Agricultural Water Management 98 (2011) 532–540

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Phosphorus dynamics in tile-drain flow during storms in the US Midwest

P. Vidon[a,*], P.E. Cuadra[b]

[a] *Department of Forest and Natural Resources Management, The State University of New York College of Environmental Science and Forestry, 1 Forestry Drive, Syracuse, NY 13210, USA*

[b] *Department of Earth Sciences, Indiana University-Purdue University, Indianapolis, 723 W. Michigan Street, Indianapolis, IN 46202, USA*

ARTICLE INFO

Article history:
Received 2 March 2010
Accepted 17 September 2010
Available online 1 November 2010

Keywords:
Non-point source pollution
Macropore flow
Matrix flow
Particulate phosphorus
Soluble reactive phosphorus
Rainfall events
Drainage

ABSTRACT

Excess phosphorus (P) in freshwater systems has been associated with eutrophication in agro-ecosystems of the US Midwest and elsewhere. A better understanding of processes regulating both soluble reactive phosphorus (SRP) and total phosphorus (TP) exports to tile-drains is therefore critical to minimize P losses to streams while maintaining crop yield. This paper investigates SRP and TP dynamics at a high temporal resolution during four spring storms in two tile-drains in the US Midwest. Depending on the storm, median concentrations varied between 0.006–0.025 mg/L for SRP and 0.057–0.176 mg/L for TP. For large storms (>6 cm bulk precipitation), for which macropore flow represented between 43 and 50% of total tile-drain flow, SRP transport to tile-drains was primarily regulated by macropore flow. For smaller tile-flow generating events (<3 cm bulk precipitation), for which macropore flow only accounted for 11–17% of total tile-drain flow, SRP transport was primarily regulated by matrix flow. Total P transport to tile-drains was primarily regulated by macropore flow regardless of the storm. Soluble reactive P (0.01–1.83 mg m^{-2}/storm) and TP (0.10–8.64 mg m^{-2}/storm) export rates were extremely variable and positively significantly correlated to both mean discharge and bulk precipitation. Soluble reactive P accounted for 9.9–15.5% of TP fluxes for small tile-flow generating events (<3 cm bulk precipitation) and for 16.2–22.0% of TP fluxes for large precipitation events (>6 cm bulk precipitation). Although significant variations in tile-flow response to precipitation were observed, no significant differences in SRP and TP concentrations were observed between adjacent tile-drains. Results stress the dominance of particulate P and the importance of macropore flow in P transport to tile-drains in the US Midwest. Although only spring storms are investigated, this study brings critical insight into P dynamics in tile-drains at a critical time of the year for water quality management.

1. Introduction

Increased fertilizer usage in the United States over the last 50 years has lead to a significant increase in phosphorus (P) concentration in streams (David and Gentry, 2000). Excess P in freshwater systems has been associated with eutrophication and has been identified by the U.S. Environmental Protection Agency as the greatest impediment to achieving water quality goals stated in the Clean Water Act (David and Gentry, 2000; Martin et al., 1999). Phosphorus is therefore a contaminant of national importance and it is critical to thoroughly understand the processes regulating P transport to streams in a variety of landscapes. Because P is used as a fertilizer, agricultural lands often contribute large amounts of P to streams (David and Gentry, 2000; Kronvang et al., 1997; McDowell and Wilcock, 2004; Royer et al., 2006). Phosphorus in freshwater systems can be found as soluble/dissolved reactive phosphorus (SRP/DRP) (primarily composed of orthophosphates) and particulate phosphorus (PP) (primarily composed of organic phosphorus). The sum of SRP and PP is usually referred to as total phosphorus (TP). Because TP and SRP are generally what is actually measured in water samples, most studies report P concentrations as TP and SRP (David and Gentry, 2000; Royer et al., 2006; Vidon et al., 2008). Only a few studies report PP concentrations (Kronvang et al., 1997). For three Illinois streams, Royer et al. (2006) found that SRP generally accounted for less than 50% of TP in streams over a 12-month period, with average SRP exports of 0.31 kg ha^{-1} yr^{-1} and TP exports of 0.71 kg ha^{-1} yr^{-1} for the 1994–2005 period in the Embarras, Kaskaskia and Sangamon rivers in Illinois. In New Zealand, McDowell and Wilcock (2004) found that SRP in streams typically represented between 26.9% of TP in summer/fall and 35.3% of TP in winter/spring. Soluble reactive phosphorus is the most bioavailable form of P; however, it generally represents less than 50% of total P exports in watersheds. It is therefore critical to understand both SRP and TP dynamics in streams to thoroughly characterize P export in watersheds.

Most P exports occur during high flow periods. For instance, Royer et al. (2006) indicated that more than 80% of SRP exports occurred during high flow periods ($Q > 90$th percentile) in three

---

[*] Corresponding author. Tel.: +1 315 470 4765; fax: +1 315 470 6535.
E-mail address: pgvidon@esf.edu (P. Vidon).

0378-3774/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.agwat.2010.09.010

Illinois streams. In Indiana, Vidon et al. (2008) indicated that the probability of TP concentrations in streams to exceed the 0.125 mg/L benchmark during high flow periods ($Q > 75$th percentile) was much higher (58–79%) than over a 12-month period (35–48%) or the summer/fall period (33–64%). Nevertheless, in spite of these studies quantifying P export to streams, much uncertainty still remains about the processes regulating P export to streams during high flow periods. For instance, Kronvang et al. (1997) indicated that 7% of PP originated from overland flow, 11–18% from tile-drain flow and the rest from stream bank erosion during storms in a catchment in Denmark. In Illinois, Royer et al. (2006) indicated that subsurface drainage was an important flow pathway for SRP export to streams, and that both tile-drainage and overland flow likely significantly contributed to TP exports during storms. Gachter et al. (1998) also showed that P leaching to streams via preferential flow in the subsurface was an important P export mechanism in Switzerland. In Indiana, Baker et al. (2006) indicated that SRP concentrations in the stream during storms were generally similar to SRP concentrations in tile-drains, suggesting that most SRP exports were associated with tile-drainage. Using ^{137}Cs as a tracer, McDowell and Wilcock (2004) also identified tile-drainage as an important P export mechanism and suggested that management should focus on decreasing P loss via tile-drainage. Although stream bank erosion and overland flow certainly contribute to P losses to streams during storms, several studies have therefore identified tile-drainage as an important export mechanism for both SRP and TP (Kronvang et al., 1997; McDowell and Wilcock, 2004; Royer et al., 2006).

Research also suggests that P transport from the soil surface to tile-drains via preferential flow through soil macropores is likely an important transfer mechanism as several studies have shown that macropore flow can be important in solute (including P) transport in artificially drained soils (Shalit and Steenhuis, 1996; Kladivko et al., 1999; Kung et al., 2000a,b; Geohring et al., 2001; Stone and Wilson, 2006). For instance, Kung et al. (2000a) showed that solute transport to tile-drains can occur quickly (<1 h) through soil macropores in a study where artificial precipitation was used to monitor the mobility of adsorbing and non-adsorbing tracers immediately after application to the soil surface in a tile-drained field in Indiana. Stone and Wilson (2006) also showed that preferential flow through soil macropores during storms in a tile-drained field in Indiana contributed between 11 and 51% of total tile-drain flow, with peak contributions between 40 and 81% coinciding with the peak in tile-drain flow. Geohring et al. (2001) focused on identifying the importance of macropores on P transport and showed that more P transport via macropore flow occurred under wet conditions than dry conditions. Nevertheless, in spite of these studies investigating the importance of macropore flow on solute export in tile-drained landscapes, the extent to which macropore flow actually regulates SRP and TP export to tile-drains is still poorly quantified at best. Further, many cultural practices (e.g. conventional tillage vs. no till) affect soil structure (including surface macropores) and the connectivity of surface macropore to tile-drains. Determining to what extend macropore flow regulates SRP and TP losses to tile-drains in artificially drained landscapes of the Midwest is therefore also important in order to optimize cultural practices to minimize P losses to streams while maintaining crop yield. A better understanding of the impact of precipitation characteristics on macropore flow and SRP and TP losses to tile-drains is also important because many global climate change models predict an increase in the intensity and frequency of large storm events in many regions around the globe.

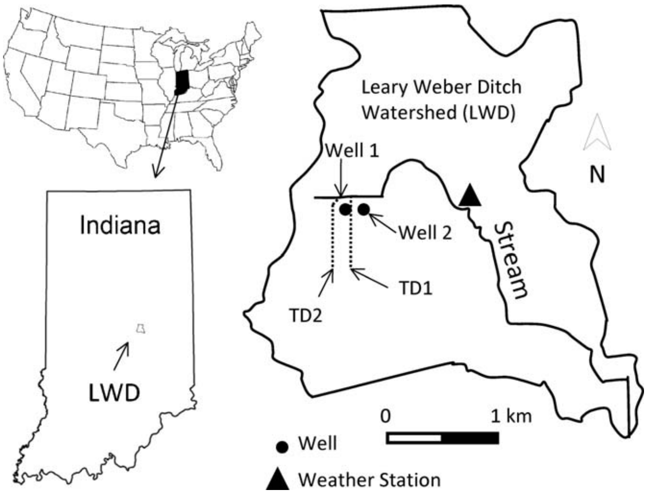

Fig. 1. Experimental site location. TD1 and TD2 correspond to the location of the two tile-drains monitored in this study.

In order to address these research needs and provide a better understanding of the processes regulating SRP and TP transport to tile-drains during storms in artificially drained landscapes of the US Midwest, the objectives of this study are threefold: (1) to determine how precipitation characteristics affect SRP and TP exports to tile-drains in artificially drained landscapes of the US Midwest; (2) to determine how important macropore flow is in regulating SRP and TP losses to tile-drains; and (3) to determine the relative importance of SRP in TP fluxes and export rates in tile-drains during storms. In order to address these objectives, SRP and TP concentrations were monitored at a high temporal resolution in one tile-drain for four storms in spring 2008. A second tile-drain was also monitored for two of these four storms to document natural variations in SRP and TP export patterns during storms for adjacent tile-drains. Precipitation and tile-flow were also continuously (15-min intervals) monitored throughout the study period to characterize the hydrology of the watershed. Whenever water samples were collected for P analysis, specific electrical conductivity (EC), oxygen-18 in water, and chloride (Cl^-) were also measured to further characterize the hydrology of the tile-drained field where the study took place, and identify the relative importance of macropore flow and matrix flow in total tile-drain flow during storms (Vidon and Cuadra, 2010). Chloride is conservative, soluble and typically associated with pre-event water as Cl^- concentration is generally low in precipitation (Vidon and Smith, 2007). Analyzing Cl^- concentration patterns along with SRP and TP concentration patterns during storms therefore brings additional insight into the hydrology of the study watershed and the export mechanisms regulating SRP and TP losses to tile-drains.

2. Materials and methods

2.1. Experimental site description

Leary Weber Ditch (LWD) is located in the larger Sugar Creek watershed, approximately 20 km east of Indianapolis, Indiana (Fig. 1). Climate at the site is classified as temperate continental and humid. The average annual temperature for central Indiana is 11.7 °C with an average January temperature of −3.0 °C and an average July temperature of 23.7 °C. The long-term average annual precipitation (1971–2000) is 100 cm (NOAA, 2005). Soils in the watershed are dominated by well-buffered poorly drained loams or silt loams and typically belong to the Crosby–Brookston association. Crosby–Brookston soils are generally deep, very poorly drained to somewhat poorly drained with a silty clay loam texture in the first 30 cm of the soil profile. Soils in LWD are suited for row crop agriculture such as corn and soybean but require artificial drainage to lower the water table, removing ponded water, adding