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STREAM WATER QUALITY CHANGES FOLLOWING TIMBER HARVEST IN A COASTAL PLAIN SWAMP FOREST

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Abstract—The Goshen Swamp, a fourth order blackwater creek in southeastern North Carolina, was clearcut of 130 acres of riparian and seasonally flooded forest in late May through September 1998. Downstream water quality had been monitored monthly for 2½ years before the clearcut, during the clearcut, and for two years following the clearcut. The objective of this paper was to test the hypothesis that clearcutting in the Goshen Swamp watershed negatively impacted downstream water quality. To do so, data from the Goshen Swamp were compared with data collected from a neighboring control creek (Six Runs Creek) of similar size, land use, and hydrologic characteristics. Compared with the control creek, the post-clearcut Goshen Swamp displayed significantly higher suspended solids, total nitrogen, total phosphorus, total Kjeldahl nitrogen and fecal coliform bacteria, and significantly lower dissolved oxygen over a 15 month period. Longer-term deleterious effects included recurrent nuisance algal blooms that had not been present during the 2½ years before the clearcut. Although a 10 m uncut buffer zone was left streamside, this was insufficient to prevent the above impacts to stream water quality. © 2001 Elsevier Science Ltd. All rights reserved

Key words—water quality, forestry, clearcut, silviculture, North Carolina, blackwater, bottomland forest, nutrients, sedimentation, chlorophyll

INTRODUCTION

The North Carolina Coastal Plain contains numerous blackwater creeks and rivers with extensive riparian swamp forests. Silviculture is a major land use in this region, clearcutting being the most common method of floodplain hardwood harvesting (Walbridge and Lockaby, 1994). Impacts of clearcutting on coastal plain watershed hydrodynamics have been documented. Decreased evapotranspiration following clearcutting results in rising water tables in poorly drained soils (Shepard, 1994; Riekerk, 1983; Beasley and Granillo, 1988). Consequently, clearcutting increases storm water flows and allows overland sheet flow (Beasley and Granillo, 1988) leading to increased annual water yields and peak discharge rates (Beasley and Granillo, 1988; Lebo and Hermann, 1998).

In contrast to upland areas, the effect of silviculture on water quality in lowland habitats of the coastal plain have not been as well-described (Shepard, 1994; Herz, 1996; Lockaby *et al.*, 1997a). In a recent review of silviculture activities in floodplain forests of the southeastern US, Lockaby *et al.*

(1997b) concluded that clearcutting followed by natural regeneration and accompanied by best management practices has a small and brief effect on water quality. Similarly, a review by Shepard (1994) of logging in wetlands concluded that silviculture has temporary effects on water quality, with water quality parameters returning to pre-harvest levels within periods of months to several years. A review of timber harvest in the Southeastern Coastal Plain concludes that the short term effects of forestry activities on water quality can negatively impact the coastal environment (Herz, 1996). These studies and others cite that the cumulative water quality impacts from forestry activities is slight and transient compared with other land uses, because timber harvests in the Southeast are performed infrequently (every 25 to 50 years—Herz, 1996).

A review of research conducted in the southeastern US Coastal Plain shows that certain water quality trends can be anticipated after clearcutting activities. Response of stream temperature, dissolved oxygen, suspended solids, and some nutrients (except inorganic nutrients) to logging activities have been replicated by several studies. Sedimentation has been cited as the most important water quality concern related to forestry practices in the United States (Binkley and Brown, 1993). The impact of silviculture on erosion in lowland sites is thought to be

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relatively less compared to upland areas with increased slope (Shepard, 1994; Beasley and Granillo, 1988). A review of Eastern forestry practices concluded that timber harvesting leads to minor changes in stream nutrient concentration (Corbett *et al.*, 1978). These changes in stream water chemistry have been attributed to alterations of biogeochemical cycles in the harvested watershed (Lynch and Corbett, 1990). Research of clearcut effects in the Southeastern United States has not included a biotic water column component such as chlorophyll *a* to represent phytoplankton responses to light and nutrient changes. However, recent research by Mallin *et al.* (1997, 1998a) indicates that blackwater streams in the North Carolina Coastal Plain do exhibit phytoplankton blooms in response to nutrient inputs.

In 1990, the North Carolina Division of Forest Resources (NCDFR) established nine Performance Standards with which all forestry activities must comply in order to remain exempt from the Sedimentation Pollution Control Act (Deal and Hamilton, 1989). The first of these standards (Rule 15 NCAC 1J .0201) describes the Streamside Management Zone (SMZ) that must be established and maintained along stream margins. This rule requires that the SMZ be wide enough to trap any visible sediment resulting from forested site erosion. Though this rule does not require a minimum SMZ width, the NCDFR suggests a minimum width of 50 feet (15.2 m) for perennial, warm water streams with adjacent slopes of 0–5%. While selective cutting

is allowed within this SMZ, the NCDFR recommends that at least 50% of preharvest shade be preserved to avoid in-stream temperature changes.

One hundred and thirty acres of the Goshen Swamp watershed were clearcut beginning May 27, 1998 and concluding on September 11, 1998 (T. Tew, Corbett Timber Co., pers. comm.). This bottomland forest was comprised of gum (*Nyssa* sp.; *Liquidambar* sp.), oak (*Quercus* sp.), pine (*Pinus* sp.), and cypress (*Taxodium* sp.) (D. Robinson, Corbett Timber Co., pers. comm.). The Fish and Wildlife Service National Wetland Inventory (1994) categorizes the majority of the site as palustrine, forested, broad leaved deciduous, and partially flooded. Timber was harvested using a track cutter and shovel logger. Road construction was minimal (one single ditch road was extended into the tract), and was not located adjacent to surface waters. A 10 m SMZ was preserved on either riverbank. All best management practices were observed, and North Carolina Forest Service personnel (R. Darden, NC Forest Service, pers. comm.) found no violations. No seeding or fertilization activities were performed, and natural regeneration was allowed to occur.

Site description

The Goshen Swamp is a fourth order blackwater stream located in Duplin County, North Carolina (Fig. 1). It is a tributary of the Northeast Cape Fear River and the watershed area is 479 km². Within the

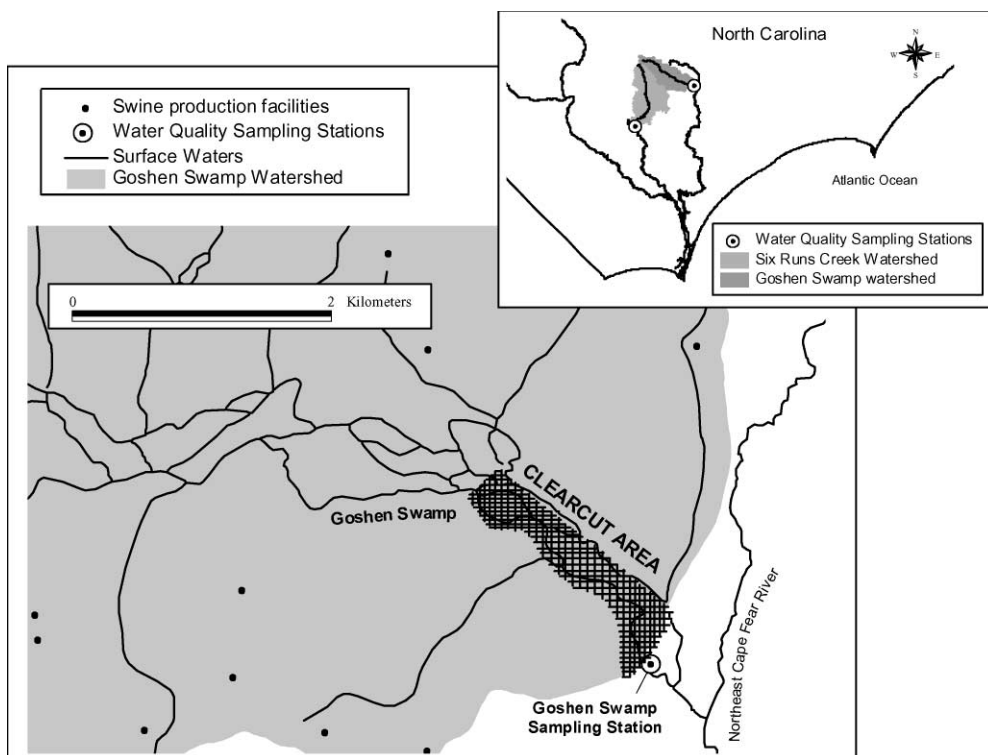


Fig. 1. Location of the Goshen Swamp and Six Runs Creek watersheds and sampling locations in southeastern North Carolina, and detailed view of Goshen Swamp clearcut area.

watershed are the towns of Faison and Calypso with a combined 1990 population of 1200. These urban areas are in the upper part of the watershed, > 26 km upstream from the sampling station. Predominant land coverages include forest (52.5%), agriculture (46%), and urban/residential (1%) (USGS, 1990). The watershed contains 107 concentrated swine production operations, giving the basin an estimated concentration of 705 swine km⁻² (information provided by the North Carolina Division of Water Quality). This land use represents a significant source of non-point source nutrients. The University of North Carolina at Wilmington's Lower Cape Fear River Program (LCFRP) maintains a water quality monitoring station immediately downstream of the clearcut at the Highway 11 bridge over the Goshen Swamp, 0.4 km upstream from the confluence with the Northeast Cape Fear River (Fig 1.). The LCFRP has monitored 15 water quality parameters monthly at this station since February 1996 (Mallin *et al.*, 1998b). The creek is sampled mid-stream, where the channel of the creek is approximately 14 m wide and 1 m deep at high water. The Goshen Swamp stream channel upstream from the sampling site is dendritic, shallow (<2 m), and ca. 18 m wide. The bridge abutments at the sampling station serve to funnel this dendritic flow into one stream channel. Soils underlying the clearcut site are classified as Swamp soils by the USDA Soil Survey of Duplin County, with texture ranging from fine sand to sandy clay loam (Goldston *et al.*, 1954). This is the only water quality monitoring station on the Goshen Swamp.

Six Runs Creek, a fourth order tributary of the Black River, drains a watershed of 708 km². The LCFRP has maintained a sampling station at Six Runs Creek since February of 1996 and monitors the same 15 parameters as the Goshen Swamp station. The station is sampled mid-stream from the Lisbon Road bridge in Sampson County, North Carolina, 0.5 km upstream from the confluence with the Black River. Predominant land coverages in the watershed include forest (62.6%), agricultural (36.4%), and urban/residential (1.1%) (USGS, 1990). There are 131 concentrated swine operations in the watershed, giving the basin an estimated concentration of 665 swine km⁻² (information provided by the North Carolina Division of Water Quality). The creek is approximately 28 m wide and is more channelized than the Goshen Swamp site. This sampling site is 49 km from the Goshen Swamp sampling site. The sampling stations in this study were chosen because they represent the farthest downstream reach of each stream system and are accessible from bridges.

METHODS

Temperature, pH, specific conductance, dissolved oxygen and turbidity were measured monthly with a YSI 6820 sonde linked to a YSI 610 Display. Probes were calibrated the morning of sampling, and proper calibration was

verified upon return from the field. Samples for nutrient and biological analyses were collected mid-stream from the sampling station. Orthophosphate-P was analyzed from filtered samples using a Technicon AutoAnalyzer (Clindis Technologies, Paramus, NJ, USA). Ammonium-N, nitrate + nitrite-N, total phosphorus (TP), and total Kjeldahl nitrogen (TKN) were analyzed using techniques from Standard Methods (APHA, 1995). TN was computed as the sum of TKN plus nitrate + nitrite-N. Total suspended solids (TSS) were assessed using the gravimetric technique described in Standard Methods (APHA, 1995). Fecal coliform bacteria were enumerated using membrane filtration (APHA, 1995) and chlorophyll *a* was quantified using the fluorometric method of Welschmeyer (1994).

No water quality data was collected upstream of the clearcut area; this limits our analysis of timber harvest impacts to using the next-best source of data available to us. We analyzed the effects of clearcutting on stream water quality by comparing Goshen Swamp with a non-clearcut control stream draining an adjoining watershed (Fig. 1). We chose Six Runs Creek as a control site because it is the closest watershed basin that approximates the Goshen Swamp's land coverages, land uses and size. A 15 month period was used for analysis of post-clearcut effects so that the influence of large-scale flooding from Hurricane Floyd (September 15, 1999) was not included.

The before and after data sets from both creeks were tested for normality using the SAS univariate procedure (Schlotzhauer and Littell, 1987). Whenever possible, non-parametric data sets were normalized using log transformation. Testing for significant difference between data sets was done with a two-sample *t*-test for parametric data and a Wilcoxon Rank Sum test for non-parametric data. First, parameters from both creeks were tested for significant between-creek differences in the pre-harvest data set (February 1996–May 1998). Next, parameter data sets from the 15 month post-harvest period (June 1998–August 1999) were tested for between-creek significant difference. On the condition that a parameter was not significantly different before harvest, differences between the Goshen Swamp and Six Runs Creek data after clearcutting began were considered to be attributed to change in the Goshen Swamp caused by the clearcut.

Correlation analyses of rainfall with water quality parameters were performed for both creeks to assess any potential parameter increases caused by increased runoff and stream flow. Precipitation during the day of sampling and the previous 48 h was compared with water quality data from both creeks using the SAS Univariate Procedure. The Warsaw 5E and Clinton 2 NE State Climate Office of North Carolina meteorological stations were used for the Goshen Swamp and Six Runs Creek, respectively. The Warsaw 5E station is 21 km west of the Goshen Swamp station, and the Clinton 2NE station is 27 km north of the Six Runs Creek station.

Analysis of watershed area, land use/land cover, and concentration of intensive livestock operations were performed using ESRI's ArcView with Spatial Analyst extension software. United States Geological Survey 1:250,000 Land Use/Land Cover digital data and spatial data provided by the North Carolina Division of Water Quality were used in the analysis.

RESULTS

Physical parameters

Temperature did not show a significant difference between creeks before or after clearcutting at the Goshen Swamp (Table 1, Fig. 2). No difference in pH was observed before or after clearcutting (Table 1,

Table 1. Mean and standard deviation of 15 water quality parameters at the Goshen Swamp and Six Runs Creek Stations. Pre harvest = February 1996–May 1998 ($n = 28$), Post harvest = June 1998–August 1999 ($n = 15$)

Parameter	Goshen Swamp		Six Runs Creek	
	Pre-harvest	Post-harvest	Pre-harvest	Post-harvest
Temperature ($^{\circ}\text{C}$)	15.9 \pm 5.8	19.0 \pm 7.7	16.0 \pm 5.8	19.1 \pm 6.4
Dissolved oxygen (mg/L)	6.3 \pm 2.9	4.7 \pm 4.1 ^b	7.3 \pm 2.1	7.1 \pm 2.0
Specific conductance ($\mu\text{S}/\text{cm}$)	143 \pm 45 ^a	200 \pm 56 ^b	98 \pm 39	104 \pm 12
pH	6.6 \pm 0.5	6.2 \pm 0.34	6.7 \pm 0.41	6.2 \pm 0.48
Turbidity (NTU)	6 \pm 8	14 \pm 27	7 \pm 6	9 \pm 9
Total suspended solids (mg/L)	3 \pm 2	10 \pm 12 ^b	3 \pm 4	2 \pm 3
Total nitrogen ($\mu\text{g}/\text{L}$)	1349 \pm 348	1584 \pm 902 ^b	1486 \pm 431	979 \pm 332
Nitrate-N ($\mu\text{g}/\text{L}$)	287 \pm 294 ^a	56 \pm 135 ^b	524 \pm 280	389 \pm 285
Total Kjeldahl-N ($\mu\text{g}/\text{L}$)	1058 \pm 408	1531 \pm 942 ^b	962 \pm 417	590 \pm 180
Ammonium-N ($\mu\text{g}/\text{L}$)	71 \pm 75	184 \pm 256	72 \pm 50	121 \pm 128
Total phosphorus ($\mu\text{g}/\text{L}$)	116 \pm 72	240 \pm 187 ^b	113 \pm 48	119 \pm 41
Molar N:P	40 \pm 54	20 \pm 11	35 \pm 22	22 \pm 15
Orthophosphate-P ($\mu\text{g}/\text{L}$)	30 \pm 17	112 \pm 185	35 \pm 17	43 \pm 22
Chlorophyll <i>a</i> ($\mu\text{g}/\text{L}$)	3.9 \pm 5.9 ^a	28.0 \pm 47.8 ^b	1.1 \pm 1.1	0.5 \pm 0.3
Fecal coliform bacteria (col/100 mL)	116 \pm 103	1993 \pm 5986 ^b	143 \pm 268	244 \pm 768

^aIndicates a significant difference ($p < 0.05$) between Goshen Swamp and Six Runs Creek pre-harvest data.

^bIndicates a significant difference ($p < 0.05$) between Goshen Swamp and Six Runs Creek post-harvest data.

Fig. 2). Conductivity showed significant differences between creeks before clearcutting, and therefore was not included in the post-clearcut analysis (Table 1, Fig. 2).

Dissolved oxygen was significantly lower at the Goshen Swamp in the post-harvest period than Six Runs Creek, while no difference existed before clearcutting (Table 1, Fig. 2). At the Goshen Swamp, algal blooms occurring in August 1998 and June 1999 likely became a biochemical oxygen demand (BOD) source as they senesced, causing low dissolved oxygen in September 1998 and July 1999.

Total suspended solids showed a significant difference between creeks after clearcutting, but not before (Table 1, Fig. 2). Rainfall in the 24 h preceding sampling during June, July, and August 1998 was likely responsible for flushing suspended solids from the denuded landscape. Interestingly, the extreme rainfall associated with Hurricane Bonnie (late August 1998) did not have a notable effect on TSS (Fig. 2).

No significant difference in turbidity was detected before or after clearcutting (Table 1, Fig. 2). However, the large peak in turbidity (111 NTU—greater than twice the NC State Standard of 50 NTU) during the first month of clearcutting is worth noting.

Nutrients

TN and TKN were significantly greater at Goshen Swamp than Six Runs Creek after clearcutting but not before (Table 1, Fig. 3). Total nitrogen during the first 8 months of post-harvest data was predominantly organic in speciation.

Nitrate + nitrite-N was significantly different between creeks in the before-harvest periods (Table 1, Fig. 3). Therefore, a comparison cannot be made to determine effects of timber harvest. Ammonium-N

was not significantly different in either the before or after data sets between creeks (Table 1, Fig. 3).

The increase in TP in the post-clearcut period was significantly different than Six Runs Creek's mean TP (Table 1, Fig. 3). However, no difference was detected in pre-harvest means. The month logging commenced, TP began a four month rise that peaked in October 1998 at 700 $\mu\text{g}/\text{L}$ (six times the pre-logging average). High levels of orthophosphate-P (Fig. 3) were reached in September and October 1998 following senescence of an August phytoplankton (i.e. chlorophyll *a*) bloom (Fig. 4). Orthophosphate-P was not significantly different between creeks in either the before or after data sets (see Fig. 3, Table 1).

Biological parameters

Chlorophyll *a* levels in the Goshen Swamp and Six Runs Creek were not found to be statistically different in either the before or after data set (Table 1, Fig. 4). Though we did not find statistically significant increases in this parameter after clearcutting began, post-clearcut peaks in chlorophyll *a* deserve attention. Chlorophyll *a* concentrations were unusually high in July and August 1998 (75 and 166 $\mu\text{g}/\text{L}$, respectively), followed by a decrease to normal levels following Hurricane Bonnie in August. There is evidence that the clearcut had a more long-term effect on stream phytoplankton. In June 1999 chlorophyll *a* concentration was 60 $\mu\text{g}/\text{L}$ and in August 1999 was 85 $\mu\text{g}/\text{L}$. The August phytoplankton bloom consisted mainly of the blue-green alga *Microcystis aeruginosa*, accompanied by euglenoids (*Euglena* and *Phacus* spp.). Prior to the clearcut, the highest chlorophyll *a* concentration recorded since the onset of the study in February 1996 was 30 $\mu\text{g}/\text{L}$ in July 1997.

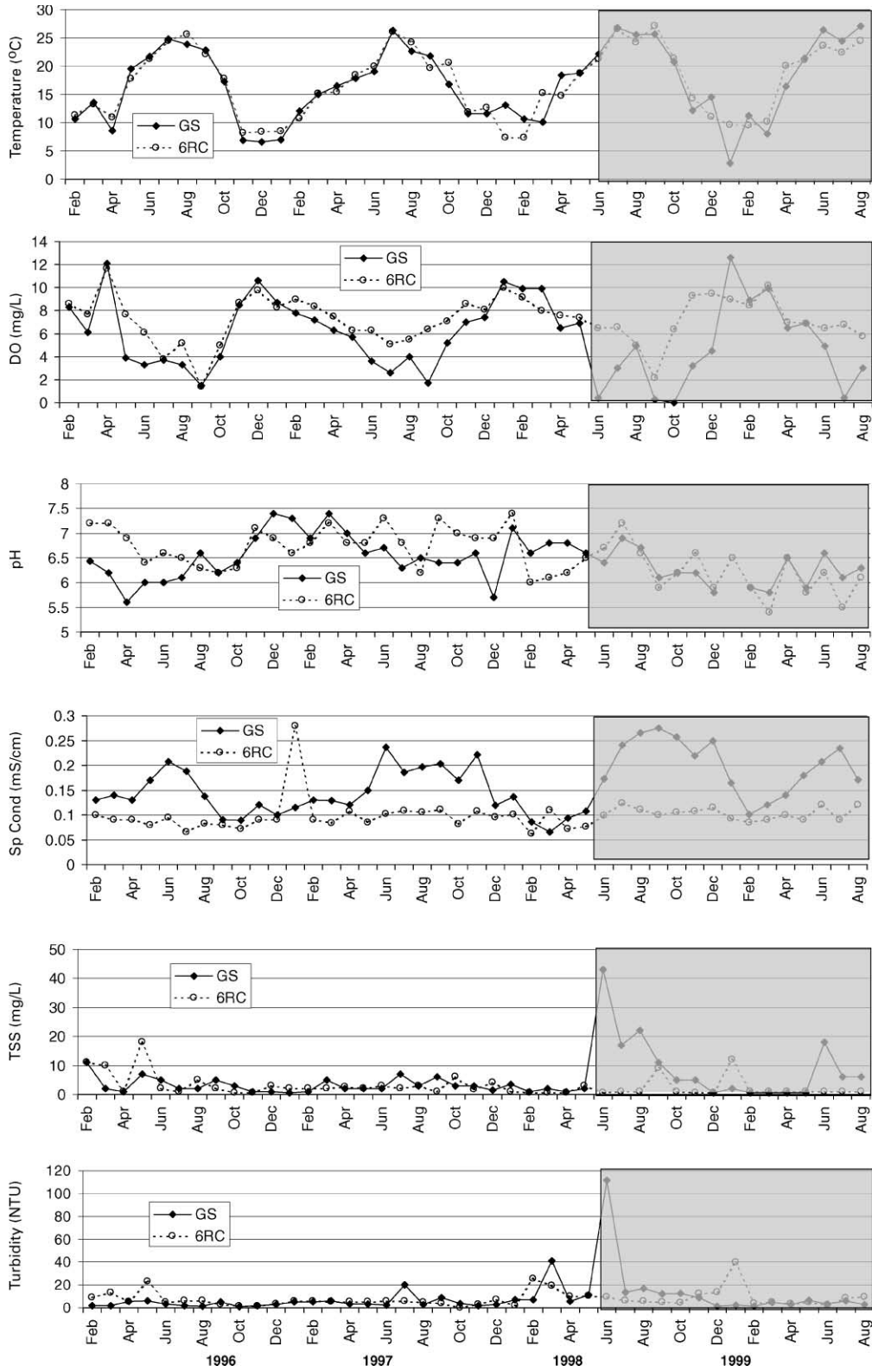


Fig. 2. Physical water quality data from Goshen Swamp sampling site before and after June 1998 clearcut. Hurricane Bonnie arrived between the August and September 1998 sampling.

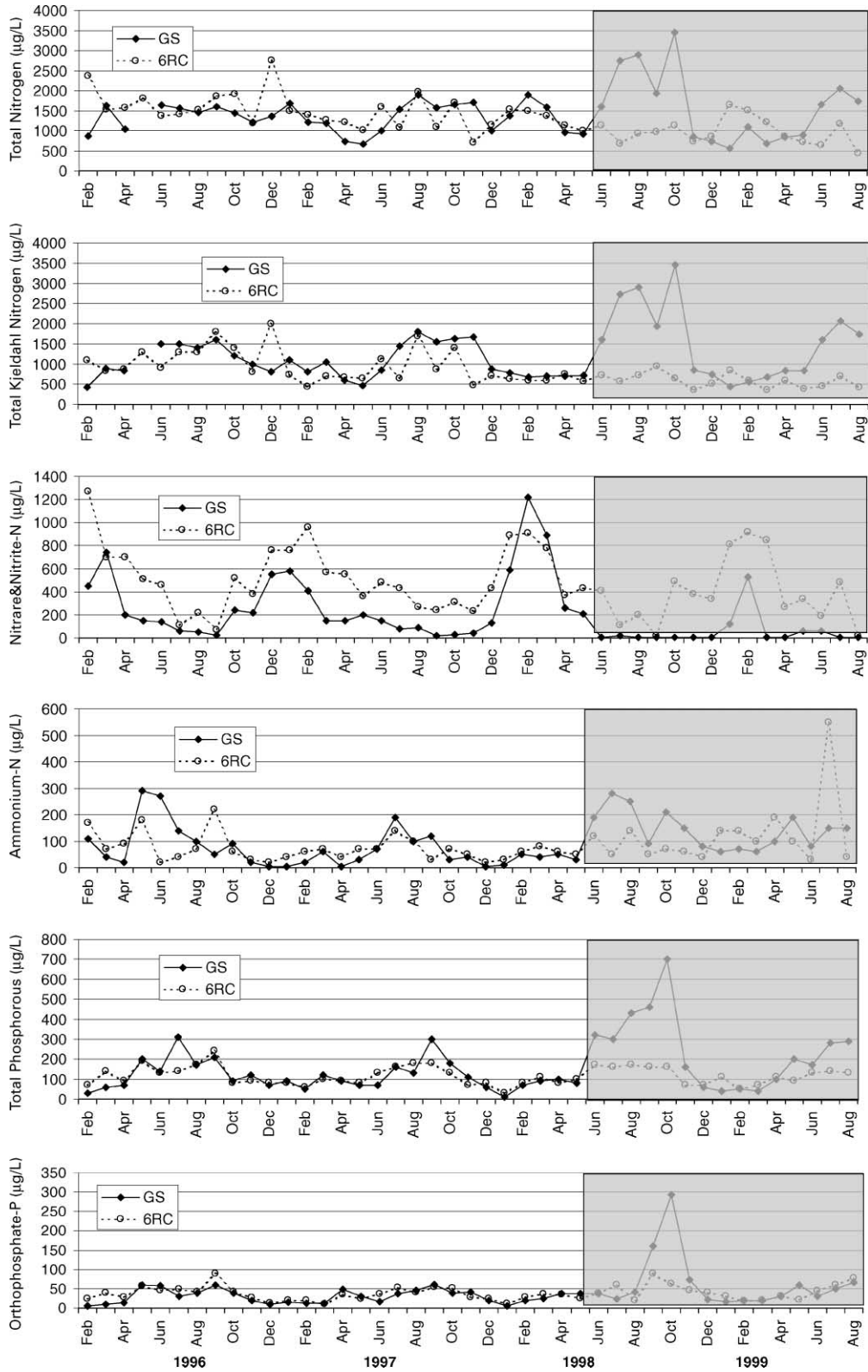


Fig. 3. Nutrient concentration data from Goshen Swamp sampling site before and after June 1998 clearcut. Hurricane Bonnie arrived between the August and September 1998 sampling.

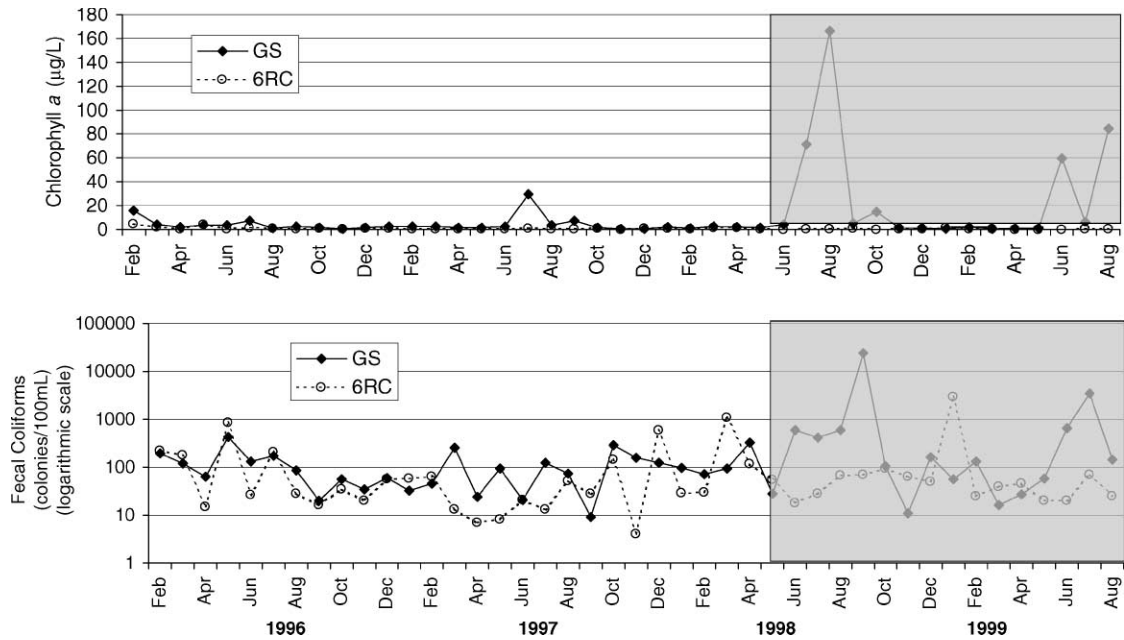


Fig. 4. Biological water quality data from Goshen Swamp sampling site before and after June 1998 clearcut. Hurricane Bonnie arrived between the August and September 1998 sampling.

Fecal coliform levels were found to be significantly greater at the Goshen Swamp than at Six Runs Creek following logging, but not before (Table 1, Fig. 4). Following logging, fecal coliform bacterial counts increased dramatically for a four month period, reaching an unprecedented level of 23,400 colony-forming units (CFU)/100 mL in September 1998 (120 times the NC State Standard for human contact waters of 200 CFU/100 mL). High fecal coliform levels in June and July 1999 (657 CFU/100 mL and 3510 CFU/100 mL, respectively) indicate a recent and persistent problem of microbial pollution at the Goshen Swamp sampling station.

Rainfall impacts

No correlations between water quality data and rainfall were found at the Goshen Swamp. In contrast, turbidity, total suspended solids, ammonium, chlorophyll *a*, and fecal coliform bacteria were all correlated with rainfall at Six Runs Creek. Of the 43 sampling dates in this study, the Goshen Swamp was sampled 20 times within 48 h of rainfall, while Six Runs Creek was sampled 32 times with rainfall in previous 48 h. This analysis assures us that the Goshen Swamp's data is not biased by the effects of immediate storm runoff. Furthermore, the correlations found at Six Runs Creek show that our comparison of stream water quality between these creeks may be conservative since Six Runs Creek data may be slightly elevated due to rain events.

DISCUSSION

Clearcutting did not significantly alter in-stream water temperature at the Goshen Swamp. Stream

water temperature rise is directly related to the amount of water surface exposed to direct sunlight (Corbett *et al.*, 1978). Tree canopy removal can raise stream temperatures 3–7°C (Binkley and Brown, 1993). Use of a buffer zone has proven to protect streams from temperature rise of more than 2°C (Binkley and Brown, 1993). This was recently demonstrated by Messina *et al.* (1997) who found no temperature increase of stream water in a clearcut site compared to a control in a Texas bottomland hardwood forest with a 20 m SMZ. It seems that the 10 m buffer zone at the Goshen Swamp preserved enough forest canopy over the creek to prevent stream water temperature increase.

Binkley and Brown's (1993) review of timber harvest effects on water quality found that dissolved oxygen is frequently depressed downstream of harvest areas. A recent study by Messina *et al.* (1997) that found no change in dissolved oxygen due to a clearcut in a bottomland forest in Texas is an exception. Decreased in-stream dissolved oxygen may likely result from a BOD load of organic material released as a result of forest disturbance (Herz, 1996). Elevated BOD within a harvested watershed relative to a downstream control site has been documented in coastal Alabama (Lockaby *et al.*, 1994). We attribute the significant decrease in dissolved oxygen at the Goshen Swamp to allochthonous (logging debris) and autochthonous (algal biomass) BOD loads. Anoxic events occurring in September and October 1998 and July 1999 each followed nuisance algal blooms one month prior.

We did not observe a statistically significant change in pH at the Goshen Swamp after clearcutting. Research done in coastal Florida showed an

increase from pH 3.9 to 4.2 the year following harvesting (Fisher, 1981). Similarly, research done in coastal South Carolina showed an increase in pH relative to a control in drainage waters of timbered land (Askew and Williams, 1986). Clearcutting of an eastern Texas forest had no significant effect on stormflow pH (Blackburn and Wood, 1990).

The significant increase in suspended solids seen at the Goshen Swamp is consistent with many other studies of logging showing a significant, though transient impact to water quality. Growth of scrub and brush within 5 months of logging is probably responsible for increased retention of sediments on the surface of the clearcut, consequently lowering sediment load to the stream (Perison *et al.*, 1997; Lockaby *et al.*, 1997b). In other research, mean annual sediment losses were shown to be significantly greater than in a control watershed for two years following a clearcut in the Alabama coastal plain (Beasley and Granillo, 1988). Fisher (1981) found that TSS concentration following harvest in coastal Florida was 137 mg/L compared to a control site value of 6 mg/L, while another study of clearcutting in Florida showed harvest activities to increase suspended sediments significantly (Riekerk, 1983). Messina (1997), however, found no increase in turbidity due to clearcutting in a Texas bottomland hardwood forest, nor did Blackburn and Wood (1990) in a study of clearcut effects on stormflows in eastern Texas.

The increase in TN and TKN (TN was mainly organic in composition) at the Goshen Swamp may have resulted from alteration of several watershed processes following clearcutting. First, mechanical disturbance of the forest floor during harvest activities allowed for the wash-down of particulate organic matter during rain events, consequently increasing nutrient levels. A second watershed source of nitrogen and phosphorus is increased decomposition of organic matter. An increase in soil temperature in a denuded watershed (due to increased light penetration to the forest floor) can increase decomposition rates (Messina *et al.*, 1997; Perison *et al.*, 1997) and increase nutrient release to soils (Walbridge and Lockaby, 1994; Corbett *et al.*, 1978). Third, as the landscape is cleared of vegetation, there is reduced uptake of the watershed nutrient load by plants, resulting in increased nutrient export (Walbridge and Lockaby, 1994; Herz, 1996). We believe neighboring land use practices contributed substantial nutrient loads to the Goshen Swamp after logging (see discussion below). Additionally, changes in forest hydrology and vegetation will alter microbial pathways of nitrification and denitrification, further affecting watershed nutrient dynamics (Walbridge and Lockaby, 1994). In other research, Lebo and Hermann (1998) noted a slight increase in TN following harvest of a coastal pine forest in North Carolina. Research in western Florida shows that TN and ammonium-N were

elevated over a control site the year following harvest of a lowland forest (Fisher, 1981). Blackburn and Wood (1990) found significant increase in stormflow TN over a control site the first year after clearcutting in eastern Texas.

The effect clearcutting has on nitrate + nitrite-N in the Southeastern Coastal Plain has been variable. Research done in coastal South Carolina showed a decrease in nitrate-N in logged areas compared with control areas (Askew and Williams, 1986). Lockaby *et al.* (1994) found no significant increase in nitrate-N in a floodplain forest harvest. Messina (1997) did not find significant changes in nitrate-N relative to a control site in a Texas bottomland hardwood clearcut. In contrast, nitrate-N was significantly increased in stormflows for 1 year after an east Texas clearcut (Blackburn and Wood, 1990). Similarly, Fisher's (1981) study shows nitrate + nitrite was elevated over a control site after clearcutting. Nitrate dynamics at the Goshen Swamp display an interesting trend worth noting on behalf of its biologic implications. Water column nitrate + nitrite-N was minimal for the 7 months after logging, reflecting both a normal summertime trend for the Goshen Swamp and increased uptake by algae during a July/August bloom (Figs 3 and 4). Furthermore, anoxic conditions during the summer of 1998 may have favored the reduced form (ammonium-N) rather than nitrate + nitrite-N.

Our analysis shows TP (mostly organic in composition) to increase downstream of a clearcut. Sources of phosphorus after logging are similar to those mentioned for nitrogen: decreased uptake by vegetation in the denuded watershed and influx of particulate matter containing phosphorus (Walbridge and Lockaby, 1994). Again, we believe adjacent agricultural land use is responsible for significant nutrient loading (see discussion below). In a western Florida lowland, Fisher (1981) found TP to be greater than at a control site the year after a harvest. Lebo and Hermann (1994) found slight increases in TP concentration after harvest of a coastal pine forest in North Carolina. Blackburn and Wood (1990) found significantly increased TP in stormflows the first year following an eastern Texas clearcut.

Binkley and Brown's (1993) review of forestry activity as a source of non-point source pollution found that elevated orthophosphate levels are usually not found below timber operations. This generalization holds true in coastal bottomland sites as demonstrated by Lockaby (1994) and Messina (1997). However, Fisher (1981) found increased orthophosphate and ammonium-N and Blackburn and Wood (1990) found significantly increased orthophosphate-P in stormflows the first year after clearcutting. Orthophosphate-P and ammonium-N concentrations in the Goshen Swamp appear consistent with the notion that logging does not significantly increase inorganic nutrient levels (Lockaby, 1997a).

The biological monitoring (chlorophyll *a* and fecal coliform bacteria) in our study of the Goshen Swamp seem to be unique to studies of in-stream water quality following clearcutting. We attribute recurring chlorophyll *a* peaks (July and August 1998, June and August 1999) to nuisance algal blooms brought about by increased nutrient availability. Research conducted in blackwater stream systems has shown organic nitrogen to stimulate phytoplankton growth (Mallin *et al.*, 1998a). Furthermore, these phytoplankton blooms senesce and have been documented to cause water column hypoxia in blackwater systems (Mallin *et al.*, 1997), just as was seen in the Goshen Swamp after the August 1998 and June 1999 chlorophyll peaks. The peaks in algal biomass following the clearcut may be due in part to the increase in solar irradiance to the water as the tree canopy was reduced on the periphery of the SMZ (Corbett *et al.*, 1978). Immediate increases in TN and ammonium-N following the clearcut (see Fig. 3) were likely sources of nutrients for the bloom. Increased flow following the rains of Hurricane Bonnie probably flushed out the algal bloom, replacing it with a BOD load of organic matter, causing dissolved oxygen impoverishment. The increase in fecal coliform bacteria is likely an indirect effect of clearcutting, and is explained below in a comparison between two tropical rain events caused by Hurricanes Bonnie and Fran.

Hurricane Bonnie impacted the North Carolina coast on August 26–28, 1998, three months after logging commenced at the Goshen Swamp. The State Climate Office of North Carolina rainfall gauging station in Warsaw, NC, located 21 km from the Goshen Swamp and 30 km from the Six Runs Creek sampling station, recorded 8.5 cm of rain in the 8 days between Bonnie's landfall and the September 1998 sampling (State Climate Office of North Carolina at North Carolina State University). This weather system influenced the Goshen Swamp September samples with heavy overland runoff, resulting in peak fecal coliform levels (23,400 colonies/100 mL). A three-year maximum in TN, TKN, TP, orthophosphate-P and ammonium-N occurred in October 1998 (Fig. 2). In contrast to Hurricane Bonnie's impact on Goshen Swamp fecal coliform levels is the lack of water quality impact following Hurricane Fran in September 1996, well before the clearcut (Figs 2–4). The Clinton, NC State Climate Office gauging station recorded 27.7 centimeters of rain in the 12 days between Fran's landfall and the September 1996 sampling (data from the Warsaw station is unavailable). Fran, however, did not detrimentally influence any of the physical, chemical, or biologic parameters measured at the Goshen Swamp (Mallin *et al.*, 1999). Given the heavy overland flow conditions expected after both storm events, the contrast in nutrient and bacteria levels suggests that the clearcut landscape was the variable responsible for increases in these parameters found in

the Goshen Swamp. Likewise, Hurricane Bonnie's impact on TN, TP, and fecal coliform bacteria was minimal in the non-clearcut Six Runs Creek in September 1998 (Figs 2 and 3). The extremely high bacteria levels found in September 1998 at the Goshen Swamp suggest a non-point source, possibly concentrated swine operations due to their abundance in the watershed.

Industrial swine farms in the Goshen Swamp watershed (107 operations containing a total of >400,000 swine by 1996 records) represent a significant potential source of nutrients to the Goshen Swamp. These facilities store hog waste in outdoor lagoons, and periodically spray liquid waste from the lagoons onto surrounding fields (Burkholder *et al.*, 1997; Mallin *et al.*, 1999). Surface application of organic waste material, especially when coinciding with heavy rainfall, can contribute nitrogen and phosphorus to adjacent waterways (McLeod and Hegg, 1984). Subsurface drainage of nitrate and phosphorus from surface application of animal waste material can pollute streams as well (Evans *et al.*, 1984). Crane *et al.* (1983) found runoff from livestock operations to contain fecal bacteria levels of 10^3 – 10^5 organisms/100 mL. It seems likely that the Goshen Swamp receives significant nutrient and bacterial loading from adjacent concentrated animal operations, but large peaks in these parameters are normally buffered by the extensive riparian forests. The loss of riparian forest in Goshen Swamp by the clearcutting may have led to less retention of nutrients and fecal coliform bacteria and consequent high post-clearcut concentration of TN, TKN, TP, and fecal coliform bacteria.

CONCLUSIONS

This study concludes that clearcutting lowered dissolved oxygen, increased TN, TKN, TP, TSS, and fecal coliform bacteria at the Goshen Swamp. These parameters were significantly elevated for 15 months after timber harvest began. Our results are consistent with the short-term water quality impacts on most physical and nutrient parameters reported in previous research of clearcutting in the Southeastern Coastal Plain. However, recurrent chlorophyll *a* peaks after the fifteen months represented in our statistical analysis show a longer-term algal bloom problem following timber harvest. Previous research of clearcutting effects on water quality have not incorporated the biotic component of water column chlorophyll levels. As our research demonstrates, the increase in nutrient levels found after clearcutting can stimulate algal blooms, which in turn can cause hypoxic conditions downstream as the algal bloom senesces. Along with biochemical changes in the disturbed forest floor, we believe the high nutrient and bacteria levels found after timber harvest may be due in part to agricultural sources in the watershed.

The clearcut landscape may not have been able to assimilate a watershed-derived nutrient load after periods of intense rainfall. While a 10 m vegetated buffer zone was left streamside, this was not sufficient to protect stream water quality from the short-term impacts listed above, as well as the longer-term recurring phytoplankton blooms.

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