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Hydrologic and biogeochemical controls on phosphorus export from Western Lake Erie tributaries

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ABSTRACT

Understanding the processes controlling phosphorus (P) export from agricultural watersheds is essential for predicting and mitigating adverse environmental impacts. In this study, discharge, dissolved reactive P load, total P load, and suspended sediment time-series data (1975–2014) from two Lake Erie tributaries, the Maumee and Sandusky rivers, were evaluated to determine whether hydrologic or biogeochemical processes were responsible for observed patterns in P export. Findings indicate that hydrologic processes in these watersheds controlled P loading patterns, as P export was transport-limited (i.e., P loading was strongly correlated to watershed discharge) and P concentrations exhibited effective chemostatic behavior (i.e., low variability in concentration relative to discharge). The nature and behavior of observed P transport likely stems from a large, ubiquitous source of P present within each watershed as results were similar to those found for geogenic constituents (i.e., silica). Results suggest that changes in both precipitation patterns (e.g., precipitation variability) and watershed hydrologic response (e.g., water residence time) are likely explanations for observed increases in water and P loading in the Maumee and Sandusky watersheds. Future P loading in these watersheds should be expected to continue to be proportional to water flux as long as the magnitude and availability of the P source remains at its current level. Current P management strategies may therefore need to be reevaluated to better balance agricultural P requirements and watershed P loadings.

Introduction

Intensive agricultural land management in watersheds around the world has been associated with both hypoxia (Boesch et al., 2001; Conley et al., 2002; Rockwell et al., 2005; Chen et al., 2007; Rabalais et al., 2010; Scavia et al., 2014) and harmful algal blooms (HABs) in receiving surface waters (Michalak et al., 2013; Smith et al., 2015). Hydrology and biogeochemistry, which together determine the fate and transport of water and nutrients, are closely related to these water resource concerns. Indeed, the magnitude and severity of hypoxic zones and HABs have been linked to, among other factors, temporal fluctuations in nutrient loadings from their contributing drainage areas (Rabalais et al., 2010; Stumpf et al., 2012; Smith et al., 2015). Understanding the dominant processes controlling nutrient loading from intensively managed agricultural watersheds is therefore critical for predicting and mitigating associated adverse environmental impacts.

Previous research has indicated that treating a watershed as a 'filter' can be a useful approach for identifying the dominant processes controlling watershed hydrology and nutrient loading in managed landscapes (Basu et al., 2010, 2011; Guan et al., 2011; Jawitz and Mitchell, 2011; Gall et al., 2013). As a reactive filter, a watershed's response (e.g., discharge) relative to an external driver (e.g., precipitation) is typically characterized by phase shifts and changes in amplitude and frequency. The watershed filtering of external drivers also depends upon the initial conditions (e.g., soil moisture) and the magnitude of the input (e.g., precipitation amount). In intensively managed agricultural landscapes, watershed discharge and nutrient export are largely controlled by a combination of natural (e.g., climatic) and anthropogenic (e.g., management) drivers (e.g., Gall et al., 2013). For instance, both precipitation (e.g., Masaki et al., 2014) and subsurface drainage (e.g., King et al., 2014, 2015a) can influence watershed hydrology and nutrient transport. The role of a watershed as a hydrologic filter in managed landscapes has been widely studied in the literature; however, biogeochemical filtering as driven by watershed hydrology has only recently begun to receive attention (Godsey et al., 2010; Guan et al., 2011; Gall et al., 2013). The transport of nutrients is affected by precipitation events and their hydrologic filtering, but is further complicated because not every precipitation event generates a nutrient flux, similar precipitation amounts do not necessarily result in the same response, and

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nutrients interact with vegetation and the surrounding soil matrix during transport (e.g., sorption, uptake, nutrient cycling) (Harman et al., 2011).

In this study, the watershed is conceptualized as a nonlinear, hierarchical filter, which transforms input signals from natural and anthropogenic drivers to produce patterns in observed hydrographs, chemographs, and nutrient loads (Basu et al., 2011; Guan et al., 2011; Gall et al., 2013). Using this approach, we evaluate hydrologic and water quality time-series records from two Lake Erie tributaries, the Maumee and Sandusky rivers, which have experienced substantial shifts in P concentration and load over the past 40 years. Elevated dissolved reactive P (DRP) and total P (TP) loads that were observed in the rivers during late-1960s and early-1970s substantially decreased through the early-1990s (Makarewicz and Bertram, 1991; Richards and Baker, 1998, 2002). Increasing trends in DRP loads and flow-weighted mean concentrations since the 1990s, however, have prompted renewed concern, as Lake Erie has been returning to a more eutrophic state (Depew et al., 2011; Stumpf et al., 2012; Zhou et al., 2013; Scavia et al., 2014). The cause of increasing DRP concentrations and loads has been the subject of much debate (e.g., Smith et al., 2015); therefore, we sought to 1) examine the impact of natural and anthropogenic drivers on observed watershed hydrologic response, and 2) determine whether hydrologic or biogeochemical processes were primarily responsible for past patterns in watershed P load. Given the vast anthropogenic modifications to the hydrology of these watersheds (i.e., subsurface drainage) (Sugg, 2007; NASS, 2016) and accumulation of P on the landscape (Powers et al., 2016), we hypothesized that hydrologic processes would be the dominant control on watershed P export rather than biogeochemical processes. In addition, we hypothesized that changes in climatic factors, such as precipitation amount and timing, over the 40-year record would drive watershed hydrology. Ultimately, understanding these past watershed hydrology and P export patterns will help improve predictions of future watershed response.

Materials and methods

Maumee and Sandusky watersheds

The Maumee and Sandusky rivers are located in northwestern Ohio, USA and flow into the Western Basin of Lake Erie (Fig. 1). Both watersheds are characterized by poorly drained soils, which has resulted in the installation of vast artificial surface and subsurface drainage networks. Agricultural row crop production is the primary land use classification, accounting for approximately 75% of the watershed areas (Table 1). The National Center for Water Quality at Heidelberg University (Tiffin, OH) initiated monitoring of nutrient concentrations in the Maumee and Sandusky rivers in 1974 following severe hypoxia in Lake Erie during the late-1960s. DRP loads in both rivers declined during the initial 20 years of monitoring (1975–1995), but have substantially increased since then (1995–2014) (Fig. 2). Increased DRP loading to Lake Erie has resulted in an increase in the magnitude and extent of harmful and nuisance algal blooms in the western basin of the Lake (e.g., Stumpf et al., 2012) and hypoxic zones in the central basin (e.g., Scavia et al., 2014). The effects of increased P loading on water quality in Lake Erie culminated in August of 2014 when microcystin toxin produced by cyanobacteria was detected and approximately 500,000 residents in Toledo, OH were left without drinking water (Landers, 2014). While numerous hypotheses have been proposed to explain the cause of increasing P loading to Lake Erie (Smith et al., 2015), our objective herein was to differentiate between hydrologic and biogeochemical controls on watershed P loading.

Discharge and water quality data

DRP, TP, suspended sediment (SS), and silica concentrations as well as discharge data from the Maumee and Sandusky rivers were

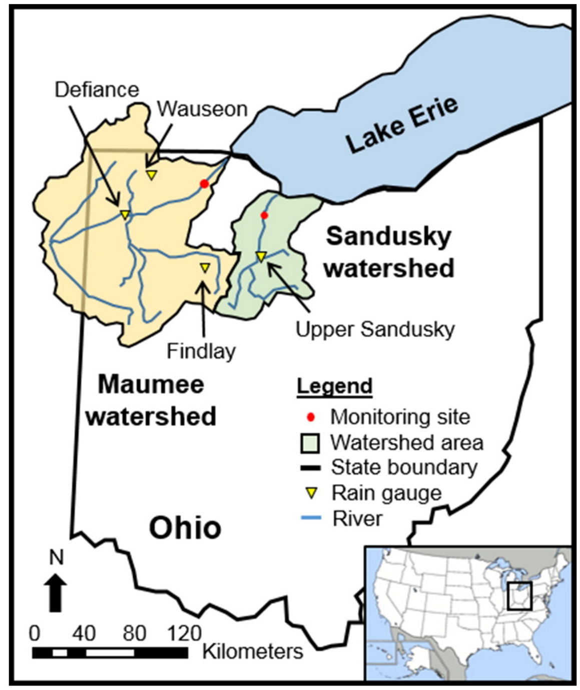

Fig. 1. Maumee and Sandusky watersheds located in northwestern Ohio, USA.

downloaded from the Heidelberg University, National Center for Water Quality Research, Tributary Loading Website (http://www.heidelberg.edu/academiclife/distinctive/ncwqr/data). Discharge, DRP, TP, and SS data were available from 1975 to 1978 and 1982–2014 for the Maumee River and from 1975 to 1980 and 1982–2014 for the Sandusky River. Silica data were only available from 2000 to 2014 for both rivers. While datasets were nearly complete at a daily time scale, linear interpolation was used to account for missing data points (Dataset completeness: [Maumee – discharge: 99.9%; DRP: 95.5%; TP: 99.4%; SS: 98.9%; silica: 98.1%]; [Sandusky – discharge: 99.8%; DRP: 94.3%; TP: 99.4%; SS: 99.0%; silica: 99.0%]). Information on sampling procedures and analytical methods are available in the Tributary Loading Program User Guide (http://www.heidelberg.edu/academiclife/distinctive/ncwqr/data/guide). Nutrient loads were calculated by multiplying the river discharge by the analyte concentration. Precipitation data from four rain gauges within the Maumee and Sandusky watersheds (Findlay, OH; Wauseon, OH; Defiance, OH; Upper Sandusky, OH) were obtained from the National Climatic Data Center (http://www.ncdc.noaa.gov/cdo-web/) (Table 1). Data from 1915 to 2014 were used from each gauge, with daily datasets being >90% complete.

Data analysis

To evaluate the impact of external drivers on watershed hydrologic response and determine whether hydrologic or biogeochemical processes were responsible for observed trends in watershed P load, Lorenz inequality and the degree of memory in the time-series data were evaluated. Details of these analyses are described in subsequent sections.

Lorenz inequality

For a given time-series of stochastic events, some events may make an unequal or disproportionate contribution compared to the other events. For instance, a flood event may represent a significant portion of annual discharge from a watershed. Lorenz curves are useful for quantifying this temporal inequality in time-series data (Jawitz and Mitchell, 2011; Gall et al., 2013). Here, the Lorenz curve is a plot of the cumulative percent of watershed responses (i.e., discharge and nutrient

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