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Research papers

Upland and in-stream controls on baseflow nutrient dynamics in tile-drained agroecosystem watersheds

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A B S T R A C T

In landscapes with low residence times (e.g., rivers and reservoirs), baseflow nutrient concentration dynamics during sensitive timeframes can contribute to deleterious environmental conditions downstream. This study assessed upland and in-stream controls on baseflow nutrient concentrations in a low-gradient, tile-drained agroecosystem watershed. We conducted time-series analysis using Empirical mode decomposition of seven decade-long nutrient concentration time-series in the agricultural Upper Big Walnut Creek watershed (Ohio, USA). Four tributaries of varying drainage areas and three main-stem sites were monitored, and nutrient grab samples were collected weekly from 2006 to 2016 and analyzed for dissolved reactive phosphorus (DRP), nitrate-nitrogen (NO_3-N), total nitrogen (TN), and total phosphorus (TP). Statistically significant seasonal fluctuations were compared with seasonality of baseflow, watershed characteristics (e.g., tile-drain density), and in-stream water quality parameters (pH, DO, temperature). Findings point to statistically significant seasonality of all parameters with peak P concentrations in summer and peak N in late winter-early spring. Results suggest that upland processes exert strong control on DRP concentrations in the winter and spring months, while coupled upland and in-stream conditions control watershed baseflow DRP concentrations during summer and early fall. Conversely, upland flow sources driving streamflow exert strong control on baseflow NO_3-N, and in-stream attenuation through transient and permanent pathways impacts the magnitude of removal. Regarding TN and TP, we found that TN was governed by NO_3-N, while TP was governed by DRP in summer and fluvial erosion of P-rich benthic sediments during higher baseflow conditions. Findings of the study highlight the importance of coupled in-stream and upland management for mitigating eutrophic conditions during environmentally sensitive timeframes.

1. Introduction

Increases in systematic tile-drainage in low-gradient agricultural landscapes have significantly impacted watershed hydrology and nutrient fate and transport over the past 50 years (Blann et al., 2009; King et al., 2014a; Christianson et al., 2016). For instance, in the Western Lake Erie Basin, increasing occurrence of harmful cyanobacteria algal blooms (HABs) has been linked to increases in dissolved reactive phosphorus (DRP) loading, potentially caused by several compounding factors including increased drainage intensity (Smith et al., 2015). Much emphasis has been placed on nutrient loading dynamics during storm flows given the disproportionate control of events on nutrient fluxes (e.g., Sharpley et al., 2008). Notwithstanding the significance of large nutrient fluxes during storm events, tile drainage can be a major component of stream baseflow (Shilling and Helmers, 2008; King et al., 2014a, b) and baseflow nutrient concentrations (Schilling and Zhang, 2004). Baseflow nutrient concentrations, which constitute less than 10% of annual nutrient loads, may play a significant role in HAB formation in small lakes and riverine environments given the low water retention times in these systems (Shore et al., 2017). In order to identify the most effective management strategies at a watershed-scale, a need exists to better understand the underlying upland and in-stream mechanisms controlling nutrient concentrations in tile-drained landscapes.

Intra-annual variability in baseflow stream nitrate (NO_3-N) concentration has been reported due to seasonal differences in the rates of in-stream and riparian biochemical reactions and time-varying contributions of drainage sources (Pionke et al., 1999; Peterson et al., 2001; Mulholland et al., 2008; Griffiths et al.,

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2012; Exner-Kittridge et al., 2016; Ford et al., 2017a). As recently highlighted in Exner-Kittridge et al. (2016), stream baseflow NO_3-N concentrations have been observed to increase in the winter and decrease in the summer within temperate tile-drained landscapes. Denitrification and algal uptake are pronounced in the summer and can deplete NO_3-N resulting in either permanent or transient removal of N; yet, algal assimilation is often neglected in watershed mass-balance calculations (Mulholland et al., 2008; Ford et al., 2017a). The source of NO_3-N and flow pathway for delivery may also influence concentrations in these watersheds. Nitrate may originate from subsurface seepage in the variably saturated vadose zone and/or deeper saturated aquifers (Exner-Kittridge et al., 2016). High stream NO_3-N concentrations in winter may reflect the prominence of N-laden shallow vadose-zone water from tile drains during wet antecedent conditions. Conversely, low stream NO_3-N concentrations in summer may reflect minimal contributions of systematic drainage (Williams et al., 2015a) and higher saturated zone flow from deeper aquifers that are depleted in N due to extended residence time for denitrification. While both in-stream and upland processes likely exert some control on stream NO_3-N concentration, the extent to which processes control NO_3-N at increasing watershed scales is not well understood.

While dissolved reactive phosphorus (DRP) trends from long-term records have shown mixed results in terms of seasonal max-min dynamics, studies specifically targeting baseflow have shown peak DRP concentrations during summer; however, the mechanisms controlling these dynamics are not well-understood (Mulholland and Hill, 1997; Pionke et al., 1999; Stow et al., 2015; Shore et al., 2017). Elevated DRP concentration in summer could reflect several potential in-stream and upland pathways. Regarding upland soil drainage, greater DRP could reflect enhanced weathering and dissolution of phosphorus (P) bearing substrata, evapotranspiration in the vadose zone, or enhanced mineralization of organic matter (Jarvie et al., 2014; Hartmann et al., 2014; Ford et al., 2015a). In many agricultural watersheds, soil bound P tends to be highly stratified, with elevated levels in surface soils; hence, we would not suspect high connectivity to subsurface drainage for baseflow concentrations (King et al., 2014a,b; Baker et al., 2017). However, macropore flow through desiccation cracks could resupply shallow aquifers below tile-drains with enriched P concentrations during dry summer months, which is subsequently leached to the stream (Williams et al., 2016; Ford et al., 2017b). In streams, elevated DRP concentrations could be associated with enhanced release of DRP by polyphosphate accumulating organisms in benthic biofilms, dissolution of phosphate precipitates (analogous to soil drainage), or desorption of legacy sediment P immobilized in transient storage zones (Wang et al., 2008; Jarvie et al., 2014; Wu et al., 2014; Saia et al., 2017).

The objective of the present study was to utilize ambient long-term records of nutrient concentrations (namely NO_3-N, DRP, total N (TN), and total P (TP)) to identify upland and in-stream controls on nutrient concentrations at baseflow conditions. We focus on tile-drained midwestern watersheds given the rampant acute and chronic nutrient flux problems that are well documented in these landscapes. Specifically, we aim to identify and discuss the following questions: (1) do seasonal baseflow nutrient dynamics agree with common perceptions?; (2) to what extent are watershed fluxes reflective of in-stream and upland controls?; and (3) what are the environmental and management implications for tile-drained agroecosystems? To answer these questions, we use a 10-year dataset and time series analysis of longitudinal watershed data in the Upper Big Walnut Creek (UBWC) USDA benchmark watershed located in central Ohio, USA and compare the data to critical upland drainage nutrient concentrations and in-stream water quality indicators.

2. Methods

2.1. Study sites

The HUC 11 Upper Big Walnut Creek watershed (HUC 05060001-130) located in central Ohio, USA is a benchmark United States Department of Agriculture (USDA) Agricultural Research Service (ARS) research watershed and is one of the 24 watersheds selected for the Conservation Effects Assessment Project, CEAP (Arnold et al., 2014; Fig. 1). The watershed drains through the Hoover Reservoir, which is a major drinking water source for the Columbus, Ohio metropolitan area (Richardson et al., 2008; Fig. 1). The UBWC has a drainage area of 492 km^2 and is predominantly (~60%) composed of cropland for production agriculture with major crops including corn, soybeans, and wheat (King et al., 2008). Extensive tile drainage networks in the watershed stem from fine, clayey soil texture which primarily consist of Bennington-Pewamo-Cardington soil associations (60%) (Table 1; King et al., 2008). We refer the reader to King et al. (2008) for further site characterization.

Eight HUC 12 watersheds are nested within the UBWC basin, of which four (T-1, T-2, T-3, and T-4) were monitored from 2006 through 2016. Three additional sites located on the main-stem (MS-1, MS-2, and MS-3) of the watershed were also monitored and each main-stem monitoring site incorporates an additional HUC 12 watershed. A U.S. Geological Survey real-time gauging station co-located at MS-2 (USGS 03228300) has historical water quality data spanning much of the nutrient data collection timeframe (late 2007-Present). Hydrologic and water quality data at MS-2 includes flowrate, water temperature, specific conductivity, dissolved oxygen (DO), and pH. Topographic, drainage, soil, and land use characteristics of the HUC 12 watersheds are summarized in Table 1. Information in Table 1 for the main-stem sites reflect the additional drainage area added at the monitoring location. Two small municipal wastewater treatment facilities are in the UBWC watershed between MS-2 and MS-3 and have maximum allowable loadings of 0.617 kg P/km^2/yr and 2.18 kg N/km^2/yr (as ammonium) respectively per EPAs Discharge Monitoring Report Pollutant Loading Tool (U.S. EPA, 2017). Such loadings are small in comparison with agricultural watershed P loadings reported in the UBWC of 98 kg P/km^2/yr.

2.2. Data collection and analysis

Weekly grab samples were collected from the middle of the stream at each of the seven study locations using standard U.S. EPA protocol for collection and preservation of water samples for N and P analysis (U.S. EPA, 1983). Water level at each of the monitoring locations was also measured at the time of sample collection. Water samples were immediately brought back to the lab and refrigerated (4 °C) until they were filtered through 0.45 μm Glass Microfibre filters. DRP and NO_3-N concentrations in filtered samples were determined colorimetrically by flow injection analysis using a Quik Chem 8000 FIA Automated Ion Analyzer (Lachat Instruments). Total N and TP analyses were performed on unfiltered samples following alkaline persulfate oxidation (Koroleff, 1983). All water samples were analyzed within 28 days following collection.

2.3. Statistical analysis

Empirical mode decomposition was selected as the preferred method for the analysis since the method is purely empirical (e.g., does not use sine-cosine functions), makes no limiting assumptions about the dataset, can be applied to a wide class of