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Research Letter

# Are Floodplain Soils a Potential Phosphorus Source When Inundated That Can Be Effectively Managed?

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## Core Ideas

- Dissolved phosphorus is released from floodplain soils when inundated.
- Phosphorus release rates are positively correlated with soil test and water-extractable P in soil.
- Water treatment residuals decrease P release rates, providing a potential mitigation option.

**Abstract:** The growing concern over phosphorus (P) and water quality has led to questions as to where the loads originate and how to control landscape inputs from the watershed. We collected soil cores from two locations in the Illinois River watershed to examine the relationship between stored soil P and the amount of soluble reactive P (SRP) released into the water when soils are flooded. After inundation, P flux calculations for durations of ~24 h ranged from less than 0.1 to 9.3 mg SRP $m^{-2}$ $h^{-1}$. Soil test P (STP), measured as water-extractable P and Mehlich-III P, correlated with SRP flux, where higher STP resulted in increased P flux to the overlying water. Floodplain soils have the potential to be a P source, potentially releasing more than 1600 mg $m^{-2}$ $yr^{-1}$ (>16 kg $ha^{-1}$ $yr^{-1}$) depending on length and frequency of inundation and on STP content. Applying water treatment residuals (WTRs) significantly reduced P flux from the cores. Hence, WTR application to critical source areas provides a mitigation strategy to manage floodplain soils and potential SRP release.

Eutrophication of lakes and rivers occurs when there is an overabundance of nutrients in the water. Nutrients such as phosphorus (P) play a vital role in sustaining plant and aquatic organism growth, but in excess they can lead to harmful algal blooms, a depletion of dissolved oxygen, large fish kills, and odor and taste issues (Daniel et al., 1998). These negative effects have prompted researchers to investigate the myriad sources within watersheds from which P might originate.

Phosphorus may reach streams and rivers from a variety of sources within watersheds. The effects of effluent discharges on P concentrations, transport, and loads have been well documented (e.g., Marti et al., 2004; Haggard, 2010; Figueroa-Nieves et al., 2014). Nonpoint P sources have historically come from soils, fertilizers, and animal manures (Abrams and Jarrell, 1995; Sharpley et al., 1999; Kleinman et al., 2002; Westra et al., 2002), especially where manures have been applied to meet the crop nitrogen needs while exceeding P needs. This has resulted in a buildup of P near the soil surface (Sharpley et al., 1993; Eghball and Power, 1999), which interacts with runoff water during rainfall events. The P concentrations in runoff and overlying waters are positively correlated with the amount of P in soils, measured via agronomic soil tests or through water extraction (Pote et al., 1996, 1999; Young and Ross, 2001). Thus, historical land applications have resulted in legacy P within the landscape in agricultural settings.

Water treatment residuals (WTRs) have been proposed as a mitigation strategy to keep P from leaving soils (Dayton et al., 2003; Makris et al., 2005; Agyin-Birikorang et al., 2007, 2008). The mixing of WTRs with soils has resulted in significant decreases in P availability, measured via agronomic soil tests or through water extraction. The application of WTRs to soil surfaces would potentially decrease soil P availability, as well as potentially adsorb P from runoff or overlying waters. For example, several studies

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**Abbreviations:** M3P, Mehlich-III phosphorus; SRP, soluble reactive phosphorus; STP, soil test phosphorus; WEP, water-extractable phosphorus; WREC, Watershed Research and Education Center; WTR, water treatment residual.

(Haustein et al., 2000; Dayton et al., 2003; Novak and Watts, 2004) showed that runoff P concentrations from field plots treated with WTRs were significantly less than untreated field plots with similar soil test P (STP) content.

The overall goal of this study was to evaluate the potential for P release from floodplain soils during inundation (i.e., flooding). The specific objectives were to measure the release of P from soils into aqueous solution over time during artificial inundation, to quantify P release rates across a gradient of soil P availability, and to evaluate the use of WTRs to reduce P loss from soils. The use of WTRs could be an effective strategy to reduce soil P inputs into streams and rivers during flood events, essentially capping the soil surface and potentially removing dissolved P from floodwaters.

### Study Site Description

The larger Illinois River watershed has been the focus of many studies understanding trends in P concentrations and loads (Haggard, 2010; Scott et al., 2011), evaluating the effect of small impoundments (i.e., Lake Frances; Søballe and Threlkeld, 1985; Haggard and Soerens, 2006), and investigating water quality as part of civil litigation (e.g., Cooke et al., 2011; Welch et al., 2011; Stevensen et al., 2012). The concern in this watershed is elevated P concentrations in the Illinois River, and the potential P sources in this basin have focused on effluent inputs, poultry litter applications, and watershed characteristics (Haggard, 2010; Olsen et al., 2012; Cox et al., 2013; Engel et al., 2013). While effluent inputs and poultry litter applications have been reduced, the P stored within soils is still a potential source to the Illinois River, especially in areas that are hydrologically connected during rainfall-runoff events. The floodplains represent areas that are connected to the Illinois River, and our study focused on two areas within the larger watershed: Lake Frances at the Arkansas and Oklahoma border and the Watershed Research and Education Center (WREC) in the headwaters. Lake Frances floodplain soils were sampled in summer 2013 across multiple sites within the former lake boundary and river floodplains, where Mehlich-III P (M3P) was less than 120 mg kg$^{-1}$. The floodplain soils at WREC were sampled in December 2013 at multiple sites near the stream, where P availability was greater in the soils (40–300 mg kg$^{-1}$ M3P). The site with the highest STP was sampled again in February 2015 to evaluate the use of WTRs on floodplain soils.

## Methods

Soils cores, in replicates of three per site, were collected from multiple sites in the Lake Frances and WREC floodplains to evaluate P release under simulated flood conditions. Plexiglas tubes (6.3 cm i.d.) were pushed about 10 cm into the soil at each site and carefully removed, resulting in an intact soil column. The cores were sealed with stoppers and electrical tape on the bottom end, preventing potential water leakage. The soil cores were flooded to a known volume (e.g., 1.0 L) using either tap water or double deionized water, where soluble reactive P (SRP) concentrations were at or below method detection limits (0.005 mg L$^{-1}$). Tap water conductivity was ~200 μS cm$^{-1}$ (Beaver Water District, 2014), and $CaCl_2$ and NaCl were added to double deionized water in equal molar ratios to reach ~200 μS cm$^{-1}$, which is typically observed in floods at the Illinois River. The overlying water was also spiked with 0.05 or 0.20 mg P L$^{-1}$ during one experiment, replicating SRP concentrations in floodwaters. Air was bubbled through the water in all cores, keeping the water well oxygenated to replicate conditions of floodwaters.

The overlying water was sampled almost immediately after flooding and then again within 24 h. Water samples were filtered through 0.5-μm glass fiber filters and then acidified with HCl to pH less than 2. The water samples were analyzed for SRP using the ascorbic acid reduction method at the certified water quality laboratories within the Arkansas Water Resources Center (see http://arkansas-water-center.uark.edu/water-quality-lab.php). The mass released (mg) into the overlying water as a function of time (h) and surface area (m$^2$) within the cores was used to provide SRP release rates (mg m$^{-2}$ h$^{-1}$).

Following incubations, the top 5 cm of the soils in the cores were pushed out, collected, and dried for analysis of water-extractable P (WEP) and M3P (Pierzynski, 2000). The extractants were then measured for P using inductively coupled plasma optical emissions spectrometry (ICP–OES), providing P content (mg kg$^{-1}$) for each soil sample. The amounts of WEP and M3P were then related to SRP release rates from the soil using simple linear regression.

The site at WREC with the highest measured M3P content was used to evaluate how WTRs could reduce SRP release rates from floodplain soils. Eight cores were collected in the same manner and then transported back to the laboratory. Before the overlying water was added, liquid WTRs (~2% solids w/w) from Beaver Water District were applied at a rate of 1.7 kg m$^{-2}$ or ~0.25 L to four cores and the same volume of water to the other four cores; the application rate was within the range reported in the literature (see previous citations). All cores were allowed to drain for 48 h until no standing liquid was visible at the soil surface, and all cores were then flooded with tap water to an overlying volume of 0.75 L. These cores were sampled in the same manner as the previous experiment to allow for SRP release rates to be measured and compared between the control and WTR-treated cores.

## Results

In the cores flooded with only water, SRP concentrations in the water column over the soils ranged from near zero to more than 0.5 mg L$^{-1}$ 1 h after flooding the soil cores. There was an overall increase in SRP concentrations in the overlying water in the cores from nearly all sites over the duration of inundation. After 24 h, in those same cores, SRP concentrations ranged from 0.004 to more than 1 mg L$^{-1}$ in the overlying water. The soil cores at WREC generally had the greatest SRP concentrations in the overlying water at the end of the incubations, whereas the least concentrations were observed in the overlying water of the soil cores from Lake Frances sites.

The SRP release rates from soil to the overlying water in the cores varied between sites. The SRP release rates ranged from less than 0.1 mg $m^{-2}$ $h^{-1}$ to 6.9 mg $m^{-2}$ $h^{-1}$ in the overlying water of cores from the Lake Frances area. The highest SRP release rate for all cores was 9.3 mg $m^{-2}$ $h^{-1}$ from a WREC site, nearly 1.5 times greater than the highest observation from the soil cores collected near Lake Frances.

The SRP release rates varied by an order of magnitude across the cores from WREC and Lake Frances, which seemed to correspond to patterns in M3P and WEP content (Fig. 1). The M3P content of the soils showed a positive relationship with release rates of SRP from the soil to the overlying water ($R^2$ = 0.69, $p$ < 0.01). The amount of M3P in the upper soil layer in the cores varied from 23 to 337 mg $kg^{-1}$, corresponding to SRP release rates from less than 0.1 to 9.3 mg $m^{-2}$ $h^{-1}$, respectively. Water-extractable P was also strongly correlated with SRP release ($R^2$ = 0.72, $p$ < 0.01), and the WEP content varied from 3 to 66 mg $kg^{-1}$ across the soil samples. There was a strong relationship between M3P and WEP ($R^2$ = 0.80, $p$ < 0.01) across these soil samples, where WEP averaged about 20% (range 10–35%) of M3P found in the soil cores after incubation.

After 24 h of inundation, SRP concentrations in cores flooded with P-spiked water (0.05 and 0.20 mg $L^{-1}$) declined in 5 of the 12 cores, resulting in negative release rates. However, the other seven cores had increasing SRP concentrations over the short inundation, resulting in fluxes ranging from 0.8 to 6.4 mg $m^{-2}$ $h^{-1}$ (Fig. 2). As with the other cores, WEP was strongly correlated with SRP release ($R^2$ = 0.88, $p$ < 0.01), while M3P and SRP were still significant but less strongly ($R^2$ = 0.53, $p$ < 0.01). The soils acted as a P source and sink when inundated with water

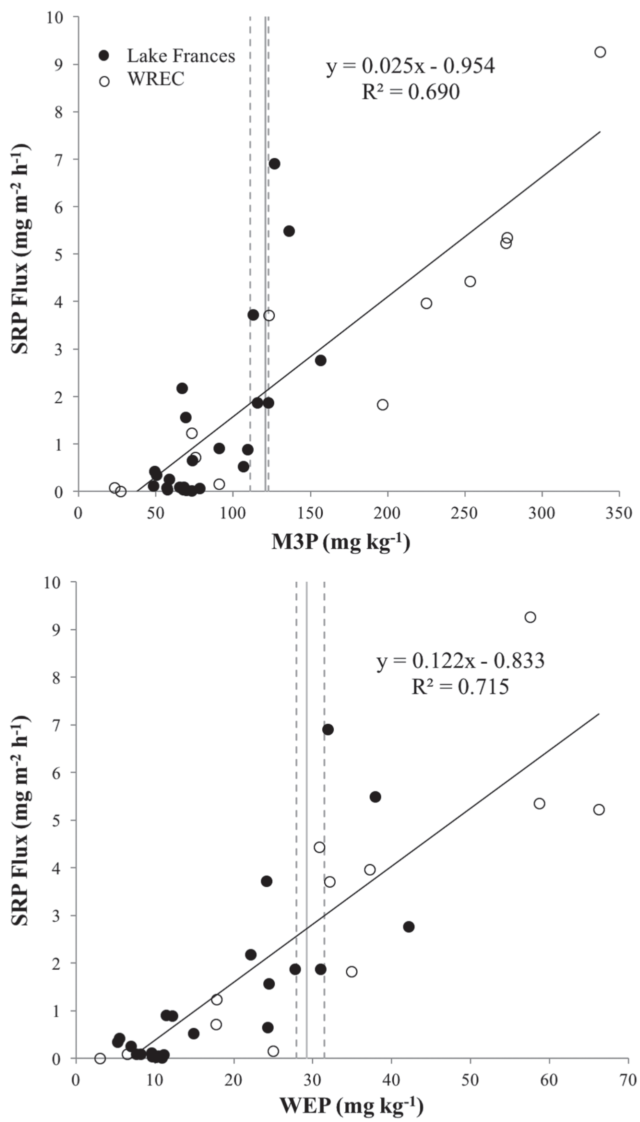


**Fig. 1. Relationships between soluble reactive phosphorus (SRP) release rates to the overlying water with Mehlich-III P (M3P) and water-extractable P (WEP) in soil cores from Lake Frances floodplains and the Watershed Research and Education Center (WREC). Gray vertical line denotes the nonparametric change point in the data with 95% confidence intervals.**

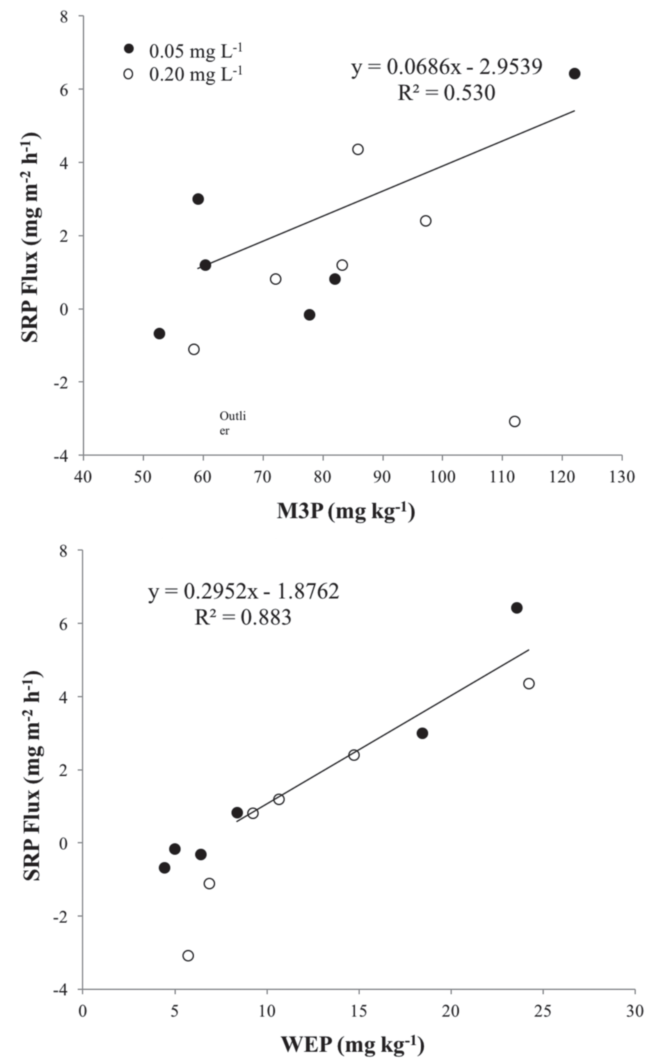


**Fig. 2. Relationship between soluble reactive phosphorus (SRP) release rates to the overlying water with initial SRP concentrations of 0.05 and 0.20 mg $L^{-1}$ with Mehlich-III P (M3P) and water-extractable P (WEP) in soil cores from Lake Frances floodplains.**

containing SRP, where net uptake by soils occurred only when WEP was less than ~9 mg $kg^{-1}$. However, net uptake or release occurred over a broader range of M3P contents.

For the second experiment on WREC soils with high STP, SRP concentrations in the overlying water of the flooded cores at 1 h ranged from near zero to 0.05 mg $L^{-1}$. After 24 h, SRP concentrations in the overlying water of untreated (control) cores ranged from 0.3 to 0.4 mg $L^{-1}$, while concentrations in the cores treated with WTRs were near method detection limits (MDL = 0.005 mg $L^{-1}$). The SRP release rates from flooded soils not treated with WTRs were consistent with those in the first experiment at the same site, ranging from 2.2 to 3.9 mg $m^{-2}$ $h^{-1}$. However, soils cores treated with WTRs showed a 97% reduction in SRP release, averaging less than 0.1 mg $m^{-2}$ $h^{-1}$ at STP levels in the upper soil layer, which were, presumably, not different.

# Discussion

The literature has well established that STP is positively correlated to SRP concentrations in runoff waters from pastures and grassland when manure or fertilizer has not been applied (Pote et al., 1996, 1999; Schroeder et al., 2004; Tarkalson and Mikkelsen, 2004). These studies have also shown that water- or $CaCl_2$-extractable P in soils was generally more strongly correlated to runoff STP concentrations relative to various agronomic soil tests (e.g., M3P). In fact, McDowell and Sharpley (2001) suggested the use of water or $CaCl_2$ extraction to estimate runoff SRP concentrations, as well as that in subsurface drainage. Our results are consistent with those found in studies relating runoff or flooding and STP, showing that SRP release rates from inundated soils increased with STP (i.e., M3P and WEP) and that WEP was a better predictor (based on higher $R^2$) than M3P. Bostic and White (2007) also showed that P release during inundation was greater in wetland soils with a greater initial P content.

In addition to soil P content, other factors may influence the release of P from soils to overlying water, whether runoff or floodwaters. It is likely that P release from floodplain soils would be temperature dependent, with greater release occurring with increased temperature (Holdren and Armstrong, 1980; Koerselman et al., 1993). Thus, P release from floodplain soils likely shows some temporal variation associated with rainfall and temperature changes across the seasons. Release rates might also vary with antecedent conditions (i.e., wetting and drying) leading up to the flood event, where SRP release might be greatest after soils have dried out in between inundation (Baldwin, 1996; Bostic and White, 2007).

The SRP release rates were highly variable (<0.1–9.3 mg $m^{-2}$ $h^{-1}$) across the soils, depending on P availability in the soil (i.e., M3P and WEP) and other factors. Novak and Watts (2005) also suggested that P release would peak within the first 12 to 24 h of flooding. Scaling up these numbers from our experiments, we could derive an average SRP flux from floodplain soils over time at the watershed scale. For example, if these soils were flooded on average 15 times per year for approximately 12 h per event, then these floodplains (~12 ha at WREC) could potentially release over 1600 mg $m^{-2}$ (>16 kg $ha^{-1}$) a year with elevated STP (e.g., 300 mg $kg^{-1}$ M3P and 60 mg $kg^{-1}$ WEP; Fig. 1). At WREC, floodplain soils might contribute 5 kg $ha^{-1}$ $yr^{-1}$ on average relative to the 4 kg $ha^{-1}$ $yr^{-1}$ from the catchment area (Metrailor, 2012). Thus, floodplains could be a proportionally greater P source within the watershed than upland soils, depending on stored P in the soil, floodplain area, and duration of inundation.

The question is, how significant of a P source are floodplains relative to upland areas? Typical P yields from grasslands and cultivated fields would be <5 kg $ha^{-1}$ $yr^{-1}$, including both fertilized and unfertilized fields (data from White et al., 2014); a few fields did stray above the typical range up to almost 30 kg $ha^{-1}$ $yr^{-1}$. White et al. (2015) predicted export coefficients for grasslands in a variety of settings in the United States to be <2 kg $ha^{-1}$ $yr^{-1}$. Floodplain soils could in fact be a hotspot for P release to streams and rivers, although the area within a catchment would likely be much less than typical agricultural landscape in the uplands. This critical source area (i.e., floodplain soils) is a potential target for mitigation strategies that would reduce P export at the watershed scale, especially given the proximity to streams (Gburek and Sharpley, 1998) and smaller area relative to uplands.

One such mitigation strategy is the use of WTRs, which have the potential to reduce SRP released from soils. Water treatment residuals are largely made up of aluminum and iron oxides, and these materials increase P sorption capacity of soils (Agyin-Birikorang et al., 2008; Young and Ross, 2001) and decrease P available to runoff (Agyin-Birikorang et al., 2007; Habibiandehkordi et al., 2015). Our study showed that WTR application at typical rates reduced the SRP yield by 97%, likely immobilizing WEP and M3P in the soil. At WREC, WTR application to only the floodplain and near stream soils (within 30 m of the fluvial channel) would possibly reduce the annual P yield by 0.6 kg $ha^{-1}$ $yr^{-1}$. Water treatment residuals also seem to be more effective on soils with high P content (Novak and Watts, 2005), so soils with a history of fertilizer application or inputs from upland sources, particularly floodplain soils, would be prime locations for WTR application, which could greatly reduce annual SRP release within catchments.

In this experiment, soils with WEP less than 9 mg $kg^{-1}$ were a sink for SRP (Fig. 2), actually removing P from the overlying water during artificial inundation. The application of WTRs to soils high in P would increase the P sorption capacity of soil and decrease available soil P (Ippolito et al., 2011), as well as the equilibrium P concentration (Taylor and Kunishi, 1971; Froelich, 1988) at the soil surface. Thus, floodplain soils could become a P sink for upslope runoff and even floodwaters. However, because the effectiveness of WTRs decreases over time (Habibiandehkordi et al., 2015), repeated applications might be needed to effectively manage this potential P source and important release process.

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