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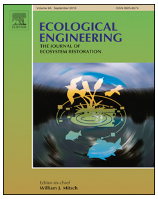

Estimating nitrate-nitrogen retention in a large constructed wetland using high-frequency, continuous monitoring and hydrologic modeling

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ABSTRACT

Wetlands are an effective edge-of-field conservation practice for reducing agricultural nitrate-nitrogen (NO_3-N) loads, but their removal performance varies with hydrologic conditions and other factors difficult to capture with traditional grab sampling schemes. We quantified NO_3-N retention in a large Iowa constructed wetland using high-frequency (15-min) in situ NO_3-N sensors and a physically-based hydrologic model that estimated discharge. Monitoring from May–Nov over a 3-yr period (2014–16) indicated the wetland reduced incoming NO_3-N concentrations 49% and loads by an estimated 61 kg day^{-1} (0.48 g m^{-2} day^{-1} based on wetland area removal). Monthly and seasonal (May–Nov) wetland retention performance were significantly influenced by hydrologic conditions, as NO_3-N concentration reductions ranged from 23% in a year that received nearly 50% more seasonal precipitation than average (2016) to 59–65% in years that received average seasonal precipitation (2014–15). On a monthly basis, NO_3-N mass retention was highest in Jun when NO_3-N loading was highest, while retention efficiency – the percent of the incoming NO_3-N load retained by the wetland – was highest in Jul and Aug when water temperature and hydraulic residence time were higher. The high-frequency monitoring captured NO_3-N dynamics not possible with lower-frequency sampling. Extrapolating the May–Nov 3-yr average wetland NO_3-N retention estimated in this study to a much larger scale, over 5600 wetlands treating more than 60% of Iowa's area and totaling an estimated $1.5 billion in design and construction would be required to reduce the state's baseline NO_3-N load by 45%, indicating the sizable investment in wetland construction and restoration needed to achieve Gulf of Mexico Hypoxia water quality goals.

1. Introduction

Nitrogen export from agricultural areas in the Midwestern U.S. impairs aquatic ecosystem health at local and regional scales through eutrophication caused by nutrient enrichment (Hynes, 1969; USEPA, 2008, 2016). The U.S. EPA has called for a 45% reduction in annual nitrogen and phosphorus loading (relative to the 1980–1996 average annual load) in the Mississippi-Atchafalaya River Basin (MARB) to reduce the 5-yr average size of the summer hypoxic zone in the Gulf of Mexico to 5000 km^2 or less by 2035 (NTF, 2008, 2015). The Upper Mississippi River Basin (UMRB), which accounts for 15% of the MARB by area and comprises large portions of several Corn Belt states including Iowa, delivered 45% of the annual nitrate-nitrite nitrogen (NO_x-N) load in the MARB from 2000–2015 (Aulenbach et al., 2007). Iowa and Illinois (9% of the MARB by area) account for an estimated 35% of the total nitrogen flux in the MARB and as much as double this in flood years (Goolsby et al., 1999). Therefore, implementing and quantifying the performance of conservation practices that target nutrient reduction in agricultural areas like Iowa is critical to achieving Gulf Hypoxia water quality goals.

Conservation practices are particularly needed to reduce nitrate-nitrogen (NO_3-N) export from tile-drained landscapes. Subsurface tile drainage removes excess soil water to improve crop yields but also hastens delivery of NO_3-N to streams (Robertson and Saad, 2011) and is a major source of NO_3-N loading to streams and rivers in the Corn Belt region (Schilling et al., 2012; McLellan et al., 2015). An estimated 37% of the Corn Belt is tile-drained (Fausey et al., 1995), and average NO_3-N concentrations and yields (NO_3-N load divided by drainage area) in tile-drained corn-soybean systems often exceed 20 mg l^{-1} and 40 kg ha^{-1} yr^{-1}, respectively (Jaynes et al., 2001; Ikenberry et al., 2014).

Wetlands are one effective edge-of-field strategy for reducing NO_3-N loads in cropped, tile-drained landscapes (Kovacic et al., 2000; Crumpton et al., 2006; Groh et al., 2015). NO_3-N removal in wetlands occurs through denitrification and plant assimilation (Ingersoll and Baker, 1998). Denitrification can account for 60–80% of the NO_3-N removal in natural wetlands (Cooke, 1994; Crumpton and

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Table 1

Summary of mean NO_3-N retention characteristics in several natural and constructed wetlands treating predominantly agricultural runoff. Standard deviations listed in parentheses, when available. NO_3-N loading and retention are normalized by wetland pool area. (HLR: hydraulic loading rate).

Wetland Location and Type	Study Years	Monitoring Period	HLR (m day^{-1})	Inlet NO_3-N Concentration (mg l^{-1})	Inlet NO_3-N Loading (g m^{-2} day^{-1})	NO_3-N Mass Retention (g m^{-2} day^{-1})	NO_3-N Mass Removal Efficiency	Refs.
Slough Creek wetland, constructed	2014–16	May–Nov	0.13 (0.20)	10.6 (2.7)	1.41 (2.19)	0.48 (0.67)	49% (27%)	This study
Iowa, constructed (3)	2004, 2006	Annual	0.08 (0.09)	13.9 (2.9)	1.01 (1.08)	0.33 (0.22)	57% (23%)	Crumpton et al. (2006)
Illinois, constructed	1995–97	Jan–Feb (4 °C)		8.4	0.21	0.05	25%	Xue et al. (1999)[1]
		May–Jun (25 °C)		10.5	0.80	0.28	40%	
Illinois, constructed (3)	1995–97	Annual	0.03–0.04	7.5–14.5	0.50	0.19	38%	Kovacic et al. (2000)[1]
Illinois, constructed (2)	2012–13	Annual (2012, drought)	0.01	11.2–15.5	0.06	0.04	60%	Groh et al. (2015)[1]
		Annual (2013, flood)	0.03		0.35	0.19	55%	
Ohio, constructed river diversion	1994–2003	Annual	0.09 (0.02)	1–8	0.30 (0.12)	0.11 (0.06)	35% (2%)	Mitsch et al. (2005)[1]
Ohio, constructed river diversion	1994–2013	Annual	0.11 (0.004)		0.27 (0.01)	0.04 (0.007)	15.6%	Mitsch et al. (2014)[1]
North Carolina, natural	1993–96	Annual	3.0×10^{-7} (4.5×10^{-7})	6.6 (1.2)	0.62 (0.50)	0.32 (.20)	51% (28%)	Hunt et al. (1999)
		May–Nov	1.1×10^{-7} (1.6×10^{-7})		0.48 (0.30)	0.37 (0.17)	76% (13%)	
Spain, natural (2)	2007–08	Annual		24.5 (6.1)	0.33 (0.28)	0.22 (0.17)	72% (15%)	Garcia-Garcia et al. (2009)

[1] Study conducted on the same set of Illinois or Ohio wetlands.

Goldsborough, 1998) and more than 90% in constructed wetlands (Xue et al., 1999; Lin et al., 2002). Denitrification is a temperature dependent process in which nitrate is reduced to nitrogen gas by anaerobic bacteria (Rolston, 1981). Unlike plant assimilation, denitrification is a dissimilatory process that permanently removes nitrogen (Jones et al., 2017c) and is favored in wetlands because of the anoxic sediments and organic carbon energy source provided by aquatic plants for anaerobic bacteria (Ingersoll and Baker, 1998). Wetland NO_3-N removal performance is determined by a number of factors, including hydrologic conditions (discharge and hydraulic residence time), inflow NO_3-N concentration, and water temperature (Crumpton et al., 2006).

NO_3-N reduction benefits of both natural and constructed wetlands receiving agricultural runoff have been quantified by others (Table 1). These studies cover a wide range of influent conditions and indicate wetland NO_3-N retention can be highly variable. In general, however, it appears annual NO_3-N retention rates of 0.1–0.3 g m^{-2} day^{-1} (300–1100 kg ha^{-1} yr^{-1}) and removal efficiencies of 20–70% are feasible for natural and constructed agricultural wetlands on an annual (Jan–Dec) basis, with retention varying seasonally (Xue et al., 1999; Hunt et al., 1999). Water quality monitoring in these studies typically consisted of weekly or monthly grab sampling which was sometimes combined with more frequent (e.g. hourly) automated storm sampling.

Development of robust and accurate real-time, continuous measurement devices (Pellerin et al., 2013; Rode et al., 2016) has provided opportunities for greater insight into streamflow-nutrient dynamics. Pellerin et al. (2014) compared high-frequency and regression-based NO_3-N load estimates on the lower Mississippi River over a 2-yr period and showed that regression-based techniques tended to underestimate NO_3-N loads during the spring months critical to Gulf Hypoxia formation and overestimate loads during the rest of the year. Bieroza et al. (2014) used high-frequency nitrogen and phosphorous monitoring to reveal greater (18–30%) loading patterns than those estimated from low-frequency grab sampling in two agricultural streams of England over a 17-month period. Previously undetected nutrient loading patterns at seasonal, individual event, and diurnal time scales were illustrated by hourly monitoring in northwestern Tasmania (Bende-Michl et al., 2013). High-frequency, continuous sampling in the Thames River Watershed (U.K.) revealed both increasing and decreasing NO_3-N concentrations during storm events and that the delivery mode was dependent on antecedent moisture and nutrient supply (Wade et al., 2012). Diurnal and seasonal NO_3-N patterns in the Mississippi River have been assessed using continuous NO_3-N sensors (Bark, 2010). High-frequency NO_3-N monitoring was used to decipher retention and dilution processes in a low order agricultural stream in eastern Iowa (Jones et al., 2017c) and to quantify transport and supply limitations in a tile-drained catchment of central Iowa (Jones et al., 2017a). Reynolds et al. (2016) subsampled 15-min NO_3-N measurements at 17 sites across Iowa to quantify uncertainties connected to conventional, labor-intensive sampling schemes and concluded that manual and automated sampling often do not capture the spatial and temporal variability of NO_3-N concentrations the way continuous monitoring can. These studies demonstrate the advantages of high-frequency, continuous monitoring for quantifying seasonal and storm event stream nutrient flux and improved nutrient load estimation.

In this study, we used high-frequency (15-min) in situ NO_3-N sensors coupled with a hydrologic model to evaluate NO_3-N concentration, load, and retention patterns in a large Iowa constructed wetland from May–Nov over a 3-yr period (2014–16). Automated water quality sensors upstream and downstream of the wetland measured NO_3-N concentration and other water quality variables, and a hydrologic model was developed to estimate discharge for computing loads. The objectives of this study were to 1) quantify the average daily NO_3-N retention and removal efficiency of the wetland on a seasonal (May–Nov) and monthly basis; 2) quantify benefits of the high-frequency monitoring data; and 3) estimate the extent of wetland implementation needed in Iowa to achieve a 45% reduction in NO_3-N loading. This study is unique