

Sediment phosphorus dynamics in tile-fed drainage ditches

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Abstract Stream sediments may regulate aqueous phase phosphorus (P) concentrations. The objectives of this work were to study the equilibrium P concentrations between the aqueous phase and sediments in tile-fed drainage ditches. Sediments from three ditches in Indiana, USA, were sampled and evaluated as P sources or sinks. Sediments that potentially release P to aqueous solutions could be chemically amended to sequester labile P. Sediment deposition from episodic storm events could increase the P buffering capacity of drainage ditches. In fluvium studies (initial concentration of 0.55 mM P), aqueous P concentrations after 120 h were 0.075 mM and 0.111 mM for pre-dredged and dredged sediments, respectively. Phosphorus release from sediments to the aqueous solution was greater from the dredged sediments. These studies are expanding our understanding of the dynamic nature of P in agricultural ditches, and aiding in the development of ditch management practices to reduce downstream P transport.

Key words artificial drainage networks; phosphorus; sediment dredging; water quality

INTRODUCTION

Agricultural lands have contributed to nutrient loss from the landscape and subsequent water quality problems, such as eutrophication and hypoxia (Schindler, 1977; Daniel *et al.*, 1998; Rabalais *et al.*, 2002). Responsible land management remains crucial to reducing the nutrient transport from agricultural lands. However, despite tremendous efforts, nutrients continue to be transported to surface waters in sufficient quantities to induce or prolong water quality problems.

Phosphorus has been a primary concern in many fresh water systems, and recent research has evaluated P transport and fate in streams and rivers (Froelich, 1988; Klotz *et al.*, 1988; Haggard *et al.*, 1999; 2004; McDowell & Sharpley, 2003); however, most of this work has been conducted in natural streams. Much of the Midwestern United States has been artificially drained, using sub-surface tile drains that convey water into man-made, managed drainage ditches, that eventually feed natural streams or rivers. Little information has been gathered about the transport and fate of P in these managed ditch ecosystems. The objectives of these studies were to evaluate the ability of ditch sediments to buffer P transport in these artificial drainage networks, and to determine how physical or chemical treatment of ditch sediments affects aqueous phase P concentration and transport.

MATERIALS AND METHODS

Three ditches (A, B and C) near Waterloo, Indiana, USA, have been monitored for discharge continuously since 2002, from which samples have been collected daily for water quality analysis. Sediment samples have been collected from multiple sites at these ditches, and these sites drain catchment areas from 300 to 4650 ha (Table 1; Fig. 1). Hydrological characteristics of the three watersheds, as measured by cumulative runoff for the larger (1420–2180 ha) watersheds, has been shown to be similar. Row crop agriculture dominates the land use of all the watersheds, representing greater than 73% of the catchment area of all seven sediment sampling sites at the three ditches.

A study was conducted to determine the impacts of sediment resuspension and deposition on aqueous P concentrations and transport in ditches. Sediment samples from all seven sites were collected in June and July 2003. Between the sediment collection periods, a series of storm events occurred that produced flooding in the surrounding area. Phosphorus sorption isotherms on sediment samples were used to calculate the equilibrium phosphorus concentration (EPC_o), or the point at which there was neither net adsorption nor desorption of P by the sediments from the aqueous phase. Ditch sediments were also treated with aluminium sulphate (alum) and calcium carbonate, and the P sorption isotherm experiments repeated.

Another study was conducted to determine the impact of ditch dredging (mechanical removal of sediments) on aqueous P concentrations and transport in these systems. Ditch B was dredged December 2004, and sediments were collected in bulk from ditch B, at the site where dredging was actively occurring, by removing sediment before dredging, and sediments exposed after dredging. Pre-dredged and dredged sediments were placed 2 cm deep in a fluvium (0.2 × 8.0 m), similar to the one described by McDowell & Sharpley (2003). Water was adjusted to 2.5 mM $CaCl_2$ and 0.55 mM KH_2PO_4 , and then pumped to flow over the sediments in the fluvium for 120 hours. After water samples were collected, water was removed from the system, and the fluvium was replaced with water that was adjusted with 2.5 mM $CaCl_2$ and 0.0 mM P. Again, water samples were collected periodically and analysed for dissolved P. Aqueous P concentrations from the adsorption experiment were fit to a logarithmic decay function using the formula:

Table 1 Water-column P concentrations for water samples collected in June and July 2003, and Exchangeable P (ExP) and Equilibrium P Concentration (EPC_o) of sediment samples collected in June and July, 2003, and aluminium sulphate treated samples (Alum) collected June 2003 from seven locations in three watersheds.

Watershed	Location	Catchment area (ha)	June	July	June	Alum	July	June	Alum	July
			water-column P (mg L ⁻¹)	water-column P (mg L ⁻¹)	ExP (mg L ⁻¹)	ExP (mg L ⁻¹)	ExP (mg L ⁻¹)	EPC_o (mg L ⁻¹)	EPC_o (mg L ⁻¹)	EPC_o (mg L ⁻¹)
A	Small	338	0.02	0.06	4.79	2.50	1.01	0.078	0.017	0.033
	Large	2180	0.03	0.07	1.01	0.43	0.49	0.055	0.008	0.020
	X-Large	4650	0.05	0.06	1.57	0.17	0.70	0.067	-0.002	0.107
B	Small	311	0.08	0.12	9.35	1.73	1.32	0.050	-0.023	0.080
	Large	1420	0.06	0.08	0.49	0.59	0.63	-0.020	-0.001	0.023
C	Small	374	0.06	0.06	1.72	1.08	0.61	0.051	0.004	0.035
	Large	1340	0.09	0.06	1.79	0.72	0.60	0.110	-0.011	0.068

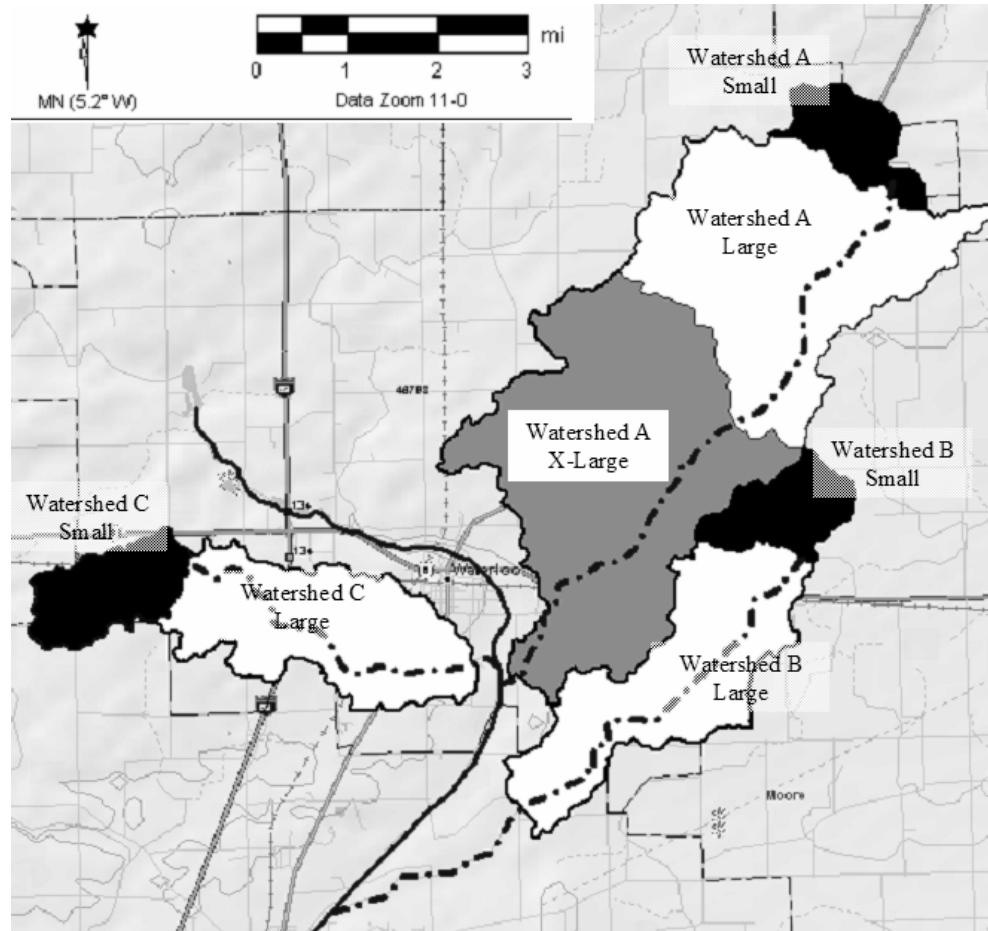


Fig. 1 Map showing the three ditches (A, B and C), and the watershed boundaries for each of the watersheds (small, large and X-large).

$$C = C_{\infty} + \alpha e^{-\beta t} \quad (1)$$

where C_{∞} is the concentration at $t = \infty$; and α and β are constants. Aqueous P concentrations from the desorption phase of the experiment were fit to an exponential increase to a maximum function, using the formula:

$$C = C_0 + \alpha(1 - e^{-\beta t}) \quad (2)$$

where C_0 is the initial concentration at $t = 0$.

Results from these studies were statistically analysed using the general linear model or regression procedures in SAS v 8.0, with an *a priori* level of significance ($\alpha = 0.05$).

RESULTS AND DISCUSSION

Sediment dynamics before and after high discharge

Discharge in the ditches increased with increasing watershed size, resulting in the presence of larger particles distributions in the large watersheds than the small

watersheds in all three ditches. Sand (0.02–2 mm) accounted for approximately 18% of ditch sediments in the small watersheds, and 84% of ditch sediments in the large watersheds. Similarly, organic matter content was greater in the small watersheds (8.8%) than the large watersheds (2.0%), due to increased velocity of the water at the large sites. The ditch sediments at the small watershed sites, therefore, have much greater surface area compared to the sediments at the large sites, an important factor for adsorption of contaminants, particularly P. Thus, the greater surface area from the silt and clay size particles, as well as the organic matter have a greater capacity to remove P from aqueous solutions, when sorption sites are not saturated with P. Interestingly, ditch sediment organic matter from these watershed sites was strongly correlated to the P buffering capacity of ditch sediments (Smith *et al.*, 2005). Several studies have shown biotic processes are important in P sorption by stream sediments (Haggard *et al.*, 1999; Khoshmanesh *et al.*, 1999).

Water-column P concentrations in June 2003 increased by 0.03 mg L⁻¹ in ditches A and C (Table 1). Water-column P concentrations decreased by 0.02 mg L⁻¹ as it moved from the small to large sites at ditch B in June 2003, and decreased by 0.04 mg L⁻¹ in July 2003. There were no changes in P concentrations in the water-column between sites in ditches A and C in July 2003.

Readily exchangeable P (ExP) concentrations were generally 2 to 20 times greater in the small watersheds than the large watersheds, probably related to particle size distribution in the ditch sediments (Table 1). Treatment of sediments with aluminium sulphate reduced sediment ExP, likely as a result of precipitation as amorphous aluminium oxides and subsequent P adsorption to these aluminum oxides. When comparing sediment ExP before and after the high flow event in July 2003, ditch sediments collected following the high flow event contained less ExP than ditch sediments collected in June 2003 (Table 1). These data indicate either the removal of P enriched sediments, the deposition of “fresh” sediments with less ExP, or a combination of both these mechanisms between June and July 2003.

Sediment EPC₀ concentrations ranged from -0.02 to 0.11 mg L⁻¹ in sediments collected June 2003 (Table 1). The greatest increase in sediment EPC₀ values between sites on a ditch occurred on ditch C, in which an increase of 0.05 mg L⁻¹ was observed between sediments from the small and large sites. Drainage and surface runoff water from the only confined animal feeding operation (CAFO) in these watersheds is located between the small and large sites on ditch C. If a CAFO is considered a point source, then the results from ditch C concur with other research that suggests that prolonged exposure of sediments to high water-column P concentrations from point sources will result in an increase in sediment EPC₀ (Haggard *et al.*, 2004). Alum treatment reduced sediment EPC₀ values at most sites in June 2003, indicating that chemical treatments could be a potentially important tool to enhance the ability of sediments to remove P from the ditch waters and reduce P transport. Sediment EPC₀ values were less in July 2003 than June 2003 at sites on ditches A and C. However, sediment EPC₀ values increased during this period at ditch B. Unlike the sediments taken prior to sediment disturbance, alum treatment of the samples collected in July 2003 did not consistently reduce EPC₀ values. As with the readily ExP for these sediments, it would appear that the alum treatment did not increase P buffering capacity of the ditch sediments after the high flow event. This may be further evidence

that the high flow event deposited “fresh” sediments with increased P sorption capacities.

Soluble P in the ditch water was plotted against sediment EPC_0 (Fig. 2), where data on or near the 1:1 line indicate that aqueous P concentrations are in equilibrium with ditch sediments. Sediments may release P to the water-column when samples are below the 1:1 line, and sediments may remove P from the water-column if they are plotted above the 1:1 line. Four of the seven sediment samples collected in June 2003 were observed to have greater EPC_0 values than P in the water-column. This was observed at all three sites from ditch A, and the large site from ditch C. Following the addition of alum to these sediments, all sites were observed to be above the line, as the points on the graph shifted to the left (Fig. 2). Should this relationship hold true, when chemical treatment occurred *in situ*, these sites would start removing P from the water-column, thereby reducing the downstream delivery of P. Only the X-large site from ditch A and the large site from ditch C were observed to be sources of P from the water-column for the samples collected in July 2003. These two sites contained the least organic matter content in the June 2003 sediment sampling, and displayed the least P buffering capacity in both the June and July 2003 sampling.

Dredging effects on phosphorus dynamics

Chemical parameters of sediments collected before and after dredging are presented in Table 2. Pre-dredged sediments contained greater P, Al, and Fe than sediments

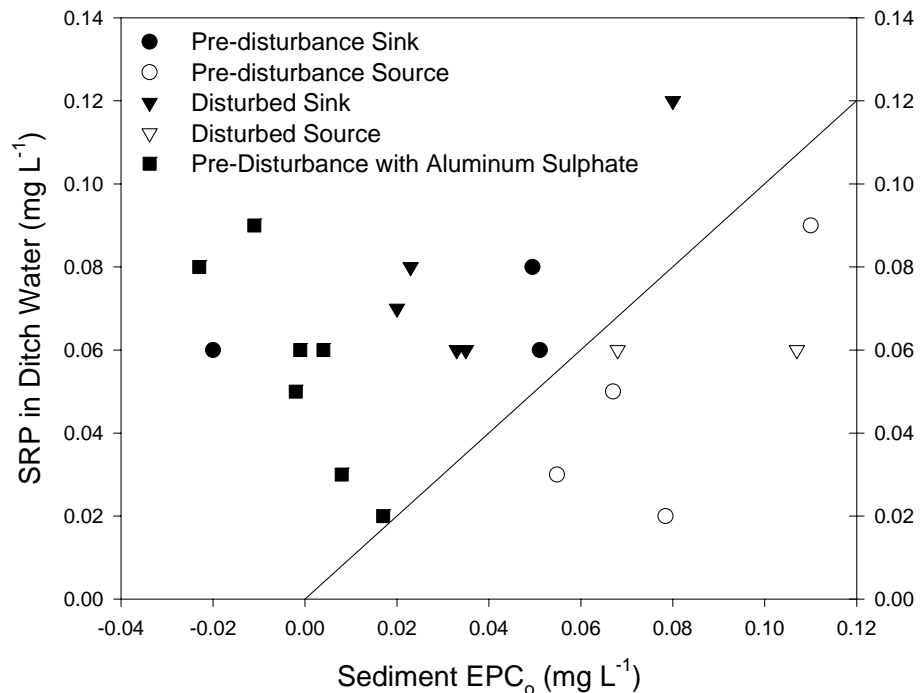


Fig. 2 Relationship between soluble P in ditch water and sediment equilibrium P concentration (EPC_0). The line represents a 1:1 line. Sediments that are above the line will act as a sink for P in the water-column, and sediments will release P to the water-column when they lie below the line.

Table 2 Chemical parameters of sediments used for stream simulations of P kinetics, and kinetic parameters from P adsorption and desorption experiments. Phosphorus sorption ratio (PSR) is calculated from the molar ratio of Mehlich 3 P to Mehlich 3 Al and Fe.

Treatment	P (mg kg ⁻¹)	Al	Fe	PSR	EPC ₀ (mM)	C _∞	C ₀	α	β	r ²	Final P (mM)	dC/dt at t = 0 (μM h ⁻¹)
Adsorption												
Pre-Dredged	121	313	2180	0.077	-0.0090	0.0870	0.55	0.435	0.0371	0.99	0.075	-14.3
Dredged	82	90	1190	0.119	0.0261	0.0946	0.55	0.392	0.0240	0.85	0.111	-8.8
Desorption												
Pre-dredged	151	475	2310	0.081	-0.0071	0.0067	0.0033	0.0034	0.0609	0.27	0.006	+0.205
Dredged	118	125	1260	0.150	0.0048	0.0097	0.0058	0.0039	0.125	0.44	0.010	+0.488

collected after dredging. The dredged sediments also had a coarser texture, and less organic matter than the pre-dredged sediments. Furthermore, redoxomorphic features (e.g. gleyed and mottled surfaces) were observed during sediment collection where sediments had already been dredged. This would suggest a reduced environment. Ferric phosphates are known to be less soluble than ferrous phosphates, so exposure of reduced conditions would be detrimental to P sequestration by the sediments.

The phosphorus sorption ratio (PSR; Maguire & Sims, 2002) of the sediments was less in the pre-dredged sediments (Table 2), suggesting that these sediments would be able to sorb more P from the aqueous phase, since fewer of the theoretical sites available for P sorption from aluminum and iron oxides and hydroxides would be occupied with P in the pre-dredged sediments. Sediment EPC₀ was also less in the pre-dredged sediments compared to sediments in the undredged ditches.

The pre-dredged sediments were better able to remove P from the water-column than the dredged sediments, as noted by the greater α and β parameters for the sorption experiment (Table 2). The greater rate of adsorption, and lower final P concentrations in the water-column at the end of the adsorption phase also indicate that pre-dredged sediments were better able to buffer water-column P at lower concentrations, thereby reducing downstream delivery of P to receiving waters.

During the desorption phase, the pre-dredged sediments released the P added during the adsorption phase at a slower rate than the dredged sediments (Table 2). The final P concentrations in the water-column were 67% greater from the dredged treatment than the pre-dredged treatment. The lower buffering capacity of the dredged sediments was most likely due to the lower specific surface area of the sediments, and the reduced Fe exposed during the dredging process.

CONCLUSIONS

Stream and ditch sediments play an important ecological role by buffering aqueous P concentrations. These sediments likely serve as temporary P storage in the ditches, delaying P transport to receiving waters and often acting as sources to the water-column. Removal/deposition of sediments during a series of storms resulted in reduced EPC₀, and thus the potential to remove P from the water-column, particularly in the small watersheds. Treatment of sediments with aluminum sulphate prior to the storms

resulted in reduced EPC₀ from the sediments, but did not consistently affect EPC₀ after the storms. Dredging sediments exposed sediments that were unable to buffer the P concentrations in the water-column as well as those present prior to dredging.

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