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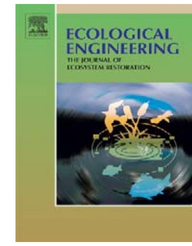


# Dissolved phosphorus concentrations and sediment interactions in effluent–dominated Ozark streams☆

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ABSTRACT

Phosphorus (P) loads from point sources have a significant influence on dissolved P concentrations in streams and sediment-water column dynamics. The goal of this study was to quantify dissolved P concentrations and sediment-P interactions in Ozark (USA) headwater streams with high point source P loads. Specifically, the objectives were to: (1) compare soluble reactive P (SRP) upstream and downstream from wastewater treatment plant (WWTP) effluent discharges; (2) examine longitudinal gradients in SRP downstream from WWTPs; (3) evaluate the effect of WTTP P inputs on sediment-water column P equilibrium and sediment exchangeable P. Water and sediment samples were collected, extracted and analyzed from July 2002 through June 2003 at these Ozark streams. Mean SRP concentrations in the select Ozark streams were significantly greater downstream from effluent discharges (0.08–2.10 $mg\,L^{-1}$) compared to upstream (0.02–0.12 $mg\,L^{-1}$). Effluent discharge from the WWTPs increased equilibrium concentrations between stream sediments and the water column; mean sediment equilibrium P concentration ($EPC_0$) was between 0.01–0.07 $mg\,L^{-1}$ upstream from WWTP and the increase downstream was proportional to that observed in water column SRP. Sediment exchangeable P (EXP) was greater downstream from the effluent discharges (0.3–6.8 $mg\,kg^{-1}$) compared to upstream (0.03–1.4 $mg\,kg^{-1}$), representing a substantial transient storage of P inputs from WWTPs. Furthermore, P was generally not retained in these stream reaches when dilution was considered using a hydrologic tracer and was released in one stream reach where effluent P concentrations decreased over the study period. Thus, the effect of the WWTPs was profound in these streams increasing water column and sediment-bound P, and also reducing the ability of these stream reaches to retain P. In P-enriched streams, effluent P discharges likely regulate sediment and aqueous phase P equilibrium and sediment bioavailable P, not the sediments.

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## 1. Introduction

Although substantial improvements in water quality have been made following implementation of the 1972 Clean Water Act in the United States, point sources such as municipal wastewater treatment plant (WWTP) effluent discharges still exert a prominent influence on dissolved phosphorus (P) concentrations and transport in Ozark streams, particularly in Northwest Arkansas, USA (Haggard et al., 2001, 2004, 2005). Dissolved P concentrations have been observed in Ozark streams as great as 10 mg $L^{-1}$ downstream from regional municipal WWTPs (Haggard et al., 2005). In some Ozark catchments, municipal WWTP inputs are 25–45% of estimated annual P export in streams (Haggard, unpublished data).

Effluent discharges from municipal WWTPs not only increase water column P concentrations in streams, but several studies have also shown an increase in benthic sediment-bound P (House and Denison, 1997; Dorioz et al., 1998; Haggard et al., 2001). The influence of WWTP effluent discharge on benthic sediments is generally much greater than other external factors, such as agricultural land use and nonpoint source pollution in the Ozarks (Popova et al., 2006). Dissolved P in the water column has an affinity for benthic sediments, and it is likely that adsorption and desorption processes may regulate dissolved P concentrations in streams (Klotz, 1988; Froelich, 1988), especially in P-enriched streams (Haggard et al., 2004, 2005). However, the ability of benthic sediments to adsorb P is often much less downstream from effluent discharges compared to sites upstream (House and Denison, 1997; Dorioz et al., 1998; Haggard et al., 2001). The adsorption of P from the water column to benthic sediments represents only a temporary transient storage zone, because sediments may release P back into the water column when effluent concentrations are low (Haggard et al., 2005). Sediment P release mechanisms are likely controlled by the equilibrium P concentration ($EPC_0$) (Froelich, 1988) between benthic sediments and the water column (Novak et al., 2004), and the amount of easily exchangeable P in the sediments (Haggard et al., 2005).

The overall goal of this study was to quantify dissolved P concentrations and sediment-water column P dynamics in effluent–dominated headwater Ozark streams. Specifically, the objectives were to: (1) compare soluble reactive P (SRP) concentrations upstream and downstream from WWTP effluent discharges; (2) examine longitudinal gradients in SRP concentration downstream from WWTP effluent discharges; (3) evaluate the effect of the effluent discharge on dissolved P equilibrium between stream sediments and water; (4) assess changes in $MgCl_2$ extractable P (sediment EXP) in benthic sediments upstream and downstream from the effluent discharge. The focus of this study was on four headwater streams in the Illinois River Drainage Area (IRDA) in Northwest Arkansas, USA that receive municipal WWTP effluent discharge. The Illinois River drains a *trans*-boundary watershed between Arkansas and Oklahoma and has recently been a subject of political concern, environmental debate and litigation. Thus, the intent of this study was to focus data collection on the headwater streams receiving effluent discharge in the Illinois River Basin and understand the influence of these effluent discharges on stream P retention mechanisms.

## 2. Materials and methods

### 2.1. Study site description

The headwater streams of the Illinois River Basin originate in Northwest Arkansas, and the Illinois River and other tributaries flow from Northwest Arkansas into Northeast Oklahoma. Phosphorus sources in the IRDA include municipal WWTPs and various potential nonpoint sources (commercial fertilizers, biosolids, poultry litter, and other animal manure). The Illinois River and its two main tributaries (Flint Creek and Baron Fork) are designated as scenic rivers in Oklahoma. The Oklahoma Water Resources Board (OWRB, 2002) recently established total P criterion of 0.037 mg TP $L^{-1}$ in rivers designated as scenic. In 1992, the U.S. Supreme Court rendered a decision that the U.S. Environmental Protection Agency (USEPA) may require upstream states to meet downstream state water quality standards at the state border (Arkansas versus Oklahoma, 503 U.S. 91; http://laws.findlaw.com/us/503/91.html). Consequently, P concentrations in these Arkansas streams may be required to meet the TP criterion promulgated in Oklahoma Scenic Rivers where these streams cross the Arkansas and Oklahoma state boundary. Green and Haggard (2001) measured average annual flow-weighted TP concentration at the Illinois River near the Arkansas-Oklahoma border to be approximately 0.40 mg $L^{-1}$, 10 times greater than the Scenic River TP criterion. The average annual TP load in the Illinois River is about 208,000 kg, and almost half of this load (45%) is attributed to inputs from municipal WWTPs. Elevated P concentrations near the Arkansas-Oklahoma border at the Illinois River can be largely traced to one municipal WWTP over 47 km upstream in the headwaters of Spring Creek (Haggard, unpublished data).

Specifically, we selected study reaches on Mud Creek, Osage Creek, Spring Creek, and Sager (and Flint) Creek, which receive WWTP effluent discharge from the cities of Fayetteville, Rogers, Springdale and Siloam Springs, respectively, in Northwest Arkansas, USA (Fig. 1, Table 1); the Siloam Springs WWTP discharges into Sager Creek, which is a tributary to Flint Creek. The Illinois River and its headwater streams are representative streams of the central United States (Brown and Matthews, 1995), and the southwestern Ozark streams in this study are located in USEPA Region VI of the conterminous USA. The headwater streams of this region are unique because of their uniformly spaced alluvial gravel riffle-pool geomorphology (Brussock et al., 1985). All these stream reaches commonly exhibit a typical riffle-pool geomorphology with bedrock outcroppings at some sites. The study reach length selected at each headwater stream was variable from 3.3 to almost 14 km (Table 1). In general, the upper portions of the catchments drained a mixture of small urban neighborhoods, pasture and forest, but the proportion of urban–suburban land use varied between streams, with Mud Creek draining the greatest urban proportion.

Only Fayetteville's WWTP had effluent P limits of 1.0 mg $L^{-1}$ in its discharge. The other facilities had no P limits or regulations during this study period, although Rogers WWTP has operated with voluntary P management practices (effluent P concentration less than 1.0 mg $L^{-1}$ since circa 1997). For the