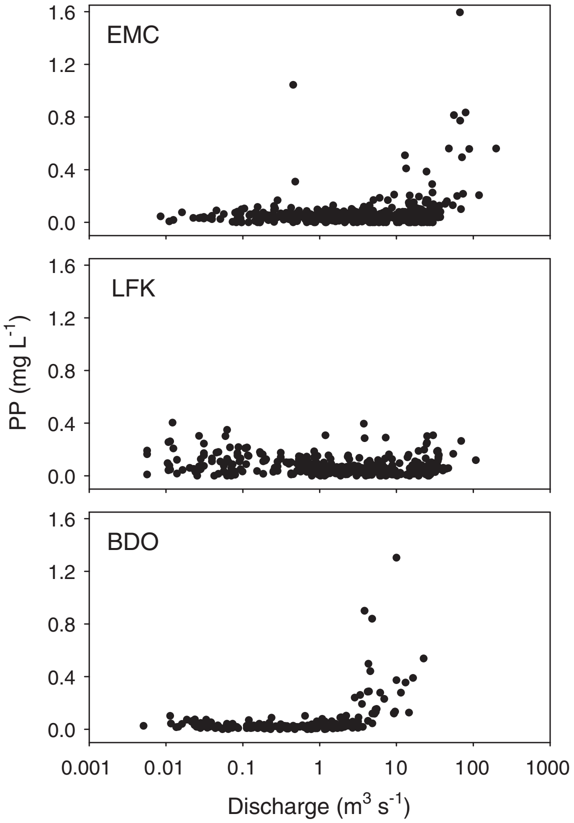

Fig. 5. Relationship between discharge and particulate phosphorus (PP) concentrations for three streams in central Illinois. See text for the period of record for each site. EMC, Embarras River site; LFK, Lake Fork site; BDO, Big Ditch site.

0.75 Mg yr^{-1} (average of 0.45 Mg yr^{-1} for the period of record) of soluble reactive P was contributed by sewage to the P load at EMC. Although these loads do not add greatly to the annual P load at EMC, the input from the wastewater treatment plant impacts water quality during low discharge periods in the summer and fall.

Phosphorus in Tile Drainage

Agricultural tile drainage water has been shown to transport elevated DRP concentrations, and Xue et al. (1998) reported annual flow-weighted mean DRP concentrations of 0.08 to 0.20 mg L^{-1} for four agricultural drainage tiles in the Embarras River watershed. As in ditch and stream water, DRP concentrations in tile water increased with discharge. However, contrary to leaching patterns of nitrate or herbicides during a first flush following application (Gentry et al., 2000), DRP continues to be present at elevated concentrations in successive tile flow events (Fig. 6). As shown by Gächter et al. (2004), these data suggest that there was an available pool of soil P that readily desorbed during preferential flow of solutes through the soil and into tiles.

Tiles monitored in the Big Ditch watershed were analyzed for DRP and TP, and PP was found to be important during high flow events; however, PP concentrations decreased more quickly than DRP concentrations following peak discharge (Fig. 7). Based on Beauchemin et al. (1998), we speculate that PP in tiles was likely associated with the transport of fine clay particles during periods of preferential flow. Flow-weighted DRP and PP concentrations in tiles near BDO were greater during the wetter year of 2002 than for 2001, and areal losses of TP through the tiles were 1.4 to 3.3 times greater in 2002 than in 2001 (Table 4). During 2001 and 2002 the watershed loss of TP at BDO was 0.66 and 0.76 kg ha^{-1}, respectively, and the corresponding loss of P via the monitored tiles averaged 0.30 and 0.69 kg ha^{-1}. The smaller relative contribution from tiles in 2001 reflects the extent to which P losses in these watersheds can be influenced by the timing and magnitude of precipitation events, as we describe below.

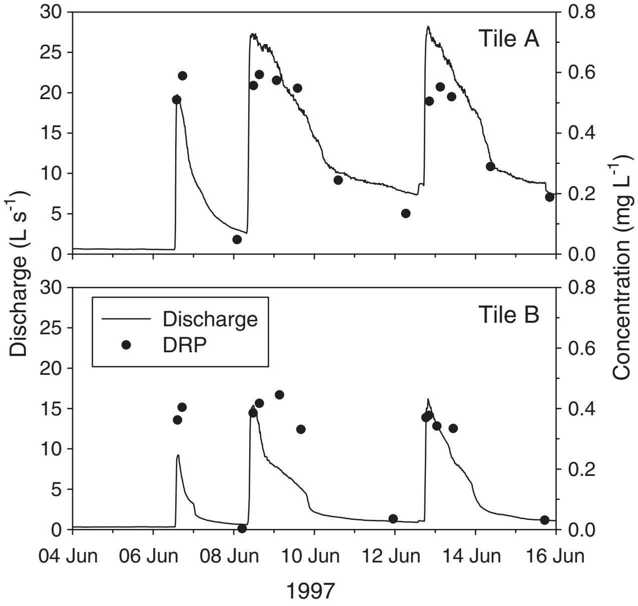

Fig. 6. Discharge and dissolved reactive phosphorus (DRP) concentrations from two agricultural tile drains in the Embarras River watershed showing three successive rain events during June 1997.

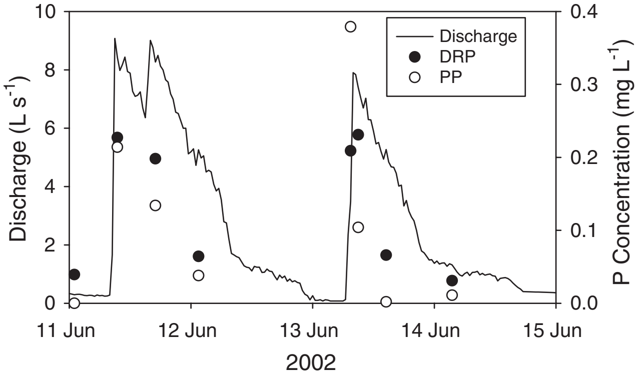

Fig. 7. Discharge, particulate phosphorus (PP), and dissolved reactive phosphorus (DRP) concentration from an agricultural tile drain in the Big Ditch watershed showing two successive rain events during June 2002.

Winter Snowmelt Event

The greatest DRP concentration (0.63 mg L^{-1}) during the 10-yr period at EMC occurred during a period of moderate discharge following a period of snowmelt combined with 2.3 cm of rainfall on 30 Jan. 2001 (Fig. 2). This date also produced the greatest DRP concentrations during the period of record at both LFK and BDO with values of 0.75 and 1.25 mg L^{-1}, respectively (Fig. 3 and 4). Although tile discharge increased moderately during this event, DRP concentrations in tile water were not elevated. Soils during this event were partially frozen and stream discharge was largely due to surface runoff; however, stream PP concentration was less than DRP suggesting the event did not cause severe soil erosion.

Concomitant with elevated stream P concentrations, NH_4–N concentrations on that day were also the greatest observed for each watershed during the period of record (data not shown). As part of a larger water

Table 4. Flow-weighted mean concentrations and leaching losses of dissolved reactive phosphorus (DRP) and total phosphorus (TP) for three tiles located in the Big Ditch watershed.

			Flow-weighted concentration		Leaching losses	
Tile	Area	Discharge	DRP	TP	DRP	TP
	ha	m^3	—mg L^{-1}—		—kg ha^{-1}—	
2001						
1	2.5	4536	0.078	0.212	0.14	0.38
2	20.3	39 508	0.027	0.068	0.05	0.13
3	2.7	5000	0.188	0.218	0.35	0.40
2002						
1	2.5	8446	0.101	0.160	0.34	0.54
2	20.3	62 222	0.038	0.076	0.12	0.23
3	2.7	8715	0.314	0.406	1.01	1.31

quality study, we sampled 11 stream locations in the Embarras, Kaskaskia, and Sangamon River watersheds (including EMC, LFK, and BDO) on 30 Jan. 2001 (Fig. 1). There was a significant increase in DRP (Mann–Whitney Test, W = 66.0, $p < 0.001$) and NH_4–N (W = 67.0, $p < 0.001$) in streams throughout east-central Illinois (Fig. 8). The highest concentrations observed occurred in the smallest watershed (the unnamed tributary in the Big Ditch watershed) measuring 5.0 mg L^{-1} of DRP and 9.1 mg L^{-1} of NH_4–N.

Climatic conditions preceding 30 Jan. 2001 may have influenced how P fertilizer was applied that winter. Phosphorus fertilizer is commonly surface-applied in the form of DAP following soybean harvest. December of 2000 was the second coldest December on record and temperatures were below freezing for nearly 3 wk (Illinois State Climatologist Data, 2006). In addition, there was snow cover from 11 Dec. 2000 to 30 Jan. 2001. To avoid soil compaction, a common practice is to broadcast DAP fertilizer on frozen soils. Based on DRP and NH_4–N concentrations found in surface waters throughout east-central Illinois on 30 Jan. 2001, we believe unincorporated DAP fertilizer was transported over frozen soils via the combination of snowmelt and precipitation.

Following this rain-on-snow event, there was a substantial P load (80% in the form of DRP) exported from the three watersheds (4.6, 3.8, and 1.7 Mg at EMC, LFK, and BDO, respectively) in a 7-d period, which represented approximately 40% of the annual TP load for each stream. This single event increased the annual flow-weighted mean DRP and TP concentrations for all three streams during the 2001 water year. These data likely document a worst-case scenario for DRP transport from fields to streams and highlight how agricultural practices, climate, and precipitation interact to influence stream nutrient concentrations.

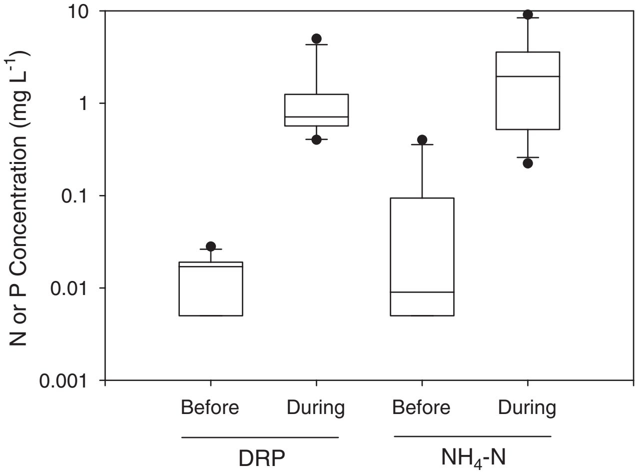

Fig. 8. Box-and-whisker plots of dissolved reactive phosphorus (DRP) and NH_4–N concentrations ($\log_{10}$) from 11 streams throughout central Illinois before and during a rain-on-snow event that occurred 30 Jan. 2001. Horizontal lines in the box indicate the 25th, 50th, and 75th percentiles; the 10th and 90th percentiles are indicated by the whiskers and solid circles indicate concentrations outside of the 10th and 90th percentiles.

CONCLUSIONS

Extreme discharge events accounted for the majority of annual stream TP load as both DRP and PP concentrations increased with stream discharge, especially during high sediment loads in these tile-drained watersheds. Although there were several years with less than average precipitation, flow-weighted mean concentrations of TP in surface waters of central Illinois exceeded 0.1 mg L^{-1} in all 16 watershed by water year combinations. Total P loads were greatly increased by overland runoff and extreme discharge in some years; however, tile drainage was likely an important contributor of DRP every year, beginning in late fall or early winter and ending in early summer. Overall, these data further our understanding of P transport pathways from agricultural fields to surface waters and underscore the difficult challenges facing the agricultural sector in reducing nonpoint source pollution of P to streams in extensively tile-drained watersheds. In addition, we observed conditions that created a worse case scenario for widespread P transport from agricultural fields to streams. The practice of applying P fertilizer on frozen soils or on top of snow can result in large inputs of P to surface waters when rain-on-snow events generate overland runoff which transports unincorporated P fertilizer to streams.

ACKNOWLEDGMENTS

Funding was provided by the state of Illinois through the Council on Food and Agricultural Research (C-FAR) Water Quality SRI. We thank L. Keefer and E. Bauer for Big Ditch data, and S. Duke and R. McKeehan for Villa Grove sewage effluent data. We thank C. Davidson and J. Benson for field sampling, and S. Sippel for the site map.

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