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Short communication

Temporal analysis of stormwater control measure effluent based on windows of harmful algal bloom (HAB) sensitivity: Are annual nutrient EMCs appropriate during HAB-sensitive seasons?

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ABSTRACT

Nutrient removal by stormwater control measures (SCMs) is typically reported in terms of an average annual percent removal or effluent concentration. However, when the performance of these systems is considered in light of downstream receiving aquatic ecosystems, which display seasonal sensitivities to nutrient loadings, the use of an annual-based metric seems arbitrary. To investigate the potential temporal mismatch between nutrient-sensitive periods in receiving water bodies and average annual reporting periods adopted for SCM performance metrics, a case study is presented for four SCM types (constructed stormwater wetlands, bioretention, vegetated filter strips, and swales) draining to the Neuse River Estuary (NRE) in North Carolina, USA. Outbreaks of harmful algal blooms (HABs) in the NRE have been related to different nutrient forms at different times of the year, resulting in a "window" of importance for a given nutrient. These windows were utilized herein to define seasons of interest for various pollutants, and thus how SCM effluent data should be grouped to evaluate seasonal differences in performance. Effluent SCM nutrient concentrations were analyzed on an annual and HAB-sensitive seasonal basis. Although the use of annual performance metrics was deemed either appropriate or conservative for total phosphorus and nitrate–nitrite, effluent concentrations of total ammonia–nitrogen were significantly higher during HAB-sensitive seasons from both bioretention areas and stormwater wetlands. In the case of the NRE, these data suggest SCMs such as bioretention and stormwater wetlands may perform less effectively during periods of HAB sensitivity and that the contribution of SCMs to HAB control in sensitive water bodies may be overstated using presently accepted annual evaluation metrics. Though the seasonal analysis presented is specific to HAB formation in the Neuse River Estuary, evaluation of SCM effluent nutrient concentrations on the basis of nutrient-sensitive periods in receiving water bodies has broad application to evaluation of SCMs in any nutrient-sensitive watershed. The present study suggests that evaluation of SCM performance with respect to nutrient-sensitive periods in receiving aquatic ecosystems warrants further study.

1. Introduction

Nutrient inputs from urban stormwater runoff have been cited as one of the most common causes of cultural eutrophication in freshwaters (Carpenter et al., 1998), estuaries (Bricker et al., 2008), and marine coasts (Anderson et al., 2002; Lewitus et al., 2008). Cultural eutrophication has been linked to deleterious effects such as hypoxia, biodiversity loss, foul odors, impaired aesthetics and, more recently, to stimulation of harmful algal blooms, or HABs, in fresh and marine waters alike (Burkholder et al., 2008; Heisler et al., 2008; Song et al., 2009). The environmental conditions under which algal blooms, including harmful species, proliferate are complex, and include variables such as nutrient loads and forms, discharge, salinity, food web interactions, temperature, and seasonality (Glibert et al., 2007, 2010; Rothenberger et al., 2009b; Stoecker et al., 2008). While natural factors may promote bloom development, excessive anthropogenic nutrient loadings are now recognized as a primary factor in the development and persistence of most HABs (Heisler et al., 2008), and periods during which receiving water bodies are most sensitive to bloom formation through nutrient inputs have been identified (Rothenberger et al., 2009b). Though difficult to isolate, the role of urban runoff in initiating and/or helping to sustain HABs is of concern given (1) linkages between coastal development and the occurrence of

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blooms (Burkholder, 1998; Anderson et al., 2002; Bricker et al., 2008; Lapointe and Bedford, 2011), (2) relative bioavailability of nutrients in urban runoff (as reviewed by Pellerin et al., 2006; Seitzinger et al., 2002), (3) observations of phytoplankton community shifts to potentially harmful species in stormwater plumes (Corcoran and Shipe, 2011) and (4) observations of HAB formation in stormwater ponds draining residential areas (Lewitus et al., 2008).

Efforts to manage runoff-borne nutrient pollution have spurred the proliferation of stormwater control measures (SCMs) designed to reduce nutrient loads from urban runoff. SCMs include management practices such as street sweeping as well as structural facilities, including ponds and sand filters. More recently, ecologically engineered systems such as constructed stormwater wetlands, bioretention systems, and level spreader-grassed filter strips have become popular. These SCMs employ a combination of physical, chemical, and biological processes to reduce stormwater pollutant loads. In the case of nitrogen and phosphorus, the primary removal pathways are biological denitrification and chemical sorption, respectively. These processes, however, rarely result in complete removal of nutrients from these constructed ecosystems; rather, internal nutrient cycling within microbial and vegetation pools results in a natural release of both inorganic (Kadlec et al., 2005) and organic (Hathaway and Hunt, 2010; Kadlec and Wallace, 2008; Moore et al., 2011) nutrient forms. SCM performance is typically evaluated with respect to influent runoff concentrations (Strecker et al., 2001) (e.g., percent pollutant removal), though more ecologically relevant metrics such as evaluation of SCM effluent concentrations with respect to receiving waters have been developed (e.g., Lenhart and Hunt, 2011; McNett et al., 2010). Seasonal variation in nutrient removal by vegetated SCMs has also been observed (Line and Hunt, 2009; Lucas and Greenway, 2011; Spieles and Mitsch, 2000); however, such considerations have been limited to growing season dynamics of SCM vegetation and have not been put into the context of seasonal "windows" during which receiving water bodies may be most sensitive to blooms of undesirable algal species (e.g. Rothenberger et al., 2009b). That is, SCM effluent concentration data have not been grouped by these seasonal windows to see if performance during these periods varies from average annual performance. Furthermore, nutrient exports from SCMs are typically reported as average *annual* loads or concentrations, an approach which may result in a "temporal mismatch" given the ephemeral nature of algal blooms, including those of toxic species (Glibert et al., 2010).

In the following analysis, we investigate whether the annual average reporting approach conventionally adopted for SCM performance evaluations may indeed result in such a temporal mismatch due to varied SCM performance during nutrient-sensitive periods in receiving water bodies. Given the global significance of HABs, a case study focused on bloom-sensitive periods in the Neuse River Estuary (NRE) in North Carolina, USA – a system in which repeated HAB outbreaks have afforded opportunities to study seasonality of bloom dynamics with respect to nutrient concentrations (e.g., Paerl, 2006; Rothenberger et al., 2009b) – is presented. A major tributary to the second largest estuary in the U.S., the Neuse is characterized by chronic, elevated nutrient loadings from its watershed (Burkholder et al., 2006; Rothenberger et al., 2009a) and slow flushing rates (Christian et al., 1991), conditions under which the system has suffered repeated mass fish kills associated with harmful algal blooms (Burkholder et al., 2006, and references therein). Using ordination analysis, Rothenberger et al. (2009b) found that the occurrence of harmful algal species has increased concomitantly with ammonium ($NH_4{}^+N$) in particular, and also with total phosphorus (TP) concentrations in recent years. The seasonal timing of nutrient delivery was also correlated with changes in species dominance within the algal assemblages. To examine potential differences in SCM effluent concentrations as reported on an average annual versus a nutrient-sensitive seasonal basis, nutrient effluent concentrations from North Carolina-monitored SCMs were grouped into periods of nutrient sensitivity for stimulating HABs in the NRE, as identified by Rothenberger et al. (2009b), and compared to annual data. Sensitive periods of nutrient delivery included early summer to fall (June to September), during which potentially harmful alga such as "pfiesteria-like" species were associated with elevated TP concentrations. $NH_4{}^+N$ concentrations were linked to blooms of potentially toxic *Prorocentrum minimum* during late winter and early spring (February to April), and with increased abundance of the potentially toxic raphidophyte *Heterosigma akashiwo* in summer and fall. Formation of diatom blooms was correlated with nitrate ($NO_3{}^-$) concentrations in late fall to early spring (November to March). Although this analysis is specific to the climate, hydrology, and ecosystem of the NRE, the method has broad application to assessing the performance of SCMs draining to any nutrient-sensitive surface water body.

The questions addressed in the following analysis are: (1) does the performance of SCMs vary between annual periods and nutrient-sensitive periods of receiving aquatic ecosystems? (2) does the practice of reporting nutrient removal as a lumped annual average mask such connections?, and (3) how do four different SCM types compare?

2. Materials and methods

2.1. Data selection

Data were compiled from vegetated SCMs studied throughout North Carolina, including constructed stormwater wetlands (wetlands), bioretention areas, level spreader/grassed filter strips (filter strips), and vegetated swales (swales) (Fig. 1). North Carolina, located at the southern end of the Mid-Atlantic US coast, has a generally warm and humid climate. Annual precipitation ranges between 1000 and 1300 mm for most of the state. Temperatures in the Piedmont and Coastal Plain physiographic regions range from an average monthly maximum of approximately 32 °C (90 °F) in July to an approximate average monthly low of −1 °C (30 °F) in January (SCO-NC, 2012). Vegetated SCMs throughout the state were included because estuaries receive drainage from entire watersheds, from headwaters to lower rivers. A range of contributing land uses is represented in these data, including commercial sites, residential areas, and a golf course. Further detail for SCMs is presented in the references located in Table 1.

Constructed stormwater wetlands are modeled upon naturally occurring wetlands, and are characterized as predominately shallow water systems with emergent vegetation and varying internal microtopography (Kadlec and Wallace, 2008). Wetlands offer sedimentation, chemical sorption, and a host of microbial pollutant removal mechanisms. The wetlands examined herein ranged from flow- through systems with no appreciable storage to those with up to 30 cm of extended storage. Watershed-to-practice-area ratios varied from 0.6 to 9%, with surface areas from 0.03 to 1.05 ha.

Filter strips are wide grassed slopes through which diffuse stormwater flows, encouraging sedimentation and vegetative filtering (Deletic and Fletcher, 2006). All filter strips in this study were preceded by a level spreader to induce sheet flow across the filter strip. Filter strip characteristics were variable, with systems from 7.6 m to 20 m long on slopes from 1% to 7% being represented. Watershed- to-practice-area ratios for filter strips ranged from 1% to 7.6%. The top 30.5 cm of two of the filters in the data set