Streamflow Changes after Forest Clearing in New England

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Abstract. Clearing a hardwood forest cover and preventing regrowth with herbicides on a 39-acre watershed in central New England increased annual water yield an average 12.2 area-inches for the first two water years after treatment. Most of this increase occurred during the critical low flow months of June through September, and the amount was governed in large part by rainfall in this period. There was a small advance of snowmelt runoff and a consistent increase in growing season high flow values. Our data agree with others showing that sizeable streamflow increases can result from forest clearing in the uplands of the eastern United States.

At the Hubbard Brook Experimental Forest located near West Thornton, New Hampshire, eight small, gaged watersheds are being used to study watershed management problems associated with northern hardwood forests. In late fall 1965, one of these watersheds was cleared of all timber and woody vegetation. Follow-up herbicide treatments were made for three growing seasons thereafter in an attempt to maintain vegetation-free conditions.

Our major objective was to obtain maximum streamflow during summer low flow periods by eliminating transpiration, and we wanted to see how clearing affects snowmelt runoff and nutrient cycling.

In New England, snowmelt runoff poses a flood threat nearly every year, yet low flow in late summer creates critical problems of both water quantity and quality for municipalities, industry, and water dependent recreation. Forest management has potential for ameliorating these seasonal extremes in streamflow, particularly since New England is 80% forested. Research at several locations across the United States has left no doubt that streamflow responds to forest treatment [*Hibbert*, 1967], but these responses vary widely with type of treatment and location.

This report summarizes and discusses the changes in quantity and timing of water yield during the first three years after clearing the New England watershed.

STUDY AREA

Two adjoining watersheds are being used for this study. Watershed 2, the one cleared, is 39 acres in area; watershed 3, an untreated control, is 105 acres (Figure 1). Both watersheds have southerly aspects and average slopes of 20% to 30%.

Annual precipitation is about 48 inches and, on the average, is fairly evenly distributed through the year. One-fourth to one-third of the precipitation occurs as snow, and a snow cover usually persists from mid-December to mid-April. Peak snow accumulation is generally in March, when 40 to 50 inches of snow containing 9 to 12 inches of water usually accumulates. Analyses [*Hart*, 1966] of the period before forest clearing showed that there were no important differences in precipitation between watersheds 2 and 3.

Soils are of coarse-textured materials (sands and sandy loams) derived from glacial till. They average about 5 feet in depth. The upper 2 feet of soil is very permeable, and soil frost seldom forms under the insulation provided by several inches of forest humus and the continuous winter snow cover [*Hart et al.*, 1962]. As a result, infiltration capacities remain high throughout the year, and practically all water reaching the stream channels does so as subsurface flow [*Pierce*, 1967].

Before treatment, both watersheds were completely forested, mainly with the following

Fig. 1. Watershed 2 upon completion of forest clearing. Control watershed 3 is the adjacent drainage on the right.

uneven-aged, deciduous northern hardwoods: beech (*Fagus grandifolia* Ehrh.), birch (*Betula alleghaniensis* Britton and *B. papyrifera* Marsh.), and maple (*Acer saccharum* Marsh. and *A. rubrum* L.). Scattered patches of red spruce (*Picea rubens* Sarg.) grew on ridges and rock outcrops. A pretreatment plot inventory, of trees 5.0 inches diameter breast height and larger, showed the basal area to be 72 square feet per acre and the volume to be 1600 cubic feet per acre.

THE EXPERIMENT

Watershed 2 was cleared between November 18 and December 31, 1965. All trees were felled and left in place; branches and stems were lopped to a maximum height of 3 feet above ground. A snow cover of at least 12 inches existed during the entire cutting period. Stump sprouts and ground cover that developed after forest clearing were sprayed by helicopter in June 1966. The herbicide bromacil was applied at a rate of 25 pounds per acre in a mixture of 1 pound of 80% bromacil per gallon of water [*Pierce*, 1969].

Seedling regeneration and stump sprouting reoccurred in the spring of both 1967 and 1968. Consequently, a mixture of 4 parts 2, 4, 5-T (4 pound acid equivalent) to 100 parts water was applied to the regeneration and sprouts during June through July of both years by backpack mist blowers. Data from camera points and general observations indicated that the amount of regrowth before spraying was uniform among the three summers after clearing. All herbicide applications were equally effective in eliminating most of the vegetative regrowth, so there was little variation in vegetative cover for the first three summers after forest clearing.

Logging was not included as part of the clearing operation because the soil surface disturbances that accompany logging may cause hydrologic changes unrelated to the effects of elimination of vegetation. Logging disturbances and the removal of large quantities of nutrients in the forest products would also have upset a separate segment of this study, the measurement of nutrient cycling for the watershed [*Likens et al.*, 1967, 1969; *Bormann et al.*, 1968; *Fisher et al.*, 1968].

Treatment effects on streamflow have been determined using the control watershed concept. Data from an eight year, pretreatment calibration period were used to develop linear regression equations between streamflow from watershed 2 and control watershed 3. Following the clearing operation, watershed 3 streamflow values were inserted in the equations to determine untreated estimates of streamflow values for watershed 2, or in other words, estimates of what streamflow values would have been in the absence of treatment. Differences between measured watershed 2 streamflow and the untreated estimates were ascribed to forest clearing (considered statistically significant) if the deviations exceeded the 95% confidence intervals placed about the calibration regressions.

Separate regressions were prepared for individual months, for growing and dormant seasons, and for the water year. Thus seasonal and annual streamflow changes shown in later tables do not always equal the sum of the monthly changes for a given season or year.

Pretreatment streamflow on watershed 2 averaged 10% higher than on watershed 3. When estimating changes in water yield, the regression approach accounted for this difference, but annual precipitation minus streamflow on watershed 2 appears to underestimate annual evapotranspiration. It is possible that watershed 2 receives soil water from outside the apparent watershed boundary.

EFFECTS OF CLEARING

Water year and season. As a result of nearly eliminating transpiration and of reducing canopy interception losses, streamflow has increased greatly during each of the first two water years after clearing (a June 1 to May 31 water year is used at Hubbard Brook). The greatest streamflow increase, 13.5 area-inches or 40% more than the untreated estimate, occurred during the water year immediately following cutting (Table 1). The second year increase of 10.8 area-inches was smaller, apparently because less rain fell during the second summer.

The larger part of the annual increase occurred in the growing season, the period of maximum transpiration and evaporation (Table 2). During the first water year after clearing, increases were 12.4 inches for the 4-month growing season and 1.0 inch for the 8-month dormant season. This increase for the first growing season was 344% of the untreated estimate of discharge. The second growing season was somewhat drier, but the increase was still 310% of the untreated estimate.

The increase during the third growing season was considerably smaller. This illustrates the importance of precipitation distribution in achieving yield increases. Precipitation was excessive for the first month of the third (1968) growing season, then well below average during the last three months. The result was an increase in streamflow of only 4.9 inches. Because of this drier growing season in 1968, streamflow increases extended further into the dormant season than in previous years.

Streamflow increases during the two complete dormant seasons following forest clearing have been small and are not statistically significant. This is because complete soil moisture recharge at Hubbard Brook usually occurs early in the dormant season. Following recharge, dormant season streamflow is similar for both the control and treatment watersheds with the exception of some timing changes during snowmelt runoff.

Months. Monthly analyses (Table 1) confirm the seasonal patterns. Sizeable increases occurred in the growing season months of June through September. These increases tapered off in October, except in 1968 when the below average precipitation delayed soil moisture recharge by several months. Streamflow changes through the winter months were small and not significant until the start of snowmelt in March.

During all three snowmelt seasons since clearing, the effect of forest clearing has been to advance snowmelt discharge. Flow increased sizeably in March and decreased in April and in two of the three Mays. However, the melt season monthly analyses are somewhat misleading because they tend to indicate a greater advance in snowmelt discharge than actually occurred. Most snowmelt on these two watersheds occurs at the end of March and at the beginning of April, so an advance of several days can shift large amounts of streamflow from April to March. *Hornbeck and Pierce* [1970] and *Federer* [1968] have shown that the actual advance of cumulative snowmelt runoff due to forest clearing on this watershed was about 4 to 8 days during periods of major snowmelt.

The monthly deviations from regression (Figure 2) exceeded the 95% confidence intervals

TABLE 1. Effect of Treatment on Monthly and Water Year Discharge (all values are area-inches)

Period	11-Year Mean Precipi-tation	1965–1966 Discharge			1965–1966	1966–1967 Discharge			1966–1967	1967–1968 Discharge			1967–1968	1968–1969 Discharge			1968–1969
		Un-treated Estimate	Meas-ured	Change	Precipi-tation	Un-treated Estimate	Meas-ured	Change	Precipi-tation	Un-treated Estimate	Meas-ured	Change	Precipi-tation	Un-treated Estimate	Meas-ured	Change	Precipi-tation
June	3.5	**	**	**	**	1.4	3.3	1.9*	4.2	0.8	2.0	1.2*	3.2	4.4	5.6	1.2*	6.3
July	4.2	**	**	**	**	0.2	3.1	2.9*	3.9	0.4	2.8	2.4*	4.4	0.8	2.3	1.5*	2.3
Aug.	4.0	**	**	**	**	1.2	5.8	4.6*	7.7	0.6	3.6	3.0*	5.4	0.0	1.1	1.1*	2.2
Sept.	3.8	**	**	**	**	1.0	3.8	2.8*	4.6	1.4	3.9	2.5*	5.3	0.1	1.6	1.5*	2.7
Oct.	4.9	**	**	**	**	2.1	2.9	0.8*	3.2	4.4	5.1	0.7*	4.7	0.2	1.4	1.2*	3.0
Nov.	5.3	**	**	**	**	5.2	5.2	0.0	5.3	3.2	3.0	−0.2	4.4	1.3	1.6	0.3	5.1
Dec.	4.3	**	**	**	**	2.4	2.2	−0.2	3.9	3.3	3.3	0.0	5.9	2.3	3.2	0.9*	7.2
Jan.	3.7	1.7	1.6	−0.1	2.5	1.0	1.2	0.2	2.3	0.7	0.8	0.1	2.8	-	-	-	-
Feb.	3.4	1.0	1.2	0.2	2.4	0.7	0.7	0.0	4.3	1.6	1.6	0.0	2.4	-	-	-	-
Mar.	3.2	5.5	7.6	2.1*	4.5	2.4	3.6	1.2*	2.2	8.4	10.3	1.9*	3.5	-	-	-	-
Apr.	4.3	7.1	6.1	−1.0	2.6	11.2	11.0	−0.2	5.4	7.9	6.1	−1.8*	4.4	-	-	-	-
May	3.9	4.3	4.0	−0.3*	3.5	5.1	4.4	−0.7*	4.4	5.3	6.0	0.7*	8.2	-	-	-	-
Water Year	48.5	-	-	-	-	33.6	47.1	13.5*	51.4	37.7	48.5	10.8*	54.6	-	-	-	-

* Change exceeded the 95% confidence intervals.

** Forest clearing performed November 18 to December 31, 1965.

TABLE 2. Effect of Treatment on Seasonal Discharge (all values are area-inches)

Season	Discharge for season			Precipitation for Season	Departure from 11-Year Mean Precipitation for Watershed
	Untreated Estimate	Measured	Change		
1966 growing (June–Sept.)	3.6	16.0	12.4*	20.3	+4.7
1967 growing (June–Sept.)	3.0	12.3	9.3*	18.3	+2.7
1968 growing (June–Sept.)	5.8	10.7	4.9*	13.4	−2.2
1966–1967 dormant (Oct.–May)	30.2	31.2	1.0	30.9	−2.1
1967–1968 dormant (Oct.–May)	34.9	36.3	1.4	36.3	+3.3

* Change exceeded 95% confidence intervals.

for 23 of the first 36 months following forest clearing. When expressed as a percentage of the untreated estimate, the monthly changes ranged from a 23% decrease for April 1968, to a 5000% increase for August 1968.

Flow duration. The effects of forest clearing on flow duration are illustrated by curves plotted for both the untreated estimate and the actual measured number of days that flow equaled or exceeded mean daily cubic feet per second per square mile (csm) levels (Figure 3). Growing season flow levels are typified in Figure 3*a*. Augmentation at all flow levels resulted in the entire curve for measured days being displaced to the right of the untreated estimate curve. The largest differences between actual flow and untreated estimates are at the lower flow levels. As an example of treatment effect, actual measured flow exceeded the 1.0 csm level for 116 days of the 1966 growing season. If treatment had not been performed, only 26 days would have exceeded 1.0 csm.

The effects of treatment on total dormant season flow were not large (Figure 3*b*). The curve of measured days is only slightly displaced from the untreated estimate curve and usually does not exceed the confidence intervals placed about untreated estimate values.

After examining seasonal curves, it is evident that the spread between untreated estimates and actual flow for water years 1966–1967 (Figure 3*c*) is due largely to growing season treatment effects. Perhaps a more important point is that nearly all changes in streamflow result from increases at low flow levels. The number of days when flow exceeded 10 csm was not greatly changed.

High flows. The average change in high flows (as a percent of untreated estimates) for the 3-year period after treatment is shown in Table 3. The discharge by individual storms was for individual events in which the hydrograph trace remained above 20 csm for 1 hour or more.

The growing season averages are for a limited amount of data. Since treatment, only five growing season peaks have exceeded 20 csm, and the total volume in excess of 20 csm has been less than 1 area-inch. All five of these peaks were increased by amounts ranging from 22 to 246%. Most of the variation in individual increases is due to the differences in available soil moisture storage that developed between the control and treated watersheds through the growing season. Individual storm volumes above 20 csm were affected in much the same manner; increases ranged from 115 to 300%. All growing season high flow increases were statistically significant.

Changes in dormant season high flows were more erratic. Depending on conditions at the time of the high flow events, the effect of forest clearing on flow might be an increase, little change, or a decrease. For example, although the average change in 21 dormant season instantaneous peaks was 0%, the individual changes ranged from a decrease of 23% to an increase of 68%. Changes in snowmelt rates are responsible for most of the dormant season increases and decreases. The speedup in the contribution of snow water from the cleared watershed usually caused high flow values to increase during the early part of the snowmelt season (late March and early April) and decrease during the latter part (mid and late April).

Changes in dormant season high flows not involving snowmelt were seldom statistically significant, indicating that soil moisture regimes were similar on both the control and treatment watersheds during the dormant season.

DISCUSSION

The more important effects of forest clearing on water yield at Hubbard Brook included:

1. Sizeable increases in annual water yield, most of which occurred during the growing season (June through September), and more important, during the critical low flow periods in late summer and early fall.
2. Slight changes in timing of spring flows due to speedup in snowmelt on the cleared watershed.
3. Consistent increases in volume and instantaneous peaks of growing season high flow events.

Water yield increases. The Hubbard Brook results are unique for hardwood forests in New

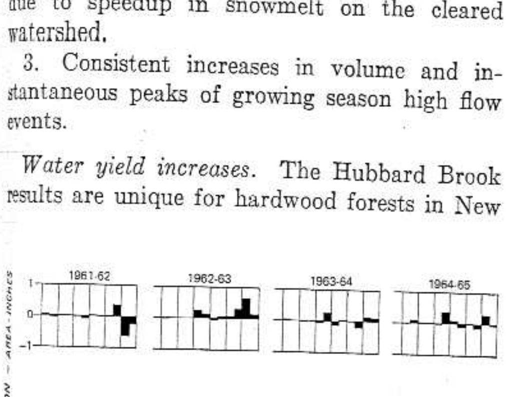

Fig. 2. Deviations from regression of monthly streamflow before and after forest clearing. Maximum deviation from regression during the calibration period was −0.62 inch for April 1962.

England, but it is interesting to compare the water yield increases with results from similar studies at other locations in the eastern United States. At the Fernow Experimental Forest located near Parsons, West Virginia, cutting that removed 80% of the basal area resulted in a streamflow increase of 5 inches the first year [*Reinhart et al.*, 1963]. As part of a more recent experiment, the upper half of one Fernow watershed and the lower half of another have been maintained essentially vegetation-free since cutting (timber products were removed and herbicides were applied repeatedly). For the three years following treatment, streamflow increases averaged 14.8 area-inches annually from the treated area for one watershed (upper half treated) and 11.4 area-inches annually for the other (lower half treated) [*Patric*, 1969].

At the Coweeta Hydrologic Laboratory in North Carolina, complete timber cutting without products removal on three watersheds resulted in annual increases ranging from 11.3 to 16.1 inches [*Hibbert*, 1967].

The annual increases after treatment of 13.5 and 10.8 area-inches at Hubbard Brook agree well with those from the similarly treated watersheds of Coweeta and Fernow, even though the average precipitation at Hubbard Brook is only 48 inches a year as compared to about 60 inches at Fernow and 80 inches at Coweeta. Detailed comparisons of results from these three areas are complicated by differences in deep seepage, precipitation, evaporation, soils, and methods of treatment. Nevertheless, it is evident that elimination of transpiration by forest clearing causes substantial increases in water yield in the uplands of the eastern United States.

Most of the increases in water yield at Hubbard Brook occurred in late summer and early fall when streamflow is normally quite low. It is important to note that during this period, the greatest absolute increases came in wet months, and the greatest relative increases came in dry months.

For example, in August 1966, when rainfall was 7.7 inches (nearly double the average), water yield from the treated area was 5.8 inches compared to an untreated estimate of 1.2 inches. The absolute increase of 4.6 inches was the greatest absolute increase for any month we have measured, but the relative increase was only about five times. In August 1968, rainfall was 2.2 inches (about half the average), treated yield was 1.1 inches, and the untreated estimate was 0.02 inch. The absolute increase is small, but the relative increase is 50 times. For most situations in the Northeast, the augmentation of extremely low flows in dry periods is of much greater importance than the larger absolute increases in the wet months.

The interaction of rainfall and yield increase is further demonstrated by reduction of the increase in growing season yield in the three years since treatment (Table 2). We are confident that the reduction with time is due in large part to the corresponding reduction in growing season rainfall, and not to the regrowth of vegetation.

The interaction of the treated area with its surroundings can only be discussed in qualitative terms. The control watershed was just to the east of the treated area. Winds are normally from the northwest or southwest, and the extra heat generated by the cleared area (low evaporation) is partly advected downwind to the control area and may have increased its evapotranspiration loss. This would have decreased the streamflow from the control and increased the yield difference. The magnitude of this effect is not directly measurable, but it is minimized because the control is 2½ times larger than the treated area.

Because our treated area is small, cool wet air is advected to it from the surrounding forest. This increases the sensible heat loss and reduces the evaporative loss from that expected for a larger treated area. Thus the larger the treated area the less will be the water yield increase, but the magnitude of this effect is not known.

Snowmelt runoff timing. How speedup in snowmelt runoff that accompanied forest clearing affected downstream flows is of interest. Desynchronization of flows from cleared and forested areas might be desirable [*Eschner and Satterlund*, 1963]. However, snowmelt in New England is rapid as the entire winter snow accumulation can melt in two weeks or less. When snowmelt is this rapid, the presence or absence of a hardwood forest canopy has little effect on snowmelt rate and subsequent runoff. Also, there is little likelihood that clearing of forest land in New England will ever be on a scale sufficient to bring about significant changes in downstream spring floods.

Increases in growing season high flow events. There is concern about the possibility of increasing the flood potential by forest removal. Our analyses showed that growing season high flow values were consistently increased by forest clearing. This analysis did not include the only summer high flow event since treatment, which has approached flood stage. On July 29 to 30, 1969, 5 inches of rain fell at Hubbard Brook,

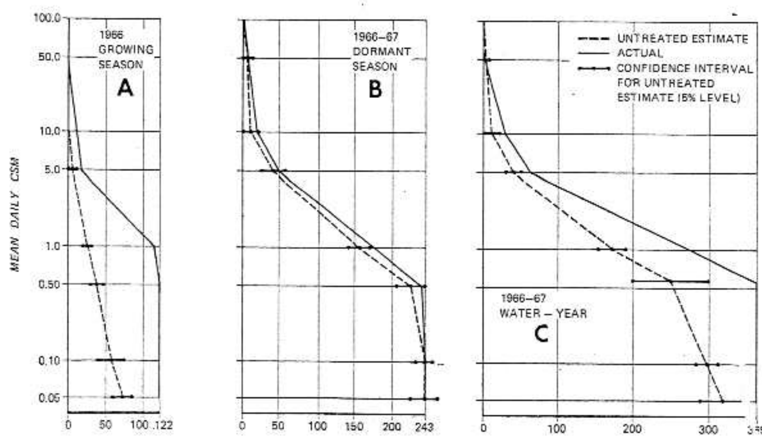

Fig. 3. Effect of forest clearing on flow duration. The untreated estimates were determined using the regression technique described in the text.

TABLE 3. Average Change in High Flows (3-year period after treatment)

Period	Instantaneous Peaks Exceeding 20 csm, %	Discharge over 20 csm by Individual Storms, %
Growing season	+118	+197
Dormant season	0	+13
Water year	+13	+21

and there was some flood damage in central New Hampshire and Vermont. Peak flow from the treated area was 323 csm compared to 109 csm from the forested control. The effect of such a flow increase due to clearing on a large watershed would depend in large part on the proportion of the watershed that had been cleared.

In the event of a rainfall large enough to cause summer flooding, we would expect total flow from the cleared watershed to exceed that from the control by an amount equal to the difference in soil moisture deficits on the two watersheds. For Hubbard Brook, this could mean a maximum storm flow difference of 4 area-inches and an average difference of 2 to 3 area-inches between cleared and forested areas.

There is one more important point with respect to flood flows: the forest floor on the cleared watershed has remained intact. The clearing operation resulted in only minimum disturbance, and even after a 3-year absence of vegetation, the mineral soil is still protected by layers of slash, litter, and humus. If the surface disturbance had been severe to the extent that soil infiltration and transmission characteristics were adversely affected, overland flow and subsequent increased peaks and erosion could have become more serious problems [*Reinhart*, 1964].

Economic considerations. The impractical and harsh treatment reported here (forest clearing without product removal and with subsequent chemical spraying to prevent vegetative regrowth) was imposed for research purposes to determine maximum possible water yields. The treatment was not intended as a practical measure to increase streamflow. However, the increased water yields merit some economic consideration. Water production from the 39-acre treated watershed netted over 35 million gallons or 900,000 gallons per acre for the 3-year post treatment period. Cost of the treatment, including cutting the forest and herbicide applications, was $14,000 or about $350 per acre. Thus the cost of additional water amounted to 39 cents per thousand gallons.

This report concludes one phase of this study. Starting with the 1969–1970 water year, natural regrowth will be allowed on the watershed. However, we plan to maintain the watershed in a high water yielding condition using aerial applications of herbicides at about 4- or 5-year intervals.

REFERENCES

Bormann, F. H., G. E. Likens, D. W. Fisher, and R. S. Pierce, Nutrient loss accelerated by clear-cutting of a forest ecosystem, *Science, 159,* 882–884, 1968.

Eschner, A. R., and D. R. Satterlund, Snow deposition and melt under different vegetative covers in central New York. 66 pp., *USDA Forest Serv. Res. Note NE-13,* Northeastern Forest Experiment Station, Upper Darby, Pennsylvania, 1963.

Federer, C. A., Radiation and snowmelt on a clear-cut watershed, *East. Snow Conf. Proc. 25,* 28–42, 1968.

Fisher, D. W., A. W. Gambell, G. E. Likens, and F. H. Bormann, Atmospheric contributions to water quality of streams in the Hubbard Brook Experimental Forest, New Hampshire, *Water Resour. Res., 4*(5), 1115–1126, 1968.

Hart, George Emerson, Jr., Streamflow characteristics of small, forested watersheds in the White Mountains of New Hampshire, 141 pp., Ph.D. dissertation, University of Michigan, Ann Arbor, 1966.

Hart, George, Raymond E. Leonard, and Robert S. Pierce, Leaf fall, humus depth, and soil frost in a northern hardwood forest, 3 pp., *Northeast. Forest Exp. Sta. Res. Note 131,* Northeastern Forest Experiment Station, Upper Darby, Pennsylvania, 1962.

Hibbert, A. R., Forest treatment effects on water yield, *International Symposium on Forest Hydrology, Proceedings,* pp. 527–543, Pergamon Press, New York, 1967.

Hornbeck, James W., and Robert S. Pierce, Changes in snowmelt runoff following forest clearing on a New England watershed, *East. Snow Conf. Proc. 26,* 104–112, 1970.

Likens, Gene E., F. H. Bormann, and Noye M. Johnson, Nitrification: Importance to nutrient losses from a cutover forested ecosystem, *Science, 163,* 1205–1206, 1969.

Likens, G. E., F. H. Bormann, N. M. Johnson, and R. S. Pierce, The calcium, magnesium, potassium and sodium budgets for a small forested ecosystem, *Ecology, 48*(5), 772–785, 1967.

Patric, James H., Changes in streamflow, duration of flow, and water quality on two partially clearcut watersheds in West Virginia (abstract), *EOS, Trans. Amer. Geophys. Union, 50*(4), 144, 1969.

Pierce, Robert S., Evidence of overland flow on forest watersheds, *International Symposium on Forest Hydrology, Proceedings,* pp. 247–252, Pergamon Press, New York, 1967.

Pierce, Robert S., Forest transpiration reduction by clearcutting and chemical treatment, *Northeast. Weed Contr. Conf. Proc. 23,* 344–349, 1969.

Reinhart, K. G., A. R. Eschner, and G. R. Trimble, Jr., Effect on streamflow of four forest practices in the mountains of West Virginia, 79 pp., *USDA Forest Serv. Res. Pap. NE-1,* Northeastern Forest Experiment Station, Upper Darby, Pennsylvania, 1963.

Reinhart, Kenneth G., Effect of a commercial clearcutting in West Virginia on overland flow and storm runoff, *J. Forest., 62,* 161–171, 1964.

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