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Impacts of a raw sewage spill on water and sediment quality in an urbanized estuary

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Abstract

A sewer main serving a large municipal wastewater system ruptured, discharging approximately 3,000,000 gallons (11,355,000 L) of raw human sewage into a multi-branched tidal creek estuary along the US East Coast. The biochemical oxygen demand caused severe hypoxia in the system, causing a large fish kill. The sewage load led to high fecal coliform bacteria concentrations in the creek (maximum of 270,000 CFU 100 ml^{-1}), which declined in an approximate logarithmic manner over the first few days. The spill caused elevated sediment fecal coliform bacteria and enterococcus counts that declined much more gradually than water column counts. Persistence of relatively high concentrations of fecal indicator bacteria in sediments for several weeks after the spill suggests that sediment sampling should be included in response to major sewage spills. The high concentration of nutrients in the spilled sewage led to several algal blooms. However, nutrient concentrations in the water column declined rapidly, demonstrating the value of conserving marshes because of their pollutant filtration function.

Keywords: Sewage; Fecal coliform bacteria; Sediments; Nutrients; Chlorophyll *a*; Estuary

1. Introduction

Raw human wastewater contains a potent mixture of contaminants, including biochemical oxygen demand (BOD), high concentrations of nitrogen and phosphorus, numerous chemicals, and a variety of bacteria, protozoans, and viruses that are pathogenic to humans. Modern sewage treatment plants are technologically capable of reducing sewage contaminants to concentrations harmless to humans. However, even in industrialized nations problems with sewage treatment systems continue to occur, contributing to restrictions on shellfish harvest, beach closures, and other environmental problems. In 1995 routine or accidental discharges from wastewater treatment systems were involved in 24% of the United States public waters closed to shellfish harvest (NOAA, 1998). An analysis of US beach closings and advisories in 2004 showed that sewage spills and overflows caused or contributed to 25% of the beach closing/advisory days where a cause of the contamination causing the closing could be determined (NRDC, 2005). Here we describe the multiple environmental effects that a raw sewage spill caused in an urbanized tidal creek and make recommendation for improving sampling methods to increase public protection from microbial contamination.

Hewletts Creek is a tidal, brackish tributary of the US Atlantic Intracoastal Waterway (ICW), located in southeastern North Carolina, USA (Fig. 1). Tides in this region are semidiurnal with a range of 1.1 m (Dame et al., 2000). It drains a 2393 ha watershed with a population of approximately 16,000 with approximately 22% impervious surface coverage. The entire creek contains approximately 74.7 ha of water and 31.3 ha of marsh. The upper portions of the creek consist of three tributaries stretching from 3 to 5 km inland, with fresh water in the uppermost reaches.

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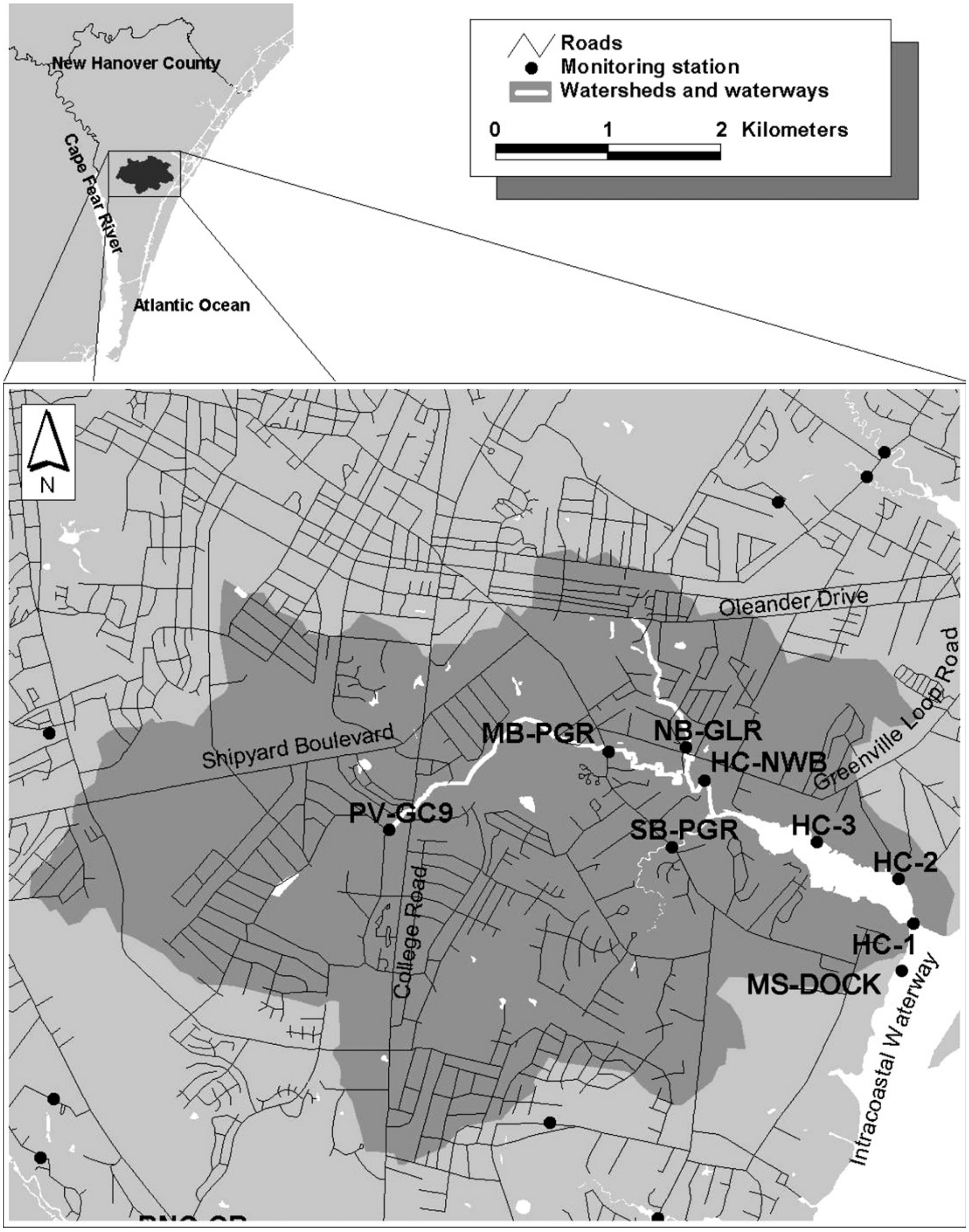

Fig. 1. Location of Hewletts Creek watershed in Wilmington, along the southeast coast of North Carolina, USA, showing sampling stations. The spill occurred at Station MB-PGR.

Middle and lower reaches are generally mesohaline, with near-marine salinities near the ICW. The middle and lower creek is bordered by salt marsh vegetation (especially *Spartina alterniflora*) with the main creek channel characterized by oyster reefs intermixed with sand flats (Cressman et al., 2003). The great majority of the watershed is served by a centralized sanitary sewer system operated by the City of Wilmington (population 94,000). To convey sewage from suburban areas to wastewater treatment plants located along the Cape Fear River (Fig. 1), sanitary sewer mains and pump stations are located along a number of tidal creeks in the area. Hewletts Creek has been the site of a number of ecological investigations (Mallin et al., 1999, 2000, 2004), and the pollutant spill described within occurred while various monitoring efforts were ongoing.

On Friday, July 1, 2005 the middle branch of Hewletts Creek at Pine Grove Road (station MB-PGR, Fig. 1) was subjected to a raw sewage spill of 11,355,000 L, or 3,000,000 gallons (GPS coordinates of this location are N 34.19807; W 77.87088). This occurred when a 60 cm force main coupling repair burst apart. This line carried sewage from a nearby beach community to a pump station (#34) on Hewletts Creek (near the breach) then on to the Wilmington South Side Wastewater Treatment plant located along the Cape Fear River Estuary). This line had been built in the mid 1980s using funds from the US Environmental Protection Agency. A citizen called the City at approximately 6:20 AM with a complaint; city workers were on site at 7:10 AM and found an obvious major leak. The workers turned the pump off but sewage continued to flow into the creek. During the course of the day they dug down 2–3 m to find the problem, finally finishing a temporary repair at 10:30 PM. The workers estimated that the spill had begun about 5:00 AM; thus the sewage spill occurred over a near-18 h period (Hugh Caldwell, City of Wilmington, personal communication). Some waste flowed into the creek or nearby swamp forest, and some flowed into the nearest storm drains, which drain directly into Hewletts Creek. Both the North Carolina Division of Water Quality (DWQ) and the NC. Shellfish Sanitation Section were alerted that morning. As a result, the NC Division of Marine Fisheries closed the creek and a large section of the Atlantic Intracoastal Waterway (ICW) and other nearby tributaries to shellfishing, and Shellfish Sanitation closed the same area to swimming. In the United States, shellfishing waters are required to maintain fecal coliform bacteria concentrations <14 colony forming units (CFU) per 100 ml of water. Bathing water standards are set by individual states; in North Carolina the freshwater standard is based on fecal coliform bacteria, and cannot exceed 200 CFU 100 ml^{-1}. The North Carolina marine bathing standard is based on an enterococcus standard of 33 CFU 100 ml^{-1}.

2. Materials and methods

During the first day the waste traveled down the creek into the ICW, then across the ICW and out to the ocean through the Masonboro Channel, according to strong sewage odors detected by citizens recreating on the ICW and the captain of a University of North Carolina Wilmington (UNCW) research vessel passing down the ICW. Regulators from the NC DWQ sampled the area on Saturday, July 2, then again on July 4 and 6. Researchers from UNCW sampled the water column in the area on July 3, 5, 7, 15, 21, and on August 8. A second UNCW research team collected sediment samples for fecal bacteria on July 6, 8, 11, 13, 15, 18, 20, 22, 26, 29, August 2, and August 11. Stations sampled included MB-PGR (spill site), SB-PGR (south branch at Pine Grove Rd.), NB-GLR (north branch at Greenville Loop Rd.), HC-M (creek mouth), HC-3 (at a dock on the north shore of the creek), HC-NWB (the northwest branch of the creek between HC-3 and the tributary stations) (Fig. 1). Two stations on the ICW were also sampled. Stations sampled for sediment bacteria include MB-PGR, SB-PGR, NB-GLR, and MS-DOCK, a control site located near the junction of Hewletts Creek and the ICW (Fig. 1).

Field parameters were measured at each site using a YSI 6920 Multiparameter Water Quality Probe (sonde) linked to a YSI 610 display unit. Individual probes within the instruments measured water temperature, pH, dissolved oxygen, turbidity, salinity, and conductivity. Water samples were collected for nutrient analyses (ammonium, nitrate, total Kjeldahl nitrogen, orthophosphate, and total phosphorus) and were analyzed using US EPA protocols. Samples for fecal coliform bacteria were collected by filling pre-autoclaved containers ca. 10 cm below the surface, facing into the stream. Samples were stored on ice until processing (<6 h). Fecal coliform concentrations were determined using a membrane filtration (mFC) method (method 9222, APHA, 1995). For chlorophyll *a* analysis triplicate water samples were filtered simultaneously through 25 mm Millipore AP40 glass fiber filters (nominal pore size 1.0 μm) using a manifold with three funnels. The chlorophyll *a* was extracted and subsequently analyzed using a Turner AU-10 fluorometer, following the method described in Welschmeyer (1994).

Sediment samples included fecal coliform bacteria and enterococci, and were obtained as follows. The top 2.0 centimeters of estuarine sediments were cored at each site. Three sediment cores were taken randomly at each site using sterile 2.20 cm ID acrylic tubing for sediment fecal indicator bacteria analyses. Following methods developed by Rowland (2002), each sample was transferred to a previously weighed, sterile 50 ml polypropylene centrifuge tube and placed on ice. The three samples were each mixed with 1 L of sterile phosphate-buffered rinse water inside a sterile 1 L flask with a stir bar. Each sample was gently stirred for 2 min prior to performing the membrane filtration technique. From the mixture of sterile phosphate-buffered rinse water and sediment, three 10 ml and three 1 ml samples were used for fecal coliform analysis using standard methods for membrane filtration of fecal coliform bacteria, method 9222 (APHA, 2001). The sediment and rinse water solution were mixed before each sample withdrawal to reduce fecal coliform burial and homogenize the bacteria suspension. All plates were incubated in a water bath for 24 h at 44.5 °C. After the 24-h incubation period, each plate was inspected for dark blue colonies. Each dark blue colony represented one colony-forming unit (CFU). Similar methods were used to estimate fecal enterococci following method 9230 C.3.a (APHA, 2001). Bacterial colonies satisfying the respective criteria for each method were counted after incubations using either the naked eye, or for plates with numerous colonies, an Olympus SZ-III stereo-microscope. Counts from each 10 ml sample from each of the three cores from each site were averaged and expressed as the number of colony forming units per square centimeter (CFU cm^{-2}) ± 1 SD.

3. Results and discussion

3.1. Dissolved oxygen and fish mortality

The approximate BOD5 of sewage from this system is 225 mg/L (City of Wilmington records). The day following the spill NC DWQ personnel did not report any dead fish in the creek or waterway, and creek dissolved oxygen (DO) concentrations were all at 5.0 mg l^{-1} or higher (Table 1). A day later, July 3, showed a much different situation. While the ICW remained clear, UNCW researchers sampling by boat began encountering dead fish about halfway up the creek from the ICW. About 100 were counted in the main channel, including 15 eels, 8 flounder, several mullet and numerous small fish. There were many decomposing gobs of flesh, with birds and crabs feeding on them (dissolved oxygen was 1.9 mg l^{-1}). The researchers then proceeded by truck to NB-GLR where about 200 dead fish were counted (DO 7.7 mg l^{-1}), then on to SB-PGR, where about 140 dead fish were counted, and many more seen floating upstream. There was a strong sewage odor present, and DO was 2.4 mg l^{-1}. The sewage had obviously been carried downstream from MB-GLR toward the ICW on the outgoing tide, then much of it was subsequently forced back upstream on the incoming tide into the north and south branches, where the BOD load from the sewage caused a decrease in DO. Many fish were trapped by the rising tide in hypoxic waters and died along the marsh edge. The high water temperatures (25–28 °C) led to rapid decomposition of the fish, contributing additional BOD to the sewage BOD load. The dead fish decomposed or were consumed by scavengers over the next two days; however, hypoxic waters <3.0 mg l^{-1} DO were present on July 4 and waters with DO < 4.0 mg l^{-1} were encountered on July 5. From July 6 on, all water sampled had DO values of 4.0 mg l^{-1} or higher (Table 1). Animal mortality was not confined to fish, however. On July 7 members of the research team photographed several waterfowl along the shore of the creek that were obviously sick and dying.

3.2. Water column fecal bacteria

On July 2 fecal coliform counts were elevated; at HC-3 they were 270,000 CFU 100 ml^{-1}, and in the creek mouth they ranged from 2000 to 3200 CFU 100 ml^{-1} (Table 2). However, counts were all below 100 CFU 100 ml^{-1} in the ICW. Fecal coliform bacteria counts in the water column of the creek were elevated (15,000–21,000 CFU ml^{-1}) on July 3, and then decreased to 220 CFU 100 ml^{-1} in the channel on July 4. After July 4 main channel fecal coliform bacteria counts generally stayed below 100 CFU 100 ml^{-1}.

Table 1
Water column dissolved oxygen concentrations by date and station following the July 1, 2005 Hewlett's Creek sewage spill (as mg l^{-1})

Station	7/2	7/3	7/4	7/6	7/7	7/15	7/21	8/8
HC-M	5.5	7.7		5.4	6.6	5.0	4.9	6.0
HC-3	5.0	3.5	5.7	5.1	6.3	6.3	4.0	5.5
HC-NWB		1.9			4.1			
SB-PGR		2.4	2.5	6.3	4.8	9.6	4.0	4.6
MB-PGR		7.6			7.0	6.1	6.1	6.5
NB-GLR		7.7	2.8	6.7	6.5	6.5	6.5	4.2

Blank spaces indicate no data collected.

Table 2
Water column fecal coliform bacteria counts by date and station following the July 1, 2005 Hewletts Creek sewage spill (as CFU 100 ml^{-1})

Station	7/2	7/3	7/4	7/6	7/7	7/15	7/21	8/8
HC-M	3200	176		1	9	5	46	1
HC-3	270,000	21,000	220	69	21	24	96	2
HC-NWB		15,800			242			
SB-PGR			3000	358	211	312	362	30
MB-PGR		2100	780		224	900	291	128
NB-GLR				3200	546	2900	655	180

Blank spaces indicate no data collected.

In contrast the tributaries (SB-PGR and NB-GLR) had maximum counts of approximately 3000 CFU 100 ml^{-1} until July 6, after which there was brief decrease. From July 13 to 15 about 4.5 cm of rain fell, and fecal coliforms showed an increase again on July 15 to 2900 CFU 100 ml^{-1} (Table 2). From then on, tributary fecal coliform counts decreased over the next few weeks to normal levels (approximately 100–400 CFU 100 ml^{-1}, Mallin et al., 1999, 2000). In the main channel during the first few days, daily loss of fecal coliforms from the water column followed a roughly logarithmic decrease. Loss of fecal coliforms from the water column can occur from predation by protozoans, mortality from sunlight (UV radiation), dilution by incoming tides and sedimentation. As will be seen in the following section, sedimentation of fecal bacteria was a critically important issue following this sewage spill.

3.3. Sediment fecal bacteria

Post-spill sediment bacteria sampling was initiated on July 6. Reference samples were available for Hewletts Creek as a related project regarding sediment fecal bacteria had been ongoing from 2004 (Cahoon et al., in review). Results (Tables 3 and 4) showed that post spill samples were an order of magnitude higher than pre-spill counts. Counts appeared to decrease after a few days, but the rain event (noted above) caused high sediment counts again (July 15). Previous research in this region had shown that sediment fecal coliform counts were significantly related to rainfall within the previous 24 h period (Toothman, 2006). Sampling was continued until early August. The latter dates showed a general decrease to background levels, with high counts periodically occurring. Fecal coliform and fecal enterococcus bacteria showed very similar patterns of increases and decreases in response to the original spill and the rain event of July 13–15. The fecal bacteria in the sediments form a reservoir of viable fecal microbes that is available to enter the water column following a mixing/stirring event such as a rainstorm or people or pets wading or otherwise disturbing the sediments. As an on-site test, on July 7 researchers collected a fecal coliform sample from the water at HC-3, and then proceeded to pass the boat motor over the site, stirring the water and sediments below. Counts taken from before the stirring were 21 CFU 100 ml^{-1} while counts taken after the stirring were nearly

Table 3
Sediment fecal coliform bacteria counts by date and station following the July 1, 2005 Hewletts Creek sewage spill (as CFU cm^{-2})

Station	10/31/04	1/28/05	7/6	7/11	7/15	7/22	8/2	8/11
MS-DOCK			0	0	23	0	0	11
SB-PGR	488	358	2740	526	5330	396	732	1890
MB-PGR			5110	1150	1450	777	457	80
NB-GLR	53	579	3510	442	991	663	1310	914

Samples collected 10/31/04 and 1/28/05 are shown as control (pre-spill) counts for comparison. Blank spaces indicate no data collected.

Table 4
Sediment fecal enterococcus bacteria counts by date and station following the July 1, 2005 Hewletts Creek sewage spill (as CFU cm^{-2})

Station	10/31/04	2/14/05	7/6	7/8	7/11	7/13	7/15	7/18	7/22	7/26
MS-DOCK			0	0	0	0	229	0	0	0
SB-PGR	137	221	152	229	0	381	10,300	76	686	114
MB-PGR			4570	5030	457	0	7770	152	229	305
NB-GLR	38	366	533	76	152	610	9370	457	76	229

Samples collected 10/31/04 and 2/14/05 are shown as control (pre-spill) counts for comparison. Blank spaces indicate no data collected.

three times greater, 60 CFU 100 ml^{-1}. The relatively high fecal indicator bacteria levels in water and sediment samples within Hewletts Creek and very much lower concentrations in water and sediment samples taken outside the creek suggest that for the most part these bacteria were retained within the creek itself. Studies of the flushing rate of Hewletts Creek showed that about 52% of the water in the middle and lower creek is exchanged with each tidal cycle (Hales, 2001), so high retention of fecal bacteria indicates that sedimentation and other processes were very important in preventing broader dispersal of the particulate or suspended contaminants generated by this spill.

We calculated daily attenuation coefficients for water column and sediment coliforms and sediment enterococcus, using the ten largest initial values that led to subsequent decreases, and using the equation: $k = \ln(N_t/N_o)$/days. Resulting values were: water column coliforms: range = −0.07 to −4.56, mean value = −1.54; sediment coliforms: range = −0.04 to −0.41, mean = −0.20; sediment enterococcus: range = −0.45 to −1.64, mean = −0.95. There is a bias in that sediment sampling began several days later than the water column sampling, but the data do bear out the contention that attenuation in the water column was initially very fast, although the sediment coliforms and enterococci appear to behave differently (i.e. diminish at different rates).

The presence and persistence of the sediment fecal bacteria demonstrate that water column sampling of fecal bacteria is insufficient when analyzing an area for human contact safety after a pollution event; sediment sampling also produces necessary data. Rapid sedimentation of fecal indicator bacteria from the water column may falsely indicate a return to safe conditions, when contact with polluted sediments is actually hazardous. Although no regulatory standard for sediment-associated fecal pathogen indicators exists *per se*, a useful comparison is to consider that 200 CFU cm^{-2} of sediment fecal coliform bacteria, if suspended in a 1-m deep water column corresponds to the 200 CFU 100 ml^{-1} standard for human body contact. Similarly, sediment fecal enterococcus counts of 33 CFU cm^{-2}, if suspended in a 1-m deep water column correspond to the human body contact standard of 33 CFU 100 ml^{-1}. Persistence of relatively high concentrations of fecal indicator bacteria in sediments for several weeks after the spill, and long after water column values had declined, suggests that sediment sampling should be included in response to major sewage spills, especially in situations in which direct human exposure is possible.

That was not the only pollution incident to affect Hewletts Creek in 2005, however. Another sewage spill occurred in the Hewletts Creek watershed September 15 when a 60 cm line ruptured and spilled an unknown volume of sewage onto Shipyard Drive and ditches and yards along Pine Valley Drive. Some of the waste entered storm drains, and from there entered Hewletts Creek. Repairs were completed the next morning. Samples collected in Hewletts Creek by the research team found elevated fecal coliform bacteria counts in the upper tributary stations (PVGC-9 – 2487 CFU 100 ml^{-1}; MB-PGR – 2790 CFU 100 ml^{-1}; SB-PGR – 2195 CFU 100 ml^{-1}; NB-GLR – 840 CFU 100 ml^{-1}). Station MB-PGR is located downstream from PVGC-9 (Fig. 1). Subsequent sampling on September 19 showed a considerable water-column decrease in fecal coliform bacteria (PVGC9 – 380 CFU 100 ml^{-1}; MB-PGR – 700 CFU 100 ml^{-1}; SB-PGR – 160 CFU 100 ml^{-1}; NB-GLR – 400 CFU 100 ml^{-1}) to levels commonly found at these locations (Mallin et al., 1999, 2000), although the main channel sites were still elevated (HC-3 – 60 CFU 100 ml^{-1}; HC-2 – 100 CFU 100 ml^{-1}). Sediment samples collected after this spill on September 19 also showed high levels of fecal coliform and fecal enterococcus bacteria persisting for at least a week after the spill (Table 5).

3.4. Nutrients and algal blooms

Nutrient concentrations in the raw sewage passing through this pipeline are high (total Kjeldahl nitrogen (TKN) = 40.2 mg l^{-1}; ammonium = 23.3 mg l^{-1}, total

Table 5
Sediment fecal coliform (FC) and enterococcus (FE) bacteria counts by date and station following the September 15, 2005 Hewletts Creek sewage spill (as CFU cm^{-2})

Station indicator		9/19/05	9/23/05
MS-DOCK	FC	0	0
	FE	0	0
SB-PGR	FC	1670	1600
	FE	1220	152
MB-PGR	FC	2360	6020
	FE	76	305
NB-GLR	FC	380	1300
	FE	229	381

phosphorus (TP) = 5.3 mg l^{-1} – City of Wilmington records). Upon reaching the creek following the spill, nutrient concentrations apparently decreased at a surprisingly fast rate. Even on July 2 at the mid-channel station HC-3, TKN levels were <2.0 mg l^{-1}, ammonium <1.0 mg l^{-1}, nitrate <0.3 mg l^{-1}, and TP was <0.06 mg l^{-1}. Because sewage is anaerobic with a high BOD, the principal inorganic nitrogen form is ammonium rather than nitrate. By July 5 TKN decreased to <0.7 mg l^{-1} and ammonium, nitrate, and orthophosphate concentrations were at approximate background levels (Mallin et al., 2004). Some of the nutrients were clearly taken up by phytoplankton; blooms were recorded at NB-GLR on July 7 and July 21 of 43 and 80 μg l^{-1} chlorophyll *a*, respectively, and blooms of 30, 133, and 60 μg l^{-1} chlorophyll *a* were recorded at SB-PGR on July 7, July 15, and July 21, respectively (Fig. 2). One of the blooms (July 15) was analyzed by microscopy. At SB-PGR the bloom was dominated by cryptomonads, primarily *Chroomonas amphioxiae*. AT NB-GLR the flora was a mixture of *Nitzschia closterium*, small naviculoid diatoms, cryptomonads, the euglenoid *Eutreptia* sp. and the dinoflagellate *Gymnodinium* sp. Ammonium is readily utilized by phytoplankton and ^{15}N enrichment studies in the moderately eutrophic Parker River estuary in New England showed that planktonic diatoms were the principal conduit of the added nitrogen to the food web (Hughes et al., 2000). In Hewletts Creek nutrient addition bioassays have demonstrated that the phytoplankton community is strongly stimulated by nitrogen inputs (Mallin et al., 2004).

The rapid decrease in nutrients can in part be attributed to tidal flushing. Two dye tracer experiments performed by Hales (2001) during 1999 and 2000 indicated that in the mid-to-lower portion of Hewletts Creek 52% of the water is exchanged with water from the ICW over a 12.4 h tidal cycle. During the start of the sewage leak the tide was going out, and continued to do so for about 4 h. The tide then reversed, coming in for 6 h and polluting the upper north and south tributaries. The tide was outgoing for another 4 h before the leak was repaired. The spill therefore occurred during both outgoing and incoming tides, but the nutrient load declined within 24–36 h; thus, other mechanisms clearly must have accounted for much of the nutrient removal.

In addition to phytoplankton uptake and dilution from flushing, clearly the salt marsh must have absorbed a large amount of the nutrient load from the sewage, either onto the sediments (Wetzel, 2001) or into the sediment microbial community (Tobias et al., 2003a) and into *Spartina* and other macrophytes (White and Howes, 1994; Tobias et al., 2003b). Benthic microalgae (Tobias et al., 2003a) can be a significant sink for nitrogen inputs in a marsh estuary system. Data from a related project (Fig. 3) showed low springtime concentrations of benthic chlorophyll *a* at SB-PGR and NB-GLR (5.4 and 20.8 mg m^{-3}, respectively). However, by September 2005 there was an increase in benthic chlorophyll *a* at NB-GLR to 210 mg m^{-3}, though SB-PGR remained low at 3.5 mg m^{-3}. Thus, the benthic microalgae at NB-GLR may have been stimulated by the anthropogenic N load. However, in the main creek at HC-3 benthic chlorophyll a actually showed a decrease from pre-spill to September concentrations (Fig. 3). By winter all sites had elevated benthic chlorophyll *a* concentrations ranging from 150–282 mg m^{-3}, though this increase may have been due to increased water clarity in winter. Thus, the benthic microalgae at NB-GLR may have been stimulated by the anthropogenic N load, but that did not appear to be the case with other stations. Denitrication probably was not a major sink as the bulk of the inorganic

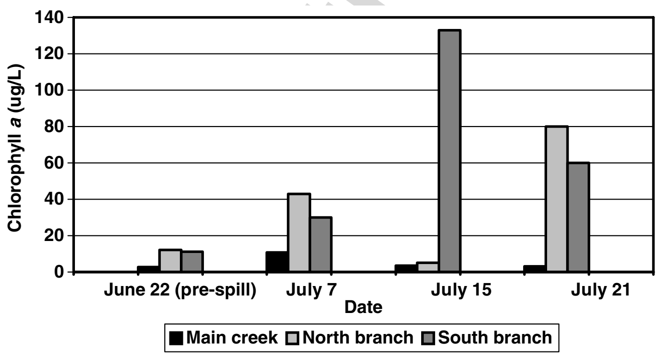

Fig. 2. Mean phytoplankton chlorophyll *a* concentrations in three areas of Hewletts Creek before and after the July 1, 2005 raw sewage spill (mean of three replicate samples).

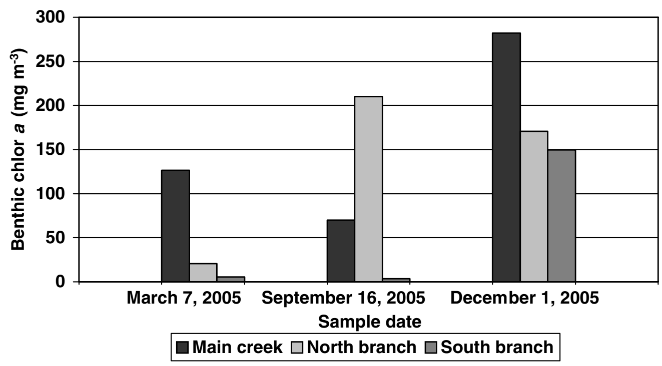

Fig. 3. Mean benthic microalgal chlorophyll *a* concentrations before (March) and after the July 1, 2005 sewage spill into Hewletts Creek (mean of six replicate samples).

nitrogen load was in the form of ammonium rather than nitrate, which is the inorganic nitrogen form processed during denitrification (Wetzel, 2001). Since hypoxic conditions predominated in upper creek areas for several days following the spill (Table 1) there was likely little opportunity for nitrification followed by denitrification. However, direct bacterial uptake of nitrogen, especially in the reduced form of ammonium, was likely an important N sink.

The TP load from the raw sewage likewise decreased rapidly. Besides uptake by primary producers, uptake into the marsh bacteria was probably a strong sink for this nutrient. Marsh bacterial communities are limited by phosphorus rather than nitrogen (Sundareshwar et al., 2003), and bacteria can often outcomplete algae for phosphorus (Cotner et al., 2000; Wetzel, 2001). Collectively the various nutrient cycling and removal capabilities of the tidal marsh argue for strong wetland conservation measures. The estimated monetary value that estuaries/tidal wetlands provide in nutrient cycling and waste treatment is considered to be high (Costanza et al., 1998); the aftermath of this wastewater spill demonstrates this, at least in terms of excess nutrient removal.

4. Conclusions

Regulatory authorities lifted the ban on swimming in the ICW after a 2-week period. However, due to the persistence of the fecal bacteria in the sediments and the increases noted after rain events, the ban on swimming in Hewletts Creek remained in effect for the remainder of the summer of 2005. Anecdotally, several individuals who were swimming or otherwise recreating in the ICW during the Fourth of July weekend reported various infections. The City made permanent repairs on the break Tuesday August 9 with a heavy-duty coupler made of cast iron. As an additional complementary measure a low flow alarm was installed at the Southside Wastewater Treatment Plant to detect low flow from the pump station on Hewlett's Creek.

The July 1 sewage spill demonstrated that following a major pollution incident where human or animal waste is involved, sampling the water column for fecal bacteria is not sufficient to obtain a complete picture of the system in terms of human health issues. Large quantities of the fecal bacteria settled to the sediments and remained viable for several weeks, and were clearly subject to resuspension in the water column after a mixing event. This has been demonstrated previously following a large swine waste lagoon spill that entered the New River, North Carolina, and its estuary (Burkholder et al., 1997). There, significant quantities of fecal bacteria remained in the sediments for nearly three months. Fecal bacteria on or in the sediments are largely protected from UV radiation, a principal means of death or deactivation in the water column. Also, the sediments contain carbon, nitrogen, and phosphorus, key nutrients for survival and growth. We recommend that regulatory authorities devise sampling and assessment plans for pollution incidents that consider sediment-associated fecal bacteria.

The sewage spill also illuminated the function of the salt marsh-tidal creek system as a nutrient removal or recycling mechanism. Raw sewage has very high nutrient concentrations, yet the nutrients rapidly disappeared from the water column. While post-spill phytoplankton blooms indicated rapid nutrient uptake by these primary producers, it is likely that additional uptake occurred into benthic and epiphytic microalgae (periphyton) salt marsh macrophytes (principally *Spartina*), and the sediment microbial community.

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