Bald Head Creek Water Quality:

Before and After Dredging

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Executive Summary

Bald Head Creek is a brackish tidal creek located along the southwest side of Bald Head Island, Brunswick County, in southeastern North Carolina. The island is located on the eastern shore of the Cape Fear River estuary immediately before it enters the Atlantic Ocean. Bald Head Creek was closed to shellfishing due to excessive fecal coliform counts in 1992, with the mouth area reopened in December 2006. A study had concluded that tidal exchange rates were low in the creek, compared with other area tidal creeks. The Village of Bald Head Island requested permission from regulatory agencies to dredge the mouth of the creek to improve tidal exchange and reduce fecal bacterial contamination levels. Permission was obtained and the creek mouth was dredged in January 2006. As part of the agreement the Village funded the University of North Carolina Wilmington to perform a before-and-after dredging study of the creek's water quality. Sampling was performed in 2002-2003 and 2006-2007.

The results demonstrated that the dredging did not improve water quality in the creek. There were no statistical before-and-after differences in fecal coliform bacterial counts, or nutrient, chlorophyll *a* or dissolved oxygen concentrations. However, total suspended sediments and turbidity significantly increased at selected stations following dredging. A companion study that tested tidal flushing rates in the creek found that tidal exchange rates were almost exactly the same eight months after dredging as they were before dredging. It is hypothesized that the Cape Fear River rapidly moves suspended sediments across and into the mouth of the creek on the incoming tide, and frequent maintenance dredging would be required to elevate tidal flushing in this creek.

Since the creek mouth area is presently open to shellfishing, and impervious surface coverage in the creek watershed is presently low (< 10%) we advise the Village to make strong efforts to keep the creek mouth area open to shellfishing by preventing future increases in fecal bacterial counts. These efforts would include increasing the use of pervious pavement in newly developing areas of the island, utilizing rain gardens to capture and treat stormwater runoff where impervious pavement occurs, and strictly enforcing pet waste ordinances.

Introduction

Bald Head Creek is a brackish tidal creek located along the southwest side of Bald Head Island, Brunswick County, in southeastern North Carolina. Bald Head Island is on the terminal portion of Cape Fear, the southernmost cape in North Carolina. The island is located on the eastern shore of the Cape Fear River estuary immediately before it enters the Atlantic Ocean, and while considered an island, the shoreline is technically connected to the mainland at Fort Fisher since New Inlet closed in 1999. Bald Head Creek is a second order stream that begins in a maritime forest and terminates in the lower Cape Fear Estuary (Fig. 1). It is approximately 6 km (3.7 miles) long, and separates Bald Head Island from its central and northern portions, Middle Island and Smith Island. Bald Head Creek was closed to shellfishing due to excessive fecal coliform counts in 1992 (LMG 2004). The mouth area has subsequently been reopened to shellfishing, but the rest of the creek remains closed.

The Village of Bald Head Island is largely recreational with a population that can range from 100 during winter to 5,000 in the summer (NCDEH 2001). Most of the residents are served by a tertiary wastewater treatment plant with a 200,000 GPD capacity, and treated and chlorinated effluent is discharged into an infiltration pond on the golf course (NCDEH 2001). There are some septic systems in use in the Bald Head Creek watershed.

The elevated fecal coliform bacteria counts in the creek that caused it to be closed for shellfishing were apparently due to non-point source pollution. North Carolina Shellfish Sanitation has stated that a dye study indicated that the septic systems on the island were not contributing fecal coliforms to groundwater discharge (NCDEH 2001). That study also concluded that wildlife were the most likely source of fecal coliform contamination in Bald Head Creek, compounded by the low rates of tidal flushing. Tidal exchange rate dye studies conducted by Jason Hales of the University of North Carolina at Wilmington in 1998 and 1999 found that percent exchange rates varied between 18% and 33%, which is low compared with other area tidal creeks (Hales 2001).

Based on a study performed in Futch Creek, located in northern New Hanover County along the Atlantic Intracoastal Waterway (Mallin et al. 2000a), creek mouth dredging was suggested as a means of reducing fecal coliform pollution. This was based on the fact that higher salinity kills fecal coliform bacteria more quickly than fresh or low salinity waters (Evison 1988; Mallin et al. 1999), and the potential that dredging will also improve dilution of the pollutants by allowing greater tidal exchange. The Aquatic Ecology Laboratory at the UNC Wilmington Center for Marine Science also performed a water quality study of the water bodies located in and near Mason Inlet before the dredging and moving of that inlet. That study concluded that water quality, including fecal coliform bacteria concentrations, was good before Mason Inlet dredging and remained so following inlet movement (Mallin et al. 2003a). In 2003 the Village of Bald Head requested permits to dredge the mouth of Bald Head Creek to improve water quality. In 2003-2004 the UNCW Aquatic Ecology Laboratory performed a baseline water quality study on Bald Head Creek to gather information relevant to the proposed dredging and construction activity at the mouth of the creek. The Village of Bald Head Island subsequently obtained permission to dredge the creek mouth, and the dredging was completed between January 3 and January 24, 2006. In 2006-2007 the UNCW Aquatic Ecology Laboratory completed a follow-up sampling program to examine the creek water quality for changes following dredging.

Methods

During both studies samples were collected at four stations on the creek. Station A was located off a private dock near the creek mouth, Station B was off the old Boat House Dock on the south side of the creek, Station C was off a dock on the north side of the creek about four km upstream from the mouth of the creek, and Station D was off a small dock in the creek headwaters (Table 1; Fig. 1). During the pre-dredging phase, nine collections were made, during June, July, August, September, October (two collections), November and December 2003 and one collection in January 2004. Following dredging, eight more collections were made in July, August, September, October, November and December 2006, and in January and February 2007. Samples were collected at or just after high tide so comparisons could be made with data from a project analyzing urbanized tidal creeks along the Atlantic Intracoastal Waterway (ICW) in New Hanover County (Mallin et al. 2004a).

Table 1. Locations and coordinates of sampling sites in Bald Head Creek

Site	Location
BH-A	Off first private dock on Tanbark Court near mouth of Bald Head Creek
BH-B	Off old boathouse dock at end of Boat House Path
BH-C	Off public floating dock on north shore of creek, accessible from Cape Creek Road
BH-D	Off small community dock at headwaters of creek adjacent to Cape Creek Road just after the terminus of South East Beach Road

Field parameters (water temperature, pH, dissolved oxygen, turbidity, salinity, and conductivity) were measured at each site using a YSI 6920 Multiparameter Water Quality Probe (sonde) linked to a YSI 650MDS display unit. The instruments were calibrated prior to each sampling trip to ensure accurate measurements.

For nitrate+nitrite (hereafter referred to as nitrate) and orthophosphate assessment, three replicate acid-washed 125 mL bottles were placed ca. 10 cm below the surface, rinsed, filled, capped, and stored on ice until processing. In the laboratory the triplicate samples were filtered simultaneously through 25 mm Gelman A/E glass fiber filters (nominal pore size 1.0 micrometer) using a manifold with three funnels. The pooled filtrate was stored frozen until analysis. Samples for ammonium were collected in duplicate, field-preserved with phenol, stored on ice, and analyzed in the laboratory according to the methods of Parsons et al. (1984).

Chlorophyll *a* concentrations were determined from the filters used for filtering samples for nitrate+nitrite and orthophosphate analyses. All filters were wrapped individually in aluminum foil, placed in an airtight container with dessicant and stored in a freezer. During the analytical process, the glass fiber filters were separately immersed in 10 mL of a 90% acetone solution. The acetone was allowed to extract the chlorophyll from the filter for 18-24 hours. The extracted material was then analyzed for chlorophyll *a* concentration using a Turner AU-10 fluorometer.

This method uses an optimal combination of excitation and emission bandwidths that reduces the errors inherent in the acidification technique (Welschmeyer 1994).

Bacteria samples were collected by lowering pre-autoclaved 500 ml glass containers about 10 cm below the water surface, facing into the current. Samples were kept on ice in coolers until processing at the laboratory, within six hours of collection. The method used in this study to assess fecal coliform concentrations was the membrane filtration method (mFC), described in Standard Methods (APHA 1995). This method utilizes an elevated temperature incubation to distinguish fecal coliforms from the total coliform group. Total suspended solids, or TSS, were collected in 500 mL containers, placed on ice, and analyzed using Method 2540-D according to Standard Methods (APHA 1995).

The two sets of samples (pre-dredging and post-dredging) were tested statistically by station and parameter for significant difference ($p < 0.05$). All statistical analyses were performed using SAS Institute's JMP v. 6.0. The data sets were first tested for normality using the Shapiro-Wilk test. Differences between sampling events were determined using a Paired-Difference t-test for normally distributed data and using the Wilcoxon Signed Rank Test for non-normally distributed data.

Additionally, YSI 6920 instruments were deployed in-situ at docks at Stations A and B in order to obtain short interval data over two diel cycles (August 2003 and January 2004, and again in November 2006 and march 2007). The data were compared to determine if salinity and other parameters changed following dredging.

A post-dredging dye study was conducted on Bald Head Creek in January 2007 (ESP Associates 2007). Methods, sampling sites, and lead personnel were the same as those in the previous study (Hales 2001). This provided researchers with a solid physical basis to analyze the effectiveness of creek mouth dredging in improving tidal exchange rates in Bald Head Creek.

The watershed boundary was generated using data from the NC Floodplain Remapping Project (20 ft grid Digital Elevation Model for Bald Head Island and surrounding area) A 20 ft DEM is a digital model of terrain with each grid cell measuring 20' by 20' on the ground. Each cell has a Z or elevation value representing "bare earth" elevation. Relationships between adjoining cells can be analyzed in the software cited below. The data were processed using ESRI ArcMap 9.1 with the Spatial Analyst extension and ArcHydro Tools V1.2 The 20ft cell DEM was used to find the watershed boundaries for Bald Head Creek. A minimal amount of manipulation of the data was performed and no independent verification of data against known elevations was done. In order to improve performance of the terrain model for delineating the watershed, the elevation values along the creek centerline were lowered. This line was not very accurate but it has the effect of pulling the overland flow towards the creek. In this process we reconditioned the terrain model by raising all cells by 123ft and then "burning in" the creek centerline and filled all sinks so overland flow would continue to an outlet point. The result of this was an estimation of the watershed boundary based on terrain only, with no regard to any constructed or subsurface drainage features. Giving time and resources the model could be improved by digitizing legitimate sinks (such as golf course ponds), computing flow direction, flow accumulation, and streams (overland flow patterns) from the terrain model, delineating catchments, specifying catchment outlet points and grouping catchment areas into watersheds based on outlet point locations.

For estimating impervious surface in the watershed data from the Brunswick County GIS unit and Tax Assessors office were acquired. The data included parcel lines, road centerlines, and detailed tax assessors data. Parcels were classified as either inside or outside of the watershed and no further analysis of those properties classified as outside of the watershed was performed. Road centerlines were corrected according to road features visible in an April 2006 aerial photo. Road centerlines were terminated at the boundary of the watershed and any road features existing outside of the watershed boundary were deleted. The road centerlines were buffered by 5, 7, and 10 ft to derive a total impervious area for roads in the watershed if roads were assumed to be either 10ft, 14ft, or 20ft width. Using tax assessor's data and visual review of the aerial photos, parcels having non-single family type development or parking lots were selected and impervious surface for these areas was digitized in the GIS to derive the total impervious surface area. All remaining parcels were classified as either developed or undeveloped and assumed to have a total impervious area of 2500 sq ft if developed. All these data were compiled using the GIS and an estimate of total area of impervious surface within the watershed boundary was generated.

Roads estimated at 20 ft wide totaled 2,285,234 ft^2 of road surface in the watershed; roads estimated at 14 ft wide totaled 1,607,319 ft^2 of road surface in the watershed; roads estimated at 10 ft wide totaled 1,151,832 ft^2 of road surface in the watershed. Total digitized impervious surface yielded 536,729 ft^2 of building/parking lot footprint. The number of parcels developed but not digitized totaled 379 X 2,500 ft^2; the estimated impervious surface for the lots is 947,500 sq ft of house, driveway, etc. Total area of watershed was thus estimated at 69,933,987 ft^2.

Results and Discussion

Water Temperature: In the pre-dredging study water temperature at all four sites averaged from 21-22 ^{o}C for all sampling events. There were no incidents of freezing and no extremely warm periods (maximum of 31.6 ^{o}C). In the post-dredging period (2006-2007) temperatures averaged 19 ^{o}C , and there were no incidents of freezing or excessive heat (maximum of 29.2 ^{o}C).

Salinity: Based on samples collected in conjunction with the chemical and biological parameters, pre-dredging salinities were polyhaline to euhaline (polyhaline ranges from 16-25 ppt and euhaline ranges from 26-34 ppt) on average at all four sites (Table 2; Fig. 2), with a general decrease from the mouth (29.2 ppt) to the headwaters station BH-D (21.2 ppt). We emphasize that these samples were collected on the outgoing tide, shortly after high tide, thus salinities during sample collection represent near maximum salinities normally experienced at the sample sites. Average and minimum (14.8 ppt) salinities at the uppermost station BH-D indicate that there was only minor freshwater influence into this creek from the watershed. Post-dredging average salinities (Table 3; Fig. 2) ranged from 30.0 ppt at the mouth station to 24.0 ppt at BH-D (Table 3). Minimum salinity at BH-D was 16.6 ppt, again indicating relatively low freshwater inputs into the headwaters.

For the pre-dredging period diel data were collected every 30 minutes at BH-A and BH-B, from August 19-20, 2003 and from December 17-18, 2003. December 2003 data show that salinity ranged from 14.5 ppt at low tide to 29.1 ppt at high tide near the creek mouth at BH-A, while there was a narrower range of 15.3 ppt to 19.4 ppt farther upstream at BH-B (Fig. 3). Salinities collected during the diel measurement in August 2003 at BH-A were considerably lower, ranging from 10.9 at low tide to 26.5 ppt at high tide, while values at BH-B ranged from 10.0 ppt at low tide to 15.3 at high tide. The August 2003 diel study was conducted during a period of high river discharge when salinities were lower than normal in the Cape Fear Estuary. The river appears to play the major role in regulating creek salinity, as opposed to freshwater inputs to the headwaters.

Post dredging diel data were collected on November 27-28, 2006 and March 5-6, 2007, at the same locations. November 2006 salinity data ranged from 8.5 to 27.2 ppt near the creek mouth and from 9.1 to 18.7 farther upstream at BH-B. The 8.5 ppt minimum seen at BH-A indicates strong river influence of salinity at this station. In March 2007 salinity at BH-A ranged from 17.2 to 29.8 ppt, and at BH-B it ranged from 17.9 to 23.3 ppt. During March 2007 low rainfall conditions persisted in the watershed, while in November 2006 wetter conditions (and lower river salinities) were evident.

Dissolved oxygen: The pre-dredging samples indicated that dissolved oxygen concentrations in the creek were typical of area tidal creeks, with highest concentrations during winter and lowest during summer (Fig. 3). Concentrations less than the North Carolina state standard of 5 mg/L were seen twice at BH-C and three times at BH-D, during the June to September 2003 period, with a minimum level of 3.7 mg/L at BH-D in September (Table 2). As a comparison, dissolved oxygen concentrations at Channel Marker 18 in the lower Cape Fear Estuary near Southport averaged 8.1 mg/L (Mallin et al. 2003b), slightly higher than those at BH-A which had a mean of 7.6 mg/L (Table 2). In the post-dredging period (Table 3) a number of samples were well below the state standard, and average dissolved oxygen concentration for all four sites combined were below 4.0 mg/L during both July and August 2006 (Fig. 3). The study minimum was 3.1 mg/L at site BH-C in July 2006; again overall lowest dissolved oxygen levels occurred at the two uppermost stations. Statistical comparisons indicated that the two data sets did not differ significantly at any station.

Turbidity: The pre-dredging samples showed a pattern of highest turbidities at the mouth and uppermost creek stations, with somewhat lower turbidities at the two mid-creek stations (Table 2). There was only one incident when turbidity exceeded the NC State standard of 25 NTU (33 NTU at BH-D on October 29, 2003). During the post-dredging sampling period turbidities were less variable among sites, and on average among the four sites ranged from 11-14 NTU with no incidents of turbidity exceeding the state standard occurring (Table 3; Fig. 4). Turbidity in the post-dredging set was significantly higher than the pre-dredging set at BH-C ($p = 0.004$). As a comparison, average 2002-2003 turbidity concentrations at Channel Marker 18 in the lower Cape Fear Estuary near Southport were identical to those at BH-A (Mallin et al. 2003b), and turbidities at M18 in 2005 were similar to those at BH-A in 2006-7 (Mallin et al. 2006). Thus, we suspect that turbidity enters the creek from the river, and is also a function of eroded particles from soils in the headwaters of Bald Head Creek.

Total Suspended Solids (TSS): In the pre-dredging period average TSS concentrations were quite consistent across the four sampling sites (Table 2). Concentrations were slightly higher at the creek mouth (BH-A), possibly a result of tide and river current activity resuspending and moving sand. Average 2002-2003 TSS concentrations at Channel Marker 18 were 13 mg/L (Mallin et al. 2003b), considerably lower than those at BH-A in the 2003-2004 period. In the post-dredging period TSS was highest at BH-A and BH-B, with a peak of 123 mg/L at BH-A (Table 3). On average TSS was considerably higher than it was in the 2003-2004 period (Fig. 5), with overall averages for the four sites ranging from 47-66 mg/L. In particular the winter 2006-7 period from November through February had particularly high TSS levels (Fig. 5). TSS concentrations at BH-A, BH-B, and BH-D were all significantly greater during the post-dredging period than during the pre-dredging period ($p < 0.05$). TSS concentrations in the river at Channel Marker 18 in 2005 were on average 14 mg/L (Mallin et al. 2006), much lower than 2006-2007 concentrations within Bald Head Creek. However, Channel Marker 18 is located on the other side of the estuary in deep water. Suspended sediments are carried along the shore of Bald Head Island on the flood tide and are likely a source to the creek proper.

<u>Ammonium-N</u>: In the pre-dredging period ammonium concentrations presented a pattern of lowest values nearest the river and highest values in the headwaters (Table 2). Ammonium concentrations at BH-A, BH-B, and BH-C were in the same range as concentrations in Futch, Howe, and Hewletts Creeks along the ICW, but concentrations at BH-D were somewhat higher (Mallin et al. 2004b). Ammonium is a decomposition product; thus, the higher values in the headwaters may reflect decomposition of accumulated biotic material in that area, retained because of less tidal flushing than is seen in the tidal creeks along the ICW (Hales 2001). During the post-dredging period ammonium concentrations and patterns on average almost mirrored those of the pre-dredging period (Fig. 6), and there were no significant statistical differences between the periods at any site (Table 2).

<u>Nitrate-N</u>: In the pre-dredging period nitrate concentrations presented an unusual, but consistent pattern of highest concentrations in the mid-creek stations and lower concentrations at the creek mouth, with lowest levels upstream at BH-D (Table 2). Average nitrate concentrations at Channel Marker 18 in the river were 116 µg/L, considerably greater than those at BH-A, thus the river could serve as one source of nitrate to the creek. Concentrations at BH-A were much higher than concentrations normally found at tidal creek mouth stations in the urbanized creeks along the ICW, but concentrations at BH-D were far lower than upstream nitrate concentrations in the urbanized creeks (Mallin et al. 2004b). Nitrate is a common signal of human impact, and is derived largely from lawn, garden, and golf course fertilizers, as well as domestic and wild animal manure.

In the post-dredging period nitrate concentrations showed a similar spatial pattern to the pre-dredging period (Table 3). Nitrate was highest in midcreek and lowest at the uppermost station, with nitrate at the mouth again higher than what is normally seen in area tidal creeks (Table 3). Seasonally the pattern differed from the pre-dredging period, with lowest concentrations in summer 2006 and highest in late winter 2007 (Fig. 7). There were no statistically significant nitrate concentration differences between periods at any of the sites.

The peak nitrate levels in mid-creek are unique among area creeks, and may reflect groundwater inputs into that region. Evidence for nitrate loading from groundwater has been documented from Futch Creek springs (Roberts 2002). Nitrate moves easily through porous coastal soils. Potential sources for the nitrate in Bald Head Creek may include golf course fertilizers or inputs from septic systems. However, State regulators did not find malfunctioning septic systems in terms of fecal coliform inputs (NCDEH 2001), and most residences are presently hooked into the wastewater treatment plant. Most human development along the creek is presently located in the area from mid-creek downstream to the creek mouth. Construction in the upstream areas was ongoing during our post-dredging sampling. The present nitrate inputs may on occasion be problematic, as indicated by the recent moderate algal blooms noted in this study (see below).

Orthophosphate-P: During the pre-dredging period orthophosphate concentrations displayed a pattern of increasing values upstream (Table 2). This would indicate that the primary phosphorus source is in the headwaters region; a similar situation to what is seen in the urbanized New Hanover County tidal creeks (Mallin et al. 2004b). Orthophosphate concentrations in Bald Head Creek were generally low. Mean orthophosphate concentrations at Channel Marker 18 in the Cape Fear River in 2002-2003 were 14 µg/L and in 2005 were 13 µg/L, very similar to concentrations at BH-A and BH-B. Orthophosphate concentrations in the urbanized New Hanover County tidal creeks were somewhat lower than those of Bald Head Creek, particularly in the headwaters areas (Mallin et al. 2004b). In the post-dredging period phosphate concentrations were very similar to the pre-dredging period in both magnitude and in terms of seasonal patterns (Table 3; Fig. 8), and there were no significant concentration differences between periods among the sites.

Chlorophyll *a*: Chlorophyll *a* concentrations are used to measure algal biomass and algal bloom intensity. In the pre-dredging period average chlorophyll *a* concentrations ranged from 2.5 to 3.4 µg/L among the four sites, with no algal blooms recorded (Table 2). These values represent low to moderate chlorophyll *a* concentrations compared with estuarine situations in general (Bricker et al. 1999). During the post-dredging period an algal bloom occurred in the three uppermost stations in August 2006 (chlorophyll *a* 18-20 µg/L), with a lesser bloom at the two uppermost stations in July 2006 (Fig. 9). Otherwise, chlorophyll *a* concentrations were similar to those of the pre-dredging period (Table 3), and there were no significant differnces between sampling periods at any of the sites. The algal blooms in Bald Head Creek did not exceed the state standard of 40 µg-chlorophyll *a* /L. It is notable that the seasonal patterns of nitrate and chlorophyll showed an inverse relationship, likely indicating that the algal bloom was fueled by nitrate (Figs. 7 and 9). Additionally, the lowest dissolved oxygen concentrations occurred during July and August at BH-B, BH-C and BH-D (Fig. 3), where the blooms occurred. It is likely that decaying algal bloom material led to increased biochemical oxygen demand (BOD) and lower dissolved oxygen at these locations.

In the New Hanover County tidal creek system a series of nutrient addition experiments found nitrate to be the limiting nutrient, which is the nutrient most consistently stimulating to algal growth (Mallin et al. 2004). However, the spatial pattern and magnitudes of Bald Head Creek's chlorophyll *a* concentrations vary considerably compared with New Hanover County's urbanized tidal creeks. Chlorophyll *a* concentrations at the creek mouth stations of the urbanized tidal creeks were similar to those of Bald Head Creek (Mallin et al. 2004b), but upstream chlorophyll *a* concentrations in the urbanized creeks were much higher. Average high tide chlorophyll *a* values from 1993-2001 in upstream stations in the urbanized creeks were 8.1, 31.3, and 16.1 µg/L in Futch, Howe, and Hewletts Creeks, respectively (Mallin et al. 2004b). In an additional comparison (the Cape Fear River) average 2002-2003 chlorophyll *a* concentrations at Channel Marker 18 were 4.0 µg/L in 2002-2003 (Mallin et al. 2003b) and 4.9 µg/L in 2005 (Mallin et al. 2006), very similar to those at BH-A.

Fecal Coliform Bacteria: During the pre-dredging period fecal coliform bacteria concentrations presented a pattern of lowest geometric mean concentrations at the two stations closest to the river (BH-A and BH-B), with concentrations increasing toward the headwaters (Table 2). Stations BH-C and BH-D both maintained geometric means that exceeded levels considered safe for shellfishing by Federal and North Carolina authorities (USFDA 1995; NCDEHNR 1996). Based on a defined sampling scheme, NC Shellfish Sanitation also considers waters unfit for shellfishing if the concentration of 43 CFU/100 mL is exceeded on more than 10% of sampling occasions. While the sampling scheme we employed was not the same sampling regime as performed by the regulatory agencies, for informational purposes we note that in 2003-2004 BH-A, BH-C, and BH-D all exceeded the 10% mark (Table 2). Since our samples were generally taken at or just after high tide, these fecal coliform counts were likely conservative (low in relation to low tide samples). This is because in area tidal creeks minimum fecal coliform counts are normally found at high tide and maximum counts at low tide (Mallin et al. 1999).

Fecal coliform counts following creek mouth dredging were no better than, and in some cases worse than the counts before dredging (Table 3; Figs. 10 and 11). The same basic pattern of highest counts upstream and lowest counts downstream occurred (Table 3; Fig. 11), and one sample exceeded the fecal coliform standard for human contact of 200 CFU/100 mL. For all samples taken the shellfish standard of 14 CFU/100 mL was exceeded a total of 16 times following dredging, as opposed to 14 times before dredging (Table 4). On a per station basis the shellfish standard was exceeded from two to six times following dredging (Table 4). The geometric mean of all samples taken before dredging was 13.1 CFU/100 mL while it was 14.7 CFU/100 mL after dredging. In 2006-2007 BH-B, BH-C, and BH-D all exceeded 43 CFU/100 mL more than 10% of the time (Table 3). There were no significant statistical differences between periods for fecal coliform concentrations at any of the sites.

As a comparison, fecal coliform counts at Channel Marker 18 in the lower Cape Fear Estuary were slightly lower, with a geometric mean of 1 CFU/100 mL and an average of 6 CFU/100 mL in 2002-2003 (Mallin et al. 2003b), and a geometric mean of 4 and an average of 5 CFU/100 mL in 2005 (Mallin et al. 2006). When compared with urbanized tidal creeks along the ICW (also sampled at or near high tide), counts near the creek mouths were similar; however, counts in the headwaters areas of the urbanized creeks were 2-10X higher than those in the Bald Head Creek headwaters (Mallin et al. 2000b). The exception to this was Futch Creek, the watershed of which has the lowest development among the New Hanover County tidal creeks. Geometric mean concentrations in upper Futch Creek for 2002-2003 were 17 CFU/100 mL, and in less-developed Foy Creek only 5 CFU/100 mL (Mallin et al. 2004a). However, in recent years upper Futch Creek has become more developed, and geometric mean fecal coliform bacteria counts for 2005-2006 were 116 CFU/100 mL for upper Futch and 24 CFU/100 mL for Foy Creek (Mallin et al. 2007).

Conclusions

The dredging of the mouth of Bald Head Creek did not improve the water quality in the creek. There were no statistical differences between sampling periods for most of the water quality parameters except for turbidity and suspended sediments at selected stations (higher following dredging). Peak concentrations of both chlorophyll and suspended sediments were highest in the post-dredging period, and the lowest dissolved oxygen concentrations occurred after dredging. Nutrients were low to moderate, relative to other area tidal creeks. However, there were somewhat elevated nitrate concentrations in the mid-creek stations, with an unknown source. This likely led to the mid to upper creek algal blooms in July and August 2006, and probably contributed to the low dissolved oxygen conditions at those locations as well. The nitrate may enter the creek through a groundwater source, possibly moving toward the creek from the golf course and/or septic systems in use in the watershed; but this has not been tested.

In terms of fecal coliform bacteria the overall geometric mean concentration for all samples before dredging was 13.1 CFU/100 mL, while after dredging it was 14.7 CFU/100 mL. This contrasts with the earlier Futch Creek project, in which creek mouth dredging led to improved fecal coliform counts (Mallin et al. 2000a). One reason for this disparity is that dredging did not improve tidal exchange rates in Bald Head Creek (ESB Associates 2007). Exchange rates before dredging ranged from 20 – 31% in the upper three stations, with 33% at the mouth station BH-A (Hales 2001). Following dredging (several months after dredging) tidal exchange rates were almost identical with a range of 20 – 30% in the upper three sites, and rates at the mouth station BH-A remaining at 33% (ESP Associates 2007). Pollution generated within the watershed is likely to be retained due to low tidal exchange rates and only slowly flushed out of this system. ESP Associates (2007) noted that excessive sediment transport on the flood tide in the lower Cape Fear River will continue to rapidly move sediments into and across the creek mouth. We agree with ESP Associates (2007) that to physically increase tidal exchange rates in Bald Head Creek for an extended period a constant maintenance program would have to occur.

Average fecal coliform counts at all sites in Bald Head Creek were well within the standards for human contact (200 CFU/100 mL) set by the NC Division of Water Quality. However, during this study the creek fecal coliform counts (except for the mouth area) exceeded those considered safe for shellfishing (14 CFU/100 mL) both before and after dredging. An important question is thus: What are the fecal coliform sources to Bald Head Creek? Bacterial source tracking is an expensive process that has not been undertaken in this watershed, so we can only speculate. An earlier suggestion by Shellfish Sanitation (NCDEH 2001) was that fecal coliform inputs to the creek are primarily from local wildlife, and retained because of the low tidal exchange rates documented by Hales (2001).

The generally low fecal coliform counts in Bald Head Creek (creek all-station combined geometric means 13.1 and 14.7 CFU/100 mL, respectively) provides further evidence to recent research (Mallin et al. 2000b; Holland et al. 2004) that demonstrated how low impact development, especially low impervious surface coverage, allows minimal anthropogenic tidal creek pollution. We were unable to obtain good estimates of watershed impervious surface coverage from the Village or County. Thus, we requested assistance from a Wilmington Stormwater Services GIS professional (co-author Hayes) who estimated watershed impervious coverage at approximately 9.3% for Bald Head Creek. This is relatively low among area tidal creeks (Mallin et al. 2001), which is a positive sign in terms of keeping pollutant levels low. We applied this estimate to a regression equation developed for five urbanizing New Hanover County tidal creeks (Bradley, Futch, Howe, Hewletts and Pages) over a four-year period that predicted the geometric mean fecal coliform abundance (FC) at high tide for all stations combined in a tidal creek using percent watershed impervious coverage (%IMP).

$$\mathbf{FC = 5.4(\%IMP) - 29,\ r^2 = 0.95,\ p = 0.005}$$

This equation later accurately predicted fecal coliform abundance in Whiskey Creek (Mallin et al. 2001) and was verified in Brunswick County creeks by Dr. Larry Cahoon of UNCW (Cahoon et al. 2004). We applied our estimate of 9.3% impervious coverage to this equation and it predicted that geometric mean fecal coliform counts for all sites and months combined would be 21.2 CFU/100 mL. Our actual geometric mean derived by our sampling was considerably lower, at 14.7 CFU/100 mL. Thus, provided that our equation is relevant for this situation, either our impervious coverage estimates were too high or some of the watershed runoff from impervious surfaces does not enter the creek. Likely the impervious coverage estimates were too high, as some of the driveways on BHI are porous (gravel or sand). Also, some of the runoff does not enter the creek but enters water features on the golf course. Finally, in New Hanover County there are extensive urban and suburban lawns, while on BHI much unvegetated sand (which is very porous) remains. This likely rapidly drains some volume of runoff, which helps keep some of the fecal bacteria that is entrained in stormwater runoff out of the creek.

To ensure minimal bacterial contamination of the creek in the future we recommend that the Village of Bald Head Island make efforts to keep total impervious coverage of the watershed to 12% or less, and vigorously enforce the existing domestic pet waste ordinance. We suggest maximum use of pervious pavement in all future common areas, and for driveways of residential lots. The use of rain gardens to filter stormwater runoff in high use areas is also recommended. The mouth of Bald Head Creek is open for shellfishing and tactics such as these should help keep it open in the future.

Acknowledgements

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Table 2. Water quality parameters in Bald Head Creek before dredging (2002-2003) presented as mean ± standard deviation / range; geometric mean is presented for fecal coliform bacteria.

Parameter	BH-A	BH-B	BH-C	BH-D
Temperature (^{o}C)	21.2±7.0 9.6-28.8	21.0±7.6 8.3-28.8	21.2±8.4 8.2-29.8	21.7±9.1 8.0-31.6
Salinity (ppt)	29.2±4.2 22.1-33.1	24.7±4.2 14.4-30.1	23.1±4.2 16.4-27.8	21.2±4.2 14.8-27.9
Dissolved oxygen (mg/L)	7.6±1.5 5.7-10.9	7.5±2.0 5.2-11.9	7.1±2.3 4.2-11.9	6.6±2.2 3.7-10.2
Turbidity (NTU)	12±6 4-25	8±2 5-13	9±4 5-19	15±8 4-33
Total suspended solids (mg/L)	36±16 15-67	27±10 17-49	29±16 16-64	28±18 5-64
Ammonium-N (µg/L)	25±10 11-40	34±8 16-46	42±18 15-81	61±28 18-114
Nitrate-N (µg/L)	52±28 19-115	90±40 30-168	71±26 32-103	31±15 13-52
Orthophosphate-P (µg/L)	12±7 6-27	17±8 10-30	18±6 12-29	33±18 14-60
Chlorophyll *a* (µg/L)	3.4±1.5 0.2-4.7	2.5±1.5 0.1-4.6	3.0±2.5 0.2-7.0	2.9±2.4 0.0-5.8
Fecal coliform bact. (CFU/100 mL) Range (minimum-maximum) % of samples > 43 CFU/100 mL	6 1-78 25%	6 2-22 13%	19 6-130 50%	46 11-1090 88%

Table 3. Water quality parameters in Bald Head Creek following dredging (2006-2007) presented as mean ± standard deviation / range; geometric mean for fecal coliform bacteria.

Parameter	BH-A	BH-B	BH-C	BH-D
Temperature (^oC)	18.8±7.9 10.0-10.1	18.7±8.1 10.0-29.0	19.0±8.1 10.3-28.8	18.5±8.1 10.7-28.8
Salinity (ppt)	29.5±1.3 27.0-31.1	25.4±4.9 15.0-29.2	24.3±5.1 14.1-29.7	23.6±3.7 16.6-28.6
Dissolved Oxygen (mg/L)	7.5±1.7 4.8-9.6	7.1±2.3 3.6-9.8	6.7±2.4 3.1-9.4	6.2±1.8 3.3-8.0
Turbidity (NTU)	12±5 4-20	12±6 4-23	13±5 7-19	11±3 7-14
Total Suspended Solids (mg/L)	66.4±39.6 17.0±123.0	66.0±37.1 13.0-110.0	47.1-30.7 12.0-92.0	47.1±30.7 7.0-82.0
Ammonium-N (µg/L)	24.2±10.2 11.5-39.8	35.2±26.3 12.0-93.9	38.3±22.5 18.8-89.1	52.7±35.2 14.6-131.5
Nitrate-N (µg/L)	33.6±19.0 11.0-55.9	70.6±47.6 9.7-131.1	31.5±38.0 8.5-132.8	22.7±18.4 4.6-59.3
Orthophosphate-P (µg/L)	11.1±9.1 4.5-31.3	13.5±2.9 18.4-18.4	15.6±4.0 11.3-22.2	27.4±12.5 15.7-46.1
Chlorophyll α (µg/L)	4.5±2.8 1.4-9.9	5.2±5.7 1.2-18.3	6.2±7.0 1.1-20.0	5.6±7.0 0.8-18.3
Fecal coliform bact. (CFU/100ml)	6	10	20	42
Range (minimum-maximum)	1-35	2-76	10-56	2-417
% of samples > 43 CFU/100ml	0%	13%	13%	63%

Table 4. Number of times the shellfishing standard of 14 CFU/100 mL of water was exceeded in pre (2003-4) and post (2006-7) dredging fecal coliform samples, and percent (pre, n = 9 samples; post, n = 8 samples).

Station	A	B	C	D	Total
Pre-dredging	2 (22%)	1 (11%)	4 (44%)	7 (78%)	14 (39%)
Post-dredging	3 (38%)	2 (25%)	5 (63%)	6 (75%)	16 (50%)

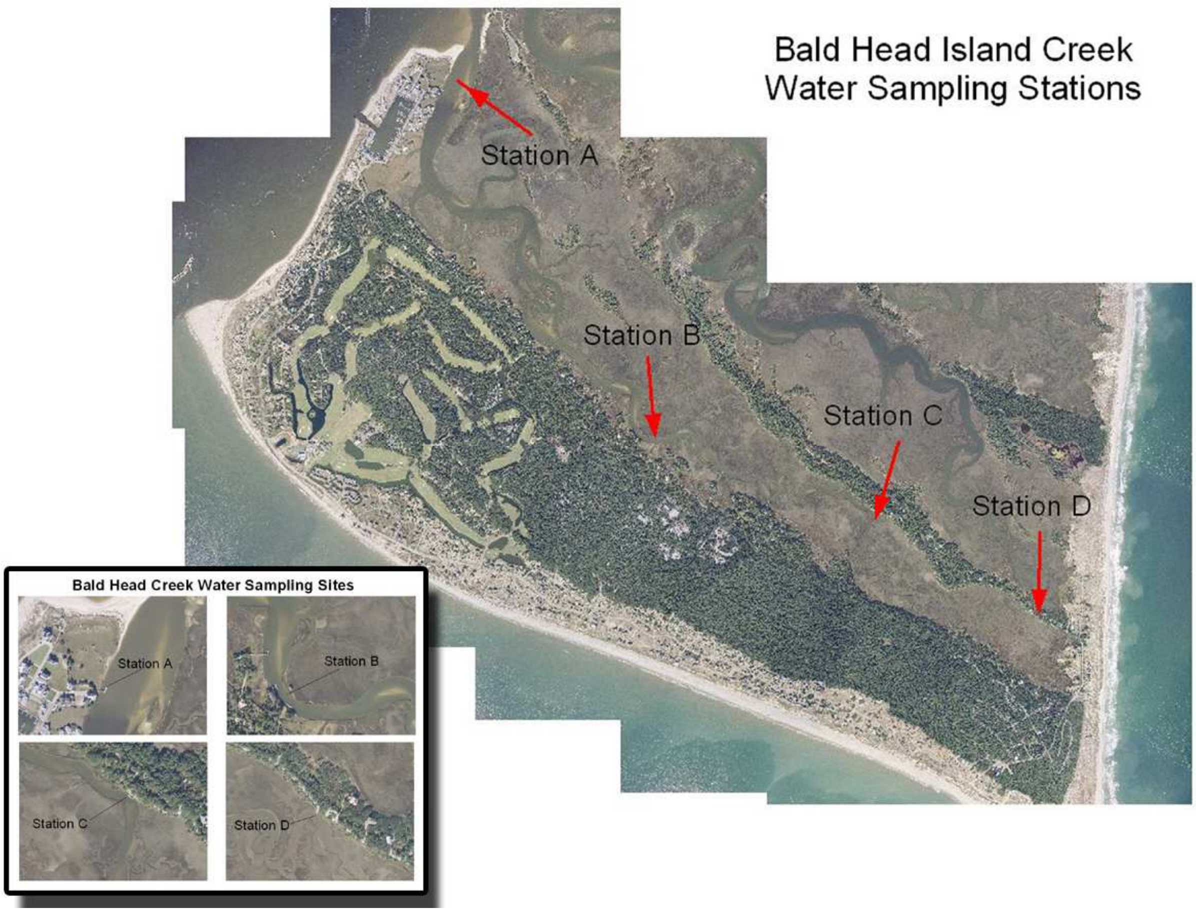

Figure 1. Sampling stations along Bald Head Creek, southeastern North Carolina.

Figure 2. Average field salinity values collected in Bald Head Creek, pre (2003-4) and post (2006-7) dredging periods.

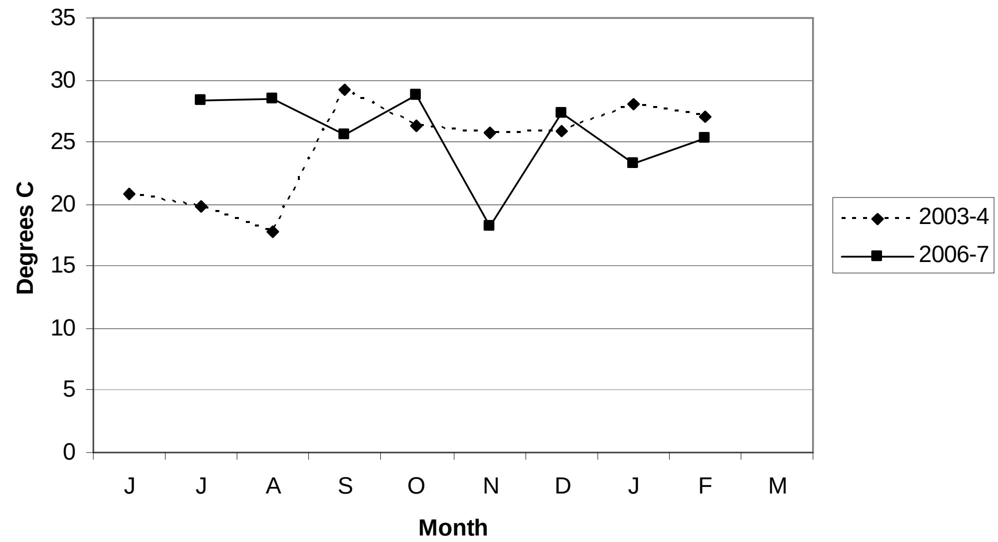

Figure 3. Average dissolved oxygen concentrations in Bald Head Creek during pre (2003-4) and post (2006-7) dredging periods.

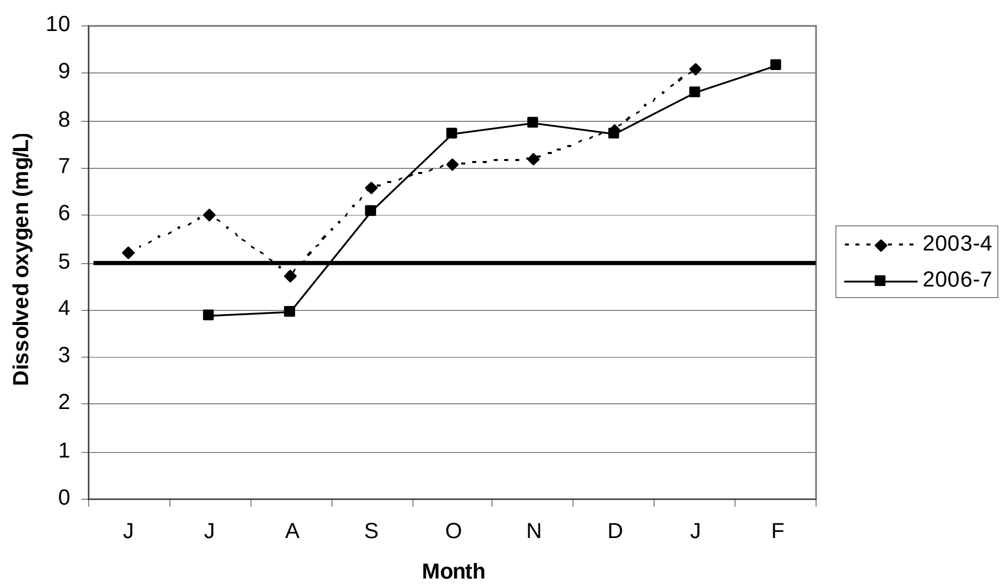

Figure 4. Average turbidity concentrations in Bald Head Creek during pre (2003-4) and post (2006-7) dredging periods.

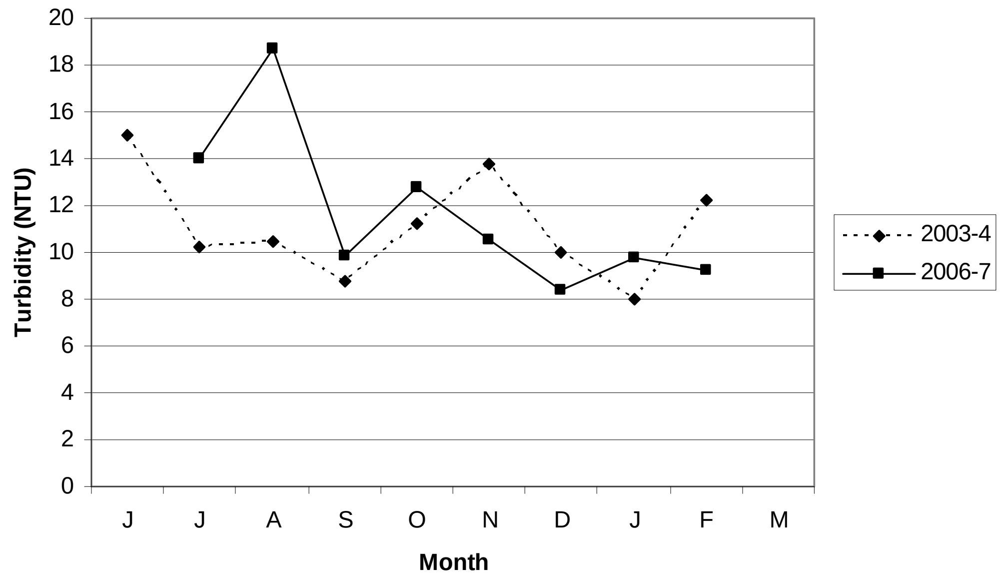

Figure 5. Average total suspended solids (TSS) concentrations in Bald Head Creek during pre (2003-4) and post (2006-7) dredging periods.

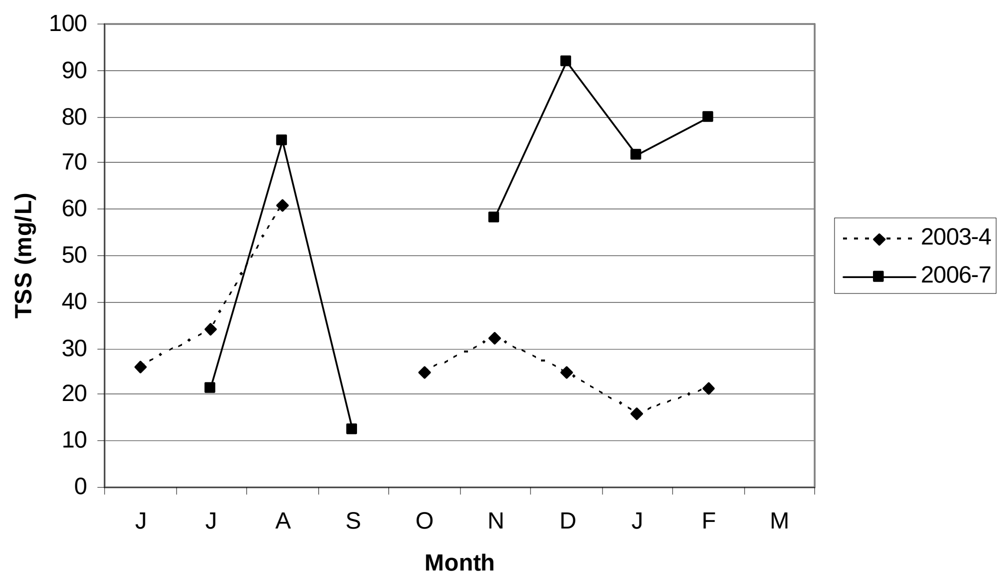

Figure 6. Average ammonium concentrations in Bald Head Creek, during pre (2003-4) and post (2006-7) dredging periods.

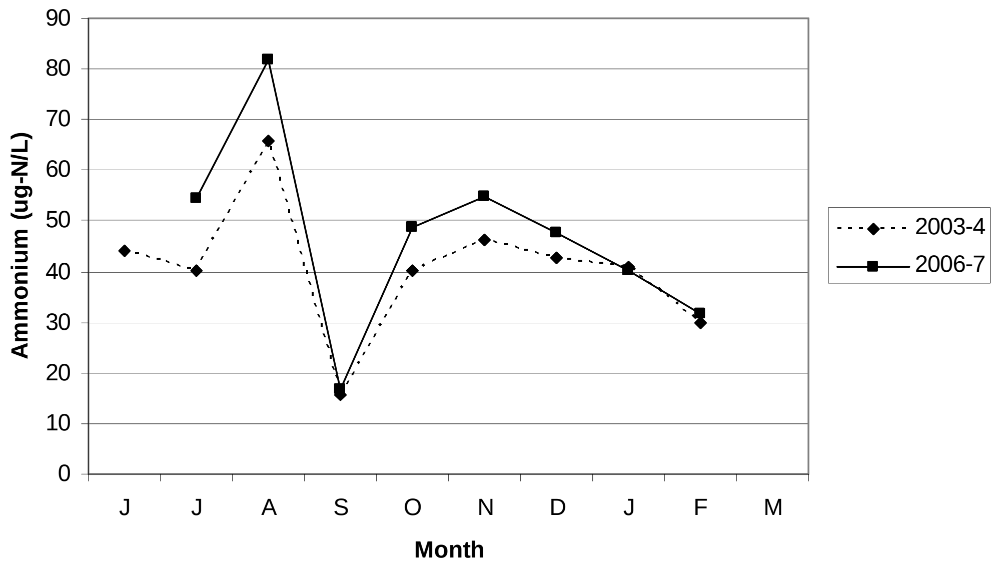

Figure 7. Average nitrate concentrations in Bald Head Creek, during pre (2003-4) and post (2006-7) dredging periods.

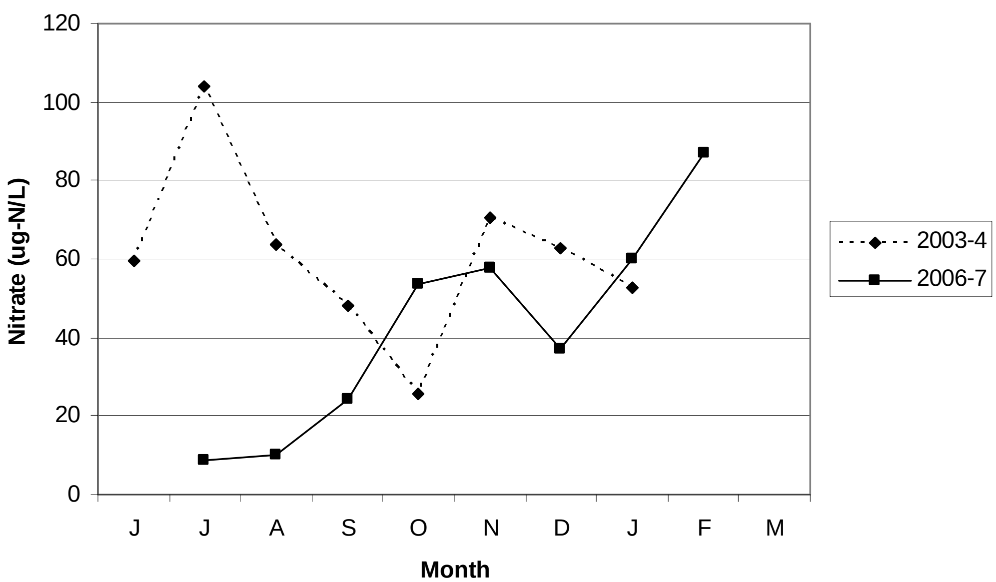

Figure 8. Average orthophosphate concentrations in Bald Head Creek during the pre (2003-4) and post (2006-7) dredging periods.

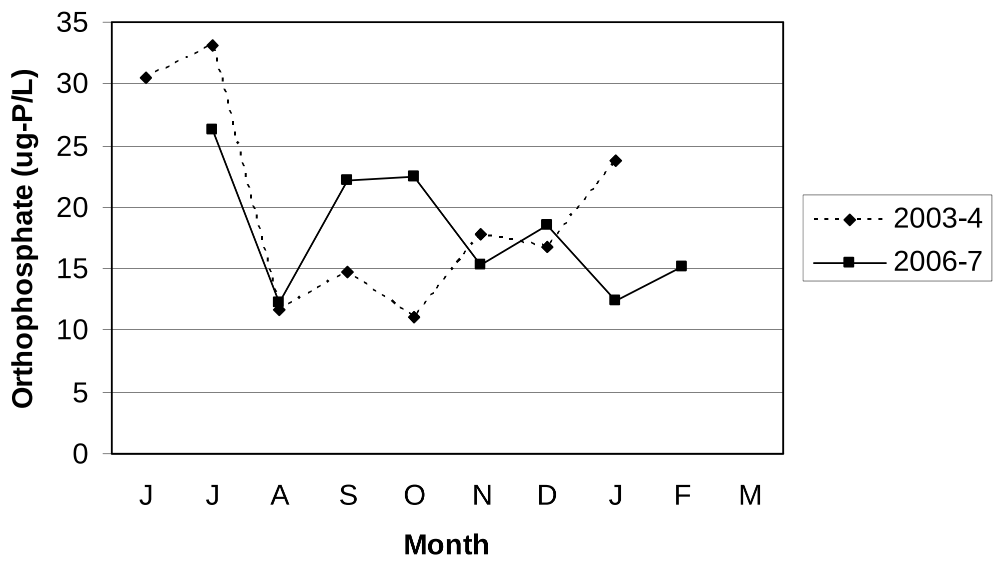

Figure 11. Fecal coliform bacterial counts for all months combined by station, before and after dredging (presented as geometric mean).

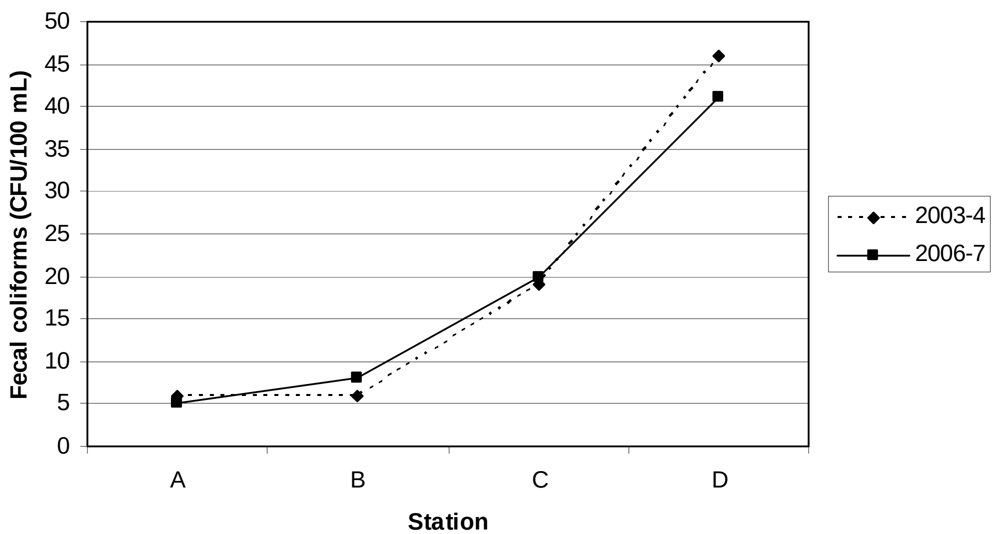

Figure 10. Average fecal coliform bacterial counts in Bald Head Creek during pre (2003-4) and post (2006-7) dredging periods.

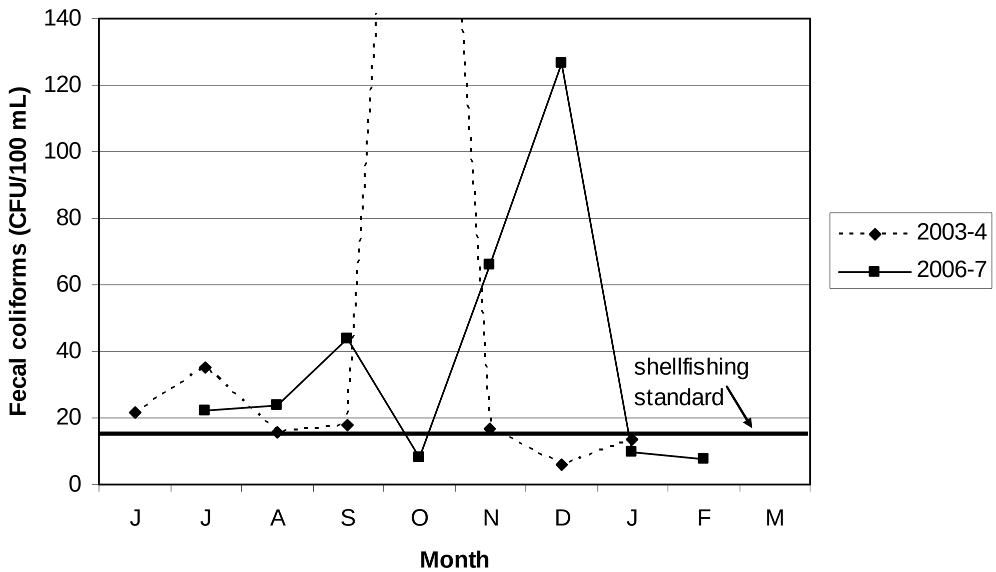

Figure 11. Fecal coliform bacterial counts for all months combined by station, before and after dredging (presented as geometric mean).

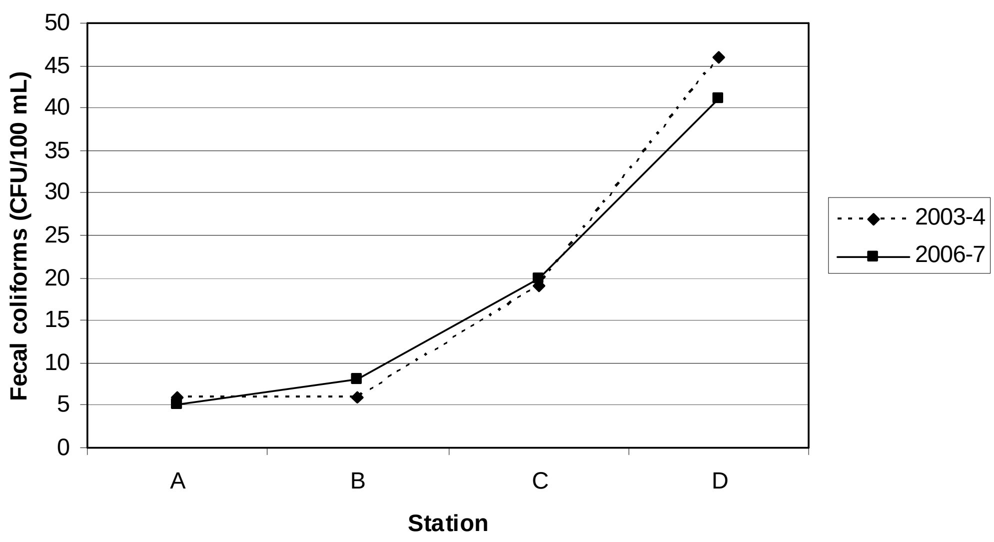

Figure 12. Watershed boundary and approximate impervious surface coverage, Bald Head Creek drainage basin.