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Uncertainty in nutrient loads from tile-drained landscapes: Effect of sampling frequency, calculation algorithm, and compositing strategy

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SUMMARY

Accurate estimates of annual nutrient loads are required to evaluate trends in water quality following changes in land use or management and to calibrate and validate water quality models. While much emphasis has been placed on understanding the uncertainty of nutrient load estimates in large, naturally drained watersheds, few studies have focused on tile-drained fields and small tile-drained headwater watersheds. The objective of this study was to quantify uncertainty in annual dissolved reactive phosphorus (DRP) and nitrate-nitrogen (NO_3-N) load estimates from four tile-drained fields and two small tile-drained headwater watersheds in Ohio, USA and Ontario, Canada. High temporal resolution datasets of discharge (10–30 min) and nutrient concentration (2 h to 1 d) were collected over a 1–2 year period at each site and used to calculate a reference nutrient load. Monte Carlo simulations were used to subsample the measured data to assess the effects of sample frequency, calculation algorithm, and compositing strategy on the uncertainty of load estimates. Results showed that uncertainty in annual DRP and NO_3-N load estimates was influenced by both the sampling interval and the load estimation algorithm. Uncertainty in annual nutrient load estimates increased with increasing sampling interval for all of the load estimation algorithms tested. Continuous discharge measurements and linear interpolation of nutrient concentrations yielded the least amount of uncertainty, but still tended to underestimate the reference load. Compositing strategies generally improved the precision of load estimates compared to discrete grab samples; however, they often reduced the accuracy. Based on the results of this study, we recommended that nutrient concentration be measured every 13–26 h for DRP and every 2.7–17.5 d for NO_3-N in tile-drained fields and small tile-drained headwater watersheds to accurately (±10%) estimate annual loads.

1. Introduction

Excessive nutrient delivery to surface water bodies from agricultural nonpoint sources has led to the proliferation of Harmful and Nuisance Algal Blooms (HNABs) around the world (e.g., Hudnell, 2010). Recent increases in the extent and severity of HNABs in inland freshwater lakes has led to the development and expansion of water quality monitoring programs at both regional and global scales (Walling and Webb, 1996; Vörösmarty and Meybeck, 2004; Richards et al., 2008). Many of these monitoring programs are focused on evaluating element cycles and budgets (carbon, nutrients, sediment, pollutants) (Moatar et al., 2013) and assessing the water quality impacts of agricultural management practices (King et al., 2015a; Smith et al., 2014). In flat, poorly drained regions of the world (e.g., Midwestern US, southeastern Canada, and northern Europe), monitoring nutrient fluxes from fields and watersheds with artificial subsurface (tile) drainage is of particular interest (e.g., Dils and Heathwaite, 1999; Gentry et al., 2007; Kinley et al., 2007). Tile drainage is required for crop production in many of these areas (see review by Blann et al.

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Table 1
Studies quantifying uncertainty in nutrient load estimates due to infrequent sampling and load estimation algorithm.

Study	Watershed size (km^2)	Watershed description[a]	Water quality parameters	Load algorithms tested
Birgand et al. (2010)	5–252	7 Ag. watersheds (France); 2 with artificial drainage	NO_3-N	8
Birgand et al. (2011)	15–40	1 Mixed land use and 1 forested watershed (North Carolina, USA); both with artificial surface drainage	NO_3-N, TN, DRP, TP, TSS	2
Bowes et al. (2009)	414	1 Ag. watershed (UK)	DRP, TP	1
Cassidy and Jordan (2011)	3–5	3 Ag. watersheds (Ireland)	TP	7
Defew et al. (2013)	11	1 Ag. watershed (Scotland)	DRP, TP	7
Guo et al. (2002)	1406	1 Ag. watershed (Illinois, USA)	NO_3-N	5
Jiang et al. (2014)	90–19,218	4 Ag., 2 mixed land use, and 1 urban watershed (Ohio, USA); 4 with artificial surface and subsurface drainage[b]	NO_3-N	2
Johnes (2007)	25–1283	17 Ag. watersheds (UK)	TP	8
Jones et al. (2012)	740	1 Mixed land use watershed (Utah, USA)	TP, TSS	1
Kronvang and Bruhn (1996)	9–103	2 Ag. watersheds (Denmark)	TN, DRP, TP	13
Moatar and Meybeck (2005)	36,970	1 Mixed land use watershed (France)	NO_3-N, DRP, TP	6
Moatar and Meybeck (2007)	1773–30,710	4 Mixed land use (France) and 2 mixed land use watersheds (Ohio, USA)	NO_3-N, TN, DRP, TP, TSS	1
Phillips et al. (1999)	499–3315	2 Mixed land use watersheds (UK)	TSS	22
Rekolainen et al. (1991)	5–15	1 Ag. and 1 forested watershed (Finland)	TP	5
Richards and Holloway (1987)	386–16,699	3 Ag. watersheds (Ohio, USA); all with artificial surface and subsurface drainage[b]	NO_3-N, DRP, TP, TSS	2
Tiemeyer et al. (2010)	0.05–16	2 Ag. fields and 2 ag. watersheds (Germany); all with artificial subsurface drainage	NO_3-N	8
Tonderski et al. (1995)	36,000–197,000	4 Mixed land use watersheds (Poland)	NO_3-N, TN, DRP	1

[a] The presence of artificial drainage is based on site characteristics described in the methods of each study.

[b] Evaluated the same watersheds in Ohio, USA.

(2009)), but it enhances the hydrologic connectivity between streams and agricultural fields that serve as a source of nutrients (Macrae et al., 2007; King et al., 2015a; Williams et al., 2015).

Nutrient load estimates derived from monitoring programs are increasingly used to guide decisions regarding water resource policy, management, and regulation (Harmel et al., 2009; Jiang et al., 2014). For instance, in the Lake Erie region, monitoring of tile-drained fields and watersheds is heavily relied upon for determining the effect of agricultural practices on water quality and assigning responsibility for nutrient loading among potential sources (Kleinman et al., 2015). Conservationists, water quality managers, and policymakers alike often presume that reported nutrient loads are accurate, but previous research has noted that nutrient load estimates can be subject to considerable uncertainty (Harmel et al., 2009; Birgand et al., 2010; Moatar et al., 2013). In some cases, errors in annual nutrient load estimates can reach ±100% (e.g., Walling and Webb, 1981). Many aspects of water quality monitoring have improved over the past several decades (i.e., discharge measurement) and have resulted in more accurate nutrient load estimates, but infrequent sample collection for water chemistry remains a large source of uncertainty in nutrient load estimation and water quality modeling (e.g., Johnes, 2007). The frequency of sample collection for water quality monitoring programs is based on a balance between the necessary resolution to estimate loads and the resource costs of sampling (Kronvang and Bruhn, 1996; Jones et al., 2012). In the case of standardized regional and national monitoring programs in streams and rivers, samples are typically collected at daily to monthly intervals.

The need for evaluating uncertainty resulting from infrequent sample collection is widely recognized in the literature (Table 1); however, only a few studies have examined uncertainty in small headwater watersheds (<5 km^2) and watersheds (and fields) with tile drainage. Collectively, results from previous research have indicated that hydrological reactivity and nutrient behavior are important factors governing the amount of uncertainty in nutrient load estimates. Small tile-drained headwater watersheds and tile-drained fields are likely to be more hydrologically reactive (Robinson and Beven, 1983) and exhibit different nutrient behavior and delivery mechanisms (King et al., 2015a) than larger, naturally drained watersheds. As a result, uncertainty associated with measured nutrient loads may be greater in these landscapes (Birgand et al., 2010, 2011; Tiemeyer et al., 2010; Jiang et al., 2014).

Quantifying nutrient loads from tile-drained landscapes remains a priority in many areas of North America and Europe (Kleinman et al., 2015), but limited funding for water quality monitoring programs often results in infrequent sample collection. Thus, the uncertainty associated with measured nutrient loads from tile-drained fields and small headwater watersheds needs to be evaluated and be made clearly visible to users of these datasets. The objective of this study was to quantify uncertainty in seasonal and annual nutrient load estimates due to infrequent sampling using high-frequency discharge and nutrient concentration data from tile-drained fields and small tile-drained headwater watersheds in the US and Canada. Nitrate-N (NO_3-N) and dissolved reactive P (DRP) were chosen because of the high loads common in tile-drained landscapes and the influence of tile drains on receiving surface water bodies including inland freshwater lakes and coastal estuaries. Specific study objectives were to (1) quantify uncertainty in annual load estimates resulting from infrequent sampling, (2) compare the uncertainties introduced by six calculation algorithms used to estimate load, and (3) examine the impact of three compositing strategies on load estimates.

2. Methods

2.1. Study sites

Datasets of discharge and nutrient concentration were collected from two small tile-drained headwater watersheds and four tile-drained fields in Ohio, USA and Ontario, Canada (Fig. 1). These sites represent prevailing soil types and management practices across the artificially drained US Midwest and southeastern Ontario (Table 2). Data was collected from each site for 1–2 years under typical regional climate patterns. In general, annual precipitation