Journal of Hydrology 559 (2018) 749–761

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

Controls of event-based nutrient transport within nested headwater agricultural watersheds of the western Lake Erie basin

Mark R. Williams [a,*], Stanley J. Livingston [a], Chad J. Penn [a], Douglas R. Smith [b], Kevin W. King [c], Chi-hua Huang [a]

[a] USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, IN 47907, United States
[b] USDA-ARS Grassland, Soil and Water Research Laboratory, Temple, TX 76502, United States
[c] USDA-ARS Soil Drainage Research Unit, Columbus, OH 43210, United States

ARTICLE INFO

Article history:
Received 18 April 2017
Received in revised form 8 January 2018
Accepted 27 February 2018

This manuscript was handled by C. Corradini, Editor-in-Chief, with the assistance of Corrado Corradini, Associate Editor

Keywords:
Tile drainage
Hysteresis
Factor analysis
Hydrograph
Phosphorus
Nitrate

ABSTRACT

Understanding the processes controlling nutrient delivery in headwater agricultural watersheds is essential for predicting and mitigating eutrophication and harmful algal blooms in receiving surface waters. The objective of this study was to elucidate nutrient transport pathways and examine key components driving nutrient delivery processes during storm events in four nested agricultural watersheds (298–19,341 ha) in the western Lake Erie basin with poorly drained soils and an extensive artificial drainage network typical of the Midwestern U.S. Concentration-discharge hysteresis patterns of nitrate-nitrogen (NO_3-N), dissolved reactive phosphorus (DRP), and particulate phosphorus (PP) occurring during 47 storm events over a 6 year period (2004–2009) were evaluated. An assessment of the factors producing nutrient hysteresis was completed following a factor analysis on a suite of measured environmental variables representing the fluvial and wider watershed conditions prior to, and during the monitored storm events. Results showed the artificial drainage network (i.e., surface tile inlets and subsurface tile drains) in these watersheds was the primary flow pathway for nutrient delivery to streams, but nutrient behavior and export during storm events was regulated by the flow paths to and the intensity of the drainage network, the availability of nutrients, and the relative contributions of upland and in-stream nutrient sources. Potential sources and flow pathways for transport varied among NO_3-N, PP, and DRP with results underscoring the challenge of mitigating nutrient loss in these watersheds. Conservation practices addressing both nutrient management and hydrologic connectivity will likely be required to decrease nutrient loss in artificially drained landscapes.

1. Introduction

Proliferation of harmful and nuisance algal blooms (HNABs) in the United States and worldwide threaten the sustainability of aquatic ecosystems and pose a significant risk to human and animal health (e.g., Hudnell, 2010). The increasing magnitude and frequency of HNABs have been directly linked, in many instances, with increasing inputs of soluble nutrients from agricultural non-point sources. For example, Lake Erie, the shallowest and most productive of the Laurentian Great Lakes, has entered a marked phase of re-eutrophication due to increased loading of dissolved phosphorus (P) from river tributaries (Michalak et al., 2013; Kane et al., 2014; Scavia et al., 2014). Nutrient reduction plans and strategies have therefore been implemented at watershed (e.g., Great Lakes Water Quality Agreement) to continental (e.g., European Water Framework Directive) scales to moderate the number of streams and water bodies failing to meet designated water quality criteria (Kleinman et al., 2015).

Understanding the hydrological and nutrient dynamics of headwater agricultural watersheds and the inherent connections between terrestrial and aquatic environs is critical for the attainment of water quality goals. Headwater streams and agricultural drainage ditches can account for >80% of the river network, provide habitats fundamental to the health of aquatic ecosystems (Meyer et al., 2007), and regulate downstream fluxes of nutrients (Bowes et al., 2003; Alexander et al., 2007). Conservation practice and policy implementation in these watersheds, however, often precedes the identification of nutrient sources and pathways for delivery resulting in unmet goals and unintended consequences (Jarvie

* Corresponding author.
E-mail addresses: mark.williams2@ars.usda.gov (M.R. Williams), stan.livingston@ars.usda.gov (S.J. Livingston), chad.penn@ars.usda.gov (C.J. Penn), douglas.r.smith@ars.usda.gov (D.R. Smith), kevin.king@ars.usda.gov (K.W. King), chi-hua.huang@ars.usda.gov (C.-h. Huang).

https://doi.org/10.1016/j.jhydrol.2018.02.079
0022-1694/Published by Elsevier B.V.

et al., 2017). Nutrient sources and flow pathways must be first recognized (Jarvie et al., 2008), followed by conservation efforts that improve nutrient use and efficiency and that disconnect the identified critical source areas from the stream network (Pionke et al., 1996; Heathwaite et al., 2005; Kovacs et al., 2012).

Defining critical source areas of nutrients in headwater watersheds is based on many well established factors (e.g., soil nutrient concentrations, proximity to the stream or water body) (Heathwaite et al., 2005). Our knowledge of how and when these areas are connected to the stream network, however, is often limited by the heterogeneity of, among other variables, antecedent moisture, surface and subsurface runoff generation mechanisms, precipitation intensity, and agricultural management practices that govern process rates (Dean et al., 2009). Nutrient mobilization, pathways for transfer, and biogeochemical processing along these flow pathways are all influenced by these variables, but they are diffuse, vary among storm events, and often are difficult to quantify at the watershed scale (Harman et al., 2011). Investigations of nutrient loading patterns in the Mississippi River (Gall et al., 2013), Lake Erie (Williams et al., 2016a; Jarvie et al., 2017), Lake Okeechobee (Jawitz and Mitchell, 2011), and Baltic Sea (Basu et al., 2010) have all highlighted the importance of hydrological variability and nutrient transport efficiency in agricultural landscapes.

Studies characterizing the nature of nutrient transport from headwater agricultural watersheds (e.g., Haygarth et al., 2005; Macrae et al., 2007; Stutter et al., 2008; King et al., 2015; Williams et al., 2015a) have widely recognized non-linear concentration-discharge relationships for many solutes. Assessment of concentration-discharge hysteresis has been used as a method of interpreting potential nutrient sources and pathways for delivery in watersheds (e.g., Bieroza and Heathwaite, 2015; Bowes et al., 2015; Lloyd et al., 2016a; Perks et al., 2015), with small scale experiments effectively producing the predicted hysteresis behavior and offering support for this indirect approach (Chanat et al., 2002; Eder et al., 2014). Using hysteresis to study the process dynamics of multiple nutrients permits the evaluation of similarities among transport mechanisms (Lloyd et al., 2016a), factors influencing nutrient delivery at multiple spatial scales (Haygarth et al., 2012), and the interplay among watershed structure, hydrologic connectivity, and flow pathway dominance under varying environmental conditions (Perks et al., 2015).

In the current study, high resolution (1–3 h) nutrient data collected during storm events over a 6 year period from nested headwater agricultural watersheds in the western Lake Erie basin were analyzed to determine the intra-storm hysteresis behavior of nitrate, dissolved P, and particulate P concentrations. Environmental factors representing the storm event conditions and antecedent hydro-meteorological conditions associated with observed nutrient dynamics were examined using factor analysis. The objective of this study was to elucidate nutrient transport pathways and examine key components driving nutrient delivery processes in headwater agricultural watersheds with poorly drained soils and an extensive artificial drainage network typical of the Midwestern U.S. Understanding nutrient transport pathways across spatial scales will help inform nutrient management decisions and policies, and ultimately facilitate the attainment of water quality goals in watersheds with artificial drainage.

2. Materials and methods

2.1. Watershed description

This study was conducted within the Cedar Creek sub-basin of the St. Joseph River watershed in northeast Indiana, USA (Fig. 1). The St. Joseph River has been studied as part of the Conservation Effects Assessment Project (CEAP) since 2002 (Mausbach and Dedrick, 2004) and is a main tributary of the Maumee River, which flows into the western basin of Lake Erie. Understanding the fate and transport of nutrients in this predominantly agricultural watershed is essential for achieving downstream load reduction targets (i.e., 40% reduction of the P load to Lake Erie) established by Annex 4 of the Great Lakes Water Quality Agreement (Annex 4, 2015).

Four nested watersheds (AME, ALG, AXL, and F34) ranging from 298 to 19,341 ha within Cedar Creek were selected for studying the dominant mechanisms controlling nutrient transport (Fig. 1, Table 1). The majority of cropped fields in these watersheds are planted in an annual corn (*Zea mays L.*) – soybean (*Glycine max L.*) rotation. Farmer surveys in the Lake Erie region indicate that most fields receive fertilizer in the spring prior to corn planting (Burnett et al., 2015; Smith et al., 2017). The most common sources of P fertilizer applied to fields are monoammonium phosphate (MAP) and diammonium phosphate (DAP) (>95% of all P applied in the region), while the most common sources of N are urea-ammonium nitrate (UAN) and ammonia (>80% of all N applied in the region) (Burnett et al., 2015; Smith et al., 2017).

Much of northeast Indiana, including Cedar Creek, is characterized by soils with slow permeability and many small closed depressions or 'potholes' that are scattered throughout the landscape (e.g., Smith et al., 2008). Average slope across the Cedar Creek watershed is between 2 and 3%. Prevailing soils found

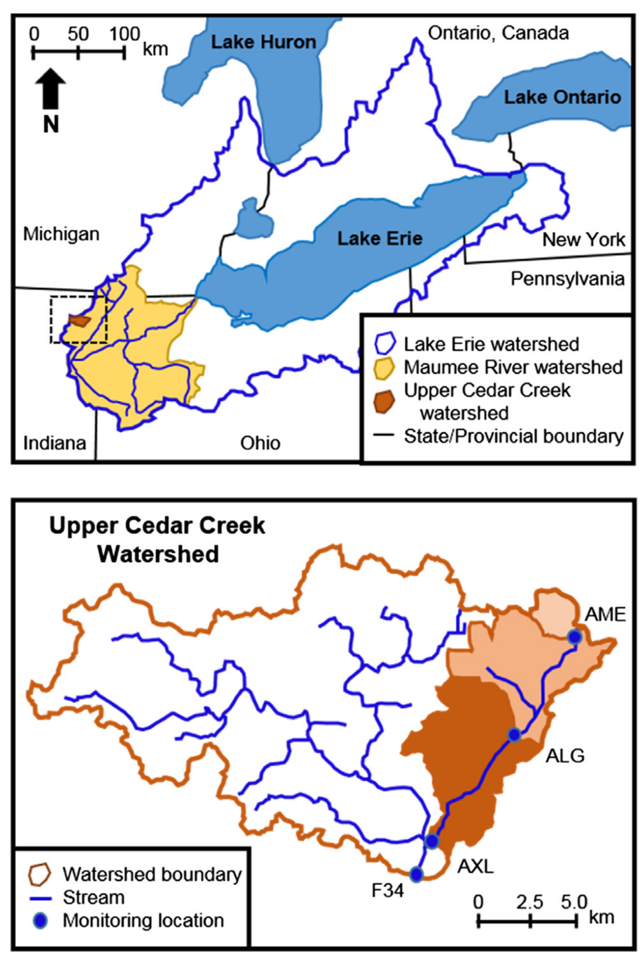

Fig. 1. Regional map showing the location of the Upper Cedar Creek watershed relative to Lake Erie. Detailed map of nested watersheds and ditch/stream monitoring locations within Upper Cedar Creek.