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EFFECTS OF FOREST HARVESTING BEST MANAGEMENT PRACTICES ON SURFACE WATER QUALITY IN THE VIRGINIA COASTAL PLAIN

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ABSTRACT. *Three small watersheds located in Westmoreland County, Virginia, were monitored to evaluate the impact of forest clearcutting on surface water quality and to evaluate the effectiveness of forestry best management practices (BMPs) for minimizing hydrologic and water quality impacts associated with timber harvesting. One watershed (7.9 ha) was clearcut without implementation of BMPs, one watershed (8.5 ha) was clearcut with the implementation of BMPs and a third watershed (9.8 ha) was left undisturbed as a control. Forest clearcutting without BMP implementation reduced storm runoff volume and did not significantly change peak flow rates. Following site preparation, both storm flow volumes and peak flow rates decreased significantly. For the watershed with BMP implementation, storm flow volume decreased significantly following harvest, while peak flow increased. Site preparation did not change storm flow volumes over post-harvest conditions, but did significantly reduce storm peak flow rates. Disruptions in subsurface flow pathways during harvest or rapid growth of understory vegetation following harvest could have caused these hydrologic changes. Harvest and site preparation activities significantly increased the loss of sediment and nutrients during storm events. Storm event concentrations and loadings of sediment, nitrogen, and phosphorus increased significantly following forest clearcutting and site preparation of the No-BMP watershed. Both the BMP watershed and the Control watershed showed few changes in pollutant storm concentrations or loadings throughout the study.*

Results of this study indicate forest clearcutting and site preparation without BMPs can cause significant increases in sediment and nutrient concentrations and loadings in the Virginia Coastal Plain. However, these impacts can be greatly reduced by implementing a system of BMPs on the watershed during harvesting activities.

Keywords. *Best management practices, Nonpoint source pollution, Forestry, Sediment, Nutrients, Water quality.*

Poorly implemented timber harvesting activities have the potential to degrade water quality. Undesirable changes resulting from forest harvesting include changes in forest hydrology and increased sediment and nutrient losses. Removal of the forest canopy affects forest hydrology by reducing interception and evapotranspiration. This can result in increased water yield and higher water tables (Likens et al., 1970; Riekerk, 1985; Van Lear et al., 1985; Blackburn et al., 1986; Beasley and Granillo, 1988; Lynch and Corbett, 1990; Ursic, 1991). The durations of these changes is limited by the re-establishment of site vegetation.

Silvicultural activities may also change the established erosion pattern of a site and cause erosion rates to increase above the natural levels. Many researchers have reported increased sediment levels as a result of forest harvest (Van Lear et al., 1985; Beasley and Granillo, 1988; Beasley, 1979; Miller, 1984; Robichaud and Waldrop, 1994). These increases typically lasted two to three years until vegetation

was reestablished. Although each of these four experiments recorded significant increases in sediment losses after harvest, only Beasley (1979) and Robichaud and Waldrop (1994) reported sediment losses above 1 t/ha/yr. Erosion on the other sites, although significantly higher than undisturbed conditions, was similar to background erosion rates. Low erosion rates on these sites were attributed, in large part, to the use of a streamside management zone (SMZ) during the harvest of each site. The SMZs have been shown to be an effective management practice to minimize sediment losses from harvesting operations (Kochenderfer and Edwards, 1991).

Experiments in the eastern U.S. have shown increased levels of nutrient export following forest harvest (Likens et al., 1970; Aubertin and Patric, 1974; Martin et al., 1986; Hornbeck et al., 1986). The suspended sediment is composed primarily of fine organic particles which have a tendency to carry attached nutrients and other contaminants.

Martin et al. (1984) surveyed water quality effects of forest harvesting in the New England region. They found nitrate (NO_3^-) to be the predominant means of nitrogen export from the forested areas. Several factors contribute to the increase in nitrate concentrations following harvest, including decreased plant uptake, increased water outflows, and increased soil temperatures, which result in higher rates of mineralization and nitrification. In contrast, ammonia measurements indicated little or no change after harvest (Martin et al., 1986; Blackburn and Wood, 1990).

Phosphorous export is closely linked to sediment loss. Aubertin and Patric (1974) reported an increase in

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phosphorous concentrations after clear-cutting a 34 ha watershed in the Fenrow Experimental Forest of West Virginia. Blackburn and Wood (1990) reported that harvesting and shearing a watershed in eastern Texas increased phosphate (PO_4^-) and total phosphorus (TP) concentrations for one year after harvest, but harvesting and chopping did not increase their concentrations. Other studies found no change in phosphorus loading following clearcutting (Riekerk, 1985; McClurkin et al., 1985).

Section 208 of the Clean Water Act (PL 92-500) recognized silviculture as a potential source of nonpoint source (NPS) pollution and required states to develop water quality management plans to specifically address silvicultural discharges. These requirements were further refined in section 319 of the 1987 amendments to the Clean Water Act (PL 100-1) and required each state to identify specific sources of NPS discharge and to develop best management practices (BMPs) to control them. Common silvicultural BMPs include pre-harvest planning, streamside management zones, broad-based dips, water bars, and post-harvest seeding.

States have the responsibility to ensure that the BMPs recommended to land managers are effective in controlling NPS discharges. This evaluation is an iterative process whereby BMP guidelines are continually updated based on the results of the monitoring (Solomon, 1989). Although the impacts of forest harvesting on water quality are well documented (Beasley, 1979; Miller, 1984; Van Lear et al., 1985; Beasley and Granillo, 1988; Riekerk et al., 1985; Blackburn and Wood, 1990), few studies have addressed the effectiveness of a system of BMPs for minimizing adverse changes to water quality and quantity in the southeastern Coastal Plain. The objectives of this study

were to determine the effects of traditional commercial timber harvesting practices on NPS pollution in the Virginia Coastal Plain and to evaluate the effectiveness of a typical system of BMPs implemented as a water quality protection measure.

METHODS

SITE DESCRIPTION

The study site is located within the Nomini Creek watershed in Westmoreland County, Virginia ($\text{N}38^\circ 00.98'$, $\text{W}76^\circ 42.62'$). Nomini Creek drains into Nomini Bay, the Potomac River, and then into the Chesapeake Bay. Three forested subwatersheds, located within the Nomini Creek watershed, were selected to evaluate the impact of forestry BMPs on water quality changes caused by timber harvest (fig. 1). Slopes in the watersheds range from 2% over most of the harvested area to 30% along deeply incised stream channels. The soils in the three subwatersheds consist of sandy loam soils of the Rumford series (coarse-loamy, siliceous, *thermic Typic Hapludults*) and Suffolk series (fine-loamy, siliceous, *thermic Typic Hapludults*) (SCS, 1981). Prior to the harvest, the treatment subwatersheds, no-BMP and BMP, were populated predominantly with loblolly pine (*Pinus taeda*) with hardwood stands (*Quercus* sp., *Liriodendron tulipifera*, *Acer rubrum*, and *Liquidambar styraciflua*) concentrated in the lowland areas, while the Control watershed was predominately hardwood (table 1). The Control subwatershed receives additional drainage from a non-forested area devoted to agriculture, located away from the stream channel.

In August 1991, runoff monitoring stations were installed at the outlets of the three forested watersheds.

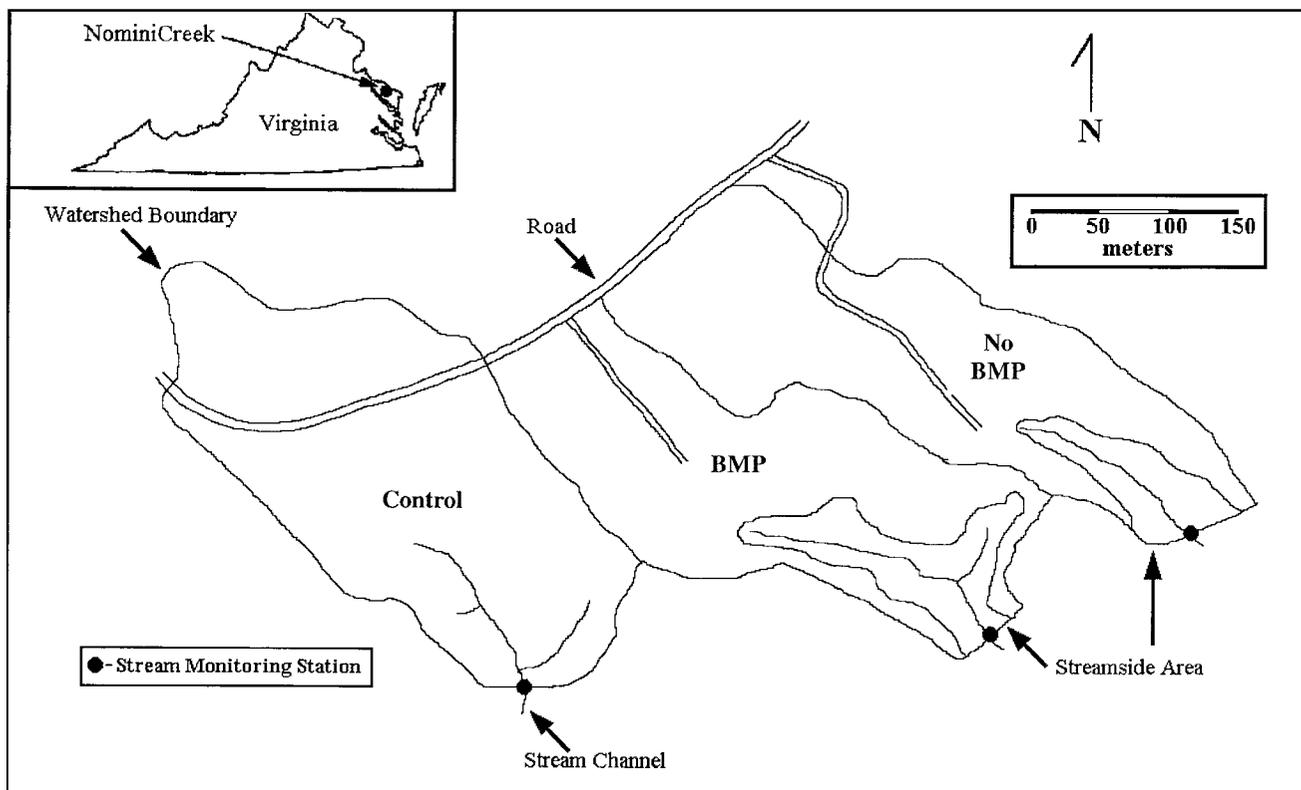


Figure 1—Location of the study watersheds.

Table 1. Watershed conditions

	No-BMP	BMP	Control
Total drainage area (ha)	7.9	8.5	9.8
Timbered area (ha)	7.9	8.1	7.8
Stream length (km)	0.18	0.22	0.19
Pre-harvest pine basal area (m ² /ha)	18.8	13.8	9.2
Pre-harvest hardwood basal area (m ² /ha)	2.8	3.4	15.6
Area disturbed by machinery (%)	100	84	0
Landing area (ha)	0.1	0.1	0.0
Skid trail length (km)	1.1	0.4	0.0
Road length (km)	0.21	0.18	0.00

Stream flow was measured using a 91.4 cm flume in combination with a paper strip chart. An electronic stage recorder also collected stream stage readings as a backup. Climatic data were recorded at a weather station and at seven tipping bucket rain gages located within or adjacent to the Nomini Creek Watershed.

Composite water samples were collected during storm events by automatic water samplers located at the outlet of each subwatershed for water quality analyses. Base flow grab samples were initiated weekly by a field observer while flow-composited storm event sampling was initiated automatically by a change in stream stage. The water samples were tested according to the Quality Control/Quality Assurance plan developed for the Nomini Creek Watershed project (Mostaghimi, 1989). The water samples were tested for the following parameters: total suspended solids (TSS), ammonia/ammonium-nitrogen (NH₄⁺-N), nitrate-nitrogen (NO₃-N), total Kjeldahl nitrogen (TKN), total nitrogen (TN), filtered TKN, total phosphorus (TP), phosphate-phosphorus (PO₄-P), and filtered TP. Detailed sample collection and data analysis procedures for this project have been reported by Frazee (1996).

Watershed monitoring began in October 1991 to assess the undisturbed conditions of each watershed. The pre-harvest period spanned approximately 28 months until January 1994 when treatment watersheds were clearcut. Firelines were installed around both harvested areas in July 1995 and a mixture of Arsenal AC (imazapyr: 0.56 kg a.i./ha) and Accord (glyphosate: 3.37 kg a.i./ha) herbicides was applied. The sites were then burned in August 1995 and hand-planted with loblolly seedlings in March 1996. Using drip torches, a moderately intense burn was achieved on both treatment watersheds. Monitoring continued through March 1997, for a total of 38 months following forest harvest.

SILVICULTURAL TREATMENTS

During the week of 31 January through 4 February 1994, harvesting activities were conducted on the BMP and No-BMP watersheds. The No-BMP watershed was clearcut with the goal of maximum timber removal, without the implementation of BMPs. The BMP watershed was clearcut with the implementation of several water quality BMPs. The Control watershed was left unharvested. The practices implemented on the BMP watershed included:

1. A pre-harvest plan, developed in cooperation with the Virginia Department of Forestry (VDOP), which described the type and location of the BMPs to be implemented in the watershed.

2. A streamside management zone with a minimum of 15.2 m width delineated on each side of the perennial stream length with minimal harvesting conducted in this area. Only 36% of the basal area in the SMZ of the BMP watershed was harvested compared to 94% of the basal area harvested in the streamside region of the No-BMP watershed. The SMZ area in the BMP watershed was approximately 1.4 ha.
3. Water bars installed after harvest on primary skid trails to divert surface flow from the trail surface to an area of undisturbed litter.
4. Landings seeded with grass to establish ground cover until the time of replanting.

DATA ANALYSIS

The data were split into three periods for analysis. The Pre-Harvest period extended from October 1991 through January 1994 when the timber was harvested. The Post-Harvest period ran from February 1994 to the site preparation burn in August 1995. The third analysis period, Post-Prep, was from September 1995 to March 1997, and included the seedling planting in March 1996.

The impacts of timber harvesting and site preparation on watershed hydrology were evaluated based on changes in storm flow volume (quickflow), storm peak flow rate, and weekly base flow volume. Flow data were summarized on a daily basis and base flow separation was conducted using the five-day minima technique (Gustard et al., 1992). This procedure produced erratic results for some storm events; therefore, the automated delineation was adjusted for these events by assuming a straight line separation. Annual base flow indices (BFIs) were calculated for each watershed by dividing the total annual base flow volume by the total annual runoff volume.

Storm flow volume and peak flow were analyzed using the paired watershed approach (EPA, 1993). Because the data were highly skewed, the linear regressions were conducted using the nonparametric Theil-Sen method (Hollander and Wolfe, 1973). Statistically significant differences between the calculated slopes were determined using the Mann-Whitney test (Neave and Worthington, 1988). The percent change in storm flow volume and peak discharge rate were determined by evaluating the regression equations at the parameter median for the Control watershed.

Analysis of the weekly base flow did not reveal the presence of the same linear trend in the storm flow data. Additionally, both weekly and monthly base flow totals were strongly serially correlated. Therefore, trends in weekly base flow were evaluated using the LOWESS (LOcally WEighted Scatterplot Smoother) smoothing method (Helsel and Hirsch, 1992).

Flow-weighted concentrations and total mass loadings were calculated on a storm-event basis. The water quality data did not show a consistently significant linear trend; therefore, the paired-watershed analysis could not be used. Differences in water quality parameters between the three analysis periods were tested for each watershed using the Mann-Whitney test (Neave and Worthington, 1988).

Annual sediment and nutrient yields were also calculated for each period to compare with previous studies. The annual yields were estimated by multiplying

the average and median weekly total flow loadings by 52 weeks/year. This method was used because harvesting and site preparation activities did not occur at 12-month intervals.

RESULTS AND DISCUSSION

HYDROLOGY

Annual precipitation during the study period varied from 1010 mm in 1993 to 1247 mm in 1996. Median weekly precipitation was greatest following site preparation (table 2). The Post-Harvest period was characterized by several storms with high intensity and high total precipitation.

This region is characterized by occasionally intense summer rains and milder winter storms (Mostaghimi et al., 1999). During the study, both maximum and average storm intensities (mm/h) were twice as great during the growing season (April-October) as during the dormant season (November-March) at a significance level of $\alpha = 0.05$.

A total of 80, 72, and 76 runoff events were recorded during the Pre-Harvest, Post-Harvest, and Post-Prep monitoring periods, respectively, for each watershed. A linear relationship was developed between the Control watershed and each treatment watershed for the three analysis periods. The regressions were all significant at the $\alpha = 0.0001$ level. The percent change in storm flow volume

Table 2. Comparison of storm events by period

Period	Median Weekly Precipitation (mm)	Median Storm Event Average Intensity (mm/h)	Median Storm Event Maximum Intensity (mm/h)
Pre-harvest	13.3 ^{a,b}	1.7 ^{a,b}	5.3 ^{a,b}
Post-harvest	16.8 ^{a,c}	2.3 ^{a,c}	6.4 ^{a,c}
Post-prep	19.2 ^{b,c}	1.7 ^{b,d}	4.1 ^{b,d}

^{a,b,c} Different letters indicate statistically significant differences based on pairwise comparisons between analysis periods at the $\alpha = 0.005$ level.

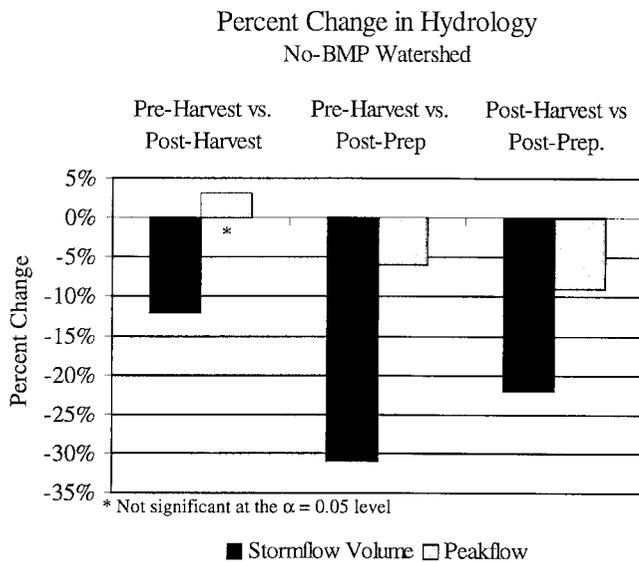


Figure 2—Percent change in storm flow volume and peak flow rates for the No-BMP watershed (based on linear regressions against the Control watershed).

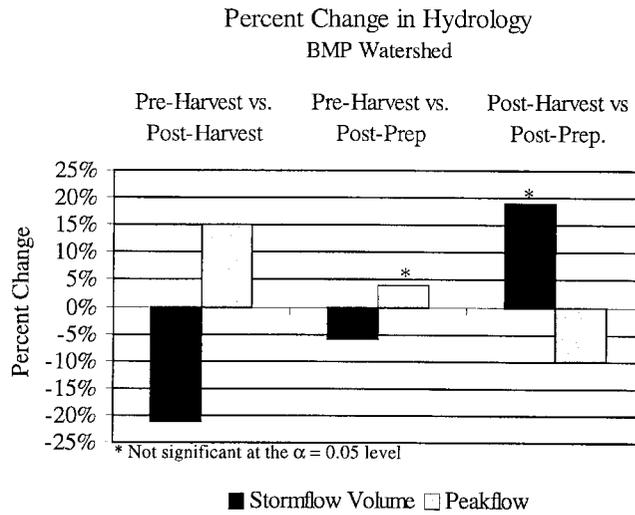


Figure 3—Percent change in storm flow volume and peak flow rates for the BMP watershed (based on linear regressions against the Control watershed).

and peak flow rates between analysis periods are presented in figures 2 and 3.

For the No-BMP watershed, there was a decrease in storm flow volume following harvest (12%) and site preparation (31%), as compared to pre-harvest conditions. Peak flow rates did not change significantly in the No-BMP watershed as a result of clearcutting, but site preparation activities caused a 6% decrease in peak flow rates. A similar response for storm flow occurred in the BMP watershed: storm flow volumes decreased 21% during the Post-Harvest period and 6% during the Post-Prep period, as compared to the Pre-Harvest period. For the BMP watershed, peak flow increased 15% after harvest. Following site preparation, peak flow from the BMP watershed was not significantly different from the pre-harvest rates.

The hydrologic changes resulting from harvesting and site preparation had a distinct seasonal component. For the No-BMP watershed, the reductions in storm flow and peak flow were generally not significant during the growing season. The only significant hydrologic change during the growing season was a 16% reduction in storm flow following site preparation, as compared to Pre-Harvest conditions. For the BMP watershed, stormflow decreased significantly during the winter and either did not change significantly, or increased, during the summer, following timber harvesting and site preparation, as compared to forested conditions. There was no significant change in peak flow during the dormant season; however, peak flow rates during the growing season increased significantly (18% Pre-Harvest versus Post-Harvest and 20% Pre-Harvest versus Post-Prep).

In general, storm flow and peak flow either increased or did not significantly change for both treatment watersheds during the growing season, as a result of the silvicultural activities. This is as would be expected, since removal of the forest canopy would reduce interception and evapotranspiration losses, while rapid growth of understory vegetation following removal of the forest canopy would have helped maintain pre-harvest conditions on the watersheds.

In contrast, storm flow and peak flow either decreased, or did not significantly change, for both treatment watersheds during the dormant season. The reductions in storm flow and peak flow following harvesting and site preparation are unexpected, especially since the rainfall intensity was the greatest during the post-harvest period (table 2). These reductions could be partially attributed to the disturbance of subsurface flow pathways. Clearcutting with heavy equipment can disturb surface and subsurface flow patterns, thus reducing storm quickflow. Miller (1984) found similar results following mechanical site preparation in Oklahoma. Under intense summer storms, reduction of macropores could lead to increased surface runoff. Combined with reduced evapotranspiration and interception, this could produce the increased storm flow and peak flow during the growing season. Disruption of the quickflow pathways would likely be more pronounced during the dormant season when the precipitation events are less intense and there is a greater opportunity for infiltration and less of a possibility of surface runoff. The presence of low-lying vegetation could also prevent runoff from concentrating and further reduce storm flow volume and peak flow rates, even during the dormant season.

The weekly base flow volumes for the three watersheds are presented in figure 4. Base flow for the Control watershed increased slightly during the post-harvest period and then decreased again. For the BMP watershed, the base flow followed a similar pattern to the Control watershed and then increased following clearcutting. This is expected, since storm flow decreased during the same period. The opposite occurred on the No-BMP watershed: after timber harvest the base flow decreased. This decrease in baseflow

from the No-BMP watershed accompanied a corresponding decrease in storm flow and peak flow overall. This is most likely the result of increased deep percolation. Similar results have been found in other areas of the Nomini Creek watershed (Mostaghimi et al., 1999). These reductions in water yield from the No-BMP watershed could be the result of changes in subsurface flow pathways resulting from the operation of heavy equipment during harvesting. Since 94% of the timber basal area was removed from the streamside zone in the No-BMP watershed (as compared to 36% in the BMP watershed), subsurface drainage to the stream channel could have been reduced, thus promoting percolation to deeper aquifers.

While changes in storm flow volumes were significant, storm flow represents a small fraction of the overall water yield. Base flow indices (BFIs) for these watersheds were high. Average annual BFIs for 1991-1996 were 0.95, 0.93, and 0.95 for the No-BMP, BMP, and Control watersheds, respectively. There was no discernible change in BFI following the timber harvest or site preparation.

WATER QUALITY

Sediment. Sediment Concentration. Median storm event total suspended solids concentrations during each analysis period for each watershed are summarized in table 3. Due to the high degree of skewness in the data, median values were used, instead of average values, to represent the central tendency of each data set. Median storm TSS concentrations increased from 0.4 g/L in the pre-harvest period to 3.3 g/L in the post-harvest period for the No-BMP watershed. This represents an 829% increase in storm TSS concentrations following clearcutting. A 14% decrease and 34% increase in TSS storm concentrations were observed for the BMP watershed and the Control watershed, respectively, at the same time. The increase in storm concentrations on the Control watershed could be the result of the increase in precipitation intensity during the Post-Harvest period, although the change in sediment concentration was not statistically significant. Correlation between TSS concentrations or loadings and maximum hourly rainfall intensity was tested using Spearman's Rho

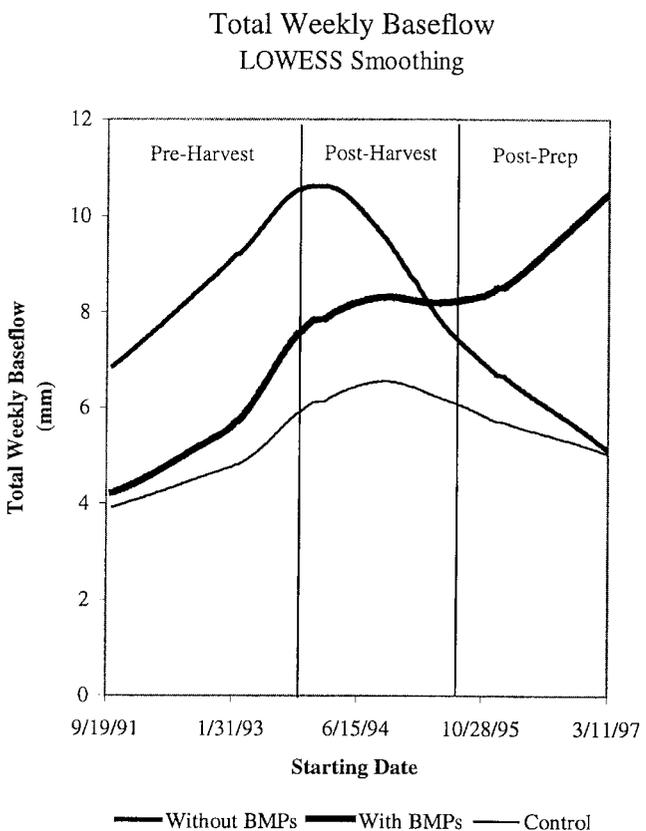


Figure 4—LOWESS smoothing of weekly base flow.

Table 3. Median storm event concentrations and loadings

		Concentrations (mg/L)*			Loadings (g/ha/storm)*		
		Without BMPs	With BMPs	Control	Without BMPs	With BMPs	Control
TSS	Pre-harvest	0.355 ^{a†}	0.116 ^a	0.124 ^a	11.49 ^a	2.31 ^a	2.07 ^a
	Post-harvest	3.299 ^b	0.099 ^a	0.166 ^{a,b}	64.26 ^b	1.96 ^{a,b}	2.49 ^{a,b}
	Post-prep	4.604 ^c	0.152 ^a	0.088 ^{a,c}	73.64 ^c	4.03 ^{a,b}	1.33 ^{a,c}
NH ₄	Pre-harvest	0.05 ^a	0.03 ^a	0.046 ^a	1.34 ^a	0.60 ^a	0.58 ^a
	Post-harvest	0.25 ^b	0.01 ^b	0.005 ^b	5.89 ^b	0.14 ^b	0.13 ^b
	Post-prep	0.07 ^{a,b}	0.03 ^{a,c}	0.058 ^{a,c}	1.25 ^a	0.69 ^a	0.89 ^a
NO ₃	Pre-harvest	1.12 ^a	0.56 ^a	2.035 ^a	28.8 ^a	12.2 ^a	27.8 ^a
	Post-harvest	0.69 ^b	0.64 ^a	2.504 ^b	17.0 ^b	13.5 ^a	39.8 ^b
	Post-prep	0.63 ^b	0.71 ^a	2.473 ^b	8.6 ^b	16.3 ^b	34.3 ^b
TKN	Pre-harvest	4.37 ^a	2.57 ^a	3.34 ^a	128.6 ^a	47.5 ^a	43.7 ^a
	Post-harvest	20.88 ^b	2.22 ^a	3.92 ^{a,b}	477.6 ^b	45.5 ^{a,b}	64.2 ^a
	Post-prep	43.74 ^c	2.16 ^a	2.18 ^{a,c}	841.6 ^b	62.6 ^{a,b}	42.5 ^a
PTKN	Pre-harvest	2.68 ^a	1.91 ^a	2.31 ^a	85.1 ^a	34.0 ^a	31.2 ^a
	Post-harvest	20.24 ^b	2.17 ^a	3.96 ^{a,b}	495.7 ^b	42.8 ^{a,b}	64.3 ^b
	Post-prep	42.74 ^c	2.00 ^a	1.63 ^{a,c}	813.9 ^b	58.2 ^{a,c}	30.5 ^a
TN	Pre-harvest	5.91 ^a	3.25 ^a	5.66 ^a	15.3 ^a	7.0 ^a	8.3 ^a
	Post-harvest	22.11 ^b	3.04 ^a	6.59 ^a	48.9 ^b	6.3 ^{a,b}	10.3 ^a
	Post-prep	45.29 ^c	3.00 ^a	5.44 ^a	85.0 ^b	9.2 ^{a,c}	9.6 ^a
TP	Pre-harvest	0.96 ^a	0.51 ^a	0.651 ^a	29.15 ^a	10.06 ^a	8.07 ^a
	Post-harvest	3.70 ^b	0.24 ^b	0.240 ^b	86.45 ^b	5.54 ^b	4.57 ^b
	Post-prep	7.36 ^c	0.27 ^{a,b}	0.062 ^c	122.81 ^b	7.47 ^a	0.85 ^c

* TSS concentrations are in g/l and loadings are in kg/ha.

† Values for each watershed with identical letters are statistically similar at $\alpha = 0.05$.

and Kendall's Tau for the Control watershed. The tests produced significant positive correlation between storm TSS concentrations or storm TSS loadings and rainfall intensity at $\alpha = 0.05$.

Following site preparation, there was a 40% increase in storm event TSS concentrations from 3.3 g/L to 4.6 g/L for the No-BMP watershed, as compared to the post-harvest period. This is a 13 fold increase over the pre-harvest conditions. Storm TSS concentrations following site preparation in the BMP watershed and the Control watershed did not change significantly from pre-harvest conditions. The best management practices were effective at maintaining pre-harvest storm TSS concentrations, even during a period of intense precipitation.

Storm Event Sediment Loading. A summary of storm event TSS loadings are shown in table 3. There was a 459% increase in storm event TSS loadings following harvest in the No-BMP watershed. Following site preparation, storm TSS loadings from the No-BMP watershed also increased by 15% from the post-harvest period and 541% compared with the pre-harvest period. Storm TSS loadings following timber harvesting and site preparation in the BMP and Control watersheds did not change significantly from pre-harvest conditions. Compared to post-harvest conditions, the site preparation activities caused a significant increase (105%) in TSS loadings during storm events on the BMP watershed. At the same time, there was a reduction in TSS loadings of 47% from the Control watershed. This decrease for the Control watershed probably resulted from the reduction in precipitation intensity during the post-prep analysis period. Based on these observations, site preparation caused a significant increase in storm-related sediment loss from both harvested watersheds as compared to post-harvest conditions, although the loadings from the BMP watershed were not significantly different from the pre-harvest period.

Annual Sediment Loading. Average and median annual sediment yields are listed in table 4. Average annual sediment yields from the No-BMP watershed were an order of magnitude higher than those from the BMP and Control watersheds during all three periods. Sediment loading from the No-BMP watershed may have initially been high because the channel in this watershed is deeply incised and is still eroding. Additionally, following construction of the monitoring stations, there was a small depression upstream of the flume in the No-BMP watershed. Sediment accumulated in this depression and may have been flushed out during several large storm events in the summer of 1993. Ursic (1979) found periodic flushing of accumulated stream sediments caused high storm-related TSS concentrations in small, undisturbed pine watersheds in the south.

Despite high sediment yields during the pre-harvest period, yields in the No-BMP watershed increased 2.6 times following harvest. During the post-prep period,

sediment yields on the No-BMP watershed remained high, 2.1 times pre-harvest levels. A similar increase was seen in the Control watershed between the pre-harvest and post-harvest period. Average annual sediment yields from the Control watershed also increased 2.2 times following harvest. After site preparation activities, the sediment yields decreased to below pre-harvest levels. These fluctuations are likely the result of changes in precipitation intensity. As can be seen in table 2, the highest average and maximum storm event intensities were during the post-harvest period. In contrast to the No-BMP and Control watersheds, average annual sediment yield from the BMP watershed remained relatively constant throughout the entire study, indicating the BMPs were effective at minimizing sediment loss, even under intense rainfall.

These annual sediment yields are similar to those found in other forest studies. Douglass and Goodwin (1980) found sediment yields over 9 Mg/ha/yr from southeastern piedmont sites receiving mechanical site preparation. Beasley (1979) recorded similar sediment yields following harvesting in the upper Gulf Coastal Plain. In the Virginia Piedmont, Fox et al. (1983) measured sediment export of 13 Mg/ha/yr from watersheds with intensive mechanical site preparation.

The average annual sediment yields from the No-BMP watershed were higher than those recorded in a nearby watershed with agricultural row crops. Annual sediment yields from this 214 ha subwatershed of Nomini Creek had an average of 1.16 Mg/ha/yr during the period 1990-1997 (Mostaghimi et al., 1999).

The median annual sediment yields show the effects of several large storms on yields from the No-BMP watershed in the pre-harvest period. Median annual sediment yield from the No-BMP watershed was similar to the other watersheds during the pre-harvest period. Following harvest and site preparation, the median annual sediment yield from the No-BMP increased an order of magnitude over the BMP and Control watersheds. While average yields from the No-BMP watershed were high during the pre-harvest period, as the result of a few large storm events, the median yields clearly indicate the impact of timber harvesting on sediment yield. Median annual sediment yields from the BMP and Control watersheds remained below 0.25 Mg/ha/yr throughout the study. Median annual sediment yields from the BMP and Control watersheds are similar to average sediment yields found in other forest studies. Several researchers have reported average sediment yields below 1 Mg/ha/yr following timber harvesting (Miller, 1984; Van Lear et al., 1985; Beasley and Granillo, 1988; Blackburn and Wood, 1990).

Nitrogen. Nitrogen Concentration. Median storm event concentrations of ammonium nitrogen ($\text{NH}_4^+\text{-N}$), nitrate nitrogen ($\text{NO}_3\text{-N}$), total Kjeldahl nitrogen (TKN), and total nitrogen (TN) are listed in table 3. Following clearcutting, median storm event $\text{NH}_4^+\text{-N}$ concentrations in the No-BMP watershed increased from 0.050 mg/L to 0.246 mg/L, an increase of 392%. These increases may have resulted from increased soil moisture following the decrease in storm runoff between the pre-harvest and post-harvest periods. Elevated soil moisture would have reduced soil oxygen levels and thus inhibited nitrification. Storm event $\text{NH}_4^+\text{-N}$ concentrations on the BMP watershed and the Control watershed decreased following clearcutting.

Table 4. Average and median sediment yield per analysis period (in Mg/ha/yr)

Watershed	Pre-harvest		Post-harvest		Post-prep	
	Average	Median	Average	Median	Average	Median
No-BMPs	3.70	0.04	9.76	2.12	7.67	2.91
BMPs	0.60	0.03	0.56	0.23	0.62	0.18
Control	0.27	0.01	0.57	0.12	0.13	0.03

These changes persisted for only 18 months. After site preparation, storm event $\text{NH}_4^+\text{-N}$ concentrations on all three watersheds returned to pre-harvest levels. The post-prep period was characterized by storms of greater volume and lower intensity, which could have led to increased soil moisture and decreased soil oxygen, resulting in reduced nitrification. In general, $\text{NH}_4^+\text{-N}$ concentrations were very low throughout the study and represented a small fraction of the total nitrogen.

Storm event nitrate ($\text{NO}_3\text{-N}$) concentrations were also low during the entire study (table 3). They were highest on the Control watershed and increased slightly following harvest to a post-harvest median of 2.50 mg/L. These higher concentrations could have been the result of agricultural activities in the upper part of the Control watershed. Median storm event $\text{NO}_3\text{-N}$ concentrations were slightly lower than median total flow (base flow and storm flow) concentrations, indicating groundwater was the source of much of the nitrate-nitrogen. There were no significant changes in storm flow $\text{NO}_3\text{-N}$ concentrations for the BMP watershed during the study. In the No-BMP watershed, there was a 39% decrease in storm $\text{NO}_3\text{-N}$ concentrations following harvest. No significant change in storm nitrate concentrations resulted from site preparation activities for the No-BMP watershed. Although the reduction in storm $\text{NO}_3\text{-N}$ concentrations is small (from 1.12 mg/L pre-harvest to 0.69 mg/L post-harvest), it could be the result of increased soil moisture following harvest. As stated previously, increased soil moisture would inhibit nitrification and promote denitrification, thus reducing nitrate concentrations.

Storm event TKN concentrations are shown in table 3. Storm TKN concentrations in the No-BMP watershed increased 378% following harvest and, following site preparation, storm TKN concentrations increased another 109%. This represents an almost 10-fold change over forested conditions. There was no significant change in storm TKN concentrations following harvesting or site preparation in the BMP watershed. In the Control watershed, there was a 17% increase in storm TKN concentrations during the post-harvest period. This was likely the result of intense storm events during this period. In the post-prep period, storm TKN concentrations from the Control watershed decreased to a level similar to the pre-harvest conditions. The BMPs appear effective at maintaining TKN concentrations during the timber harvest and site replanting.

Storm TKN concentrations in the No-BMP watershed were very high, an order of magnitude higher than storm concentrations in the other two watersheds. During the site preparation period, storm TKN concentrations in the No-BMP watershed had a median of 44 mg/L with a maximum concentration of 255 mg/L. Considering the storm $\text{NH}_4^+\text{-N}$ concentrations were below 0.25 mg/L, the majority of this TKN was in the organic nitrogen form. These high concentrations could be caused by the loss of slash adjacent to the stream during storm events. For the BMP watershed and the Control watershed, median storm TKN concentrations were below 4 mg/L throughout the study.

The majority of storm-related TKN was in the particulate organic form (TKN-filtered TKN). Webster and Swank (1985) noted that following logging, forests can lose large quantities of particulate organic matter. Table 5

Table 5. Percent of total Kjeldahl nitrogen in particulate form per analysis period

Watershed	Pre-harvest (%)	Post-harvest (%)	Post-prep (%)
No-BMP	66	96	97
BMP	62	90	58
Control	61	92	72

shows the percentage of TKN in the particulate form for each watershed during each analysis period. There is an increase in the percentage of particulate TKN in all watersheds during the post-harvest period. This could be the result of increased surface runoff caused by several strong storm events following harvest. During the post-prep period, the percentage of particulate TKN decreased in the BMP and Control watersheds, while levels in the No-BMP watershed remained high. The high proportion of particulate matter could have been caused by the continued loss of slash adjacent to the stream in the No-BMP watershed, where intensive harvesting was conducted along the stream. The practices implemented on the BMP watershed were effective at maintaining conditions similar to the forested watershed.

Total nitrogen (TN) concentrations, the sum of NH_4^+ and TKN concentrations, are listed in table 3. There was a significant increase in storm TN concentrations from 5.91 mg/L to 22.11 mg/L following harvest, and again to 45.29 mg/L following site preparation, in the No-BMP watershed. Approximately 95% of this nitrogen was in the organic form. Storm TN concentrations in the post-harvest and post-prep periods were an order of magnitude higher in the No-BMP watershed than in either the BMP watershed or the Control watershed. There were no significant changes in storm TN concentrations for either the BMP watershed or the Control watershed during the entire study.

Storm Event Nitrogen Loading. Compared to the pre-harvest period, storm TN loading from the No-BMP watershed increased 220% after timber harvest and 456% after the site burn (table 3). At the same time, storm TN loading in the BMP and Control watersheds were not significantly different from forested conditions. Between the post-harvest and post-prep periods, increases of 74% and 7% in storm TN loadings from the No-BMP watershed and BMP watershed, respectively, occurred. Due to the high variability in the storm TN loading data from the No-BMP watershed, the 74% change in loading was not statistically significant. Storm TN loading from the Control watershed did not change significantly at any time during the study.

Annual Nitrogen Loading. Average and median annual TN yields for each watershed are listed in table 6 for each analysis period. In the No-BMP watershed, average and median annual TN yield increased 3.6 and 2.3 times, respectively, following harvest. Average yields from the BMP and Control watersheds increased 1.2 times and 2.0 times, respectively, after harvest. Median annual

Table 6. Average and median nitrogen yield per analysis period (in kg/ha/yr)

Watershed	Pre-harvest		Post-harvest		Post-prep	
	Average	Median	Average	Median	Average	Median
No-BMPs	28.6	14.2	104.7	32.6	85.4	26.1
BMPs	11.9	7.9	41.8	10.2	17.1	11.2
Control	12.1	9.4	23.7	18.0	15.8	16.1

nitrogen yields followed similar trends. Increases in the Control watershed are likely the result of several intense storms during the post-harvest period. Correlation between TN loadings and maximum hourly rainfall intensity was tested using Spearman's Rho and Kendall's Tau for the Control watershed. The tests produced significant positive correlation between storm TN loadings and rainfall intensity at $\alpha = 0.05$.

During the post-prep period, average and median annual TN yields from the Control watershed were reduced while the yield from the BMP watershed increased. While the BMPs minimized TN loss following harvest, the herbicide treatments and site burning activities appear to have reduced this effectiveness. Nitrogen yield from the No-BMP watershed during the post-prep period was slightly lower than during the post-harvest period, but was still two to three times the pre-harvest level. Despite initially high yields, harvesting and site preparation activities greatly increased nitrogen loss on the No-BMP watershed.

Changes in the differences between the average and median annual nitrogen yields for each watershed during each period indicate the influence of a few large events on nitrogen loss following harvest. Following harvest, the difference between the average and median yields increases for both treatment watersheds. This indicates the data are becoming more right-skewed; there are a few events that contribute a large nitrogen load. Similar changes do not occur in the Control watershed.

Nitrogen yields from the No-BMP watershed were high (29 to 105 kg/ha/yr), as compared to other agricultural and forested watersheds. In a 214 ha agricultural subwatershed within the Nomini Creek Watershed, average annual TN loads of 21 kg/ha/yr were found for the period 1990 to 1997. Blackburn and Wood (1990) measured a maximum average annual TN loss of 3.13 kg/ha/yr the first year after three small watersheds in east Texas had been clearcut, sheared and burned. Yields from the undisturbed controls averaged 0.27 kg/ha/yr during the same period.

Phosphorus. Phosphorus Concentration. Total phosphorus concentrations (TP) during storm events increased significantly due to harvesting activities on the No-BMP watershed. Following harvest, the median storm TP concentrations increased from 0.96 mg/L to 3.70 mg/L (table 3), an increase of 285%. Median storm TP levels were further elevated to 7.36 mg/L following site preparation. Storm TP concentrations in the BMP watershed and the Control watershed were highest during the pre-harvest period, but throughout the study they remained below 0.65 mg/L.

Storm Event Phosphorus Loading. Following clearcutting, storm TP loading increased by 197% for the No-BMP watershed (table 3). Corresponding loadings from the BMP watershed and the Control watershed decreased 45% and 43%, respectively. Comparison of the post-prep and the pre-harvest periods indicated the storm TP loadings increased from the No-BMP watershed, did not significantly change from the BMP watershed, and decreased from the Control watershed. Site preparation activities caused a non-significant increase in storm TP loadings on both treatment watersheds, as compared to the post-harvest period, while the loadings on the Control watershed decreased 82%.

The majority of phosphorus lost from the treatment

watersheds during storm events was sediment-bound. Table 7 lists the percentage of storm total phosphorus that was sediment-bound for each watershed during each analysis period. There was an increase in the percentage of storm particulate TP for all three watersheds during the post-harvest period. This could be the result of several severe storms following forest harvest. The large proportion (98%) of particulate TP in the No-BMP watershed could also be caused by the runoff of decomposing slash adjacent to the stream or an increase in erosion following harvest. Similar results were found by McClurkin et al. (1985) during a study comparing clearcut watersheds to uncut controls in the upper Coastal Plain in Tennessee. The authors reported that 75% of the total phosphorus lost from the clearcut watershed was via sediment for a four-year period following timber harvest, as compared with 67% from the uncut control watersheds. For the BMP watershed in this study, a large increase in storm particulate total phosphorus occurred following site preparation activities. This could have been caused by the loss of organic materials following the site burn. Additionally, since base flow increased on the BMP watershed in the post-prep period, stream channel erosion could have occurred, thus increasing the loss of sediment-bound phosphorus.

Annual Phosphorus Loading. Average and median annual TP yields per watershed are listed in table 8 for each analysis period. Following harvest, TP yields increased by a factor of 3.4 in the No-BMP watershed. At the same time, TP yields from the BMP watershed decreased and TP yields from the Control watershed increased by a factor of 1.4. The increase in annual phosphorus loadings from the Control watershed probably resulted from an increase in precipitation volume and intensity in 1994, as well as changes in the upper cropland areas of the watershed. Storm event TP loadings from the Control watershed were positively correlated with storm maximum hourly intensity at $\alpha = 0.05$. After site preparation, average annual TP yields remained high for the No-BMP watershed, while they decreased below pre-harvest levels in the BMP and Control watersheds. Similar changes were observed with median annual TP yields. These data indicate forest clearcutting and site preparation without the implementation of BMPs greatly increased the loss of phosphorus. The practices utilized on the BMP watershed were highly effective at reducing phosphorus loss.

Table 7. Percent of sediment-bound storm total phosphorus per analysis period

Watershed	Pre-harvest (%)	Post-harvest (%)	Post-prep (%)
No-BMP	60	98	99
BMP	37	44	94
Control	27	64	51

Table 8. Average and median total phosphorus yield per analysis period (in kg/ha/yr)

Watershed	Pre-harvest		Post-harvest		Post-prep	
	Average	Median	Average	Median	Average	Median
No-BMPs	3.76	2.07	12.61	4.76	10.82	4.95
BMPs	1.96	1.19	1.72	0.55	1.60	0.41
Control	1.24	0.91	1.78	0.60	0.21	0.10

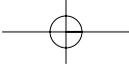
CONCLUSIONS

Results of this study indicate forest clearcutting and site preparation in the Virginia Coastal Plain without the implementation of BMPs cause significant increases in sediment and nutrient concentrations and loadings, particularly during storm events. Comparing forest clearcutting to site preparation activities, the herbicide treatments and burning during site preparation had a greater impact on water quality than the timber harvest. This study also shows that implementing a system of BMPs, as prescribed by the Virginia Department of Forestry, can greatly reduce the loss of sediment and nutrients as a result of silvicultural activities in the Virginia Coastal Plain. Additional research is needed to evaluate the impact of forest harvesting on instream erosion and the effects of streamside management zones on the hydrologic response of clearcut watersheds.

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