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Importance of Submarine Groundwater Discharge as a Source of Nutrients for the Neuse River Estuary, North Carolina

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ABSTRACT: Seepage rate and chemical composition of groundwater discharge entering the Neuse River Estuary (NRE) were quantified over an annual cycle from July 2005 through June 2006. Lee type seepage meters were deployed at eight locations within the NRE to quantify the amount of submerged groundwater discharge (SGD) entering the system. Sediment porewater nitrate (NO_3^-), ammonium (NH_4^+), and phosphate (PO_4^{-3}) were also quantified at each of these locations to determine groundwater chemical composition. Seepage rates for the system ranged from 0.004 to 0.035 $m^3\ m^{-2}\ d^{-1}$. Both the average and median value for the system-wide SGD were 0.01 $m^3\ m^{-2}\ d^{-1}$. There were no significant differences between upstream and downstream seepage rates or between those at the north and south side of the estuary. Seepage rates varied greatly in time and space. Discharging groundwater was NO_3^- deplete but highly enriched in NH_4^+. Porewater PO_4^{-3} levels varied but were usually present below Redfield values due to NH_4^+ enrichment. SGD nutrient loading represented a small part of watershed nitrogen and phosphorus loading, 0.8% and 1.0%, respectively.

Introduction

While groundwater intrusion into the coastal zone has been a recognized phenomenon for years, relatively little work has been done to document its magnitude compared to surface flow as a source of nutrients. Submarine groundwater discharge (SGD) has been shown to be a significant source of both nutrients and contaminants (Valiela et al. 1990; Gilliam et al. 1996; Moore 1999; Lipp et al. 2001; Gobler and Boneillo 2003; Celico et al. 2004). SGD, while occurring at low rates, occurs across a wide area and consequently can rival the magnitude of surface influx (Millham and Howes 1994; Garrison et al. 2003; Schwartz 2003). SGD can be made up of two components, discharge from groundwater aquifers and recirculated estuarine water that is pumped through the upper sediment matrix due to pressure differences caused by tide and wind (Simmons 1992; Shum and Sundby 1996; Li et al. 1999).

In many of North Carolina's and other United States East and Gulf Coast estuarine and coastal marine systems, the nutrient controlling or limiting phytoplankton production is typically nitrogen (N; Nixon 1995; Paerl 1997; Phlips et al. 2002; Marshall et al. 2003; Ornolfsdottir et al. 2004). Because of the critical role N plays in regulating eutrophication, many studies have generated budgetary models that track the delivery, transformations, and eventual fate of N (Christian et al. 1996; Carey et al. 2001; Lebo et al. 2001; Whitall et al. 2002; Fear et al. 2005). For the most part, SGD remains an unknown or at best an estimated term in these models. As regulation and management are enacted to restore the health and usefulness of estuarine systems, this missing term represents a source of error that could jeopardize the effectiveness of the regulatory actions. The potential of SGD to bypass the estuarine nutrient filtering mechanism completely by discharging directly into the coastal marine environment underscores the need to quantify this potential source of new N. The goals of this work were to quantify the amount of SGD entering the Neuse River Estuary (NRE), a drowned river estuarine system, and to estimate the potential N added to the system by this mechanism.

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Methods

STUDY SITE

The Neuse River estuary is a predominately N-limited system (Rudek et al. 1991; Boyer et al. 1994; Pinckney et al. 1998) located in the southern coastal plain of North Carolina, U.S. (Fig. 1). The Neuse River at the head of the Neuse estuary typically has maximum flows in winter and spring and minimal flows in summer and early fall (Christian et al. 1991; Boyer et al. 1994). Watershed nutrient loading into the NRE is dominated by nitrate (NO_3^-; Christian et al. 1989), which is rapidly removed within the upper reaches of the NRE. Tidal influence in the estuary is

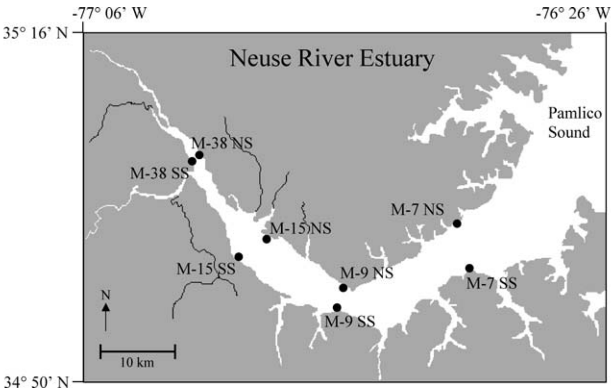

Fig. 1. Neuse River Estuary and sample site locations.

extremely small (Giese et al. 1979), as the NRE does not have a direct connection to the ocean. The estuary empties into Pamlico Sound a large lagoonal body of water with limited ocean exchange.

A confining layer separates the surficial groundwater aquifer from the deeper confined aquifers typically used for public drinking water. The most important confined aquifer underlying the NRE in terms of human usage is the Castle Hayne aquifer (Huffman 1996; Trapp and Horn 1997). Because of the shallow nature of the NRE (mean depth = 3.6 m), it is the unconfined surficial aquifer that has the potential to interact with the system and that was sampled as part of this study. The unconfined surficial aquifer is typically 15 m deep and is highly influenced by precipitation (Trapp and Horn 1997).

SGD Rate Measurement

Seepage rates were quantified using modified Lee type seepage meters (Lee 1977; Cable et al. 1997a). These meters provide an estimate of total SGD but do not allow the contributions of its two components, groundwater influx and recirculated estuarine water, to be differentiated. Seepage rates were quantified at eight locations within the NRE (Fig. 1). Sample locations were chosen to cover both the north (NS) and south (SS) shores of the system and the up and downstream areas relative to the 90° bend seen in Fig. 1. Seepage rates were measured in triplicate at each sampling location. Meters were deployed as close as possible to shore given average water depth and seepage meter height, where previous work has shown most SGD enters estuarine systems (Cable et al. 1997b; Hussain et al. 1999; Taniguchi et al. 2003; Burnet et al. 2003), and were left for 24 h. Coordinates for the sample sites were recorded using handheld GPS units and sites were marked with PVC signs so that subsequent deployments could be made in the exact same location. Distances from shore are shown in Table 1. Collection bags were prefilled with 1,000 ml of water to prevent anomalously high rates that can occur when an empty bag is used (Shaw and Prepas 1989). Seepage rates were determined by comparing pre and post deployment bag volumes and normalized by time and the area of sediment encompassed by the seepage meters (0.25 m^2). Rates from each set of triplicates were averaged to provide a single seepage rate for each time point at each sampling station. Seepage rates were quantified in August 2005, November 2005, January 2006, March 2006, and twice in June 2006.

TABLE 1. Distance from shore of sampling locations.

Station Name	Distance from Shore (m)
M-7 NS	46
M-7 SS	19
M-9 NS	32
M-9 SS	12
M-15 NS	<10
M-15 SS	72
M-38 NS	<10
M-38 SS	<10

Porewater Analyses

While Lee type seepage meters are well suited for obtaining seepage rates, the water that collects in the bags is not ideal for chemical analysis, due to microbial processing of the groundwater as it passes through the sediments and meter. In order to obtain more accurate groundwater chemical composition data, sediment cores were obtained from each location where seepage rates were measured. Cores were collected manually to a depth of 0.5 m inside 10-cm diam PVC liners. The cores were transported back to the University of North Carolina - Institute of Marine Sciences (Morehead City, North Carolina), where porewater from three depths within the core (2.5, 10, and 18 cm) were collected by needle and syringe. Porewater was analyzed for chemical composition of ammonium (NH_4^+), NO_3^-, and phosphate (PO_4^{-3}).

Nutrient samples were filtered through precombusted GF/F filters (0.7 μM pore size) and stored frozen until analyzed for NH_4^+, NO_3^-, and PO_4^{-3} using a high sensitivity autoanalyzer (Lachat Quick Chem. IV; Lachat Instruments, Milwaukee, Wisconsin). Following porewater collection, the sediment core was extruded to 2.5, 10, and 18 cm. At each depth, samples for sediment percent carbon (C) and percent nitrogen (N) analyses were obtained. These samples were stored frozen until analysis. Upon thawing, percent C and N samples were homogenized using mortar and pestle, dried for 24 h at 70°C, fumed in an HCl atmosphere to remove precipitated carbonate, and stored in a

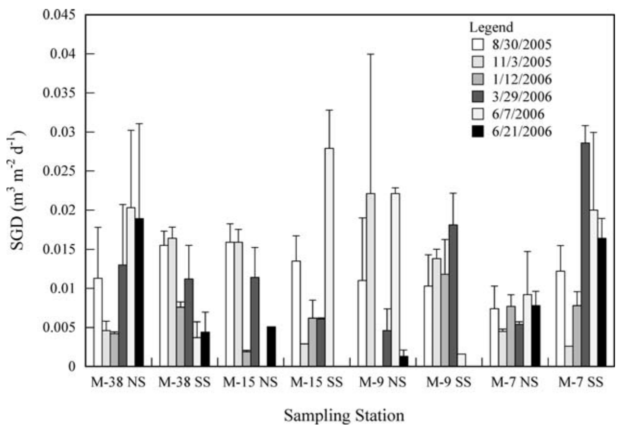

Fig. 2. Average seepage rate by sampling station and date. Error bars represent the standard deviation of the replicates.

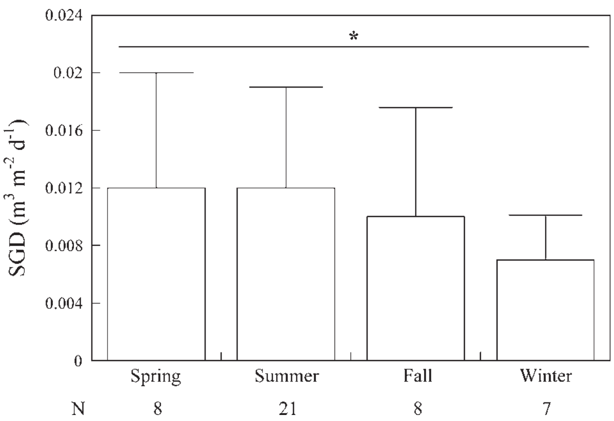

Fig. 3. Seasonally averaged submerged groundwater discharge (SGD). Error bars represent one standard deviation. * denotes significant difference based on a Kruskal-Wallis test.

desiccator until analysis. Percent C and N samples were analyzed using a Perkin Elmer model 2,400 series II CHN analyzer (Perkin–Elmer, Norwalk, Connecticut).

Data Organization and Loading Calculation

Statistical analyses were conducted using the SPSS for Windows 11.0 statistical package. Rates were compared to each other by spatial location using one-way analysis of variance. Seasonal averages were made based on the following groupings: spring (March-May), summer (June-August), fall (September-November), and winter (December-February). Rates were compared to each other by season using a Kruskal-Wallis test. The significance level used for all tests was 0.05. Reported errors represent one standard deviation of the mean. SGD rates are reported as water volume (m^3) normalized to sediment surface area (m^2) and time (d).

Loading calculations were determined using the following equation:

$$\text{Nutrient Load} = (\text{Average Discharge}) \times (\text{Average Porewater}) \times (\text{Area}) \quad (1)$$

where Average Discharge is the system-wide SGD average, Average Porewater is the system-wide average porewater nutrient concentration at the 2.5 cm core depth (see results section for these averages), and Area is the area of discharge (9.66×10^6 m^2) as estimated by Spruill and Bratton (Spruill written communication).

Results

Measured seepage rates were always positive and varied greatly across time and space. Figure 2 shows the averaged SGD rate for each sampling station during each deployment. The error bars represent one standard deviation of the mean from the triplicates. Seepage rates for the system ranged from 0.004 to 0.035 $m^3\ m^{-2}\ d^{-1}$. The overall system-wide average for SGD was 0.01 ± 0.007 $m^3\ m^{-2}\ d^{-1}$. The median value for our data set was 0.01 $m^3\ m^{-2}\ d^{-1}$. The highest SGD rate of 0.035 $m^3\ m^{-2}\ d^{-1}$ was measured at the M-9 NS site during the November 3, 2005 deployment. The lowest SGD rate of 0.004 $m^3\ m^{-2}\ d^{-1}$ was also measured at the M-9 NS site during the June 21, 2006 deployment. There were no statistical differences among the upstream, downstream, NS, and SS SGD rates. Changes in SGD were not tracked uniformly across the sampling stations between one sampling date and the next. Values at some stations increased while those at others decreased. There were significant differences among the four seasonal groupings ($p = 0.039$). Unfortunately, because of the nature of the nonparametric test, comparisons among the seasonal groups were not possible. Spring and summer had the highest seasonally averaged SGD rate, 0.012 ± 0.008 $m^3\ m^{-2}\ d^{-1}$ for spring and 0.012 ± 0.007 $m^3\ m^{-2}\ d^{-1}$ for summer. Fall had the next highest seasonal average of 0.01 ± 0.008 $m^3\ m^{-2}\ d^{-1}$, followed by winter, which had a seasonal average of 0.007 ± 0.003 $m^3\ m^{-2}\ d^{-1}$ (Fig. 3).

The sediment cores obtained were predominately sand over peat. The peat layer was usually below 18 cm and was not sampled, but sometimes the lower porewater sample did come from the peat layer. Sediment organic C values made it easy to determine when the peat layers were sampled. The peat layers exhibited high organic C values (18–40%) while the sand layers typically had sediment organic C values $< 4\%$. Porewater values were devoid of NO_3^- for the majority of the samples. Occasionally surface water NO_3^- was captured in

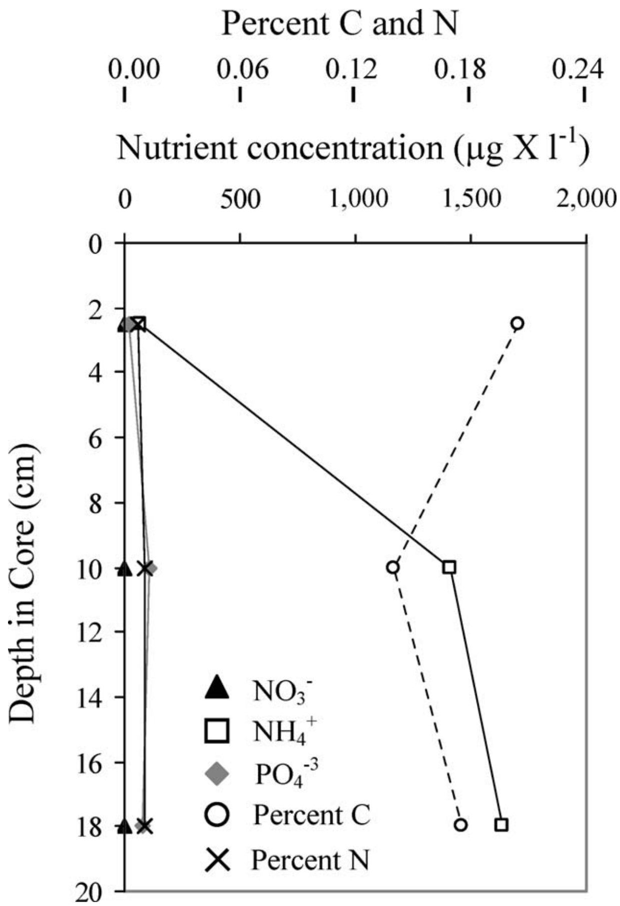

Fig. 4. Representative porewater profile showing nutrient, percent carbon (C), and percent nitrogen (N) plots. Example profile is from the M-7 SS June 21, 2006, deployment.

the upper porewater samples, but this rapidly decreased with depth of the core. On only four occasions was NO_3^- elevated in the lower porewater sample compared to porewater from upper sediment layers. Porewater NH_4^+ levels typically increased with sediment depth. NH_4^+ levels ranged between 23.2 and 11,200 μg N l^{-1}. Porewater PO_4^{-3} concentrations varied from 4.3 to 2,230 μg P l^{-1}. Phosphorus (P) levels in the porewater were below Redfield values in 64% of the porewater samples. Figure 4 shows a representative porewater profile plot.

The terms used in Eq. 1 to estimate SGD nutrient loading to the NRE are: Average SGD = 0.01 m^3 m^{-2} d^{-1}; Average Porewater = 544.4 μg N l^{-1} for dissolved inorganic N and 57.4 μg P l^{-1} for P; and Area = Spruill and Bratton's discharge area estimate of 9.66×10^6 m^2. Using these terms we calculate that 21.2 metric tons of N and 2.2 metric tons of P are being delivered by SGD to the NRE. As noted above, the majority of the N was NH_4^+.

Discussion

Our measured SGD rates (0.004–0.35 m^3 m^{-2} d^{-1}, average of 0.01 ± 0.007 m^3 m^{-2} d^{-1}) were comparable to those measured in other estuarine systems (Table 2). Staver and Brinsfield (1996) reported an average SGD rate of 0.11 m^3 m^{-2} d^{-1} for the Wye River Estuary, a tributary of the Chesapeake Bay. Kelly and Moran (2002) reported SGD rates for the Pettaquamscutt Estuary, Rhode Island, as ranging between 0.002–0.02 m^3 m^{-2} d^{-1}. Comparing rates is always difficult because as we found, local conditions have large influences on the rates and they tend to change quite rapidly. The best rate comparison we could obtain was based on work conducted by Spruill and Bratton (unpublished data). They measured seepage rates in the NRE from areas near our deployment sites April 2004 and September 2005 and calculated an overall system-wide average of 0.09 m^3 m^{-2} d^{-1} (Spruill written communication). Although this rate is higher than ours, several factors help explain the difference. Their sample locations were closer to shore than ours, so the land derived hydraulic head difference at their site was greater than at our sites as SGD has been shown to decrease with increasing distance from shore (Cable et al. 1997b; Taniguchi et al. 2003). They also did not prefill their sample bags, which could have enhanced their rate estimates (Shaw and Prepas 1989). Our study was conducted during a period of a winter-early spring drought for much of the Neuse River Basin (Fig. 5). This could have lowered our seepage rates relative to those from the previous study. The peat layer we observed could also have affected our measurements. The peat may have acted as a pseudoconfining layer forcing discharging groundwater to areas where the peat layer was not present. As most of our cores demonstrated sand over peat, this may be a consistent confounding variable in our data set. Future work should investigate the possible influence of the peat layers relative to SGD. This could be accomplished by sampling a transect from shore toward the center of the estuary for seepage rate and correlating it to presence-absence of the peat.

The random increases and decreases among the sampling stations suggest that system-wide forcing parameters are less important than local site-specific forcing variables. The lack of tidal influence in the NRE may allow local site-specific forcing variables to be observed whereas in systems with tidal influence they are masked. Potential site-specific variables could include rainfall amounts and frequency, height of the adjacent bank, porosity of the sediment, presence-absence of a benthic algal mat, and peat deposits, to name just a few. This current study cannot explore the effect of these or other

TABLE 2. Measured seepage rates compared to literature values.

Study	Location	Average SGD ($m^3\ m^{-2}\ d^{-1}$)
Kelly and Moran (2002)	Pettaquamscutt Estuary, Rhode Island	0.002–0.02
Charette et al. (2001)	Waquoit Bay, Massachusetts	0.01
Staver and Brinsfield (1996)	Wye River Estuary, Maryland	0.011
Swarzenski et al. (2006)	Loxahatchee River Estuary, Florida	0.02 to 0.074
Spruill and Bratton (unpublished data)	Neuse River Estuary, North Carolina	0.09
This study	Neuse River Estuary, North Carolina	(0.004–0.035) average = 0.01

potential influences, but it seems quite clear that they or some other local site-specific forcing factor are affecting the SGD in the NRE.

The high porewater nutrient concentrations (especially NH_4^+) coupled with the measured seepage rates suggest that SGD may be an important component of nutrient cycling within the system. Equation 1 predicts that 21.2 metric tons of N and 2.2 metric tons of P are loaded to the system via SGD annually. This loading calculation is complicated by the uncertain origin of the nutrients in the porewater. The nutrients in the porewater could be coming from two sources: transport from outside the estuary via the surficial aquifer, in which case the nutrients would be considered new; and from sediment degradation processes, which would not represent new nutrients, and would not represent loading from SGD. The data from this study do not allow separation of these two nutrient sources. The skewed N versus P enrichment in the porewater suggests that at least some of the N in the porewater is new and coming from external sources. If the majority of the N was from internal regenerated sources, then there should be analogous regenerated P as well, in near Redfield abundances. This argument is complicated by preferential binding of P to sediment particles (Lebo 1991). The N to P ratios of our porewater samples were often quite high (>100). At this ratio, it is doubtful there would be enough binding capacity in the sediments to account for the missing P. Despite these complicating factors, calculating the system load across the sediment water interface attributable to SGD in this manner is valid. For comparison, our loading estimates for N and P due to SGD represent 0.8% of the watershed N and 1.0% of the watershed P loads estimated by Stow et al. (2001) for the period 1991–1995 in the upper NRE watershed. Based on this analysis, SGD is a minor component to total system nutrient loading.

Regardless of the source of the nutrients in the porewater or the magnitude of SGD loading relative to watershed loading, the SGD represents a mechanism by which nutrients, especially N, can be transported from the sediments to the water column where they are available to support phytoplankton production. Sediment nutrient flux studies do not account for this mechanism. Cores removed from the system and incubated in the laboratory are removed from any hydraulic groundwater head, and benthic chambers are typically closed, preventing SGD from entering the chamber. Because most of the annual watershed N loading occurs during spring (Christian et al. 1991; Paerl et al 1998; Lebo et al. 2001), nutrients pumped from the sediments to the water column by SGD would be most important in late summer and early fall when the system is predominately reliant on internal nutrient sources. Summer was one of the seasons during our study with the highest measured SGD rates (Fig. 3). Kelly and Moran (2002) also noted high SGD rates in summer in the Pettaquamscutt estuary. Because only one year of data was collected and the data set was biased to the summer months due to the funding cycle, our seasonal comparison should be viewed with caution. The dry winter-early spring period that occurred during our sampling year (Fig. 5) also likely affected our winter and spring SGD averages. During a typical precipitation year, the winter and spring rates may have been higher.

If we consider the side to side seiching known to occur in the system (Buzzelli et al. 2002; Reynolds-Fleming 2003), then local small scale nutrient pumping by SGD potentially becomes an even more

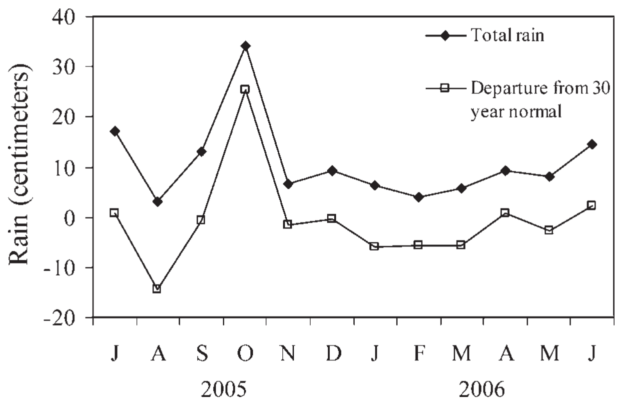

Fig. 5. Precipitation data during the study period from the National Oceanic and Atmospheric Administration-National Climate Data Center from station 316108 within the Neuse River Estuary basin at New Bern. Data show a moderate drought during the winter and early spring.

important player for main stem productivity as there is a mechanism present to move nutrients pumped into the shallow littoral zone out to the more central main stem areas of the NRE. The seiching may also be an important local driver for SGD, due to the cross channel flows it creates (Buzzelli et al. 2002; Reynolds-Fleming 2003). As noted earlier our sampling scheme was designed to observe system-wide forcings and not localized ones such as the effect of the seiching. Localized small scale nutrient pulses added to the system likely make SGD much more important than indicated by its relative contribution to total system nutrient loads as they occur throughout the estuary and throughout the entire year. This is in contrast to watershed N loading that tends to be concentrated in the late winter to spring time period and is usually attenuated quite rapidly in the upper reaches of the estuary.

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