CONTRASTING TIMBER HARVESTING OPERATIONS ILLUSTRATE THE VALUE OF BMPS

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Abstract—Our paper compares water yield, water quality, and sedimentation from a harvesting operation conducted in 1957 without BMPs to a harvesting operation in 1986 utilizing BMPs. The comparison illustrates the values of BMPs for protecting soils and streams and provides insight into causes of water quality degradation. Both logging operations were conducted on or near the Fernow Experimental Forest located in north central West Virginia. The 1957 logging operation was conducted on a 74-acre watershed using a crawler tractor equipped with an arch. Roads were unplanned "logger's choice" with no limits on grade or location. West Virginia's BMPs were used on a second 96-acre watershed logged with wheeled skidders in 1986. Results indicated that careless logging greatly accelerated sediment yields but development of erosion pavements and natural vegetation quickly reduced them, even with no post-logging care. Although the percentage of area occupied with dozed roads was actually greater (10.6 versus 3.6 percent) on the area logged in 1986 with wheeled skidders, water quality impacts were much less. Average stream turbidity during logging in the absence of BMPs was 490 ppm versus <10 when using BMPs. Sediment loss during active logging was estimated at 2,880 lb/ac on the carelessly logged watershed compared to 110 lb/ac when BMPs were used.

INTRODUCTION

Bare soil exposed during timber harvesting can be a major source of water degradation, but guidelines developed over the years reduce adverse impacts on soil and water resources (Weitzman 1952; Haussman 1960; Kochenderfer 1970; and Pierce and others 1992). Passage of the Federal Water Pollution Control Act Amendments of 1972 required use of BMPs to control nonpoint-source water pollution from forestry activities. Despite application of past research and BMPs, and the goals of present-day forest managers to sustain and protect site productivity, critics of current timber harvesting operations sometimes equate them with less careful logging operations of the past. Thus it is important to demonstrate the improvements of current logging and BMPs in terms of protecting soil and water resources. This paper does so by comparing magnitude and longevity of impacts from a harvesting operation conducted in 1957 without BMPs to a 1986 harvest utilizing them.

STUDY AREAS

Three gaged watersheds located in the unglaciated Allegheny Plateau region of north-central West Virginia were used in this study. Two of them, watershed 1 (WS1) and watershed 4 (WS4), are located on the Fernow Experimental Forest while the Haddix watershed is 4.0 miles away. WS1 and Haddix were logged while WS4 has been retained as a reference watershed to evaluate treatment effects. Precipitation is distributed evenly across the year on all three watersheds; the annual average is 58 inches on the Fernow and 54 inches on Haddix. Annual runoff from WS4 during the study periods averaged 26 inches, 6 inches during the growing season and 20 inches during the dormant season. Other pertinent characteristics are shown in Table 1.

WS1 supports a 40-year-old stand of mesic hardwoods that originated after cutting in 1957-58, plus some scattered cull trees dating to earlier cutting in 1905-10. Dominant tree species are sugar maple (*Acer saccharum* Marsh.), northern red oak (*Quercus rubra* L.), yellow-poplar (*Liriodendron tulipifera* L.), and basswood (*Tilia americana* L.). Average stand basal area in trees 1-inch and larger averages 128 ft^2/ac. Streambanks are well vegetated but considerable bare soil is still exposed at former skidroad crossing sites along the main stream. The predominant soil series on both WS1 and WS4 is Calvin channery silt loam (loamy-skeletal, mixed, mesic typic Dystrochrepts) with moderate erosion hazard (Losche and Beverage 1967). Soils are underlain with fractured sandstone and shale of the Hampshire formation.

Table 1—Characteristics of study watersheds

	Haddix	WS1	WS4
Area, acres	96	74	96
Aspect	S	E	SE
Average slope, %	40	40	25
Average stream gradient, %	11	16	13
Stream channel area, acres	.47	.26	.30
Sediment source area, acres[a]	10.8	3.0	1.1
Tree basal area, ft^2/ac[b]	109	109	154

S = South, E = East, SE = Southeast
[a] Defined as stream channel area + road area measured upon completion of logging.
[b] Basal area prior to harvest.

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The Haddix watershed supports a 12-year-old, mixed hardwood stand that originated after a 1986 harvest, along with older residuals left from earlier harvests. Approximately one-third of it contains a dense understory of rhododendron (*Rhododendron maximum* L.). After the harvest of 1986, it supported a mixed stand of oak species (*Quercus* spp.), hickory (*Carya* spp.), red maple (*Acer rubra* L.), and yellow-poplar, vegetation reflecting a somewhat xeric site. Residual basal area after the 1986 cut averaged 61 ft^2/ac, about half of the 109 ft^2/ac before harvest. The watershed is underlain by interbedded shale, siltstone, and sandstone of the Chemung geologic formation. The predominant soil series is Berks channery silt loam (loamy-skeletal, mixed, mesic, Typic Dystrochrepts), with moderate erosion hazard (Losche and Beverage 1967). Streambanks are generally well vegetated. The channel is armored with sandstone cobbles and gravel. However, as with many stream channels in the region, there is considerable bare soil along streambanks.

WS4 provided experimental control for water quality and streamflow. It has remained relatively undisturbed since about 1905 when much of the original timber was cut. Dominant tree species are yellow-poplar, sugar maple, and northern red oak, indicating a more mesic site than Haddix. In 1994, average basal area was 154 ft^2/ac for trees 1-inch dbh and larger. The stream channel is well armored with sandstone gravel and cobbles, and streambanks are well vegetated.

TREATMENTS

WS1 was commercially clearcut between May 1957 and September 1958. All merchantable trees >5.0 inches dbh were cut. Cull trees were left standing. An average volume of 8,984 bd ft/ac was harvested. Average basal area in trees >1-inch was reduced by 77 percent to 26 ft^2/ac. Logging was done with a tractor and arch, with no measures taken to protect soil and water resources. Skidroads were constructed on a logger's choice basis with no restrictions on road grade or location. For example, no culverts or bridges were used at stream crossing sites nor were normal post-logging practices such as waterbarring or seeding used. Many of the skidroads were in or immediately adjacent to stream channels (Fig. 1). There were no truck roads or landings located in WS1. Data for road area and location are in Table 2.

The Haddix watershed was cut to a 14-inch stump diameter between May 1986 and February 1987, removing an average volume of 5,344 bd ft/ac. Average basal area was reduced 44 percent in trees 1-inch and larger. A

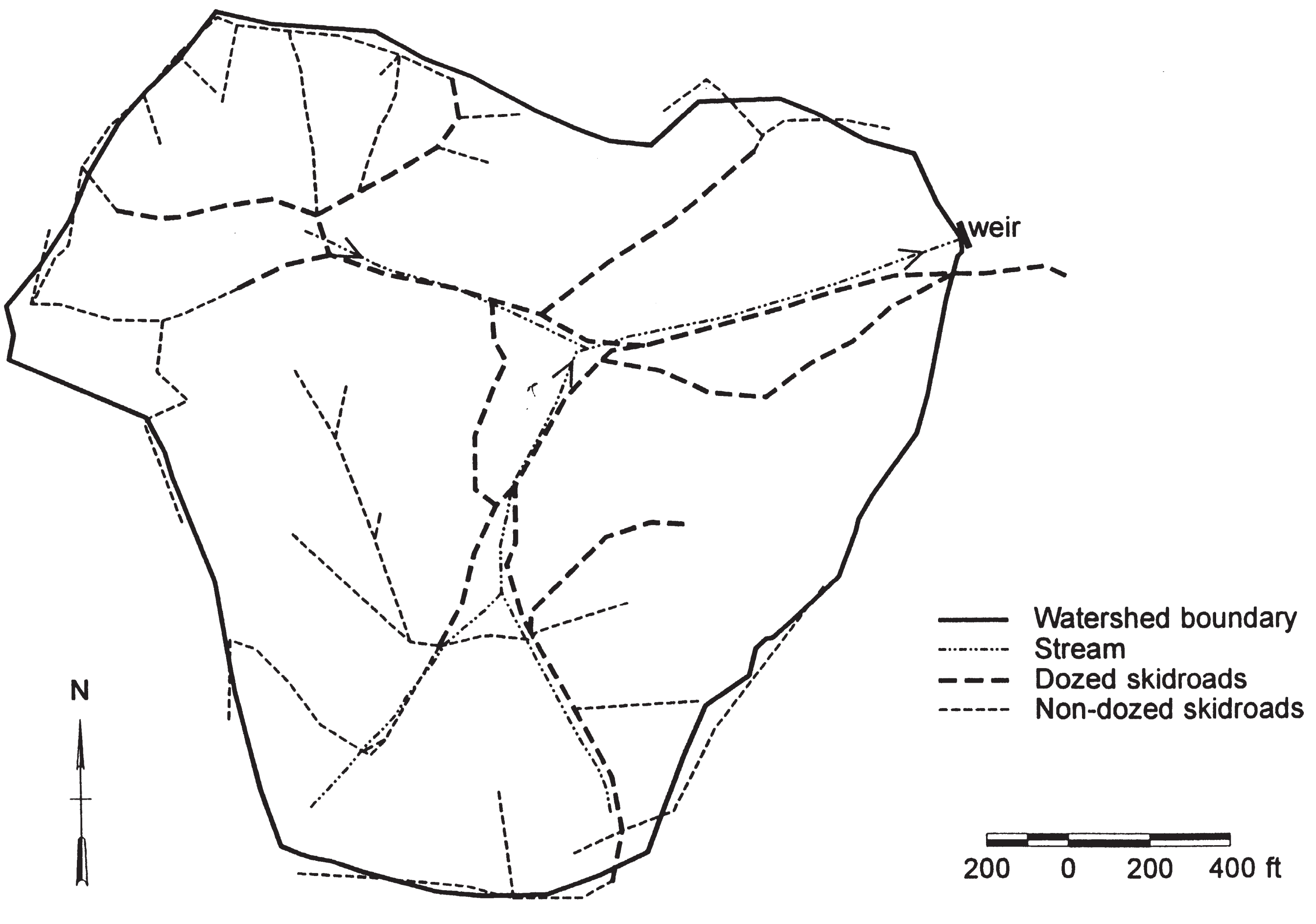


Figure 1—The unplanned road system in WS1 was used to remove 668 Mbf of timber from the 74-acre watershed. No measures were taken to protect soil and water resources.

Table 2—Roads in harvested watersheds

	WS1	Haddix
Dozed skidroads		
Length in miles	1.3	3.0
Area, acres	2.7	6.0
Percent of watershed area	3.6	6.2
By grade class, %		
0-10	22	74
11-20	32	24
21+	46	2
Within distance of stream, %		
<25 ft	40	1
<50 ft	61	3
<100 ft	66	3
Non-dozed skidroads		
Length in miles	2.2	0
By grade class, %		
0-10	31	0
11-20	35	0
21+	35	0
Truck roads		
Length in miles	0	0.9
Area, acres		4.3
Percent of watershed area		4.5
By grade class, %		
0-10	NA	100
11-20	NA	0
21+	NA	0
Within distance to stream, %		
<25 ft	NA	4
<50 ft	NA	5
<100 ft	NA	5

wheeled skidder was used to skid tree-length logs to landings. A D-4 bulldozer was used to construct skidroads as needed during harvesting.

BMPs recommended for use from 1979 to 1989 in West Virginia (West Va. Dep. Natur. Resour. 1979, 1982) were followed for this harvesting operation. The entire road system on Haddix was planned and laid out on the ground before logging to minimize roaded area and environmental impacts (Fig. 2).

A minimum-standard truck road (Kochenderfer and others 1984) was built with a John Deere 850 bulldozer. Broad-based dips (USDA For. Serv. 1940, Hewlett and Douglas 1968) spaced at about 150-foot intervals controlled overland flow. Natural grade breaks reduced the number of constructed dips needed. Except at stream crossings, roads were kept at least 100 ft slope distance from streams (Fig. 2). Metal culverts were installed at four locations where the truck road and skidroads crossed streams. A combination of metal culverts and ditches also was used on the truck road to drain three seeps. Culverts were left in place following the harvesting operation. All four landings were located on dry sites, at least 150 feet slope distance from the nearest stream.

Some rutting was tolerated on the ungraveled truck road, but hauling during extremely wet conditions was prohibited; it would have resulted in deep ruts and damage to the roadbed and water control features. Critical areas such as the two truck-road stream crossings were seeded with grass and slash was scattered on the roadfills immediately following road construction. Skidroads were smoothed and waterbarred at recommended spacing as logging progressed. Skidroads were limed, fertilized, and seeded with Kentucky 31 fescue using a cyclone seeder. In June 1987, the truck road and landings were disced, limed, fertilized, and seeded with a mixture of oats, clover, and Kentucky 31 fescue. Ground lime was applied at the rate of 3.0 ton/ac and 10-10-10 fertilizer at the rate of 500 lb/ac.

DATA COLLECTION AND ANALYSIS

Data collection began on WS1 and WS4 in May 1951 and in May 1982 on Haddix. Precipitation on each watershed was sampled by a network of recording and standard 8-inch gages. Streamflow was measured with 120° V-notch weirs on WS1 and WS4 and with a 3-foot H-type flume on Haddix. Each gaging site was equipped with an FW-1 water-level recorder. Water quality samples were collected by grab sampling above the gaging sites.

Harvesting effects on annual water yield and instantaneous peak flows were determined by using the paired watershed approach described by Hornbeck and others (1997). Since the purpose of the peakflow analysis was to compare the response of the watersheds to similar precipitation inputs, only storms for which the difference in precipitation did not exceed 0.3 inch were used to evaluate changes in peakflow. Linear regression was used to develop calibration relationships between water yield and storm peaks from WS4 and those to be harvested (WS1 and Haddix). After harvest, streamflow values from WS4 were inserted in the calibration equations to estimate what streamflow for the harvested watersheds would have been had they not been harvested. Differences between measured streamflow from the harvested watersheds and estimates of flow had they not been harvested were considered statistically significant and ascribed to forest harvest when the differences exceeded the 95 percent confidence intervals placed about the entire calibration regression.

Estimates of sediment export from WS1 and WS4 during the early 1957-58 logging period were based on turbidity and discharge measurements. Turbidities between 5-25 were determined by reference to standard suspensions in Nessler tubes and are termed Nessler turbidimeter units (NTU). Turbidities above 25 were measured with a Jackson turbidimeter and termed Jackson turbidimeter units (JTU), or filtered to determine suspended solids as parts per million (ppm).

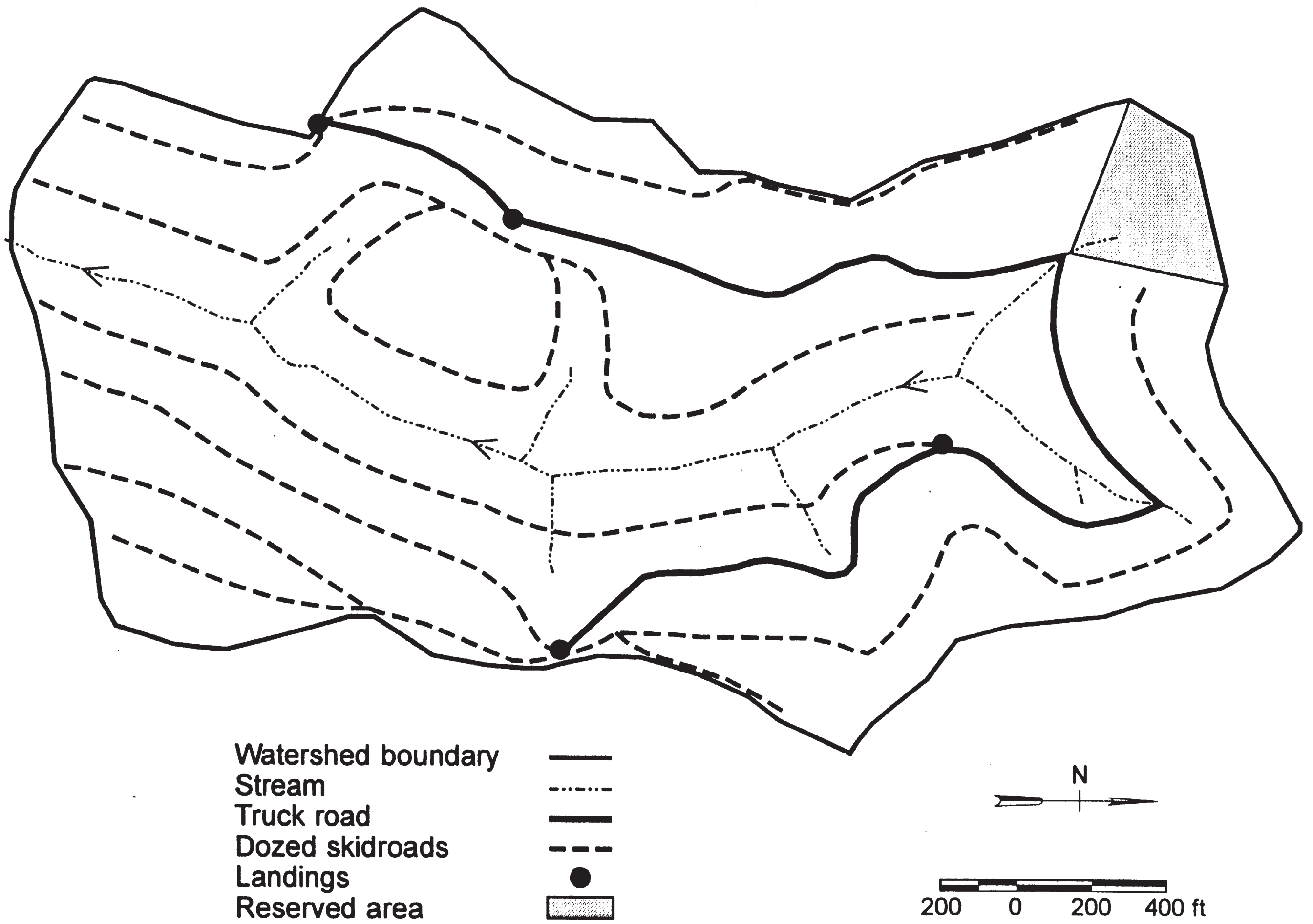


Figure 2—The road system in the Haddix watershed conformed to West Virginia's Best Management Practice Standards. It was used to remove 513 Mbf of timber from this 96-acre watershed.

During the 1982-1993 monitoring period each gaging site was equipped with a Coshocton wheel sediment sampler, which diverts 0.5 percent of the total flow into a storage tank. Two samples of tank contents were taken weekly, during base flow and before the tanks overflowed during storms. Tank contents were agitated vigorously while two 800-ml samples were drawn from spigots at the bottom of the storage tanks. Sediment produced during large storms was quantified by grab sampling and by automatic samplers. For each sample, turbidity was measured in NTU, then filtered to determine suspended sediment concentration in ppm.

Thermometers placed above the gaging stations in each watershed recorded weekly maximum and minimum stream temperatures. During the calibration period on WS1, stream temperatures were measured while collecting water quality grab samples. Beginning in May 1958, maximum-minimum thermometers were placed in the main stream above the gaging station. Water temperature records for 1958 are missing so temperatures observed during the 1959-60 period were compared with mean maximum temperatures observed during the 1961-73 period.

Grab samples for other criteria of water quality were collected weekly above the gaging stations on all three watersheds. In the beginning on WS1 and WS4, samples were analyzed for pH, alkalinity, and electrical conductivity. During the later period when Haddix was being logged, samples were analyzed for major ion concentrations at the Forest Service's laboratory. Analytical procedures and instrumentation information are given in Edwards and Wood (1993).

RESULTS AND DISCUSSION

Roads and Their Impacts

Roads and stream channels are major sources for stream sediment on the study watersheds. Road data for them are shown in Table 2. Road area was determined by length and width measurements from the top of road cuts to the toe of road fills after logging was completed. Haddix contained almost 4 times as much area in bulldozed roads as did WS1. However, when non-bulldozed roads are included, total road length in WS1 (3.5 miles) and Haddix (3.9 miles) are similar (Table 2). The differences in bulldozed road density are attributed to logging methods. The tractor and arch used on WS1 could negotiate fairly steep terrain without roads while the wheeled skidder used on Haddix was largely restricted to roads. Stream channel areas were similar among watersheds. They comprise a much smaller proportion of area than do roads in the logged watershed (Table 1), but are major sources of sediment in streams draining forested watersheds (Lull and Reinhart 1963, Patric 1976).

Area occupied by roads on the watersheds is decreasing as they revert to forest. Kochenderfer and others (1997) found that 6 years after logging, woody vegetation was dominant on half the original truck road area cleared in 1987. They concluded that reforestation should eventually reduce the original road prism area to less than half its original acreage. Several 12- to 16-inch yellow-poplar trees grow in the middle and on fill portions of skidroads in WS1.

Road grades are important from the standpoint of providing efficient access as well as soil and water protection. It is far more difficult to control erosion on steep roads, and they have less residual value for other uses once logging is completed. Roads of gentle grades, that are properly located and maintained, protect soil and water resources while providing effective access for many forest activities. Almost half of the dozed skidroads in WS1 had grades greater than 21 percent as opposed to only 2 percent of the roads on Haddix where BMPs were used (Table 2). Grades on 74 percent of the dozed roads on Haddix were in the 0-10 percent class while only 22 percent of the dozed skidroads on WS1 were in that class. All of the truck roads on Haddix fell into the 0-10 percent class.

The proximity of roads to streams is probably the single most important attribute that determines whether streams will be adversely impacted by timber harvesting operations. The importance of providing minimally disturbed protective zones between disturbed areas and streams has been recognized for a long time (Trimble and Sartz 1957, Lull and Reinhart 1963). Streamside protective zones are normally incorporated into state BMP guidelines. For example, West Virginia BMP guidelines recommend 100 feet protective zones on each side of perennial and intermittent streams and 25 feet for ephemeral streams (West Va. Dept. Natur. Resour. 1997).

There are striking differences between the unplanned road system on WS1 and the planned system on Haddix (Figs. 1 and 2). On WS1 many of the main skidroads were in or very close to stream channels. Sediment generated on roads was often carried by overland flow directly into streams. During storms, streamflow diverted into roads caused further excessive erosion (Lull and Reinhart 1963). On Haddix, the landings and contour road systems were at least 100 feet from streams except at crossing sites (Kochenderfer and others 1997). Machinery was not permitted off the road in streamside areas.

The distribution of bulldozed roads in relation to streams on WS1 and Haddix is quantified in Table 2. Forty percent of the dozed skidroads on WS1 were within 25 feet of streams (Hornbeck and Reinhart 1964) while only 5 percent of roads on Haddix watershed were that close. Sixty-one percent of the roads on WS1 were within 50 feet of streams as opposed to 8 percent on Haddix.

It is important to note that roads often generate more runoff than precipitation alone would indicate. Lull and Reinhart (1963) attributed this excess road runoff in WS1 to intercepted subsurface flow at road cuts. Kochenderfer and Helvey (1987), measuring soil losses from graveled and ungraveled road sections in central West Virginia, found that the percentage of annual precipitation measured as runoff ranged from 41.5 percent to 139 percent. Annual runoff exceeded precipitation on road segments with periodically active seeps.

Water Yield and Peak Flows

In addition to impacts of roads on overland flow, harvesting the forest reduces evapotranspiration and thereby increases water yield. The more intensive harvest on WS1 increased annual water yield 5.2 inches during the second year after harvest (Table 3). Increases disappeared quickly with regrowth and there were no statistically significant changes beyond the 6th year after harvest. Increased water yield was indicated after harvest on Haddix but was not statistically significant (Table 3).

Much of the increase in water yield occurs as augmentation to low flows during the growing season. Such increases result from increased soil water moving laterally through soil and bedrock to streams, thus having little impact on erosion. However, some peak flows also increased (Table 4). Some of the peak flow on WS1 also may have been caused by overland flow from poorly located skidroads (Reinhart and others 1963). Compared with Haddix, the lower residual basal area left after harvesting WS1 resulted in less transpiration and smaller soil water deficits, and thus greater overall increases in storm peaks (Table 4). The increases in peak flows are of interest in that they can cause additional erosion and sedimentation by scouring stream channels. However, the relatively small magnitude of the increases, plus the fairly rapid disappearance of increases with regrowth of the new forest (Table 4), suggests that harvests have minimal impacts on downstream flooding.

Sediment

Annual sediment yields and turbidity (Hornbeck and Reinhart 1964, Kochenderfer and others 1997) for WS1 and Haddix are shown in Table 5. During the logging operation sediment yield was 26 times greater on WS1 than on Haddix. These large differences reflect the characteristics of road systems discussed earlier. Although there was almost four times as much severely disturbed area on Haddix during logging, sediment yields were far less than those on WS1. The first year after logging they decreased to about 4 times more on WS1 than on Haddix and by the second year both returned to preharvest levels. Sediment yields were greatest during logging, when roads were repeatedly disturbed, then decreased rapidly after logging was completed. The rapid decrease in sediment yields on WS1 was attributed to vigorous regrowth and development of an erosion pavement on skidroads (Reinhart and others 1963). These soils contain about 50

Table 3—Impacts of harvesting on annual water yield

Year after harvest	WS1 Actual flow	WS1 Estimated streamflow if unharvested[a]	WS1 Change due to harvest[b]		Haddix Actual flow	Haddix Estimated streamflow if unharvested[a]	Haddix Change due to harvest[b]	
	Inches	*Inches*	*Inches*	*%*	*Inches*	*Inches*	*Inches*	*%*
1	21.3	19.0	2.3[c]	12	28.0	24.2	3.8	16
2	31.6	26.4	5.2[c]	20	20.5	18.1	2.4	13
3	25.1	21.4	3.7[c]	17	28.9	26.7	2.2	8
4	27.5	24.0	3.5[c]	15	37.2	33.3	3.9	12
5	23.4	22.9	0.5[c]	<1	33.9	32.6	1.3	4
6	27.5	25.2	2.3[c]	9	20.2	19.0	1.2	6
7	23.5	23.6	-0.1	<1				
8	21.7	21.1	0.6	3				

[a] Determined from calibration regression.
[b] Determined by subtracting estimated streamflow from actual streamflow.
[c] Change exceeded 95 percent confidence interval about the calibration regression.

Table 4—Impacts of harvesting on instantaneous peak flows >3 $ft^3/sec/mi^2$ (c.s.m.)

Year after harvest	Growing season No. of peaks (*n*)	Growing season Range in peak flows (c.s.m.)[a]	Growing season Statistically significant increases (*n*)	Growing season Average change	Dormant season No. of peaks (*n*)	Dormant season Range in peak flows (c.s.m.)[a]	Dormant season Statistically significant increases (*n*)	Dormant season Average change
				%[b]				*%*[b]
WS1								
1	3	20-28	2	69	12	4-77	6	18
2	7	4-14	1	27	18	3-23	8	18
3	0	–	–	–	2	4-21	1	45
4	1	25	1	46	10	4-52	4	26
5	5	4-31	1	9	7	4-70	4	18
6	0	–	–	–	8	5-30	0	–
Haddix								
1	0	–	–	–	7	3-25	1	42
2	4	11-78	2	76	8	10-46	0	–
3	2	14-63	0	–	6	7-48	2	35
4	2	18-27	0	–	9	4-33	0	–
5	1	16	0	–	11	6-31	0	–
6	0	–	–	–	8	6-26	1	36

[a] Estimated peak flows if watersheds not harvested.
[b] Average change for measured peak flows that were statistically significant.

Table 5—Annual suspended sediment yields and mean turbidity from WS1 and Haddix watersheds

	Sediment yields		Turbidity	
	WS1	Haddix	WS1	Haddix
	------ *Lb/ac* ------		*Ppm*	*NTU*
During logging operation	2,880	110	490	8.0
First year after logging	288	69	38	6.0
Second year after logging[a]	7	52	1	5.0

[a] Modern sampling techniques would probably have produced values for WS1 more comparable to Haddix.

percent stone fragments by volume and quickly developed a protective stone cover (Lull and Reinhart 1963).

While sediment yields temporarily doubled on Haddix, they remained within the range of 100 to 200 lb/ac/yr background levels expected from carefully managed forest in the eastern United States (Patric 1976). Sediment exports during a single large flood event on Haddix in 1985 (before harvest) were 2.8 times higher than annual sediment exports during logging. Others have observed that sediment exports are highly variable and related to the occurrence of individual large storms (Edwards and Owens 1991, Martin and Hornbeck 1994).

Careless logging on WS1 resulted in highly turbid water, averaging 490 ppm on WS1 during logging as compared to 8.0 NTU on Haddix (Table 5). The maximum turbidity observed during the logging on WS1 was 56,000 ppm (Reinhart and others 1963) while the maximum turbidity observed on Haddix was less than 100 NTU. Turbidity decreased rapidly on WS1, averaging 38 ppm during the first year after logging.

Water Temperature

Mean maximum growing season temperatures for selected periods are shown for all three watersheds in Figure 3. Highest temperatures usually coincided with low streamflow and high air temperatures during the July-September period. Water temperatures of 75°F are detrimental to brook trout (Embody 1921, Needham 1938). Reinhart and others (1963) concluded that the commercial clearcut on WS1 raised growing season maximum temperatures an average of 8°F during 1958-59, and reduced dormant season minima by 3.5°F. Heavy accumulations of slash covering the main stream channel might have moderated temperatures to some extent because Eschner and Larmoyeux (1963) reported that the

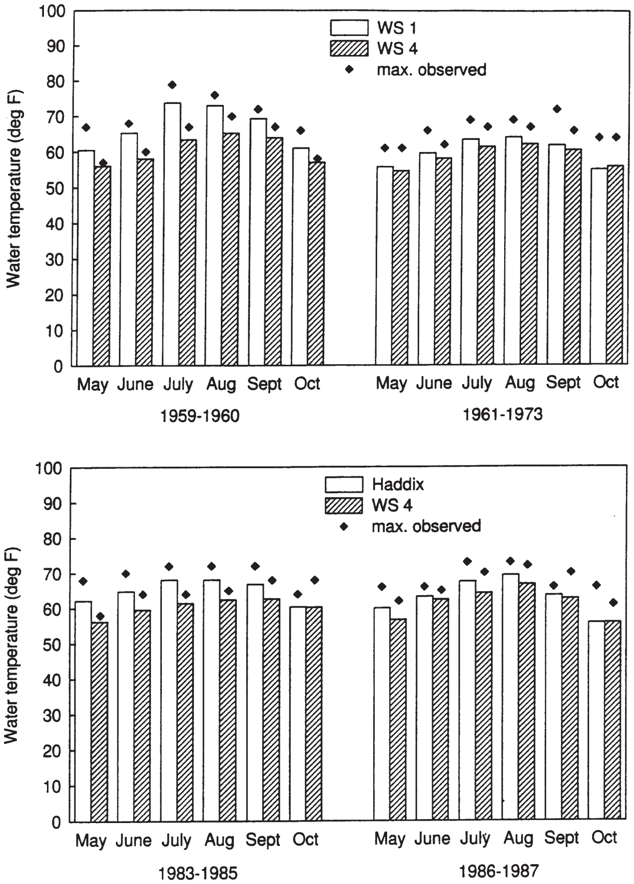


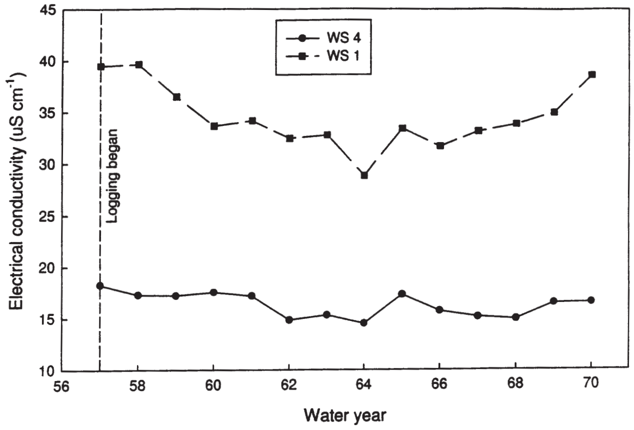
Figure 3—Mean maximum growing-season stream temperatures for WS1 (top) and Haddix (bottom) are compared with the control Fernow watershed (WS4).

highest temperature observed on WS1 (79°F) occurred in July 1959. Temperatures of 75°F and higher were observed several times on WS1 during 1959 but the highest observed in 1960 was 73°F. The highest temperature observed on WS4 during 1959 was 70°F and the maximum in 1960 was 65°F.

Temperatures during pretreatment and logging periods on Haddix are very similar (Fig. 3). Kochenderfer and others (1997) concluded that diameter limit cutting on Haddix did not affect stream temperature because of shading by residual trees and understory vegetation. Although temperatures have consistently remained higher on the more xeric Haddix watershed, they have remained below 75°F.

Electrical Conductivity

Electrical conductivity, an index of total dissolved solids, decreased on WS1 following commercial clearcutting (fig. 4) and has consistently been higher on WS1 than on WS4. These differences probably reflect differences in geology and resultant weathering contributions to streams. There was a small increase in electrical conductivity in the Haddix stream after logging (fig. 4). An earlier study by Aubertin and Patric (1974) showed minimal streamwater ion increase after clearcutting Fernow watershed 3. Thus there



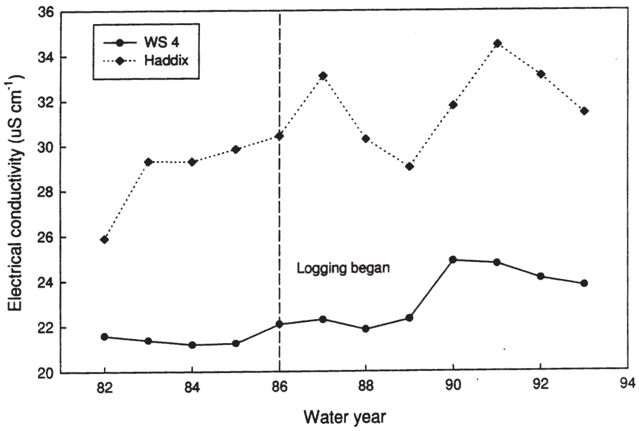


Figure 4—Time trends of electrical conductivity in streamflow from WS1 (top) and Haddix (bottom) compared with that from WS4.

is little reason to expect electrical conductivity in streams draining WS1 and Haddix to show much change after harvest.

SUMMARY

Our comparison of watersheds logged with and without BMPs clearly demonstrates their value. Logging without them on WS1 involved roads with unusually steep grades located close to or in streams, and no attempts were made to control water and revegetate the roads after logging. The result was significant erosion and sedimentation with increased stream temperatures. In contrast, careful adherence to West Virginia's BMPs when logging Haddix, resulted in only minor changes in sediment and water temperature. The changes were within background levels, clearly illustrating that harvesting operations utilizing BMPs will protect water quality.

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REFERENCES

Aubertin, G.M.; Patric, J.H. 1974. Water quality after clearcutting a small watershed in West Virginia. Journal of Environmental Quality. 3: 243-249.

Edwards, P.J.; Wood, F. 1993. Field and laboratory quality assurance/quality control protocols and accomplishments for the Fernow Experimental Forest watershed acidification study. Gen. Tech. Rep. NE-177. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 15 p.

Edwards, W.M.; Owens, L.B. 1991. Large storm effects on total soil erosion. Journal of Soil and Water Conservation. 46: 75-78.

Embody, G.C. 1921. Concerning high water temperatures and trout. Transactions of the American Fisheries Society. 51: 58-64.

Eschner, A.R.; Lamoyeux, J. 1963. Logging and trout: four experimental forest practices and their effect on water quality. Progressive Fish Culturist. 25(2): 59-67.

Haussman, R.F. 1960. Permanent logging roads for better woodlot management. U.S. Department of Agriculture, Forest Service, Eastern Region Division of State and Private Forestry. 38 p.

Hewlett, J.D.; Douglass, J.E. 1968. Blending forest uses. Res. Pap. SE-137. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 15 p.

Hornbeck, J.W.; Martin, C.W.; Eagar, C. 1997. Summary of water yield experiments at Hubbard Brook Experimental Forest, New Hampshire. Canadian Journal of Forest Research. 27: 2043-2052.

Hornbeck, J.W.; Reinhart, K.G. 1964. Water quality and soil erosion as affected by logging in steep terrain. Journal of Soil and Water Conservation. 19(1): 23-27.

Kochenderfer, J.N. 1970. Erosion control on logging roads in the Appalachians. Res. Pap. NE-158. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 28 p.

Kochenderfer, J.N.; Edwards, P.J.; Wood, F. 1997. Hydrologic impacts of logging an Appalachian watershed using West Virginia's best management practices. Northern Journal of Applied Forestry. 14(4): 207-218.

Kochenderfer, J.N.; Helvey, J.D. 1987. Using gravel to reduce soil losses from minimum-standard forest roads. Journal of Soil and Water Conservation. 42(1): 46-50.

Kochenderfer, J.N.; Wendel, G.W.; Smith, H.C. 1984. Cost of and soil loss on "minimum-standard" forest truck roads constructed in the central Appalachians. Res. Pap. NE-544. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 8 p.

Losche, C.K.; Beverage, W.W. 1967. Soil survey of Tucker County and part of northern Randolph County, West Virginia. Morgantown, WV: U.S. Department of Agriculture, Soil Conservation Service; West Virginia Agriculture Experiment Station. 78 p.

Lull, H.W.; Reinhart, K.G. 1963. Logging and erosion on rough terrain in the East. In: Proceedings of the Federal inter-agency sediment conference. Misc. Publ. 970. Washington, DC: U.S. Department of Agriculture, Agricultural Research Service: 43-47.

Martin, C.W.; Hornbeck, J.W. 1994. Logging in New England need not cause sedimentation of streams. Northern Journal of Applied Forestry. 11: 17-23.

Needham, P.R. 1938. Trout streams. New York: Comstock Publishing Co. 233 p.

Patric, J.H. 1976. Soil erosion in the eastern forest. Journal of Forestry. 74: 671-676.

Pierce, R.S.; Hornbeck, J.W.; Martin, C.W. [and others]. 1992. Whole-tree clearcutting in New England: manager's guide to impacts on soils, streams, and regeneration. Gen. Tech. Rep. NE-172. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 23 p.

Reinhart, K.G.; Eschner, A.R.; Trimble, G.R., Jr. 1963. Effect on streamflow of four forest practices in the mountains of West Virginia. Res. Pap. NE-1. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 79 p.

Trimble, G.R., Jr.; Sartz, R.S. 1957. How far from a stream should a logging road be located? Journal of Forestry. 55(5): 339-341.

U.S. Department of Agriculture. 1940. Truck trail handbook. Washington, DC: U.S. Department of Agriculture, Forest Service, Division of Engineering: 502-559.

Weitzman, S. 1952. Mountain logging. Southern Lumberman. 185: 199-202.

West Virginia Department of Natural Resources, Division of Forestry. 1979. Guidelines for controlling soil erosion and water pollution on logging operations in West Virginia. Charleston, WV: West Virginia Department of Natural Resources, Division of Forestry. 26 p.

West Virginia Department of Natural Resources, Division of Forestry. 1982. Clean streams handbook for loggers: mini-workshop manual for keeping mud out of the creeks. Charleston, WV: West Virginia Department of Natural Resources, Division of Forestry. 34 p.

West Virginia Department of Natural Resources, Division of Forestry. 1997. Best management practice guidelines for controlling soil erosion and water siltation from logging operations in West Virginia. Charleston, WV: West Virginia Department of Natural Resources, Division of Forestry. 29 p.