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EFFECTS OF FOREST MANAGEMENT ON SURFACE WATER QUALITY IN WETLAND FORESTS

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Abstract: A literature review on the effects of silvicultural practices on water quality in wetland forests was conducted. The review summarized results from nine wetland forests in five states (AL, FL, MI, NC, and SC). Silvicultural practices assessed were timber harvesting (including thinning and clearcutting), site preparation, bedding, planting, drainage, and fertilization. Many of the studies reviewed observed increased concentrations of suspended sediment and nutrients following silvicultural operations when compared with undisturbed controls. Water quality criteria were rarely exceeded by silvicultural operations, however, and effects on water quality were transient. Water quality parameters returned to undisturbed levels within a period ranging from months to several years.

Key Words: forest wetlands, palustrine, forestry, forest management, fertilization, drainage, harvest, harvesting, site preparation, bedding, water quality

INTRODUCTION

Forested wetlands are the most common type of wetlands in the conterminous United States (Dahl and Johnson 1991). The majority of these wetlands are owned by individuals and corporations and are managed for multiple benefits at various scales of intensity. Wetlands have been recognized as ecosystems that have been ill-treated by society in the past. Today, wetlands are protected to various extents by regulatory programs at scales from local to national. Some uses of wetlands by society are compatible with wetland functions. Timber production was recognized by the National Wetlands Policy Forum as a use of wetlands that produces income without significant loss of other wetland functions (The Conservation Foundation 1988). Gosselink et al. (1990) noted that timber harvesting in bottomland hardwood wetlands has minimal impact on long-term functions when conducted using best management practices.

Among the many reasons that wetlands are valued by society, is their ability to maintain or improve water quality. Some forest practices, such as timber harvesting, can result in unacceptable changes in surface water quality (Binkley and Brown 1993). Thus, it is important to assess the extent to which forest management practices affect water quality in wetland forests. This paper is a review of investigations that have assessed effects of common silvicultural practices on water quality in wetland forests. Such research is scarce. Most research on the effects of forest management on water quality has been conducted in uplands. For example, a symposium on timber harvesting in wetlands presented no quantitative data on water quality (Jackson and Chambers 1981). The proceedings of a symposium on impacts of human activities on bottomland hardwood wetlands also lacked any quantitative data on effects of forest management on water quality (Gosselink et al. 1990).

Although there are riparian wetlands associated with streams that drain upland forests, this review will be confined to those studies that investigated effects of forest management in forests that are predominantly wetland. It will not attempt to review the large body of literature that exists on effects of forest management on water quality in uplands. For such information, see Beasley (1979), Martin et al. (1984), McClurkin et al. (1985), Brown (1989), Lynch and Corbett (1990), and Binkley and Brown (1993). Some of the sites discussed in this review are in the transitional zone between wetlands and uplands, and thus, there is uncertainty whether they would be classified as wetlands by various regulatory guidelines.

DRAINAGE

Water tables often rise following timber removals in poorly drained soils due to the decrease in evapotranspiration (Trousdell and Hoover 1955, Williams and Lipscomb 1981). Minor drainage is often needed to remove surface water so that heavy equipment can be used in harvesting and to prepare the site for replanting without causing excessive soil compaction and rutting.

Askew and Williams (1984) quantified suspended sediment in drainage waters from a Carolina bay in South Carolina. The study area was a 2388 ha Carolina bay with clayey, poorly drained or very poorly drained soils. Forest types ranged from mixed loblolly pine (*Pinus taeda* L.)–hardwoods to baldcypress (*Taxodium distichum* L.)–tupelo (*Nyssa* spp.). The most common soil series were Cape Fear (Typic Umbraquults), covering 52% of the area, and Bladen (Typic Albaquults), on 29% of the area. The drainage system consisted of a main ditch (rectangular, 2–4 m wide and 2–2.5 m deep) connected to secondary ditches (triangular, 2–2.5 m wide and 1–2 m deep). Suspended sediment was quantified by sampling drainage water at twenty sampling points located across the drainage system to monitor sediment from different operations. Points were established downstream from undisturbed forests, active logging sites, site-prepared areas, 3- to 15-year-old plantations, and at numerous locations in the main ditch. Water quality was sampled during thirteen months when there was sufficient flow in 1981–1982.

On average, suspended sediment in new secondary ditches was significantly (α=0.05) greater than in natural streams draining an undisturbed hardwood stand. Ditch contribution to suspended sediment was transient. The authors monitored erosion in newly constructed ditches monthly and found that ditch erosion had culminated by the end of two years. Thus, two years after installation, ditches were no longer a major source of sediment in drainage water. In the main ditch, concentrations of suspended sediment declined as water moved toward the final discharge point from the study area. Suspended sediment concentrations at the final discharge point averaged 16.4 mg L^{-1}, compared to 2.5 mg L^{-1} in the undisturbed hardwood forest.

Askew and Williams (1986) also analyzed ditch drainage water for NO_3^--N, NH_4^+-N, SO_4^{2-}, Ca^{2+}, Mg^{2+}, K^+, total P, and dissolved oxygen. New ditches had slightly higher NO_3^--N than undisturbed hardwood area, 0.9 mg L^{-1} versus 0.5 mg L^{-1}, respectively. Concentrations of SO_4^{2-} averaged 33 mg L^{-1} in the undisturbed hardwood forest, increased to 47 mg L^{-1} in new ditches, and declined to 22 mg L^{-1} in water draining older plantations. A similar pattern was observed for Ca^{2+}. Concentrations of Mg^{2+} and K^+ were slightly elevated in new drainage ditches, then declined with time. Total P was not affected by drainage. Dissolved oxygen averaged 5.1 mg L^{-1}, was unchanged initially by ditching, and increased to 6.9 mg L^{-1} in water draining older plantations.

Effects of drainage were re-examined in this same South Carolina study area during 1982–1984 using two replicates of drained and undisturbed control subwatersheds (Williams and Askew 1988). Drained areas had significantly (α=0.05) greater suspended sediment, K^+, and Ca^{2+} concentrations than the control. There were no significant differences between drained and control concentrations of NO_3^--N, SO_4^{2-}-S, and Mg^{2+}. Hydrogen ion concentration was significantly (α=0.05) lower in the drained areas than in the controls.

From these investigations, the authors (Askew and Williams 1984, 1986, Williams and Askew 1988) concluded that pine plantations could be established without harming water quality. They observed that newly constructed ditches were a primary source of increased sediment and recommended that plantation establishment be done quickly to stabilize ditches. They also recommended that a length of main ditch be positioned between sediment sources and critical aquatic areas.

Trettin and Sheets (1987) examined effects of drainage on water quality in a forest wetland in Michigan's Upper Peninsula. The drainage system studied was a prescription type, which is intended to augment the natural drainage patterns in a catchment. The forest was comprised primarily of tamarack (*Larix laricina* (Du Roi) K. Koch), black spruce (*Picea mariana* (Mill.) B.S.P.), and jack pine (*Pinus banksiana* Lamb.). The most extensive soils were Kinross (Typic Haplaquods) and Au Gres (Entic Haplaquods), which both have histic epidedons 13 to 20 cm thick. They sampled drainage water and upstream and downstream of drainage discharge into the Sturgeon river over a 27-month period. They found that concentrations of Mg^{2+} and Fe were significantly (α=0.05) higher in drainage water than in the river by 1.1 mg L^{-1} for Mg^{2+} and by 1.4 mg L^{-1} for Fe. Differences in concentrations of Ca^{2+}, N, H^+, and suspended sediment between ditch and river water were not significant (α=0.05). Trettin and Sheets (1987) concluded that properly designed and implemented forest drainage systems can be installed without adversely affecting water quality.

The hydrology and water quality of three 25-ha loblolly pine plantation watersheds in Carteret County North Carolina has been studied intensively to develop a model for evaluating effects of alternate forest water management systems (McCarthy et al. 1991, 1992, McCarthy and Skaggs 1992). The plantations were established in 1974 following site preparation, bedding, and fertilization with N and P. The plantations were thinned and fertilized at age 15 (see additional information in Fertilization section). The soil was primarily Deloss, a Typic Umbraquult.

The water quality effects of pine plantation management, which include bedding, fertilization, drainage, and thinning were evaluated by comparing concentrations at several sampling stations (Table 1): immediately below the plantation watersheds (D1, D2,

Table 1. Two-year average water quality parameters from 15-year-old loblolly pine plantation watersheds and subsequent drainage waters in Carteret County, North Carolina. Parameters are ammonium nitrogen (NH_4-N), biological oxygen demand (BOD), fecal coliform, nitrite and nitrate nitrogen (NO_2 & NO_3-N), pH, total kjeldahl nitrogen (TKN), total phosphate (TPO_4), total suspended solids (TSS), and turbidity. Adapted from Campbell (1989).

	Sample Station[1]					
	D1	D2	D3	D4	D5	D6
NH_4-N (mg/l)	0.07	0.06	0.05	0.64	0.11	0.05
BOD (mg/l)	0.83	0.61	0.47	0.48	0.53	2.94
Fecal coliform (mpn/100 ml)	39	23	11	17	151	634
NO_2 & NO_3-N (mg/l)	0.94	0.57	0.22	0.48	0.49	0.05
pH	4.12	4.39	5.81	5.68	6.09	7.24
TKN (mg/l)	1.27	0.88	0.55	1.48	0.77	0.97
Total PO_4 (mg/l)	0.04	0.04	0.04	0.08	0.09	0.14
TSS (mg/l)	1.35	1.83	5.32	7.94	4.34	28.44
Turbidity (ntu)	1.80	1.73	8.49	9.22	7.72	16.39

[1] Stations D1, D2, and D3 are located at the outflows of plantation watersheds 1, 2, and 3, respectively. Station D4 is at a gravel road ditch that receives drainage from the plantations. Stations D5 and D6 are along a paved road, with D6 located prior to mixing with the plantation watershed drainage and D5 after mixing.

and D3), after entering a ditch adjacent to a gravel road (D4), and in a ditch adjacent to a paved road, both before (D6) and after (D5) mixing with water from the plantations. Land use in the area upstream of stations D1 through D4 is exclusively forest, consisting primarily of the three pine plantation watersheds, with a gravel road system including roadside ditches. The area upstream of D5 and D6 includes agriculture and forests, and the road is lined with residences that use septic systems for household wastewater.

Levels of NH_4^+-N, biological oxygen demand (BOD), fecal coliform, pH, total PO_4, total suspended solids, and turbidity in water draining from the plantations (D1–D3) were less than or similar to concentrations at the other sampling stations (Table 1). Levels at station D6, upstream from the plantations studied, were higher than all other stations for BOD, fecal coliform, pH, total PO_4, total suspended solids, and turbidity (Table 1). Thus, water quality draining the plantations was generally higher than that in the paved road ditch. Water quality at station D5, after mixing with water from the plantation watersheds, was improved. For example, dilution by water from the plantation watersheds lowered the fecal coliform count enough to meet state water quality standards (200 mpn/100ml, North Carolina Department of Environmental Management 1989), whereas prior to dilution, it averaged over three times the state water quality standard (Table 1).

FERTILIZATION

Fertilization with N and P is a common practice in intensively managed forests. In the North Carolina plantation watershed study described above, an investigation of the effects of operational fertilization on water quality was conducted (Campbell 1989). In March 1989, after thinning, the three watersheds were fertilized with diammonium phosphate and urea (167 kg N ha^{-1} and 28 kg P ha^{-1}) by ground-based equipment. Daily water quality samples were taken from the watersheds and receiving ditches for 30 days before and 30 days after fertilization and at lower frequencies thereafter.

Fertilization resulted in elevated concentrations of NH_4^+-N, total N, total PO_4, ortho PO_4, and urea in water draining from the watersheds. After three weeks, concentrations had returned to pre-treatment levels. Maximum concentrations during the elevated period were 3.8 mg L^{-1} for NH_4^+, 9.3 mg L^{-1} for total N, 0.18 mg L^{-1} for total phosphate, 0.1 mg L^{-1} for ortho phosphate, and 1.2 mg L^{-1} for urea. Concentrations of combined NO_2^-&NO_3^- were variable both before and after fertilization and ranged from near zero to a maximum of 1.2 mg L^{-1} during both periods.

Daily water flow data from the watershed weirs and daily concentrations were used to calculate export from the watersheds for 30 days before and 30 days after fertilization. Post-fertilization solute export rates were higher than pre-fertilization rates for all nitrogenous compounds but were lower for phosphate (Table 2). Rates were not different statistically (α=0.05) due to variability between watersheds. Net differences in pre- versus post-fertilization export were small compared to the amount of applied fertilizer. For example, net export of total Kjeldahl N was 0.3% of total N applied, net export of NH_4^+-N was 0.02% of total applied N., and net export of urea-N was 0.03% of total applied urea-N.

A similar fertilization study was conducted in Jones County North Carolina in 1983 (Herrmann and White

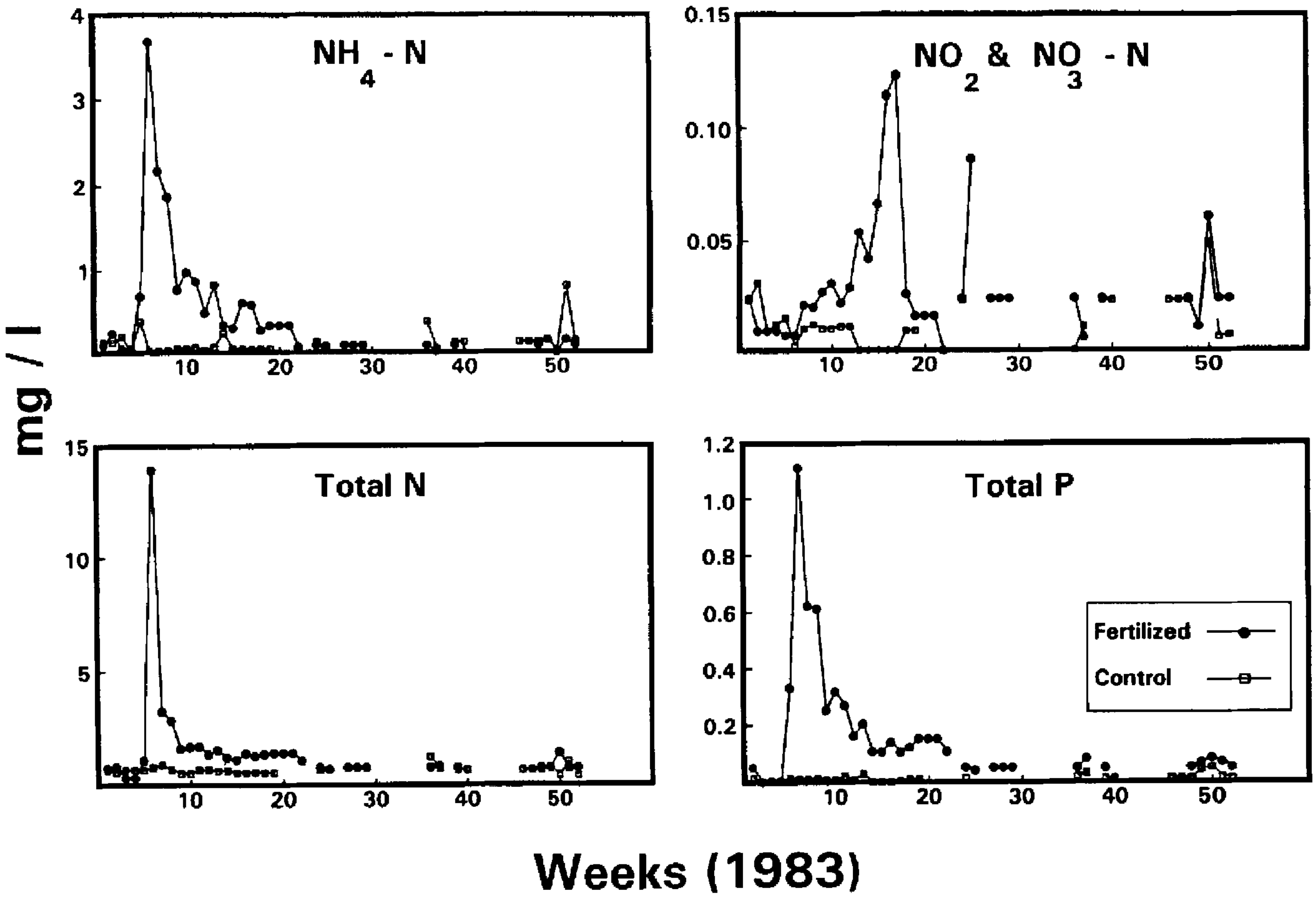

Figure 1. Weekly average solute concentrations in drainage outflow of a six-year-old loblolly pine plantation in Jones County, North Carolina. Fertilization with diammonium phosphate and urea (216 kg N ha^{-1} and 36 kg P ha^{-1}) occurred in weeks 4 and 5. Adapted from Herrmann and White (1983).

1983) and in 1992 (Fromm 1992). Two loblolly pine plantation tracts were studied. Tract 2 was 75 ha and Tract 3 was 65 ha. Soils in the tracts were predominantly Woodington (Typic Paleaquults) and Torhunta (Typic Humaquepts). In 1983, when the plantations were six years old, Tract 3 was fertilized with an aerial application of diammonium phosphate and urea (216 kg N ha^{-1} and 36 kg P ha^{-1}). Tract 2 was used as a control.

As with the Carteret County study, fertilization resulted in an immediate rise in NH_4^+-N, NO_2^-&NO_3^--N, total N, and total P in water draining from the tracts (Figure 1). Peak concentrations of these constituents occurred during week 6, one week after fertilization. Concentrations had declined to approximately the same as control concentrations by week 35. In contrast, peak concentrations of NO_2^-&NO_3^- did not occur until 12 weeks after fertilization, presumably due to oxidation of both applied ammonium and ammonium hydrolyzed from urea. Similar delayed nitrate peaks have been observed in forest fertilization experiments with urea in the Pacific Northwest (Bisson et al. 1992). Exports of N and P were increased substantially during 48 weeks following fertilization (Table 3).

In 1992, Tract 2, which had been used as the control in 1983, was fertilized with diammonium phosphate and urea (207 kg N ha^{-1} and 34 kg P ha^{-1}) using ground-based equipment. Tract 3 was used as a con-

Table 2. Comparison of pre- and post-fertilization solute export in 15-year-old loblolly pine plantation watersheds in Carteret County, North Carolina. Adapted from Campbell (1989).

Treatment	TKN	NH_4-N	NO_2 & NO_3-N	TPO_4	Urea-N
			g/ha/d		
Pre	33.50	1.96	24.40	1.03	0.59
Post	40.62	3.12	26.39	0.75	3.15
p[1]	0.49	0.38	0.74	0.47	0.21

[1] Probability that pre- and post-fertilization means do not differ using paired t-test.

Table 3. Effects of fertilizing loblolly pine plantations in Jones County, North Carolina with urea and diammonium phosphate on watershed nitrogen and phosphorus export. Adapted from Herrmann and White (1983) and Fromm (1992).

Year	Treatment	Total Kjeldahl N	Total P
		g/ha/d	
1983	Control	12.20	0.24
1983	Fertilized	41.79	5.65
1992	Control	0.18	0.02
1992	Fertilized	0.16	0.01

Table 4. Water quality in stream water following timber harvesting, site preparation, and reforestation with slash pine in Florida. Adapted from Fisher (1981).

Water Quality Parameter	Undisturbed Control Watershed	Annual Mean Concentrations (mg L^{-1}) (years after treatment) 1	2	3
NO_3^--N	0.01	0.05	0.02	0.01
NH_4^+-N	0.02	0.43	0.07	0.03
Total N	0.85	2.69	1.50	0.09
PO_4-P	0.00	0.07	0.00	0.00
Total P	0.03	0.28	0.03	0.03
pH	3.9	4.2	4.3	4.1
Total suspended solids	6.	137.	28.	8.

trol. In contrast to the 1983 results, fertilization in 1992 did not appreciably influence N and P export rates in water draining the watersheds (Table 3). Solute concentrations were not elevated during or after fertilization (Fromm 1992).

The difference in the results between the two fertilizer applications was due to the nature of the application. The 1983 fertilization was conducted at age six when the stand was not accessible to ground-based equipment; thus, fertilizer was applied by helicopter. Some fertilizer was unavoidably deposited in the ditch system during helicopter application and directly affected water quality. During the 1992 fertilization, the plantation was 15 years old, so ground-based equipment could be used. Care was taken to avoid fertilizing the ditches. Leaving unfertilized buffer ditches resulted in 17% of the tract being unfertilized and 33% being fertilized at half the intended rate but was effective in preventing elevated fertilizer concentrations in drainage water.

TIMBER HARVEST AND SITE PREPARATION

Timber harvesting can affect water quality through soil disturbance by heavy equipment and sediment production from logging decks, skid trails, roads, and ditches. Timber harvest can alter hydrology and many biogeochemical processes, and thus, surface- and ground-water concentrations of compounds such as nitrate and phosphate may be affected.

Hollis et al. (1978) and Fisher (1981) reported on effects of silvicultural practices on water quality in a coastal lowland site in western Florida. Soils were predominantly poorly drained, sandy, Inceptisols. Forest types were slash pine (*Pinus elliottii* Engelm.), mixed slash–longleaf pine (*Pinus palustris* Mill.), and mixed pine–hardwoods. A variety of wetland types were included in the study area. Two rectangular watersheds approximately 400 ha each were defined using roads and ditches. All runoff from each watershed was collected into a single ditch and was monitored at a culvert weir. One watershed was harvested, site prepared, and planted; the other watershed was left undisturbed as a control. Trees were felled with crawler tractor mounted shears, and logs were skidded tree-length. Site preparation consisted of two passes of a rolling drum chopper. The site was then bedded and planted with slash pine at a 2 × 3 m spacing.

Annual mean concentrations of all parameters measured were elevated relative to the undisturbed watershed for the first year following treatment (Table 4). The effect of silvicultural operations was observed least for NO_3^--N and most for sediment. Annual means for NO_3^--N, PO_4-P, and total P in the treated watershed had returned to undisturbed levels by the second year. By the third year, all constituents had returned to undisturbed levels (Table 4).

Ewel (1985) examined water quality in two central Florida cypress swamps before and after thinning in comparison with two control cypress swamps. Trends in water quality were not consistent. She observed increased total and organic nitrogen in one swamp following thinning. However, after three months, both thinned swamps had lower N concentrations than controls. No response to harvesting was observed for NO_3^- and NH_4^+.

Riekerk (1985) compared water quality in three watersheds in north-central Florida. The study area included mixed pine flatwoods and cypress wetlands. The flatwoods were dominated by 40-year-old slash pine, with some longleaf pine present. Shallow ponds covered about 40% of the study area and were dominated by baldcypress and sweetbay magnolia (*Magnolia virginiana* L.). Predominant soils were Mascotte (Ultic Haplaquods), covering 40% of the area, and Stilson (Arenic Plinthic Paleudults) on 20% of the area.

Two watersheds were harvested, site prepared, and planted with slash pine. One was treated to simulate minimum disturbance, whereas the other simulated maximum disturbance. For the minimum disturbance treatment, 59% of the watershed was clearcut using hand-felling, and logs were removed with a small pre-hauler. Site preparation was accomplished by double chopping with a knife-bladed drum, followed by bedding at a 4 m spacing. Slash pine was planted by machine at a 2-m spacing. For the maximum disturbance treatment, 74% of the watershed was clearcut with a feller-buncher, and logs were skidded tree-length to a delimbing gate. Logging slash was broadcast-burned then piled into windrows by a dozer with a knife-edged blade. The soil was harrowed, then bedded and planted the same as the minimum disturbance treatment. Best management practices, a means of protecting water quality, were used in the minimum disturbance treatment but not in the maximum disturbance treatment. For example, the minimum disturbance treatment left a buffer zone around areas with surface water, whereas the maximum disturbance treatment did not.

Water quality in these two watersheds and an undisturbed control was monitored by collecting samples from a drainage outlet in each watershed. Monitoring began in 1978, the treatments were applied in 1979, and monitoring continued through 1983, four years after treatment.

The treatments resulted in significant (α=0.05) increases in annual mean values for pH, suspended sediment, total N, K^+, and Ca^{2+}. Suspended sediment was significantly (α=0.05) greater in the maximum treatment than the other watersheds during the treatment year and in the fourth year after treatment, but differences were small. Surprisingly, the highest annual mean sediment concentrations in all three watersheds were observed in 1978 prior to treatment. Concentrations of Ca^{2+} and K^+ in the treated watersheds were significantly (α=0.05) greater than those from the control, and these differences were more persistent than other parameters. For example, K^+ in the minimum treatment and Ca^{2+} in the maximum treatment were significantly greater than the control in the fourth year after treatment. Concentrations were low, being less than 2 mg L^{-1} in all three watersheds. In contrast to K^+ and Ca^{2+}, total P was not significantly (α=0.05) different among the three watersheds in any year. Trends for nitrogen were not consistent with treatment. For example, the only significant (α=0.05) difference between treatments for NO_3^--N was that the minimum impact treatment had significantly (α=0.05) lower NO_3^--N during the treatment year than the other treatments. However, the first year after treatment, the minimum treatment had significantly (α=0.05) greater total nitrogen, and the maximum treatment had significantly (α=0.05) less total nitrogen than the control.

Aust et al. (1991) reported effects of clearcutting on the ability of water tupelo (*Nyssa aquatica* L.)- baldcypress swamps in the Mobile-Tensaw river delta of lower Alabama to remove sediment from flood waters. The predominant soil in the study area was Levy (Vertic Fluvaquent). The study compared sedimentation rates in three harvest treatments installed in three replicates. Harvesting for all treatments occurred in the autumn of 1986 using handfelling with chainsaws. The treatments differed post-felling: (1) helicopter log removal (treatment H), (2) helicopter log removal, followed by application of glyphosate herbicide in July 1987 and June 1988 (treatment G), and (3) simulated rubber-tired skidder log removal (treatment S). An adjacent undisturbed area was used as a control (treatment R).

Rates of sedimentation during the 1987–1988 flood season, approximately one year after harvest, averaged 2.2 mm for treatment H, 1.2 mm for treatment S, 1.1 mm for treatment R, and 0.7 mm for treatment G. The mean sedimentation rate from the helicopter treatment was significantly (α=0.05) greater than the means in the glyphosate treatment and reference area but was not statistically (α=0.05) different from the skidder treatment. Mean sedimentation rates were not significantly (α=0.05) different among the skidder, glyphosate, and reference treatments. The authors attributed differences in sedimentation rates among treatments to differences in the amount and condition of logging slash among treatments and in the nature of the vegetation. The helicopter and skidder treatments had approximately the same amount of slash, but in the skidder treatment, the slash was broken down by repeated skidder traffic and was not as able to trap sediment. The lower sedimentation value in the glyphosate treatment was attributed to lack of regrowth due to herbicide application and illustrates the importance of the woody and herbaceous vegetation regrowth following clearcutting for removal of sediment from flood water.

Another study in lower Alabama investigated effects of clearcut timber harvest on surface and ground-water quality in small floodplains (Lockaby et al. 1994). The forest was dominated by an uneven-age mixture of swamp tupelo (*Nyssa sylvatica* var. *biflora* (Walt.) Sarg.), sweetbay magnolia, red maple (*Acer rubrum* L.), yellow-poplar (*Liriodendron tulipifera* L.), American holly (*Ilex opaca* Ait.), slash pine, and laurel oak (*Quercus laurifolia* Michx.). Soils in the central portion of the floodplain were predominantly Dorovan (Typic Medisaprist), whereas those on the floodplain margins were predominantly Johnson (Cumulic Humaquept). The study was designed to assess the effects of two different types of timber harvesting on water quality and other wetland functions. One 4 ha rectangular block was clearcut in each of three separate, replicate floodplains. The two harvest treatments within each block were (1) handfelling followed by helicopter removal of logs, and (2) felling by feller-buncher on mats followed by log removal using rubber-tired skidders. Surface water quality was assessed by comparing samples taken upstream, within, and downstream from the harvested blocks. Ground-water quality was assessed by sampling PVC wells within the different harvest treatments in comparison with undisturbed upstream locations.

Nitrate and phosphate concentrations in surface and ground water following harvesting were near detection limits (0.1 mg L^{-1}) and did not differ significantly among samples taken in the undisturbed control upstream of the clearcut, those taken within the clearcut, and in a downstream uncut control. There were no significant (α=0.05) differences in suspended sediment or BOD relative to harvesting treatments. One floodplain did show elevated BOD values within the harvest area during the middle and latter portion of the first growing season following harvest. During one sample period, BOD in the harvested block of this floodplain exceeded the Alabama BOD standard (14.4 versus 10.0 mg L^{-1}). However, BOD from a sample taken in the uncut forest 15 to 45 m downstream from the harvest block was 0.4 mg L^{-1} and was thus similar to the 1.1 mg L^{-1} observed upstream from the harvest block in this floodplain.

Askew and Williams (1984) assessed the effects of timber harvesting and site preparation on suspended sediment in drainage waters from a ditched Carolina bay in South Carolina (see study description given earlier in Drainage section). Timber harvesting and site preparation alone did not result in substantially elevated suspended sediment concentrations. The combined effects of drainage, logging, planting, and skidding resulted in large suspended sediment concentrations during the rising limb of the hydrograph. Concentrations declined to levels comparable to older pine plantations during the falling limb stage of the hydrograph.

Askew and Williams (1986) also assessed the effects of logging, site preparation, and pine plantation establishment on nutrient concentrations in drainage water. Nitrate nitrogen in drainage water from logged and site-prepared areas averaged 0.2 mg L^{-1} and was lower than the 0.5 mg L^{-1} average in the undisturbed control. The NO_3^--N concentrations draining older plantations was similar to control concentrations. Concentrations of NH_4^+-N were very low in the control, as well as after logging, site preparation, and plantation development. Silvicultural operations raised pH in drainage waters relative to the control, which averaged 4.4. Following logging, pH was increased to 5.2. After site preparation, pH increased to 5.5. A peak pH of 5.8 was observed in young pine plantations, with pH declining in older plantations to 5.4. Trends in SO_4^{2-} concentrations were opposite from the pattern described for pH but were similar when compared with H^+ concentrations. Sulfate concentrations dropped during logging, site preparation, and early plantation development, then increased to higher levels in older plantations. Older plantations had SO_4^{2-} concentrations similar to the control. Trends in SO_4^{2-} concentrations, as expected, were the opposite of the pH pattern. The SO_4^{2-} concentration patterns follow the H^+ concentration. These concentrations decrease during logging, site preparation, and early plantation development. Sulfate and acidity increase progressively with age in older plantations. The cations Ca^{2+}, Mg^{2+}, and K^+ showed somewhat different patterns during silvicultural operations relative to the control. Concentrations of both Ca^{2+} and K^+ were elevated after logging and site preparation. Calcium concentrations returned to control levels by the young plantation stage, whereas K^+ concentrations remained higher than the control through the older plantation stage. Concentrations of Mg^{2+} were unchanged following logging but were slightly lower than the control during site preparation and subsequent plantation development. Concentrations of dissolved oxygen were higher than the control during all phases. Total phosphorus was below detection limit for all samples.

Effects of site preparation, logging, and pine plantation development were re-examined (Williams and Askew 1988) in this same South Carolina study area during 1982–1984 using two replicates of drained and undisturbed control subwatersheds (see study description given earlier in Drainage section). They found that logging resulted in significantly (α=0.05) higher concentrations of K^+, but concentrations of NO_3^--N, SO_4^{2-}-S, Ca^{2+}, Mg^{2+}, and H^+ were significantly (α=0.05) lower. Site preparation also resulted in significantly (α=0.05) higher concentrations of K^+, whereas concentrations of NO_3^--N and H^+ were significantly (α=0.05) lower. They compared the cumulative effects of both harvesting and site preparation in the same subwatershed against an undisturbed control. Suspended sediment, Ca^{2+}, and K^+ were significantly (α=0.05) higher in the combined treatment compared with the control. Concentrations of NO_3^--N, SO_4^{2-}-S, Mg^{2+}, and H^+ in the combined treatment were significantly (α=0.05) lower than the control.

Verry (1986) discussed effects of silvicultural practices on hydrology and water quality of upland and wetland forests in the Lake States. Phosphorus was the parameter of most concern since increased P can result in lake eutrophication. Verry (1986) cited work by Knighton and Stiegler (1981) that compared P export following clearcutting a black spruce bog and following harvest and burning in a black spruce fen. Phosphorus export in the bog was 0.89 kg ha^{-1} the first year after harvest, compared to 0.33 kg ha^{-1} pre-harvest. Phosphorus export returned to pre-harvest levels by the third year after harvesting. In the fen, P export increased from 0.71 kg ha^{-1} before harvesting and burning to a maximum of 2.18 kg ha^{-1} during the first year after disturbance. Exports of P then declined to 1.03 kg ha^{-1} for year two, 1.77 kg ha^{-1} for year three, and had declined to pre-harvest levels by year four (0.79 kg ha^{-1}).

DISCUSSION

Silvicultural operations resulted in measurable effects on water quality. Effects were typically small and water quality criteria were rarely exceeded. Effects were transient. Water quality parameters returned to undisturbed levels within a period ranging from months to several years. The duration of these effects should be viewed in comparison with their frequency. Timber harvesting in wetland forests occurs at frequencies ranging from 20 to 50 years or more, depending on forest type and management objectives. This review thus concludes that properly conducted silvicultural operations do not constitute a permanent threat to the ability of wetlands to maintain or improve water quality.

Hollis et al. (1978) noted that effects of silvicultural operations on water quality in lowland forests were less than those reported for upland forests with greater relief and shallower soils. Low relief is perhaps the most important factor underlying the minimal water quality response to silvicultural operations in wetland forests. Most wetlands have little topographic relief, and thus, surface water flow rates are low. In fact, surface water in many wetland forests is from ponding and does not flow to any appreciable extent. Thus, there is less energy available to carry sediment than in upland forests with greater hydrologic gradients.

There are numerous opportunities for additional research on effects of silvicultural operations on water quality in forest wetlands. Currently, the literature is dominated by studies from the South and the Lake States. There seems to be no published information from other regions. Silvicultural effects have not been studies in all common wetland forest types. For example, there is currently little published information on water quality effects of silviculture in bottomland hardwood wetlands, although several studies are underway (Shepard et al. 1993). There is a critical need for research to provide the technical foundations for best management practices for forest wetlands. Research is needed to test effectiveness of current BMPs in wetland forests and to test alternate BMPs (e.g., buffer strip widths).

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