Nutrient – Organic Matter Dynamics in Stormwater Ponds: Implications for Stormwater Management and the Role of Ponds as Sources of Coastal Water Quality Impairment

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EXTENDED ABSTRACT: 2012 South Carolina Water Resources Conference, held October 10-11, 2012 at the Columbia Metropolitan Convention Center

ABSTRACT. Development along South Carolina's coastal zone has resulted in a proliferation of pavement and other impervious surfaces that alter the magnitude and timing of stormwater runoff from rain events. The most common practice for managing stormwater and preventing flooding is the creation of stormwater detention ponds (hereafter, ponds). These ponds are designed to capture and retain a substantial portion of the hydrologic flow from developed land before being discharged into downstream receiving waters. As a result, these ponds also increase the residence time of surface water on the developed landscape.

The use of ponds as a stormwater management practice is particularly prevalent in the southeastern coastal plain, due to the region's flat topography, shallow water table, and storm-driven precipitation patterns. In fact, using aerial imagery taken in 2006 (color IR DOQs with a ground resolution of 1m) and digitally delineated at a screen resolution of 1:3000, over 14,000 ponds along the SC coastal zone have been identified. Although the median pond surface area was just 0.5 acre, these ponds cumulatively represented a surface area in excess of 21,000 acres. Since there are essentially no natural ponds or lakes in the southeastern coastal plain, these created ponds represent a relatively new and unique feature of the landscape.

A systematic study of the physical, chemical, and ecological condition of 26 residential ponds located throughout Georgetown and Horry counties, South Carolina, was conducted to evaluate how these ponds function as ecological systems, how they respond to nutrient enrichment associated with development, and the effects this may have on coastal ecosystem processes as a result pond discharges. Addressing these questions is a key first step toward understanding how this relatively recent increase in the abundance of ponds across the coastal landscape affects nutrient and organic matter dynamics at the terrestrial-aquatic interface, as well as its implications for managing and maintaining water quality in the coastal zone.

Ponds selected for study spanned the range from low- to high-density residential development, as defined by NOAA C-CAP classifications. In addition, two ponds that were created in 2006 for a planned unit development that was never constructed, and so currently only receive inputs from a fully forested watershed, were sampled to serve as 'no development' control sites. Across all sampling ponds, pond surface area ranged from 0.25 – 13.6 acre, with a mean of 4.3 acre. Pond depths ranged from 1.0 – 5.0 m, with a mean depth of 1.0 m. Water samples from ponds were collected 8 occasions from May to September of 2010. Water samples were collected just below the surface (~ 0.5m depth), away from shore and just above each pond's discharge structure. All water sampling was conducted in triplicate and water samples were transported on ice in the dark (< 3h) to the laboratory for analysis.

Water samples were analyzed for total nitrogen (TN), total phosphorus (TP), orthophosphate, nitrate + nitrite, ammonium, total suspended sediment (TSS), particulate organic carbon (POC), dissolved organic carbon (DOC) and chlorophyll *a* (Chl) concentrations, which were used as a measure of total algal biomass. TN, TP, orthophosphate, nitrate + nitrite, and ammonium were measured on filtered (GF/F) samples using a Bran Luebbe Technicon autoanalyzer. TN and TP were also measured on unfiltered samples to distinguish between total and dissolved nutrient fractions. The TN and TP analysis was based on the persulfate digestion method. TSS concentrations were determined by standard gravimetric methods. POC concentrations were determined on material retained on pre-ashed GF/F filter by high-temperature combustion on a Costech elemental analyzer after vapor-phase acidification to remove inorganic carbon. DOC concentrations were determined on filtered (GF/F) water samples by high-temperature combustion on a Shimadzu TOC-VCPN. Chl concentrations were determined fluorometrically on acetone-extracted (90% acetone at 4 °C for 24h) samples using a Turner Trilogy fluorometer.

Additionally, two mixing experiments were conducted in the fall of 2011 to examine the effects of pond discharges on key ecosystem processes in coastal receiving waters. Replicate (n=3) 400 mL samples of filtered (0.2 μm) pond water were combined with 1600 mL samples of coastal marine water collected from the relatively pristine North Inlet estuary. Pond water used in these experiments was collected from two of the ponds associated with medium residential development density sampled as part of the previous year's sampling efforts. This mixed sample was then allowed to incubate for three days in a flow-through incubator, to maintain temperature, under natural sunlight. Immediately after mixing and again at 12, 24, 48 and 72 hours, subsamples were drawn and analyzed for Chl concentrations, as well as rates of primary production and heterotrophic bacterial production. Chl was determined as described above. Primary production rates were assessed as rates of ^{14}C bicarbonate incorporation. Heterotrophic bacterial production rates were assessed as rates of ^{3}H-leucine incorporation. Replicate (n=3) control treatments were established by combining 400 mL aliquots of deionized water with 1600 mL samples of the same coastal marine water. In addition, a replicated (n=3) treatment was established that mixed 400 mL of deionized water containing the same amount of total nitrogen present in pond water samples (and largely as dissolved organic nitrogen) but as inorganic nitrogen (50:50 ratio of ammonium and nitrate).

Across all ponds and sampling dates, TN ranged from 287.9 to 3758.5 mg N L^{-1} while TP ranged from 3.7 to 394.0 mg P L^{-1} and displayed more variability both across andwithin ponds. Mean concentrations of TN and TP for low residential density ponds were not significantly different ($p > 0.05$) than concentrations for the undeveloped ponds. Mean TN and TP concentrations were, however, significantly greater ($p < 0.001$) in medium and high residential density ponds, compared to low residential density ponds. Although there were no significant differences in mean TN or TP concentration between medium and high residential density ponds, among-pond variability in both TN and TP was higher for the high residential density category (C. V. = 73 and 84 for TN and TP, respectively) than in medium residential density category (C. V. = 44 and 58 for TN and TP, respectively).

There was a highly significant positive relationship between TN and TP across all ponds and sampling date that was best described by a power function, due to the log-normal distribution of the data. The exponent of this relationship was, however, significantly < 1, indicating TN:TP generally decreased with increasing TP. As such, when TP concentrations were low (< 10 μg L^{-1}), TN:TP mass ratios were 63.4 ± 16.5 (mean ± standard deviation), suggestive of strong phosphorus limitation, but when TP concentrations were high (> 100 μg L^{-1}), TN:TP mass ratios were 8.5 ± 3.5 (mean ± standard deviation), approaching the mass ratio indicative of N limitation (7.2TN:1TP, Guildford & Hecky, 2000).

The relationship between TN and TP observed in these ponds had a similar intercept, but lower slope than that found in the largest study of summer-time TN and TP concentrations in natural lakes world-wide (Downing & McCauley 1992). Thus, at low TP concentrations, stormwater ponds exhibit comparable concentrations and TN-TP relationships with those of natural lentic waters, but substantially lower TN concentrations, and therefore TN:TP ratios, relative to natural waters, at the higher end of observed TP concentrations. This divergence in the TN-TP relationship between natural lakes and the ponds of this study is likely the result of the very low TN:TP ratios found in stormwater runoff from the more developed portions of the study region, which had a mean TN:TP mass ratio of just 2.5.

In addition to the fact that TN and TP concentrations differed in their relative range of variability across all ponds, they also differed in their predominant forms. The majority of TN was present in dissolved form, which accounted for a median value of 71.9% of TN. In contrast, less than half of TP present was in the dissolved form, which accounted for a median value of just 36.0% of TP. The vast majority of all dissolved TN was present as DON, such that the median percent of dissolved TN present as DIN was just 2.7%. In contrast, the percent of the dissolved TP pool present as DIP was substantially larger and more variable (mean value = 30.2%).

Algal biomass (as Chl) varied by over four orders of magnitude among ponds and sampling dates (range = 0.7 – 269.9 μg Chl L^{-1}; mean = 22.9 ± 33.5 μg Chl L^{-1}). TN and TP concentrations were both highly significant ($p < 0.001$) predictors of Chl concentrations, with TP explaining slightly more of the variability in Chl than TN. The slope of the log-transformed linear regression relating Chl to TP was not significantly different from 1, indicating a direct 1-to-1 proportionality between Chl and TP variability. Due to the relatively narrow range in TN concentrations across all ponds, relative to TP and Chl, the exponent of the relationship between TN and Chl concentrations was, in contrast, substantially greater than 1. Given the relative lack of variability in TN, it is not surprising that there was also a significant inverse relationship between Chl concentrations and TN:TP ratios (LOG10[Chl] = 3.0 – 1.2xLOG10[TN:TP]; n = 146; $r^2 = 0.43$; $p < 0.0001$).

The importance of TP concentrations in determining algal biomass (as Chl concentration) in natural lakes is one of the central tenants of limnology (Dillon & Rigler, 1974). The TP – Chl relationship found for ponds in this study is remarkably similar to those found for natural lakes (e.g., Prairie et al., 1989; Phillips et al. 2008). In contrast, the TN – Chl relationship found for ponds in this study predicts substantially more Chl per unit TN than similar relationships for natural lakes (e.g., Prairie et al., 1989; Phillips et al. 2008). This difference is most likely due to the divergence in the TN-TP relationship found in ponds due to the much higher loading of TP, relative to TN with urbanized stormwater runoff.

In general, ponds had rather high total organic carbon (TOC) concentrations (mean = 12.6 ± 7.0 mg C L^{-1}). There were no significant differences in TOC concentrations when ponds were grouped by residential development density ($p > 0.05$) and only a weak (r^2 = 0.25), but still statistically significant ($p < 0.01$) relationship between TOC and TP concentrations across all ponds and sampling dates. TOC tended to be dominated by the dissolved fraction, with DOC accounting for a mean of 82.3 ± 10.8 % of the TOC pool. Despite the limited variability in DOC concentrations across ponds, the labile portion of DOC (defined as mass consumed over 14d) was highly variable and significantly correlated ($p < 0.001$) with Chl concentrations, suggesting that in situ algal production was likely the dominant source of this labile DOC.

Results from the survey of nutrient and organic matter concentrations in ponds revealed that high algal biomass in ponds effectively converted nutrient inputs to dissolved organic forms, which were then available to be exported from ponds. The potential impacts of this carbon- and nitrogen-rich dissolved organic matter on coastal ecosystem processes when discharged from ponds was investigated in a series of controlled mixing experiments, as described above. In both sets of experiments, addition of pond-derived DON had no significant effect on Chl concentration or autotrophic primary production rates, relative to control treatments, over the course of 3 days of incubation. This is despite the fact that an equivalent quantity of nitrogen added as ammonium and nitrate stimulated primary production rates and the accumulation of Chl by over 4-fold in both experiments. The addition of pond-derived organic matter did, however, significantly stimulate rates of heterotrophic bacterial production over that of the control treatments. Thus, discharge of pond waters rich in dissolved organic carbon and nitrogen to coastal marine waters had no effect on autotrophic community processes, but almost doubled rates of heterotrophic bacterial production.

Since heterotrophic bacteria are responsible for the bulk of oxygen consumption in coastal waters (e.g., Hopkinson & Smith 2005), enhanced bacterial metabolism associated with pond discharges could potentially exacerbate low dissolved oxygen conditions present in many of South Carolina's coastal waters. Indeed, this may have direct relevance to the emergence of episodic hypoxia (low dissolved oxygen) in the near-shore waters off Myrtle Beach (Sanger et al. 2012).

Research results from the present studies suggest that, in contrast to many coastal regions of the US, the "re-plumbing" of coastal zone hydrology accompanying development in South Carolina has resulted in a spatial uncoupling of organic matter production associated with nutrient enrichment and the consumption of that organic matter and associated oxygen depletion. That is, stormwater ponds have become the loci of nutrient-driven eutrophication, with some of the excess organic production being exported to and consumed within coastal receiving waters, thus promoting declines in dissolved oxygen conditions. This presents both challenges and opportunities for how coastal development and stormwater runoff are managed to maintain water quality conditions in South Carolina's coastal waters.

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