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Lagoonal stormwater detention ponds as promoters of harmful algal blooms and eutrophication along the South Carolina coast

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ABSTRACT

In the rapidly urbanizing coastal zone of South Carolina, intensive landscape maintenance and turf management are significant sources of nonpoint source pollutant loadings. The best management practice of choice for stormwater in this region is wet detention ponds, the majority of which are brackish lagoons. Typically, stormwater is piped directly into the ponds, but ponds have limited capacity for processing pollutants. These eutrophic brackish ponds are "hot spots" for harmful algal blooms (HABs)—over 200 blooms from 23 different species were documented over the last 4 years, many associated with measured toxins, fish kills or shellfish health problems. Because these ponds exchange with tidal creeks, they are potential sources for HAB dispersion into adjacent estuaries. Also, flux measurements indicated that groundwater was both a source of nutrients to the ponds and a mechanism for transporting nutrients from the ponds. These findings suggest that manmade ponds as presently designed along the SC coast may contribute to estuarine eutrophication and HAB prevalence. A summary of HAB occurrences in SC lagoonal ponds from 2001 to 2005 is presented, and a project is described that simulates the effectiveness of constructed wetlands as a supplementary best management practice designed to process stormwater and groundwater and remove nutrients prior to entering wet detention ponds.

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1. Introduction

Maritime forests, marshes, and other wetlands in the coastal zone have many important functions, including the capacity to remove nonpoint source (NPS) pollutants before they can reach estuarine and marine waters. Loss of these habitats through coastal development has been linked to eutrophication and other symptoms of degraded water quality (Bricker et al., 1999; Vernberg and Vernberg, 2001). In the rapidly urbanizing South Carolina coastal zone, intensive landscape maintenance and turf management are significant sources of NPS pollutant loadings. Frequent fertilization, pesticide application, and watering (often tertiary sewage-treated) are used to maintain these plantings, while sandy soil allows for the leaching of nutrients. The problem of NPS loading in SC coastal regions is exacerbated by the common best management practice (BMP) for stormwater control; brackish lagoonal detention ponds. In SC, these detention ponds are often highly artificial, and receive stormwater directly through a subterranean drainpipe network, thus eliminating ecological processing of nutrients and sediment trapping that would occur if flow was allowed to infiltrate or pass through vegetated buffers. Although detention ponds are considered by residents to be aesthetic improvements and additional wildlife habitat, typically these ponds are not properly designed for sustainable NPS pollutant reduction.

Recently, an environmental hazard (and potential human health problem) has been associated with detention ponds. From 2001 to 2002, monitoring and fish kill response efforts in 45 brackish detention ponds along the SC coast revealed the widespread and common occurrence of harmful algal blooms (HABs) (Kempton et al., 2002; Lewitus and Holland, 2003; Lewitus et al., 2003, 2004). All of the HAB species observed have been associated with toxicity and/or causing fish kills (Landsberg, 2002). Those species previously associated with SC fish kills included *Pfiesteria piscicida* and *P. shumwayae*, *Heterosigma akashiwo*, *Chattonella subsalsa*, *Fibrocapsa japonica*, and *Karlodinium veneficum* (formerly *K. micrum*). Four raphidophyte species (the three above and

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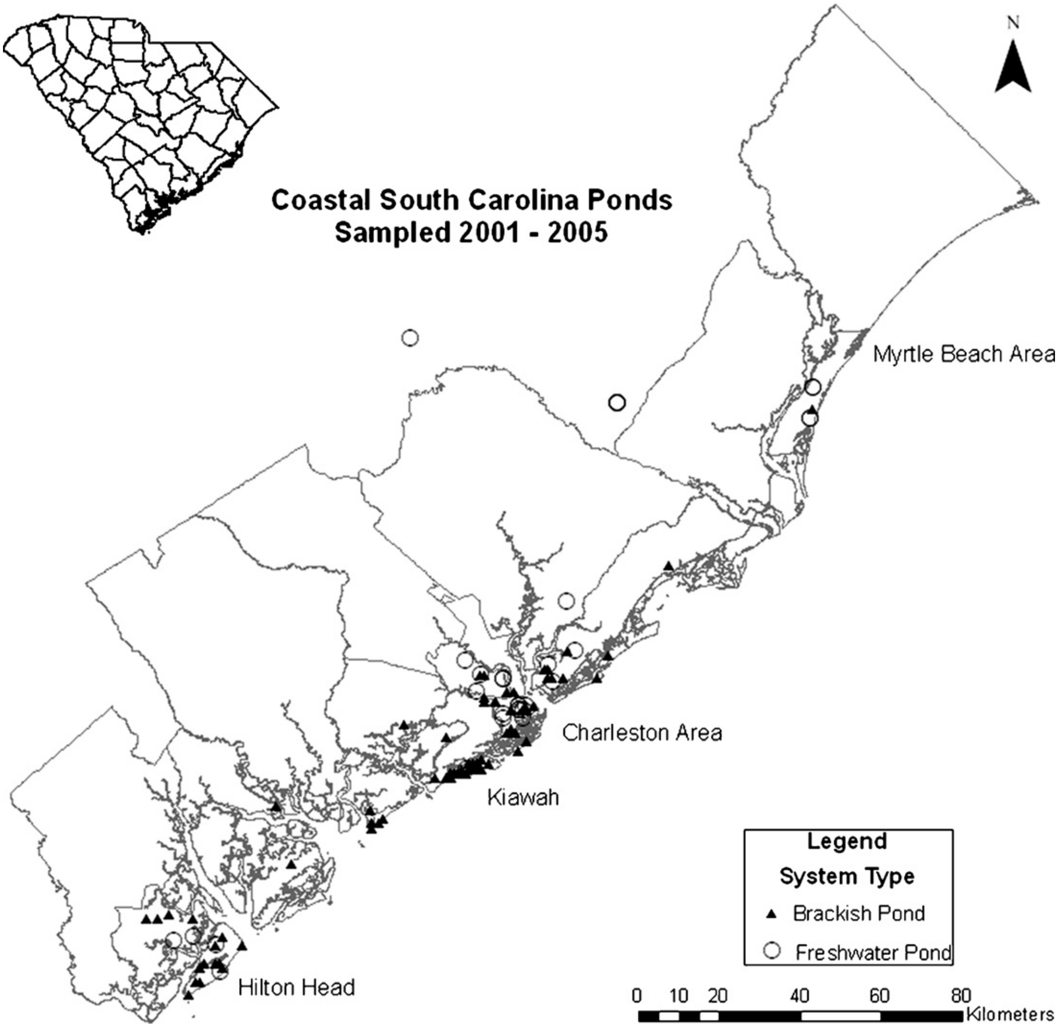

Fig. 1. South Carolina coastline, showing locations of stormwater detention ponds sampled by the South Carolina Algal Ecology Laboratory (SCAEL) from 2001 to 2005. Data from brackish ponds are presented in this paper.

Chattonella cf. verruculosa) were nearly ubiquitous in brackish ponds recently surveyed on Kiawah Island (Lewitus et al., 2003, 2004), but these same species were not present among the 240 phytoplankton taxa identified from Kiawah waters in 1974–1975, prior to development (Zingmark, 1975).

This paper presents an update on HAB distribution in SC brackish detention ponds based on monitoring efforts from 2001 to 2005 (Fig. 1). We also summarize information from a study that examined the potential application of a mitigation strategy for improving the effectiveness of SC coastal detention ponds in NPS pollution reduction—the use of constructed wetlands as supplemental BMPs to detention ponds. The goal of that study was to develop a retrofit design in which stormwater and groundwater would pass through restored terrestrial and wetland zones before entering a detention pond, and evaluate the potential benefit in nutrient processing.

2. Methods

The data on HAB distribution in SC brackish detention ponds were obtained from a combination of monitoring and fish kill response efforts conducted by the South Carolina Algal Ecology Laboratory (SCAEL), operated jointly by the University of South Carolina and South Carolina Department of Natural Resources. This paper will focus on the phytoplankton identification and quantification portion of a larger study by the SCAEL monitoring and response programs. Water was collected in triplicate with 1-l high-density polyethylene bottles from ~0.5 m below the surface. Prior to sampling, the bottles were washed in 10% HCl and rinsed six times with deionized water. Samples were kept in a cooler at ambient temperature, transported to the laboratory and processed within 4 h. Salinity, temperature, and dissolved oxygen concentration were measured at the time of sample collection using a YSI meter (YSI 85).

Fresh subsamples were observed for qualitative phytoplankton species identification under light microscopy and were preserved in Lugols fixative for enumeration. Cell abundance was estimated in fixed samples using either the Hasle (1978) counting chamber method or Guillard (1978) standard hemacytometer method.

3. Results

SCAEL surveillance and response efforts have revealed the widespread occurrence of raphidophyte blooms in brackish lagoonal ponds (Table 1, Figs. 2 and 3A). From 2001 to 2005, raphidophytes were found in 40% of 1502 pond site samples collected, and in 61 of 87 ponds sampled. Samples with high raphidophyte abundances were common (e.g. $>10^3$ cell ml^{-1} in 96 samples, from 28 different ponds). Maximum abundance for each species exceeded 10^4 cell ml^{-1}, and raphidophytes frequently

Table 1
Results from the 2001 to 2005 South Carolina Harmful Algal Bloom Database (directed by the SCAEL) listing the species with ≥5 occurrences in SC brackish detention ponds that were classified as harmful algal blooms; i.e. when abundances reached $>10^3$ cells ml^{-1} or $>10^2$ cell ml^{-1} (for *Pfiesteria* spp.)

Taxon	Class	# HABs
Chattonella subsalsa	Raphidophyceae	35
Fibrocapsa japonica	Raphidophyceae	27
Chattonella cf. verruculosa	Raphidophyceae	20
Heterocapsa rotundata	Dinophyceae	17
Oscillatoria sp.	Cyanobacteria	15
Anabaena sp.	Cyanobacteria	14
Microcystis aeruginosa	Cyanobacteria	12
Scrippsiella sp.	Dinophyceae	9
Anabaenopsis sp.	Cyanobacteria	8
Karlodinium veneficum	Dinophyceae	8
Kryptoperidinium foliaceum	Dinophyceae	7
Heterocapsa sp.	Dinophyceae	6
Heterosigma akashiwo	Raphidophyceae	5
Euglena sp.	Euglenophyceae	5
Gymnodinium sp.	Dinophyceae	5
Pfiesteria spp.	Dinophyceae	5
Prorocentrum minimum	Dinophyceae	5

dominated phytoplankton community biomass (data not shown). Raphidophyte blooms were common in the spring through summer, but rare during the winter (Fig. 2).

Tidally influenced stormwater detention ponds that were sampled by the SCAEL ranged in salinity from low brackish to marine, and not surprisingly, the type of HAB is associated with salinity properties. Dinoflagellate and raphidophyte blooms tended to be prevalent under mid-brackish to marine conditions (Lewitus et al., 2003, 2004). Four raphidophyte species were nearly ubiquitous in mid- to high-brackish ponds, *H. akashiwo*, *C. subsalsa*, *C. cf. verruculosa*, and *F. japonica*. Although salinity and temperature ranges generally overlapped, *F. japonica* was not found at salinities <10 or temperatures <22.6 °C, and *H. akashiwo* did not occur at salinities >30 (e.g. Lewitus et al., 2004). *Pfiesteria* spp. was among the most prevalent dinoflagellates in mid- to high-brackish waters, but rarely reached high abundances (Table 1, Fig. 3B). Monitoring efforts for *Pfiesteria* spp. in brackish detention ponds focused on 14 Kiawah Island ponds. Two ponds, "K2" and "K5", had a significantly higher prevalence of *Pfiesteria*-like organisms (PLOs). Based on light microscopy, PLOs were observed in 67% of the samples collected in "K2" and 80% in "K5". Using real-time PCR (Bowers et al., 2000), *P. piscicida* and *P. shumwayae* were confirmed in 47% and 82% of those samples, respectively. In a survey of 60 Kiawah Island pond sediments using real-time PCR assays (data not shown), *P. piscicida* was positive in 58% of the ponds surveyed, and *P. shumwayae* was positive in only 5% of the ponds. In surveys of tidal creeks that exchange water with these same ponds, PCR assays for *P. piscicida* were positive in approximately 50% of the sediment samples collected, including those extending up to a 1.5 km distance from the ponds. The likelihood that the sediment positives were *Pfiesteria* cysts has implications for the effects of dredging on increasing the distribution of these species.

Cyanobacteria were commonly the dominant phytoplankton species in low brackish waters (Figs. 3C and 4). For example, samples from 2001 to 2005 blooms by several cyanobacterial species spanned all salinities, but 71% of these occurred at salinity ≤10 (Fig. 4). Among the three most prevalent species, *Microcystis* bloomed most often at this low salinity range (86% of these blooms were at ≤10) but 63% of these were at salinities between 5.1 and 10. *Anabaena* bloomed mostly (72%) at salinities ≤10, while *Oscillatoria* blooms occurred in more euryhaline conditions, with 50% at salinities >10 and 29% at salinities >20.

4. Discussion

Data from brackish coastal detention ponds in SC that were sampled from 2001 to 2005 indicate that these systems are local sources for HABs. Many of these blooms were associated with measured toxins, fish kills, or shellfish health effects (Kempton et al., 2002; Lewitus and Holland, 2003; Lewitus et al., 2003; Keppler et al., 2005, 2006, SCAEL, unpublished data). These ponds are associated with residential developments and golf courses, and ponds can make up a substantial portion of area in suburban centers along the SC coast (Lewitus et al., 2003). In Hilton Head, 748 ponds exist, and Kiawah Island contains another 116 ponds (Lewitus et al., 2003; Norm Shea, personal communication). The great majority of these ponds are manmade; e.g. in 1974 (prior to development), a total of 15 freshwater or brackish ponds (considered "marsh areas") were reported on Kiawah Island (Hosier, 1975; Brock, 2006). Construction of ponds along the coast is increasing at a great rate, mainly to manage stormwater runoff. Based on 1994 aerial images, 1174 ponds >0.4 ha (1 acre) were documented east of Highway 17, a coastal highway chosen as a marker boundary for ponds that are potentially tidally influenced (Brock, 2006). These ponds covered 2693 ha (6654 acres) of surface area. By 1999, the number of ponds >0.4 ha in this same area had

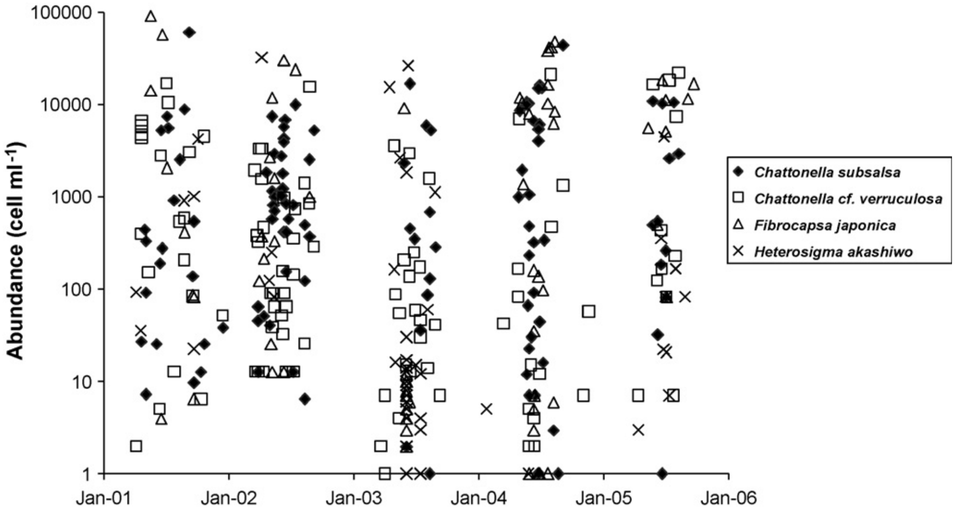

Fig. 2. Raphidophyte abundances in South Carolina pond samples during 2001–2005 (232 samples).

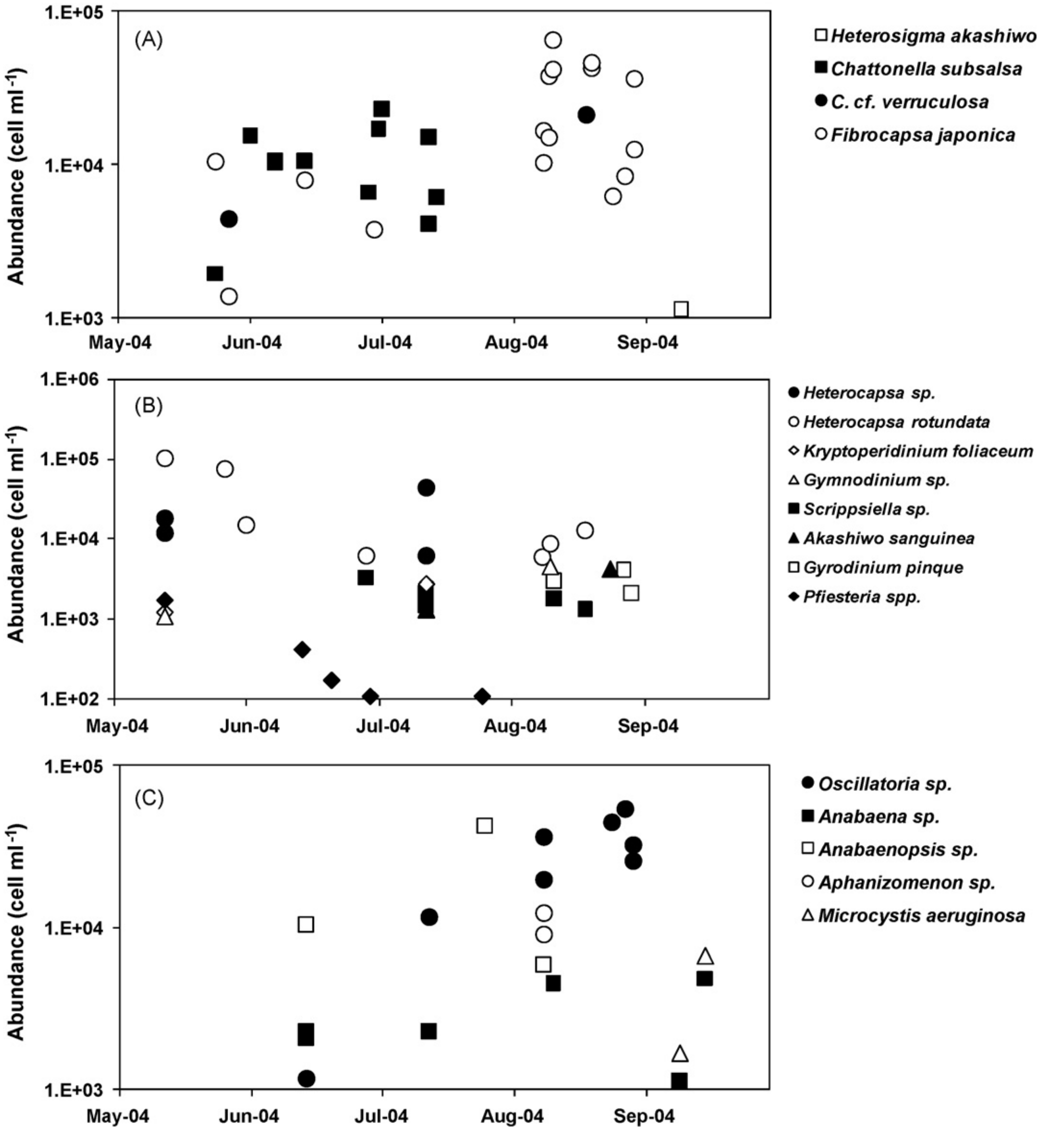

Fig. 3. Abundances of (A) raphidophytes, (B) dinoflagellates, and (C) cyanobacteria from samples collected from 10 Kiawah Island lagoonal ponds from 13 May 2004 to 16 September 2004.

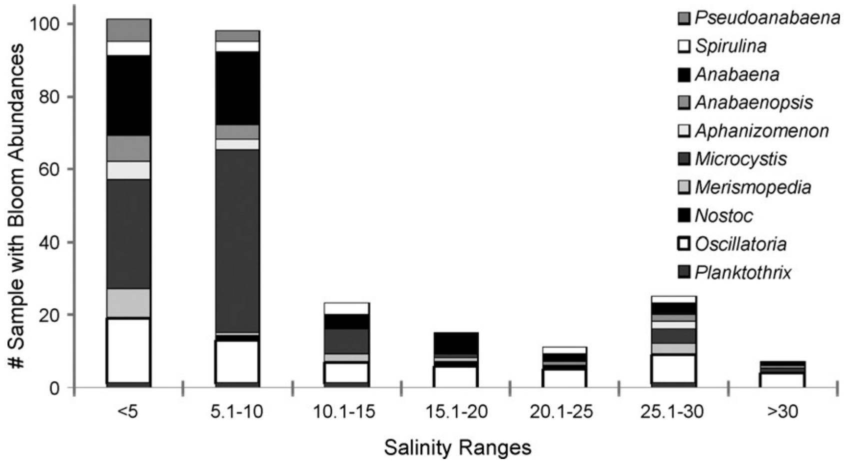

Fig. 4. Occurrence of cyanobacteria in bloom abundances (>1000 cells ml^{-1}) at various salinity ranges in samples collected in 2001–2005 from South Carolina lagoonal ponds with salinities ≥0.1.

Table 2
Mean (±S.D.) of annual mean nutrient (mg l^{-1}) and chlorophyll *a* ($\mu\text{g l}^{-1}$) concentrations from 13 SC lagoonal detention ponds monitored from 2000 to 2003

Variable	Mean	S.D.
NH_4^+	0.086	0.045
$NO_3^- + NO_2^-$	0.19	0.20
DON	1.2	0.4
PO_4^{3-}	1.0	1.1
DOP	0.03	0.05
Chlorophyll *a*	56	57

Data from Hayes et al. (Unpublished data). DON = dissolved organic nitrogen; DOP = dissolved organic phosphorus.

increased by 70% (1997 ponds), and the amount of pond acreage increased by 123% to 5995 ha (14,813 acres).

The prevalence of HABs in SC coastal ponds is an indication of their eutrophic state. In a 2000–2003 survey of 13 SC brackish detention ponds, Hayes et al. (unpublished data) found that chlorophyll *a*, total dissolved nitrogen (TDN), and total dissolved phosphorus (TDP) exceeded Bricker et al.'s (1999) threshold for "highly eutrophic" estuarine concentrations (20 $\mu\text{g l}^{-1}$ chlorophyll *a*; 1.0 mg l^{-1} TDN; 0.1 mg l^{-1} TDP) in >50%, >50%, and >80% of the samples, respectively (Table 2). The molar DIN:DIP ratio is typically <1 in these ponds (Lewitus et al., 2003; Brock, 2006) indicating that maintenance of high phytoplankton biomass would presumably be limited by nitrogen rather than phosphorus supply, and suggesting that management strategies targeting nitrogen reduction would be more effective in mitigating pond eutrophication than those targeting phosphorus.

In a hydrologic and nutrient flux assessment of the watersheds on Kiawah Island, including one containing a golf course pond, Bunker (2004) showed that stormwater and groundwater can be important sources of nutrients to the ponds. Nutrients entered through stormwater pulses and were piped directly into the ponds with no opportunity for ecological processing of pollutants. Also, Bunker (2004) found that groundwater acted as both a source of nutrients to the ponds and a mechanism for transporting nutrients from the ponds; for example, significant nitrate and ammonium fluxes were estimated to leave the pond via groundwater. These findings suggested that manmade ponds as presently designed in the SC coast may contribute to estuarine HAB proliferation and eutrophication. Because these ponds exchange with tidal creeks, they are sources for HAB dispersion into adjacent estuaries through stormwater, and of nutrient increases through surface and groundwater flow.

One mitigation strategy is in development that uses constructed wetlands as supplemental BMPs to wet detention ponds (Drescher et al., 2006; Payne, 2007; Strosnider et al., 2007). The strategy uses a combination of vegetated filter strips and restored wetlands to enhance stormwater and groundwater processing before entering the detention pond. Piping carrying stormwater to the pond would be modified to allow water to flow through a series of successional filter systems before entering the pond, similar to what may be found under more natural settings. The succession of wetland communities would function as sediment traps and zones of nutrient uptake and processing, including the key function of restoring the denitrification capacity of the landscape (Strosnider et al., 2007). Drescher et al. (2006) showed that there was a high denitrification capacity in Kiawah Island watershed soils and pond sediments that varied directly with soil carbon content. However, actual denitrification rates were low because the N-laden stormwater bypassed processing by soil microbes as it was piped directly into ponds. Strosnider et al. (2007) designed the mitigation wetland to maximize stormwater and groundwater retention time and increase opportunities for nutrient removal. They developed a continuous simulation model using STELLA software to estimate retention time, seepage rate, and quantity of spillover for water entering the proposed wetland, and effectiveness for N removal. Results predicted the removal of 90% of nitrate and 70% of ammonium currently entering the pond via stormwater and groundwater.

NPS pollution is increasingly a factor in coastal and estuarine water degradation, and detention ponds are the current BMP of choice for mitigating stormwater NPS pollution in many U.S. coastal regions, including SC. However, such ponds that are fed by subterranean stormwater piping are characterized by ineffective processing of NPS pollutants and pond eutrophication, which has led to a nearly ubiquitous pond distribution of HABs of several types. These residential and golf course detention ponds are frequented by pets and wildlife, and are commonly used for recreational activities (e.g. fishing, crabbing, boating, kayaking, and swimming). Therefore, besides the aesthetically undesirable consequences of noxious algal scum and dead fish, pond HABs pose potential health threats through direct exposure to, or trophic transfer of toxins. Furthermore, because lagoonal ponds exchange water with tidal creeks, they are a source of HABs to downstream estuarine waters through surface water flow, and a source of nutrients through surface and groundwater flow. BMP strategies (e.g. constructed wetlands) designed to restore the nutrient processing function of the landscape are needed as retrofitting options for currently impaired detention ponds. Where developments are still in the planning stages, naturally functioning riparian areas should be retained for stormwater and groundwater processing. Where natural buffers cannot be preserved, created stormwater wetlands are a sustainable low-maintenance, energy-efficient, and natural means of safeguarding pond water quality. Improving pond water quality should reduce HAB proliferation and estuarine eutrophication, resulting in benefits to estuarine ecosystems, living resources, and human health.

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References

Bowers, H.A., Tengs, T., Glasgow Jr., H.B., Burkholder, J.M., Rublee, P.A., Oldach, D.W., 2000. Development of real-time PCR assays for the rapid detection of *Pfiesteria piscicida* and related dinoflagellates. Appl. Environ. Microb. 66, 4641–4648.

Bricker, S.B., Clement, C.G., Pirhalla, D.E., Orlando, S.P., Farrow, D.R.G., 1999. National Estuarine Eutrophication Assessment: Effects of Nutrient Enrichment in the Nation's Estuaries. National Oceanic and Atmospheric Administration, National Ocean Service, Special Projects Office and the National Centers for Coastal Ocean Science, Silver Spring, Maryland.

Brock, L.M., 2006. Water Quality, Nutrient Dynamics, Phytoplankton Ecology and Land Uses Within Defined Watersheds Surrounding Six Detention Ponds on Kiawah Island, South Carolina. M.Sc. Thesis. Masters in Environmental Studies, The Graduate School, College of Charleston.

Bunker, K.N., 2004. A Hydrologic Assessment of Two Detention Pond Watersheds in an Urban Coastal Landscape. M.Sc. Thesis. Masters in Environmental Studies, The Graduate School, College of Charleston.

Drescher, S.R., Burke, M.K., Lewitus, A.J., Brown, S.D., 2006. Background, short-term, and potential long-term denitrification capacity of soils in urbanized coastal watersheds on Kiawah Island. In: Proceedings of the International Conference on Hydrology and Management of Forested Wetlands. South Carolina, USA, ASABE publication number 701PO406, pp. 167–174.

Guillard, R.R.L., 1978. Counting slides. In: Sournia, A. (Ed.), Phytoplankton Manual. UNESCO, Paris.

Hasle, G.R., 1978. The inverted microscope method. In: Sournia, A. (Ed.), Phytoplankton Manual. UNESCO, Paris.

Hosier, P.E., 1975. Dunes and Marsh Vegetation. In: Environmental Inventory of Kiawah Island, Environmental Research Center, Columbia, SC, D1–D96.

Kempton, J.W., Lewitus, A.J., Deeds, J.R., McH. Law, J., Place, A.R., 2002. Toxicity of *Karlodinium micrum* (Dinophyceae) associated with a fish kill in a South Carolina brackish retention pond. Harmful Algae 1, 233–241.

Keppler, C.J., Hoguet, J., Smith, K., Ringwood, A.H., Lewitus, A.J., 2005. Sublethal effects of the toxic alga *Heterosigma akashiwo* on the southeastern oyster (*Crassostrea virginica*). Harmful Algae 4, 275–285.

Keppler, C.J., Lewitus, A.J., Ringwood, A.H., Hoguet, J., Staton, T., 2006. Sublethal cellular effects of short-term raphidophyte and brevetoxin exposures on the eastern oyster *Crassostrea virginica*. Mar. Ecol. Prog. Ser. 312, 141–147.

Landsberg, J., 2002. Effects of algal blooms on aquatic organisms. Rev. Fish. Sci. 10, 113–390.

Lewitus, A.J., Holland, A.F., 2003. Initial results from a multi-institutional collaboration to monitor harmful algal blooms in South Carolina. Environ. Monit. Assess. 81, 361–371.

Lewitus, A.J., Schmidt, L.B., Mason, L.J., Kempton, J.W., Wilde, S.B., Wolny, J.L., Williams, B.J., Hayes, K.C., Hymel, S.N., Keppler, C.J., Ringwood, A.H., 2003. Harmful Algal Blooms in South Carolina Residential and Golf Course Ponds. Pop. Environ. 24, 387–413.

Lewitus, A., Hayes, K., Kempton, J., Mason, L., Wilde, S., Williams, B., Wolny, J., 2004. Prevalence of raphidophyte blooms in South Carolina brackish ponds associated with housing and golf courses. In: Steidinger, K.A., Landsberg, J.A., Tomas, C.R., Vargo, G.A. (Eds.), Harmful Algae 2002. Florida Fish and Wildlife Conservation Commission, Florida Institute of Oceanography, and the Intergovernmental Oceanographic Commission of UNESCO, St. Petersburg, FL, pp. 350–352.

Payne, C., 2007. Constructed wetlands to improve coastal water quality. Compass Issue 8, 28–30.

Strosnider, W.H., Hitchcock, D.R., Burke, M.K., Lewitus, A.J., 2007. Predicting hydrology in wetlands designed for coastal stormwater management. ASABE publication number 077084, pp. 1–17.

Vernberg, F.J., Vernberg, W.B., 2001. The Coastal Zone. University of South Carolina Press, Columbia, South Carolina.

Zingmark, R.G., 1975. The phytoplankton of Kiawah Island. In: Campbell, W.M., Dean, J.M. (Eds.), Environmental Inventory of Kiawah Island. Environmental Research Center, Columbia, SC, pp. P3–P38.