An Interim Report

EFFECT ON STREAMFLOW of FOUR FOREST PRACTICES

in the Mountains of West Virginia

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NOTICE

This U. S. FOREST SERVICE RESEARCH PAPER is the first of a new series of research publications by the Northeastern Forest Experiment Station. In this new series, which has been adopted as standard for all the Forest and Range Experiment Stations of the U. S. Forest Service, the symbol NE will designate publications of the Northeastern Station.

This new series replaces the Northeastern Station's series formerly known as Station Papers. In like manner, the series of Forest Research Notes previously published by the Northeastern Station will be designated from now on as U. S. FOREST SERVICE RESEARCH NOTES, and will be identified by the symbol NE and a number.

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Glossary of Terms Used

c.f.s.	—cubic feet per second.
c.s.m.	—cubic feet per second per square mile.
area-inch	—1 inch depth of water over the area considered.
p.p.m.	—parts per million; for example, parts of soil per million parts of water.
d.b.h.	—diameter breast high (4½ feet above the ground surface).
M b.m.	—thousand feet board measure.
basal area	—the area in square feet of the cross section at breast height of all the trees in a stand.
cull	—unmerchantable tree.
water-year	—May 1 to April 30.
growing season	—May 1 to October 31.
dormant season	—November 1 to April 30.

Introduction

FOR a long time we have known that the type of forest management practiced on a watershed may affect the amount and distribution of streamflow and the quality of the water produced. Studies have shown that this relationship between watershed treatment and water is not a simple one. A number of factors affect it, including soils, geology, topography, and climate. Though we know the general nature of forest treatment effects on water, we have not learned nearly enough to prescribe a specific treatment to give a specific result. We do not yet understand how to manipulate vegetation to increase or reduce water flow by specific amounts. Though we are better able to recommend practical measures to reduce erosion and sedimentation, we lack detailed knowledge of the fundamental relationships between land treatment and water pollution.

A necessary complication in managing most areas for water is that other uses must be considered also. Our mushrooming population forces us to examine means of integrating various land uses. Compromises that best serve the needs of society must be sought in the majority of cases. This is pointed up by the recent increasing emphasis on multiple use as a guiding principle of forest management in legislation, discussion, and practice.

Research, now under way in many areas, is delving into forest treatment effects on water in an effort to provide guides for such watershed objectives as flood control, increased streamflow, and clear usable water.

This report describes first results of forest watershed management research on the Fernow Experimental Forest in Tucker County, West Virginia.

Streamflow measurement was begun on five small watersheds in May 1951. For 6 years, records were gathered on rainfall, runoff, and water quality under undisturbed conditions. This was the calibration period when the natural behavior of the watersheds was measured as a yardstick to judge future runoff and water quality after the different treatments were applied. Timber was inventoried before and after treatment.

The watersheds were treated in May 1957 to February 1959. Effects of treatment are given for the 3-year period from the start of treatment through April 1960; limited data are also given for the 1960 growing season.

The study is being continued to determine changes in streamflow resulting from regrowth in the watersheds after the initial cutting and to learn the effects of future cuttings. Concurrently, forest growth and other data are being collected to measure the long-range returns from these methods of managing the timber resource. The effects of these forest practices on deer habitat[1] and on the qualities of streamflow related to trout management[2] are also under study.

The Study Watersheds

The Fernow Experimental Forest is located in northern West Virginia (fig. 1) in mountainous country west of the main ridge of the Alleghenies. Drainage is via the Monongahela River to the Ohio at Pittsburgh. The five study watersheds, which range from 38 to 96 acres in area, are contiguous or nearly so. The topography, geology, soils and forest cover (fig. 2) are generally representative of this part of the Appalachians.

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[1] Cooperative study with Division of Game and Fish, West Virginia Department of Natural Resources.

[2] Cooperative study with the Bureau of Sport Fish and Wildlife, U.S. Department of the Interior.

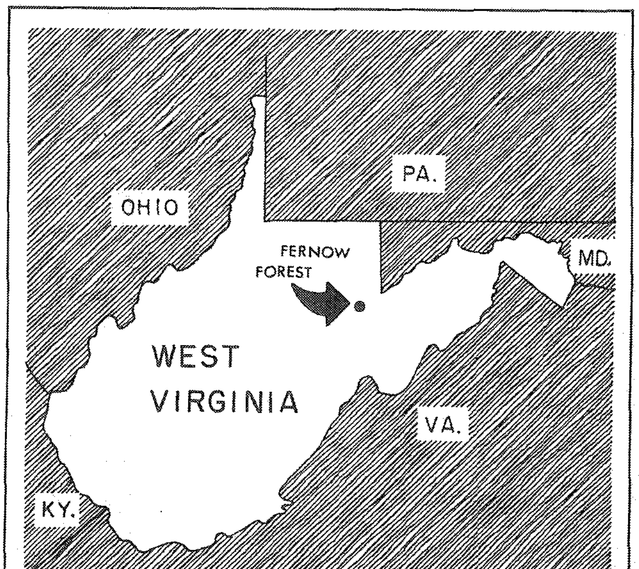


Figure 1.—Location of the Fernow Experimental Forest in the mountains of West Virginia.

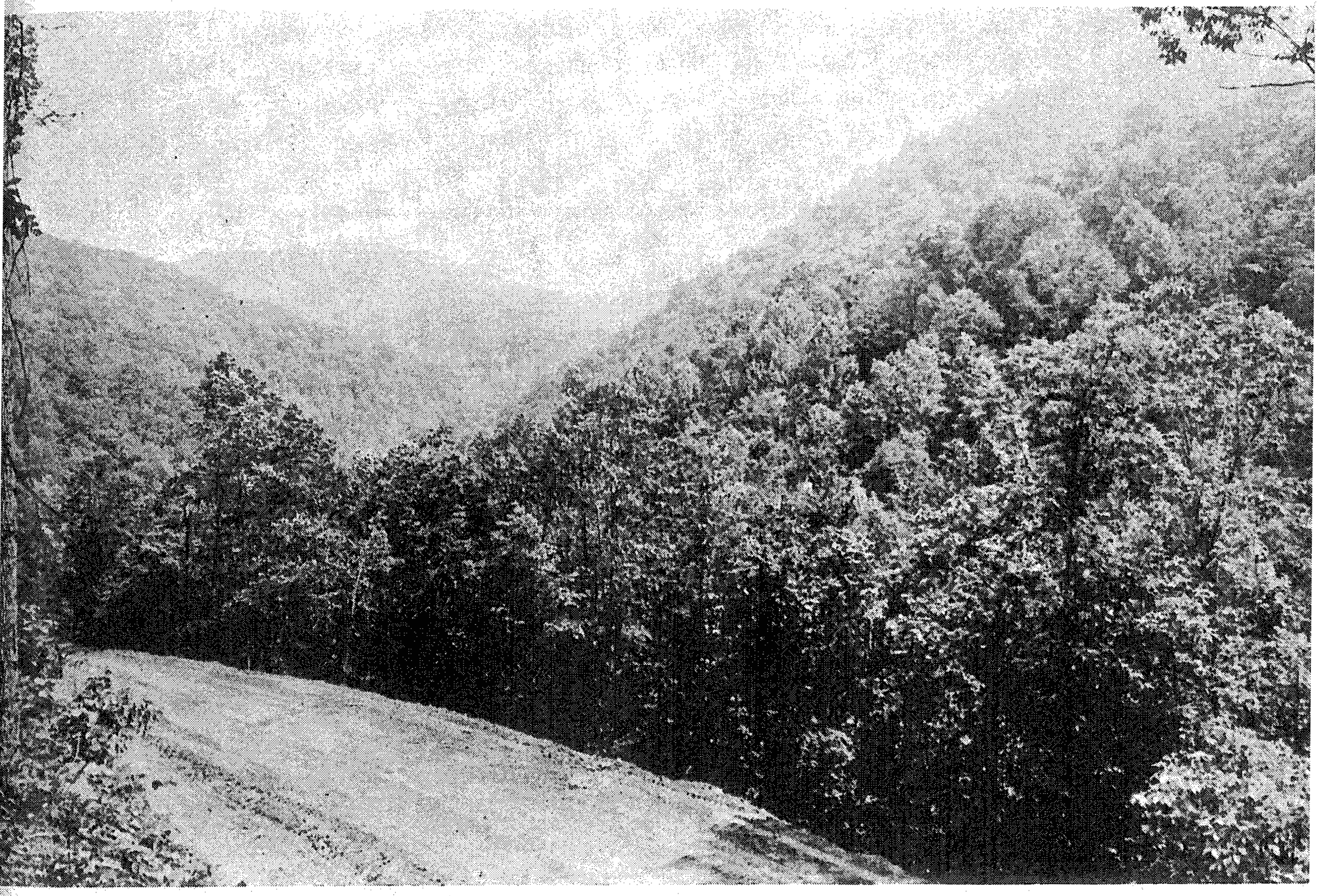


Figure 2.—Typical terrain of the Fernow Experimental Forest.

Elevation and topography.—The study area ranges in elevation from about 2100 feet above sea level to about 2850 feet. Slopes are generally steep (table 1), and logging is difficult.

Geology and soils.—The Experimental Forest lies in the Allegheny Mountain section of the Appalachian Plateau, as described by Fenneman (1938). The watersheds are underlain by rock strata composed primarily of fractured hard sandstone and softer shale. There is apparently little storage of water in the bedrock.

Most of the soil in the watersheds is silt loam with considerable stone content. Infiltration and permeability of the undisturbed soils are high. Soil depth to bedrock ranges for the most part from 3 to 5 feet. Humus depth averages about 2½ inches; over most of the area the humus is classified as a medium mull.

Table 1.—Watershed areas, and percentage of area in different slope classes

Watershed No. and treatment	Area	Slope class, in percent			
		10-20	20-30	30-40	40+
	Acres	Percent of area			
1. Commercial clearcut	74	5	--	20	75
2. Diameter limit	38	45	5	50	--
5. Extensive selection	90	5	40	40	15
3. Intensive selection	85	70	15	15	--
4. Control	96	40	30	30	--
All watersheds	383	30	20	30	20

Table 2.—Period of logging and gross timber volumes, in thousands of board feet per acre

Watershed No. and treatment	Period of logging [1]	Gross timber volumes [2]		
		Original stand	Cut and culled	Residual stand
1. Commercial clearcut	May 1957-June 1958	9.9	8.5	[3] 1.4
2. Diameter limit	June 1958-Aug. 1958	7.1	4.2	2.9
5. Extensive selection	Aug. 1958-Nov. 1958	12.0	3.7	8.3
3. Intensive selection	Oct. 1958-Feb. 1959	8.3	1.7	6.6
4. Control	Not logged	10.6	0	10.6

[1] In the Commercial clearcut, skidroads were bulldozed during the operation; in the other three watersheds, skidroads were constructed in October 1957.

[2] Gross board-foot volumes to 8-inch top, including volumes in cull trees.

[3] Cull trees.

Forest cover.—The area had been heavily cut over between 1905 and 1910. Prior to the study, the forest was essentially uneven-aged, consisting of 50-year-old second growth, residuals from early cuttings, and pole-sized trees that came in after death of the chestnut about 30 years before. The major species present were: oaks (red, chestnut, and white), sugar maple, yellow-poplar, black cherry, and beech.

At the time of treatment all watersheds were completely forested, supporting stands averaging 7,000 to 12,000 board feet per acre (table 2). No fires or grazing by domestic animals had disturbed these stands for at least 35 years.

Climate and streamflow.—The climatic conditions under which this research was conducted and those to which its results are likely to apply are described by the following mean values determined from 9 years of record on the Fernow Forest:

Mean annual precipitation	58 inches
Mean daily temperature	48° F.
Mean daily maximum temperature	57° F.
Mean daily minimum temperature	38° F.
Average date of first frost in fall	Sept. 30
Average date of last frost in spring	May 7
Average length of frost-free season	145 days

Precipitation is well distributed through the year (fig. 3). Because of fairly shallow soils, steep slopes, and relatively little groundwater storage, flow is high during periods with considerable precipitation and falls off quickly during periods with little or no precipitation.

Annual runoff from the Control Watershed during the study period (1951-60) averaged about 24 inches, of which 7 inches came during the growing season and 17 inches in the dormant season. Four of the 9 years of record had one or more months with no flow; 9 of the 108 months had no

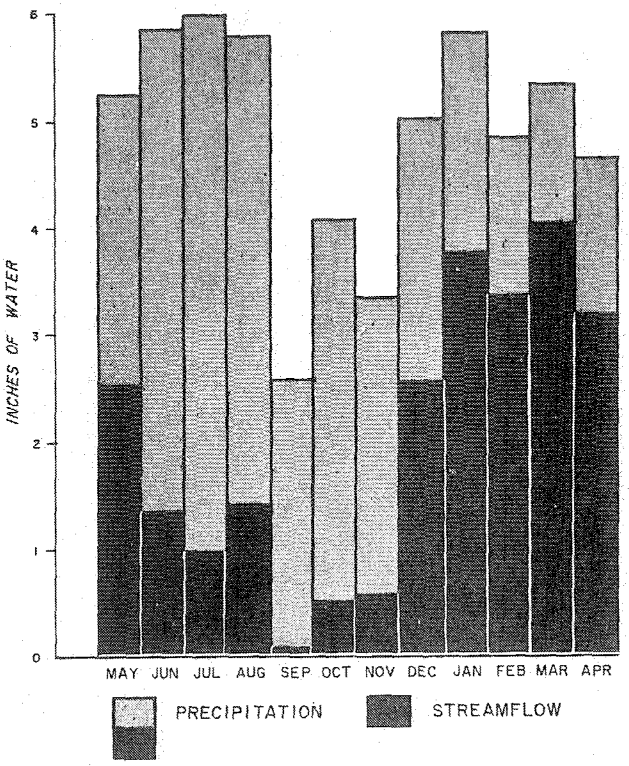


Figure 3.—Mean monthly precipitation and stream flow of the Control Watershed during the 9-year study period.

streamflow. Flow in March was the highest, with an average of 4.06 inches; September was lowest, with 0.05 inch.

On the average, 42 percent of the annual precipitation left the Control Watershed as streamflow. In the growing season, runoff was 23 percent of precipitation; in the dormant season it was 60 percent. Runoff as a percent of precipitation ranged from a high of 76 percent in March to a low of 2 percent in September. More detailed information on precipitation, temperature, and streamflow of the watersheds is given in the Appendix.

Infiltration rates are high and there is no surface runoff from these forest areas when undisturbed. Much of the precipitation from large storms reaches the stream as subsurface flow: the water passes through the soil to a less permeable layer or to bed rock; then it moves laterally downslope to the stream. It does not percolate further to groundwater.

Evapotranspiration.—Annual evapotranspiration may be estimated by subtracting annual runoff from annual pre-

Table 3.—Mean monthly precipitation and runoff of Control Watershed during 9-year study period

Month	Precipitation	Runoff	Precipitation less runoff	Runoff as percentage of precipitation
	Area-inches			Percent
May	5.26	2.53	2.73	48
Jun	5.84	1.38	4.46	24
Jul	5.99	.99	5.00	17
Aug	5.82	1.41	4.41	24
Sep	2.59	.05	2.54	2
Oct	4.03	.50	3.53	12
May-Oct	29.53	6.86	22.67	23
Nov	3.35	0.57	2.78	17
Dec	4.98	2.54	2.44	51
Jan	5.81	3.77	2.04	65
Feb	4.82	3.36	1.46	70
Mar	5.31	4.06	1.25	76
Apr	4.65	3.17	1.48	68
Nov-Apr	28.92	17.47	11.45	60
Year	58.45	24.33	[1]34.12	42

[1] As soil-moisture storage is fairly uniform at the beginning and end of the water-year this value is taken as an approximation of evapotranspiration or consumptive use. This may be an overestimate because there may be some deep seepage from the watershed.

cipitation (table 3). For the Control Watershed (No. 4) annual evapotranspiration was estimated at 34 inches in the 9-year study period. The estimates varied considerably by watershed. The following tabulation shows mean values in area-inches for the 6-year calibration period:

Watershed	*Precipitation*	*Runoff*	*Precipitation minus runoff*
1. Commercial Clearcut	60	23	37
2. Diameter Limit	59	26	33
3. Intensive Selection	59	25	34
4. Control	59	25	34
5. Extensive Selection	58	30	28

As can be seen, precipitation measured on the five watersheds was rather uniform; runoff less so. Further study of the watersheds must be made to determine whether these differences resulted from different amounts of deep seepage or from other causes.

In estimating evapotranspiration from records of precipitation and streamflow, changes in storage of water in the watershed must be considered. The water-year used in the above calculations starts and ends on May 1, when storage is generally near the maximum; and there should be little difference from year to year. For that reason, making the estimates without correction for storage should not greatly affect the result.

Potential evapotranspiration has not been calculated for these watersheds. Such investigation is planned. Indications are that actual evapotranspiration is not far below the potential.

Instrumentation and Measurement

The collection of data in this type of experimentation requires careful measurements over many years. Lack of measurement accuracy would easily mask significant differences.

Stream discharge.—On the watersheds, 120-degree V-notch weirs were used to measure stream discharge (fig. 4). Continuous records of water level were obtained on drum charts by FW-1 water-level recorders installed in concrete-block gage houses. A rating table was developed for each weir to show the relationship between gage height and discharge. From the chart record and rating table, tabulations were prepared of mean flow in c.s.m. by days. The flow was then tabulated in area-inches by month, season, and year. As needed, special tabulations of storm flow were prepared.

Precipitation.—Precipitation was measured by a network of three recording gages and nine standard gages located over

Figure 4.—A stream-gaging station on one of the experimental watersheds.

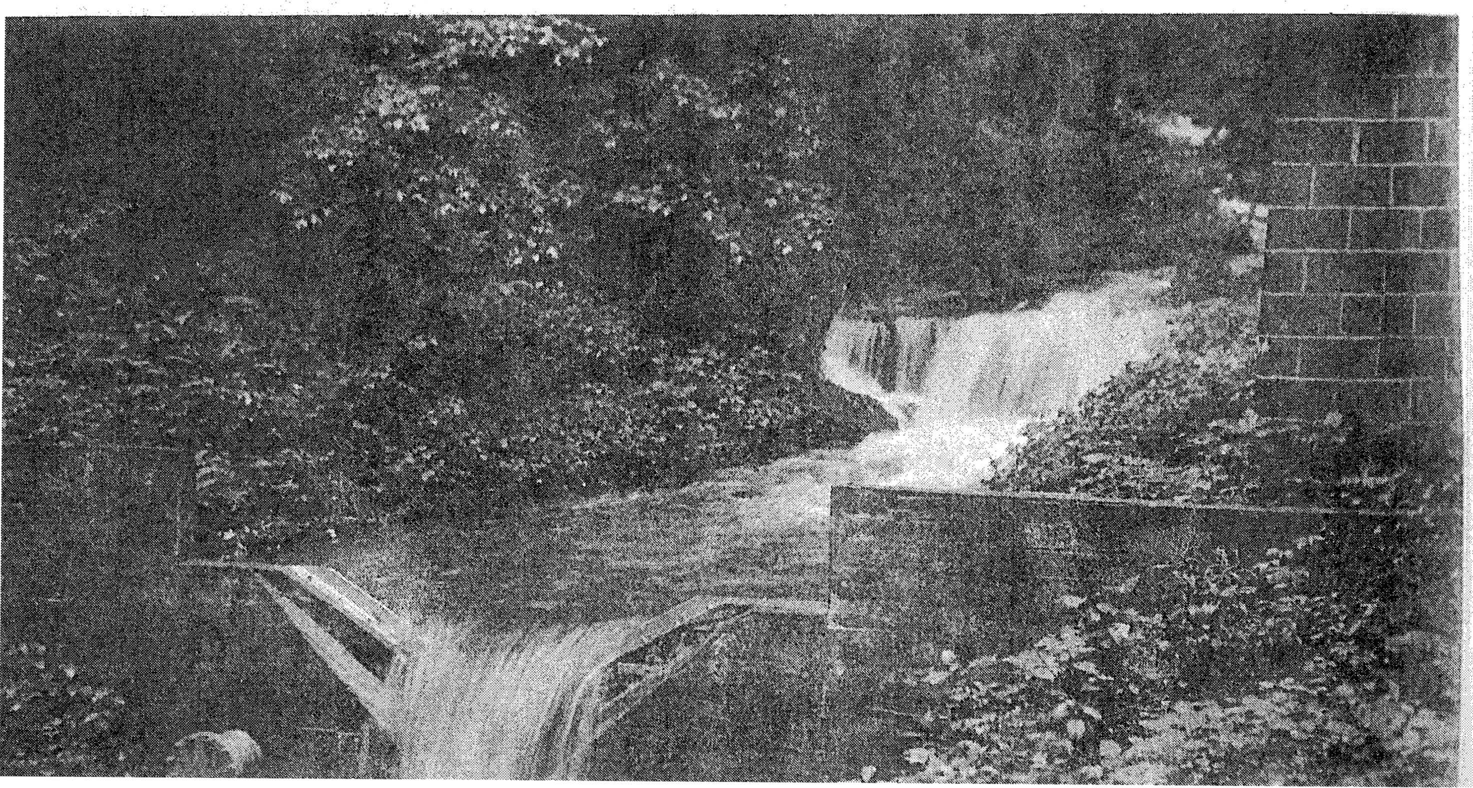


Figure 5.—Recording and standard gages installed in a clearing to measure precipitation.

the five watersheds (fig. 5). Trees were removed from the immediate vicinity of the gages to get a measure of precipitation in the open rather than under a canopy.

Air temperature and humidity.—Air temperature and relative humidity were measured at one station on the Experimental Forest area.

Water quality.—Water-quality samples were collected from the streams at sampling points a short distance above the weirs. Routine samples were taken according to schedule; special samples were obtained during storm periods. Samples were tested for turbidity and certain chemical characteristics.

In the calibration period, water temperature was measured at the time water-quality samples were taken. Starting in May 1958, maximum-minimum thermometers were placed in the streams and read and reset generally at weekly intervals.

Calibration and Analysis

During the calibration period, climatic and streamflow data were gathered as a basis upon which to predict watershed behavior after treatment. In other words, "normal" behavior pattern was established.

Changes due to treatment were determined by maintaining one of the five watersheds undisturbed as a control (Reinhart, 1958). Runoff in terms of annual, seasonal, and monthly flows and other runoff characteristics of each of the other watersheds was compared to the control during a 6-year calibration period. And mathematical equations were developed so that the runoff of each watershed could be predicted from the runoff of the control. These prediction equations were tested for validity and accuracy and were found to be statistically sound.

To illustrate simply: suppose we wish to predict annual flow of Watershed 1 (Y), or the expected discharge if there were no treatment effect, from measured annual flow of the Control Watershed (X). A linear regression equation, developed from data in the calibration period, is used. This equation is of the type: $Y = a + bX$. For this example the actual equation developed is $Y = -0.82 + 0.967X$, in which Y and X are in area-inches.

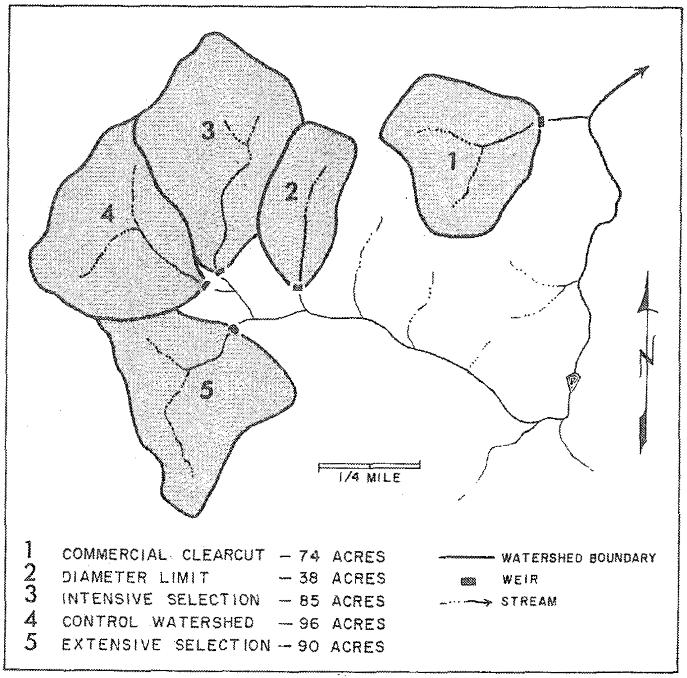


Figure 6.—Relative location and size of the five gaged watersheds on the Fernow Experimental Forest.

Now suppose we wish to test the effect of treatment on the annual flow of the Commercial Clearcut Watershed. The above equation gives a predicted or expected value. A measured value is obtained from the gaging station record. The difference between the two indicates the effect of treatment; the magnitude of this difference is then tested by routine statistical methods (Snedecor, 1956, pp. 137-138) to determine whether it is large enough to be significant.

Effects of treatment on other characteristics, say flow by season and by month, low flow, or high flow, are measured and tested in much the same way. Additional detail on calibration and analysis is given in the Appendix.

Watershed Treatment

After completion of the 6-year calibration period, timber was harvested on four of the five watersheds, each by a different forestry treatment (fig. 6). One watershed (No. 4) was left uncut to serve as a control for comparison. The four cutting practices ranged from a liquidation cutting—without concern for the future value of the property—to a conservative selection system cutting (table 4). Specifications for the four cutting practices applied were as follows:

Commercial Clearcutting.—This is the typical liquidation cutting only too commonly practiced throughout the mountain hardwood country. Everything merchantable is taken, including sawtimber and other products such as pulpwood and mine timbers in trees down to about 6 inches d.b.h. (fig. 7). All cull trees are left; no cultural work of any kind is done. Skidroads are laid out on a logger's choice basis; generally they are steep. Water values are not considered; skidroads may run up and down the stream channels, and any type of stream crossing is permissible (fig. 8). No after-logging care is practiced on the roads.

Diameter Limit cutting.—This type of cutting may be considered a crude forest management program. Every merchantable tree of long-lived species above 17.0 inches d.b.h. is cut. Every tree of short-lived species (such as black locust, sassafras, and mountain magnolia) larger than 7.0 inches is cut. The only cultural measure employed is deadening culls larger than 17.0 inches. Plans are to cut again in 20 years.

Table 4.—The four treatments applied on the Fernow watersheds

Watershed No. and treatment	Timber cut	Cutting cycle, years	Culls poisoned	Bulldozed skidroads		
				Maximum grade[1]	Water bars	Other requirements
1. Commercial clearcut	Everything merchantable	50+	None	No limit	None	None
2. Diameter limit	All merchantable trees over 17.0 inches d.b.h.	20	All over 17.0 inches d.b.h.	No limit	At 2-chain intervals	None
5. Extensive selection	Selected trees over 11.0 inches d.b.h.	10	All over 11.0 inches d.b.h.	20%	As needed	No skidding in stream channels
3. Intensive selection	Selected trees over 5.0 inches d.b.h.	5	All over 5.0 inches d.b.h. (grapevines also cut)	10%	As needed	No skidding in stream channels. Skidroads located away from stream. Grass-seeding for soil stabilization where needed.

[1] To be exceeded only for short distances where necessary.

Skidroads are logger's choice, similar to those in the Commercial Clearcutting. Only one practice is used in consideration of road values: after logging, water bars for road drainage are installed at intervals of about 2 chains (1 chain = 66 feet).

Extensive Selection management.—This is a selection management program in which harvesting and the killing of culls is limited to marked trees in the sawlog portion of the stand—trees larger than 11.0 inches d.b.h. All trees to be harvested, or deadened as culls, are marked. The only cultural measure is cull deadening and cutting of grapevines that are damaging potential crop trees. Cutting cycle is 10 years. No skidding is done in stream channels; bulldozed skidroads are limited to about a 20-percent grade except where conditions dictate a somewhat steeper grade for short stretches. Water bars are established immediately after logging wherever they appear to be needed.

Intensive Selection management.—This is a selection management program in which cutting and cultural work are done throughout the range of d.b.h.'s above 5.0 inches (fig. 9). All trees to be harvested, or killed as culls, are marked. Cutting cycle is 5 years. Bulldozed skidroads are limited to about 10-percent grade except where conditions dictate a somewhat steeper grade for short stretches. Skidroads (fig. 10) are located away from stream channels. The rule of thumb reported by Trimble and Sartz (1957) is used as a guide: distance between road and stream channel should not be less than 25 feet plus 2 feet for each percent slope of the land between road and stream. No skidding is done in stream channels; stream crossings, if necessary, are by carefully planned bridges to protect the stream. After logging, water bars are established in skidroads as necessary; and potential sediment sources, if any, are seeded to grass.

Treatment was begun on May 13, 1957; and logging on the last watershed was virtually completed on December 10, 1958. A few logs were removed from the Intensive Selection Watershed in February 1959. Data on the original stand, the amount cut, and the amount left were compiled (table 2).

In the Intensive Selection Watershed, the original volume of the stand and condition of the timber made it necessary to make a very light cutting so that sufficient volume would be available for another cut in 5 years, as scheduled under this practice. Water values were given special consideration: no logging was done in wet weather. Where necessary to insure soil stabilization, short stretches of skidroad were seeded to grass immediately after logging (fig. 11). Also, an old truck road built into the upper portion of this water-

Figure 7.—The Commercial Clearcut Watershed after logging.

Figure 8.—Tractor skidroad in the Commercial Clearcut Watershed. The road is almost in the streambed, and logging debris obstructs the channel.

Figure 9.—The Intensive Selection Watershed after logging.

Figure 10.—Tractor skidroad in the Intensive Selection Watershed just before logging. Note the gentle grade and the dip for drainage.

Figure 11.—This short stretch of skidroad in the Intensive Selection Watershed was limed, fertilized, and seeded to grass as soon as the logging operation was completed.

shed and the Extensive Selection Watershed made it possible to remove a large part of the volume from above.

In all watersheds, logging was done with a TD-9 tractor with rubber-tired sulky (fig. 12). Generally, the tractor remained on the skidroad and tree lengths were winched to it. During the course of logging no truck roads were constructed in the watersheds—only tractor skidroads.

Skidroads for the Diameter Limit Watershed and the two Selection Watersheds were constructed in October 1957, about a year before logging, to allow settling time before use and to allow a measure of the effect on streamflow of shortly after dozing of roads. In the Commercial Clearcut Watershed, skidroads were constructed as needed during the logging job.

Most main skidroads were bulldozed; though where slopes were gentle, it was sometimes feasible to operate without 'dozing. Also, some spur roads were located on relatively steep terrain and operated without 'dozing when only a few trips were scheduled to pass over them. The disturbance caused by a few trips, even on a steep gradient, has proved to be less than would result from 'dozing a road on the grade prescribed for the treatment.

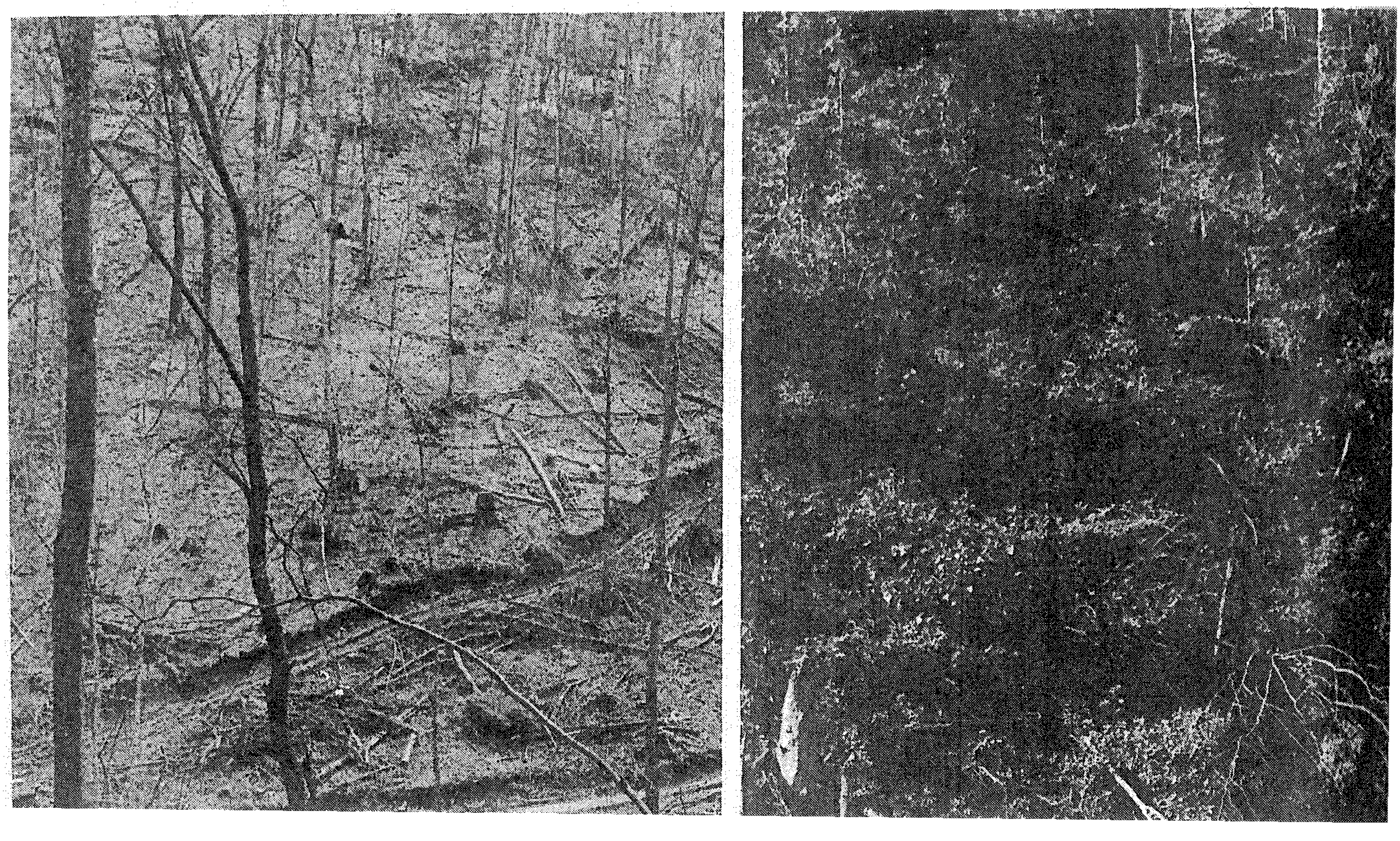
Figure 12.—Tractor with sulky skidding logs. Tree lengths were usually winched in to the skidroad.

Table 5.—Percentage of area and grade of skidroads in the four logged watersheds

Watershed No. and treatment	Percentage of watershed area		Percentage of bulldozed skidroad, by grade class--			
	In all skidroads	In bulldozed skidroads	0-10	11-20	21-30	31-40
1. Commercial clearcut	7.3	3.6	22	32	35	11
2. Diameter limit	6.2	2.5	20	72	8	0
5. Extensive selection	5.8	2.1	36	57	7	0
3. Intensive selection	1.9	.8	68	31	1	0

Detailed data were compiled separately for 'dozed and non-'dozed roads (table 5) because the amount of disturbance and impact on the watershed were much greater for the 'dozed roads. The unplanned skidroads of the Commercial Clearcut occupied the most area (7 percent of the watershed for both 'dozed and non-'dozed) and the carefully planned roads of the Intensive Selection Watershed occupied

Figure 13.—Recovery of vegetation after logging was good. Left, the Commercial Clearcut Watershed after logging was completed. Right, the same area 15 months later.



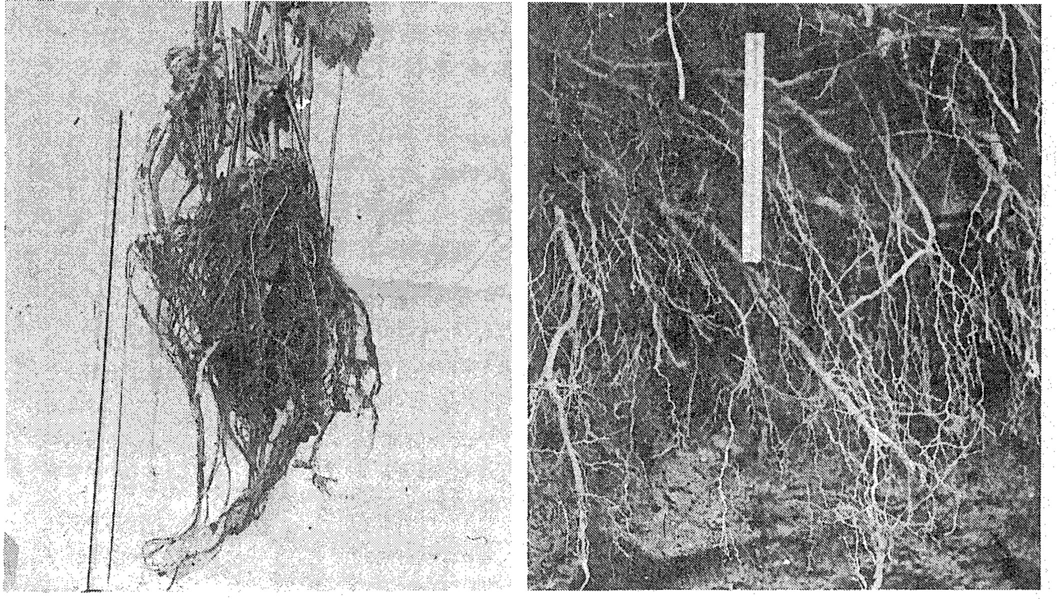


Figure 14.—Rooting depths of new and old vegetation. Left, the roots of jewel weed and nettle that came in after logging on the Commercial Clearcut Watershed. Right, roots of a large beech tree cut at edge of main skidroad in the same watershed. One-foot rule shows scale in both photos.

the least (2 percent). If the cut in the Intensive Selection Watershed had been heavier, the percent of area in skidroads would probably have been only slightly higher.

One significant feature of all treatments was the effect of logging on the forest floor. Except for the skidroad areas, the forest floor was subjected to only minor disturbance.

The recovery of the area is being watched. The forest practices used were all one-shot treatments, which will be repeated at intervals; and after each phase of the harvesting operations there is a period of recovery. Periodic inventories of trees more than 5 inches d.b.h. and periodic reproduction counts will provide a measure of the rate of recovery. Successive photographs from established photo points will provide a photo record of the changes.

Recovery was most noticeable on the Commercial Clearcut Watershed, which had the most drastic treatment (fig. 13). Shortly after logging, a good growth of new vegetation appeared, composed mostly of herbaceous plants and tree sprouts, with some admixture of tree seedlings and grass. Depth of rooting of the new herbaceous growth was much less than that of the older growth (fig. 14).

Treatment Effects

ON WATER

This study showed two things primarily: (1) that cutting of forest vegetation increases streamflow, and (2) that much of the damage to water quality due to poor skidroad practices can be avoided by proper planning of skidroads and reasonable care during logging.

The results of treatment were analyzed as to their effect on the following facets of streamflow: water quality, total discharge by year, season, and month; low flow; high flow; flow duration; and runoff as a percent of precipitation.

Water Quality

Careless logging resulted in very turbid water. This was certainly not unexpected. Maximum turbidities measured, ranging from 56,000 p.p.m. on the Clearcut to 15 on the Control (table 6 and fig. 15) illustrate the striking results of the different logging practices. Serious stream pollution was encountered on the two watersheds with unplanned skidroads—Clearcut (fig. 16) and Diameter Limit. On the Extensive Selection Watershed the effect of logging on water quality was not serious, and pollution subsided almost im-

Table 6.—Maximum turbidity measured, and frequency distribution of samples for the five watersheds, December 1957 to April 1960

Watershed No. and treatment	Maximum turbidity measured	Frequency distribution of samples, by turbidity unit* classes--				Total No. of samples
		0-10	11-99	100-999	1,000+	
	Turbidity units	Number of samples				
1. Commercial clearcut	56,000	126	40	24	13	203
2. Diameter limit	5,200	171	17	8	7	203
5. Extensive selection	210**	195	8	0	0	203
3. Intensive selection	25	201	2	0	0	203
4. Control	15	202	1	0	0	203

*Roughly parts of soil per million parts of water.

**Not included in frequency distribution. This sample was taken at a time when the other watersheds were not sampled.

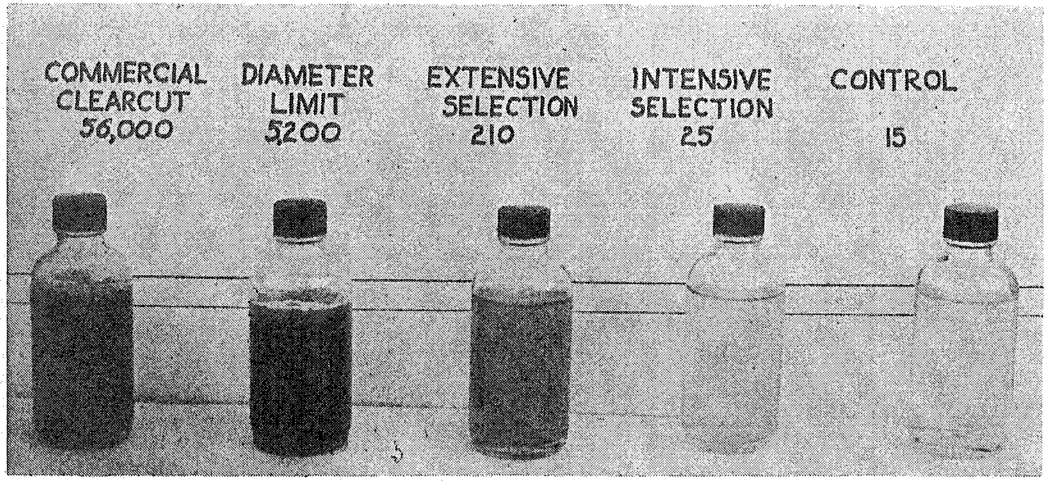


Figure 15.—Water samples showing maximum turbidities measured on each of the five gaged watersheds. Differences are due largely to differences in skidroad layout and construction.

Figure 16.—A steep, gullied skidroad in the Commercial Clearcut Watershed soon after completion of the logging operation.

Table 7.—Average turbidity of routine samples from Commercial Clearcut and Diameter Limit watersheds

(Special storm-period samples not included)

Period	Average turbidity	Range in turbidities
	Units	Units
Commercial clearcut		
During logging operation	490	0 - 5000
First year after logging	38	0 - 700
Second year after logging	1	0 - 53
Diameter limit		
Before logging (after roadbuilding)	2	0 - 68
During logging operation	897	0 - 5000
First year after logging	6	0 - 88
Second year after logging	0	0

mediately after logging ceased. The effect on water quality of logging the Intensive Selection Watershed was negligible: the water was clear, or almost clear, all of the time.

The impact on water quality was greatest during and immediately after the logging operation (table 7 and fig. 17). Repeated disturbance during logging continually brought to the road surface a new supply of fine soil particles. Erosion decreased rapidly after logging, due first to the development on our soils of a partial erosion pavement (a surface cover of small stones) and later to vegetation growth on the roads. Frost heaving brought a temporary setback to this process.

Effects of the Commercial Clearcut treatment on water temperature were noteworthy. Analysis of current temperatures in the calibration period (when extremes were not measured) indicated that there was little difference in the temperature regimes between this watershed and the Control. Thus differences during the treatment period are considered results of treatment.

Cutting in the Commercial Clearcut Watershed, as might be expected, accentuated the extremes. Growing-season maximums in 1958 and 1959 were increased on the average by 8° F. The dormant-season minimums were reduced on the average by 3½°. A slight effect in the same direction was apparent on the Diameter Limit Watershed; and no appreciable effects were evident on the two Selection Watersheds.

Figure 17.—*A*, sediment deposit at edge of main skidroad, Commercial Clearcut Watershed, one month after completion of logging operation. *B*, the same location 1 year later.

Table 8.—Effect of treatments on annual discharge

Treatment	Water-year	Discharge for year, in area-inches		Probability[1]
		Predicted	Increase	
Commercial clearcut	1957-58[2]	19.0	2.2*	0.02
	1958-59	26.5	5.1*	.001
	1959-60	21.5	3.4*	.003
Diameter limit	1958-59[2]	30.4	1.0	.12
	1959-60	24.9	2.5*	.01
Extensive selection	1958-59[2]	35.3	1.0	.07
	1959-60	29.3	.7	.12
Intensive selection	1958-59[2]	28.3	-.1	--
	1959-60	23.2	.3	.28

[1] The probability that an increase of the magnitude measured could have occurred by chance alone.

[2] Treatment in effect only part of time or on only part of the area during year.

*Statistically significant at 5-percent level.

Table 9.—Effect of treatments on discharge, by seasons

Treatment	Water-year	Growing-season discharge			Dormant-season discharge		
		Predicted	Increase	Probability[1]	Predicted	Increase	Probability[1]
		Area-inches	Area-inches		Area-inches	Area-inches	
Commercial clearcut	1957-58[2]	2.5	1.2*	0.02	16.5	0.9	0.13
	1958-59	13.1	4.4*	<.001	13.4	.6	.23
	1959-60	2.7	3.0*	<.001	18.8	.5	.25
	1960-61	5.1	1.8*	.003	--	--	--
Diameter limit	1958-59[2]	15.1	.7*	.04	15.5	.2	.43
	1959-60	3.4	1.8*	.001	21.4	.8	.19
	1960-61	6.2	.7*	.02	--	--	--
Extensive selection	1958-59[2]	--	--	--	18.2	[3] -.1	--
	1959-60	4.2	1.4*	.02	24.9	-.6	--
	1960-61	7.4	[3] -.3	--	--	--	--
Intensive selection	1958-59[2]	--	--	--	14.2	.3	.22
	1959-60	3.4	.3	.16	19.8	.0	>.5
	1960-61	6.0	.4	.08	--	--	--

[1] The probability that an increase of the magnitude measured could have occurred by chance alone.

[2] Year of treatment (treatment in effect only part of time or on only part of area).

[3] Negative value denotes a decrease.

*Statistically significant at 5-percent level.

Slight chemical changes were noted as a result of clearcutting: pH increased from a mean of about 6.1 to 6.4 and methyl orange alkalinity rose about 2 p.p.m. No appreciable changes in chemical characteristics resulted from the other three treatments.

Total Discharge

By year.—Using the equations developed from the calibration data, it was possible to predict (from the Control) the annual flow from each treated watershed if it had not been treated. When this was compared to measured flow, certain significant changes were noted (table 8).

There were large and statistically significant increases in streamflow from the Commercial Clearcut Watershed beginning the year of treatment, 1957-58. The greatest increase, 5.1 area-inches or 19 percent of the expected annual discharge, occurred the year after logging. In 1959-60, the increase was 16 percent. This drop may have been due both to increased use of water by plants as a result of vegetation regrowth and a combination of weather factors. When an after-trend has been established over a period of several years it should be possible to estimate the effect of vegetation regrowth.

The effects of treatment on the Diameter Limit Watershed, cut in mid and late summer of 1958, were not so great. In 1959-60, the first full year after logging, there was an increase of 2.5 area-inches or 10 percent.

While the record of the Selection Watersheds indicates slight increases in annual flows for the first full year after logging (1959-60) the increases were too small to be statistically significant.

Skidroads were constructed in the Diameter Limit and Selection Watersheds in October 1957. Predicted discharges and changes in flow were computed for the 1957-58 water-year; these analyses indicated that construction of skidroads, in the absence of logging, had no appreciable discharge effect on these three watersheds.

By season.—The water-year has been divided for compilation and analysis purposes into the growing season (May through October) and the dormant season (November through April). Comparisons between predicted and measured flows in these two seasons were made and tested for statistical significance (table 9).

For the first growing season after completion of logging, significant increases occurred on all but the Intensive Selection Watershed. On the Commercial Clearcut Watershed, increases were significant for all four growing seasons measured; and, as expected, the largest increase followed the completion of logging.

Increases as a percentage of expected discharge ranged up to 111 percent, which occurred on the Clearcut Watershed in 1959. The increase in 1958 was larger, 4.4 inches compared to 3.0 inches; but in the summer of 1958 precipitation and streamflow were high, which resulted in a lower percentage increase over the expected value.

Though the increase on the Intensive Selection Watershed in 1959 was not statistically significant, it amounted to 0.3 area-inch or 9 percent of the expected value and fell into a logical pattern when considered with results from the other watersheds. This 0.3 area-inch is equivalent to more than 8 thousand gallons per acre.

The effect of treatment was less in the 1960 growing season; however, increases for both the Clearcut and Diameter Limit Watersheds were still significant. In 1959 and 1960, Diameter Limit increases were about half those on the Clearcut Watershed.

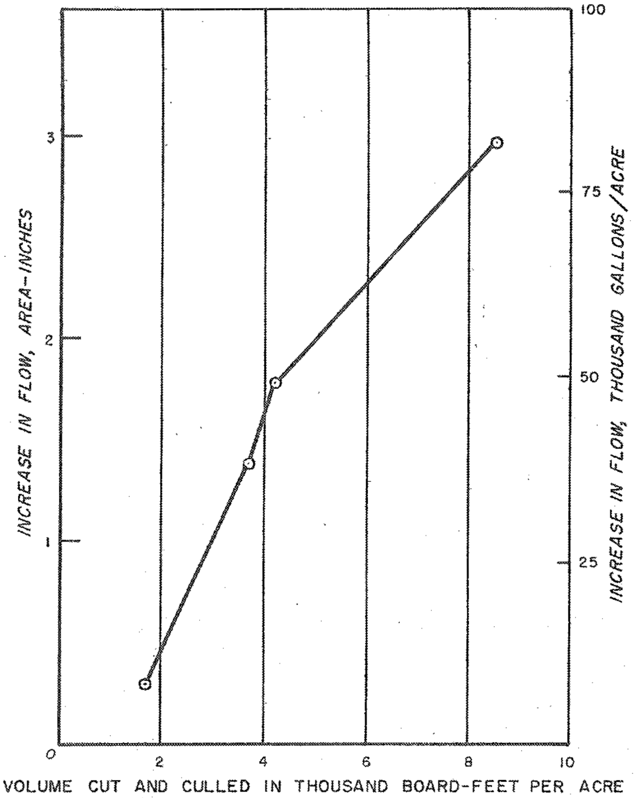


Figure 18.—Increase in flow related to volume cut and culled, 1959 growing season.

Table 10.—Increase in flow, by months, in area-inches[1]

(Increase shown only if statistically significant at 5-percent level)

Month	Commercial clearcut				Diameter limit			Extensive selection			Intensive selection	
	1957-58	1958-59	1959-60	1960-61	1958-59	1959-60	1960-61	1958-59	1959-60	1960-61	1959-60	1960-61
May	--	--	--	--	--	0.4	--	--	--	--	--	--
Jun	--	1.3	--	0.5	0.3	--	--	--	--	--	--	0.1
Jul	0.5	1.6	0.6	--	--	.4	--	--	--	--	--	--
Aug	--	1.1	.5	--	.5	.3	--	--	--	--	--	--
Sep	--	.5	.2	.7	.3	.1	0.2	0.1	0.1	--	--	--
Oct	.6	.2	1.3	.2	.1	.4	--	--	.6	--	0.1	.1
Nov	.3	.6	.9	--	.3	.5	--	--	.5	--	--	--
Dec	.5	--	--	--	--	--	--	--	--	--	--	--
Jan	--	--	--	--	--	--	--	--	--	--	--	--
Feb	.5	--	--	--	--	--	--	--	--	--	--	--
Mar	--	--	--	--	--	.4	--	--	--	--	--	--
Apr	--	--	--	--	--	--	--	--	--	--	--	--

[1] Records of runoff available for only first 6 months of water-year 1960-61.

A definite relationship appears to exist between the severity of the cut and the increase in discharge. A graph showing this relationship for the 1959 growing season, with volumes expressed in board feet, is presented in figure 18. During the dormant seasons insignificant increases were recorded in streamflow for the two most heavily cut watersheds.

Analyses were made of seasonal discharges between dozing of roads and logging on the Diameter Limit and Selection Watersheds. No significant effect of this phase of the treatment was demonstrated.

By month.—Similar analyses were made of discharges by month after start of treatment in each watershed. Table 10 presents in an abbreviated form the results of this analysis. Increases are shown only when statistically significant.

Increases in flow on the Clearcut Watershed were considerable, ranging up to 1.6 area-inches in July 1958, a month of heavy precipitation just after completion of logging. Increases in some of the drier months were small in actual amount but were large compared to expected flow; for example, in October 1957 on the Clearcut Watershed the increase was only 0.6 area-inch but measured flow was more than 10 times the expected flow.

increases in flow on the Diameter Limit Watershed; however, increases were smaller than on the Commercial Clearcut. The two Selection Watersheds had much smaller and for the most part statistically insignificant increases in the growing-season months; however, in October 1959 both watersheds showed increases significant at the 5-percent level.

Months of the dormant season generally did not show large increases in flow. November increases were significant on the Commercial Clearcut and Diameter Limit Watersheds. Decreases that occurred in certain dormant-season months may be associated with the effect of treatment on snowmelt rates and will be discussed later.

Low Flow

An analysis was made to determine the treatment effect on the number of days in the year that stream discharge was below certain rates of flow. Three levels were considered: 0.05, 0.075, and 0.10 c.s.m., approximating 50, 75, and 100 gallons per acre per day. Table 11 gives the results for 50 gallons per acre per day; the other analyses are reported in the Appendix.

For example, it was predicted (from the relationship of the

Table 11.—Effect of treatments on number of days of low flow (less than 50 gallons per acre per day)

Treatment	Year	Number of days of low flow	
		Predicted	Decrease [1]
Commercial clearcut	1957	124	72*
	1958	38	38*
	1959	99	63*
	1960	46	39*
Diameter limit	1958	22	22*
	1959	74	47*
	1960	29	27*
Extensive selection	1959	58	21*
	1960	17	14*
Intensive selection	1959	65	5
	1960	20	13*

[1] Decrease in number of days of low flow results from an increase in streamflow.

*Statistically significant at 5-percent level.

Clearcut and Control Watersheds before treatment and the performance of the Control in 1959) that the Clearcut Watershed would discharge less than 50 gallons per acre per day on 99 different days in 1959. Actually, streamflow was below this rate on only 36 days.

The analysis shows that treatment had a strong effect on low flows: the heavier the cut, the greater the effect. In 1959 and 1960 together, days of low flow on the Clearcut were reduced from 145 to 43; on the Diameter Limit from 103 to 29; on the Extensive Selection from 75 to 40; and on the Intensive Selection from 85 to 67.

High Flow (or Storm Flow)

Analyses of high flows were difficult, largely because the effect of treatment on these flows was variable. Depending on conditions at the time of a storm, the effect might be an increase, little change, or even a decrease. High flows occurred too infrequently to group by classes based on antecedent precipitation or other factors affecting treatment results. More extensive analyses of high flows were made for the Commercial Clearcut Watershed than for the partially cut watersheds because the effects of treatment were obviously greater, as expected, on the Clearcut than on the others. Under some conditions, storm flow from the Clearcut Watershed was several times that from the Control.

Figure 19 shows sample hydrographs of these watersheds before and after treatment. Before treatment, the hydrographs of the two watersheds were close together. Number 4, the Control, was slightly above Number 1, the Clearcut. The rounded peaks on both hydrographs indicated undisturbed forested watersheds with negligible overland flow.

The hydrographs after treatment represent a 3-day period shortly after completion of logging on the Clearcut at the height of the growing, or evapotranspiration, period. The flow of the Clearcut Watershed was higher at the start; this was the normal relationship of these watersheds in the growing season after treatment. The sharp peaks on the Clearcut were probably caused by quick overland flow from skidroads. The storm flow is far greater than that from the Control. Runoff for the 3-day period, July 11 to 13, was 0.52 area-inch on the Clearcut Watershed, almost 9 times the discharge of 0.06 area-inch on the Control.

Results in some periods of high flow were much different from the instance described above. For example, in late March 1960 a 2-foot snow cover melted away over a 14-day period in which some additional precipitation occurred. The following tabulation shows streamflow in area-inches of the Clearcut and Control Watersheds and the precipitation record:

	Precipitation		*Discharge in area-inches from—*	
March—	*Snow*	*Rain*	*Clearcut*	*Control*
18	0	0	0.03	0.03
19	0	0	.04	.03
20	0.31	0	.04	.03
21	.17	0	.04	.02
22	.20	0	.04	.03
23	.02	0	.03	.02
24	.07	0	.05	.03
25	.05	0	.06	.04
26	.22	0	.06	.04
27	0	0	.12	.07
28	0	0	.49	.37
29	0	0	.89	.90
30	0	.42	1.27	1.79
31	0	.27	.85	.98
14-day sum	1.04	.69	4.01	4.38

For the 14-day period, flow of the Clearcut was 92 percent of that of the Control. In the first 11 days, flow of the Clearcut exceeded that of the Control. This was more than compensated for by lower flow of the Clearcut in the last 3 days: on the day of highest flow, March 30, flow of the Clearcut was only 71 percent of that of the Control. The maximum instantaneous peak on the Clearcut (38 c.s.m.) was only 75 percent of the corresponding peak (51 c.s.m.) on the Control. Observations on the watersheds indicated that snow cover disappeared near the end of the period and that it was gone sooner on the Clearcut than on the Control. In this instance, exposure of the snow cover apparently resulted in a much lower peak flow.

To define the effects of heavy cutting on storm flow, four different types of analyses were made on data of the Clearcut Watershed. One analysis, undertaken on data of all four

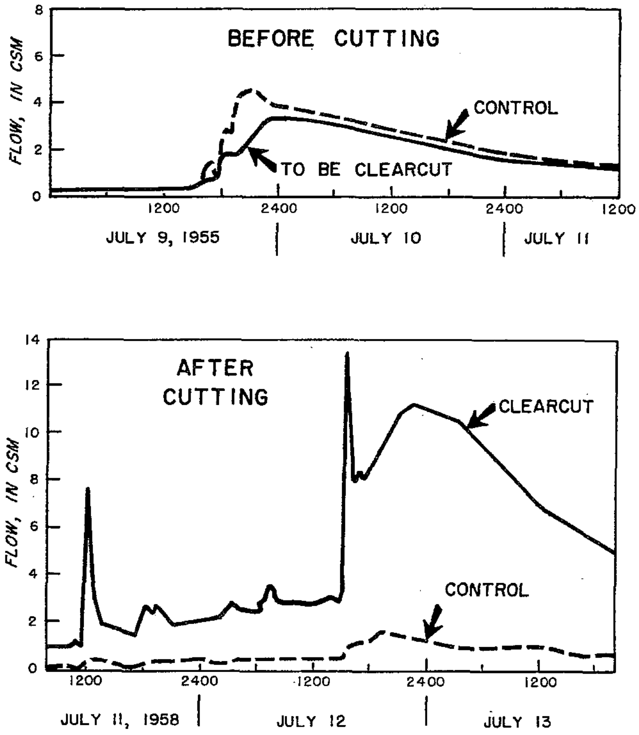


Figure 19.—Sample storm hydrographs of Clearcut and Control watersheds before and after treatment.

treated watersheds to determine effects of all cuts, showed that effects of treatment were decisive on the Clearcut Watershed but not on the partially cut watersheds.

Instantaneous peaks on the Clearcut Watershed in the growing season were increased on the average by 21 percent; in the dormant season they were reduced by 4 percent.

Considering yearly quantity of discharge above 10 c.s.m. on the Clearcut Watershed, there was an average increase of 11 percent in the 3 years after logging. The increase was 42 percent in the three growing seasons. And analysis indicated a decrease of 1 percent in the three dormant seasons.

The following pattern of treatment effects was evident: in general, heavy cutting augmented high flows in the growing season and resulted in either increases or decreases in the dormant season. The decreases usually occurred when snow melt was involved.

Flow Duration

The flow-duration curve of a stream, showing the percentage of time that specified discharges are equaled or exceeded, is a useful tool in studying effects of treatment (Searcy, 1959). Many flow-duration curves were prepared in this study; all were based on mean daily flow in c.s.m.

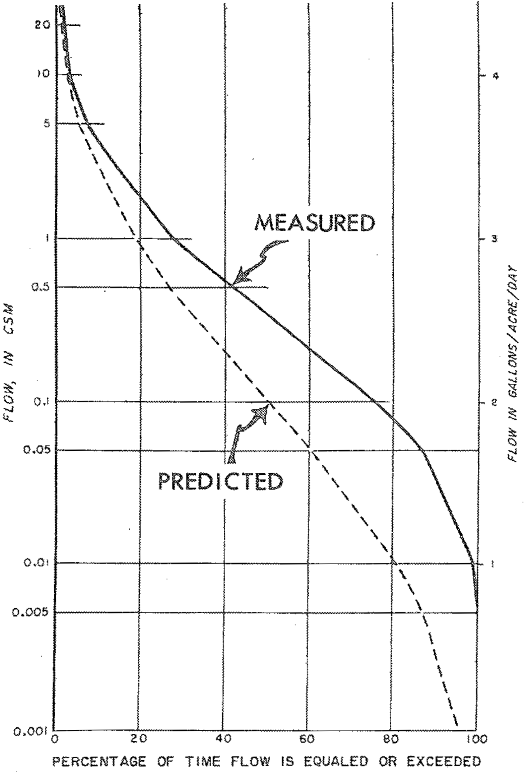


Figure 20.—Flow-duration curves for Clearcut Watershed in the four growing seasons after start of logging.

Average curves for the Clearcut Watershed in the growing seasons of the treatment period show that the treatment effect was greatest on low flows (fig. 20). Curves based on both predicted and measured values are shown; these represent flow in the 736 days of the 1957-60 growing seasons. As can be seen, the "measured" curve is far to the right of or above the "predicted" curve; this difference is a measure of the treatment effect.

The following tabulation indicates how the curves may be used and the magnitude of the treatment effect. For example, based on pre-treatment relationships, it was estimated that 25 percent of the time after treatment flow would be 560 gallons per acre per day or greater if treatment had no effect. Actually, measured flow for 25 percent of the time was 1,000 gallons per day or greater.

Percentage of time	*Flow that is equaled or exceeded, in gallons per acre per day*	
	Predicted	*Measured*
25	560	1,000
50	100	340
75	17	100

Another practical way of using these curves is indicated by an example. Assume that a certain industry or water user needs a discharge of 100 gallons per acre per day to operate at full capacity and has no facilities for impoundment. This user would have been able to operate fully only about 50 percent of the time during the growing seasons indicated if the watershed had remained in its pre-treatment condition. As a result of the clearcut treatment, it would have been able to operate fully 76 percent of the time. This advantage will diminish year by year as regrowth occurs.

The general increase in flow, the considerable augmentation of low flow, the relatively smaller increase in high flow, and the relation of these effects to severity of treatment are all readily apparent in the flow-duration curves of the four treated watersheds for two growing seasons, 1959 and 1960 (fig. 21). These were the two growing seasons immediately

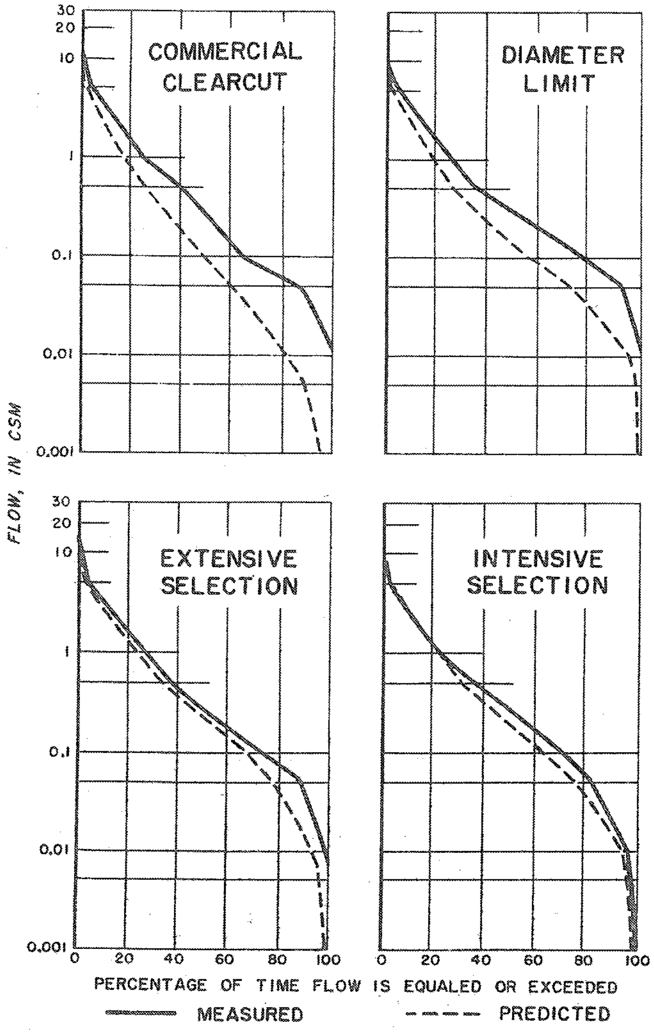


Figure 21.—Growing season flow-duration curves for the four treated watersheds in 1959 and 1960.

of precipitation on the Clearcut Watershed

Item	Predicted runoff	Change	Change as percentage of predicted
Growing season:			
1957	11	+ 3	27
1958	34	+12*	35
1959	10	+10*	100
3-season mean	18	+ 8	44
Water-year:			
1957-58	34	+ 4*	12
1958-59	42	+ 8*	19
1959-60	36	+ 7*	19
3-year mean	37	+ 6	16

*Statistically significant at 5-percent level.

after completion of logging for all watersheds except the Commercial Clearcut; for the three watersheds, these are probably the years of maximum effect.

Runoff as a Percent of Precipitation

One interesting and often computed characteristic of a watershed is runoff as a percent of precipitation. Because the Clearcut treatment had considerable effect on stream discharge, it is not surprising that runoff as a percent of precipitation also changed. An analysis made on this characteristic showed, as expected, that the growing season changes were considerably larger than changes for the year as a whole (table 12).

As for effects of the other treatments on runoff as a percent of precipitation, for the water-year the only change measured as a result of partial cutting was an increase from 43 to 47 percent on the Diameter Limit Watershed. In the growing season, increases from 41 to 42 percent and from 12 to 18 percent were measured in 1958 and 1959, respectively. The Extensive Selection Watershed showed an increase from 15 to 20 percent in 1959. No change was noted on the Intensive Selection Watershed.

Table 13.—Stand volumes per acre on the Fernow watersheds

Treatment	Original stand volume				Residual stand volume			
	Merchantable			Cull	Merchantable			Cull
	All sawtimber	Sawtimber in log grades[1] I and II	Total		All sawtimber	Sawtimber in log grades[1] I and II	Total	
	M b.m.[2]	M b.m.[2]	Cu.ft.[3]	Cu.ft.[3]	M b.m.[2]	M b.m.[2]	Cu.ft.[3]	Cu.ft.[3]
Commercial clearcut	8.5	3.6	1,958	269	0	0	92	254
Diameter limit	6.7	2.0	1,796	83	2.8	0.6	1,063	28
Extensive selection	10.6	3.1	2,412	235	8.3	3.0	2,000	20
Intensive selection	7.6	2.9	2,021	150	6.6	2.6	1,834	0
Control	9.6	4.3	2,154	167	9.6	4.3	2,154	167

[1] U. S. Forest Service Forest Products Laboratory grades 1 and 2 based on lumber.

[2] In trees over 11.0 inches d.b.h., International 1/4-inch rule.

[3] In trees over 5.0 inches d.b.h., to a 4.0-inch top.

EFFECTS ON TIMBER PRODUCTION

The watershed treatments are replicates of four timber-management practices that are being studied on other areas in the Fernow Experimental Forest. These are all package arrangements in which a given type of management with certain methods of cutting and harvesting is studied from several viewpoints: growth, timber quality, species compostion, logging costs, and net returns.

The timber-stand data (original and residual volumes) show a partial picture of operations to date (table 13). These data alone are not sufficient for evaluating the different treatments because the study has not been under way long enough.

Fortunately records are available from treatment replicates on the other areas, some of which were placed under management more than 10 years ago. A few involve not only the first cutting in unmanaged stands but a second cutting as well. A synthesis of the watershed data and the results from other compartments, along with available information on timber growth and quality from study plots, provides a basis for comparing the four treatments.

For the first cutting, the Clearcut generally showed the greatest net return per acre because of heavy removal; and the Diameter Limit cut showed the greatest net return per M b.m. removed. This last was followed closely, and occasionally preceded, by the Extensive Selection cutting, depending on the nature of the stand. These latter two programs were concerned only with sawlogs; trees too small to produce sawlogs were ignored. The Intensive Selection program generally returned the least net income per acre and per M b.m. on the first cutting because of the concentrated effort to remove poor trees above 5.0 inches d.b.h. Also, more money was expended on cultural work and after-logging care.

In general, from all replications, the first cutting in all practices paid the logging costs and some stumpage. This was not true for the Intensive Selection Watershed. Here the very light cutting did not compensate for the road and bridge costs. These were first-cutting comparisons only and did not reflect returns from long-term management.

Discussion of Results

Results of this study add to the slowly accumulating fund of knowledge about the forest's influence on streamflow. For years forested watersheds, much like those of the Fernow, have been studied in several Eastern States and many Western States. The first study in the United States, at Wagon Wheel Gap, Colorado, dates back to 1910. In the East, the center of research has been the Coweeta Watersheds in western North Carolina, which have been studied since 1934. In all, about 60 experimental watersheds in the East, and around the same number in the West, currently are being studied by U.S. Forest Service Experiment Stations.

To this research must be added a growing list of soil-moisture studies in which water use by forest trees is calculated by periodic soil-moisture and rainfall measurements.

We would like to relate the Fernow results to previous research. However, most of the published findings suggest that climatic, edaphic, and topographic conditions of other studies are quite different from those on the Fernow. Nor are sufficient data published to permit quantitative evaluation of these differences; accordingly, the Fernow findings cannot be correlated with those from other experimental watersheds. About all that can be said here is to point out possible reasons for broad agreements or differences.

However, the Fernow research cannot be dissociated from watershed research done or being done in other places. For that reason, some of the other watershed research is reviewed briefly in the Appendix.

Water Quality

The fact that poorly planned logging operations play havoc with water quality has been well demonstrated. This study has shown that, at least on areas comparable to the Fernow, care in logging can prevent most of the turbidity that results from logging. This fact has also been demonstrated on the Fraser Experimental Forest in Colorado. In most cases, a planned road system for timber harvest and methods of operation that protect the water resource will not cause appreciable increases in logging costs. Fernow records show that costs can often be reduced with these timber practices as compared with those of an unplanned "logger's choice" operation (Hutnik and Weitzman, 1957). In many locations, the greatest need is for an education and extension program to show operators how they can log more efficiently and at the same time conduct an operation that will conserve the water resource.

On the Fernow "logger's choice" watershed, erosion and stream turbidity rapidly diminished after logging was completed. This points up the fact that, for water-quality, after-logging care cannot be substituted for proper location of roads and good road drainage during the operation itself.

The importance of the research results on the other water-quality characteristics studied—pH, alkalinity, temperature before any recommendations for application can be made. However, it can be stated that under some conditions a clearcutting practice may result in increases in maximum water temperatures detrimental to trout.

Water Supply

On the Fernow, forest cutting resulted in an increase in streamflow; the increase was more or less in proportion to the severity of the cutting. The amount of the increase was considerable, ranging up to 5 inches on the Clearcut Watershed the first year after completion of the logging operation. First-year increases obtained from other heavily cut-over watersheds ranged from 17 and 15 inches at Coweeta to 4.2 and 1.4 inches at Fraser and Wagon Wheel Gap, Colorado, and 3.5 inches at Kamabuti, Japan.

Usually the results of treatment are more pronounced in well-watered areas, such as the Fernow, Coweeta Hydrologic Laboratory in North Carolina, and Kamabuti, Japan. Areas of low precipitation are likely to show less effect, such as Wagon Wheel Gap in Colorado and Sierra Ancha Experimental Forest in Arizona. Treatment effects of considerable magnitude at Fraser and on the White River Watershed, Colorado, where most of the precipitation comes as snow, may likely be due to a combination of reduced interception and transpiration following killing of the conifers.

The concept of potential evapotranspiration (Thornthwaite and Mather, 1955) helps to explain these results. Potential evapotranspiration is the amount of water that is evaporated and transpired under a given set of climatic conditions when the moisture supply is unlimited. When potential evapotranspiration far exceeds the water supply available from precipitation and soil-moisture storage, a partial reduction in evapotranspiration by removal of vegetation cannot be expected to have much effect on streamflow. When the supply exceeds potential evapotranspiration and a water surplus is available for streamflow, any reduction in the amount of evapotranspiration should increase the surplus.

On the Fernow, most of the increase came in the May-to-October period; effects of treatment were not regularly shown in May and June but were generally strong in the July-to-October period. The July-to-September increases can be explained as the direct result of decreased transpiration in those months. The October increases are associated with the effect of treatment on soil-moisture recharge: this can be considered a delayed effect of decreased transpiration in the preceding growing season. Increases in streamflow as a result of lower requirements for soil-moisture recharge often occurred in November and sometimes in December.

The timing of increases resulting from vegetation changes is not the same in all areas. In areas where the greatest effect is upon snow storage and melt, such as at Fraser, the increases will be expected to show in the spring melt period. Growing season increases are usually significant only in regions having considerable growing season precipitation, such as the Fernow, Coweeta, and Kamabuti. Often, much of the effect is shown in the soil-moisture recharge period. Depending on climate, soil depth, and other factors, there are often extreme differences in the time of year that recharge starts and in the duration of the period.

On the Fernow, with about 60 inches annual precipitation, recharge is apparently accomplished earlier than at Coshocton, Ohio, less than 150 miles away, with about 40 inches of precipitation. Streamflow changes at Coshocton were much later in the year than those on the Fernow. Maximum increases on some of the Coweeta watersheds were in the November-to-February period. This fact calls for an explanation that a detailed study of the soil-moisture regime and precipitation record might supply.

In areas with relatively low growing-season precipitation and cold winters, differences in fall soil-moisture storage due to differences in growing-season transpiration may not affect streamflow until the following spring-melt period. As evidence of this, an index of antecedent soil-moisture is often used to improve water-yield predictions based on snow surveys. Thus part of the Fraser streamflow increases, though registered in the spring, may in some years be due to reduction of transpiration the previous summer. Certainly in areas of very low growing-season rainfall, manipulating vegetation cannot be expected to provide much in the way of growing-season increases.

On the Fernow and many of the other study areas discussed, it should be stressed that the forest floor was to a large extent maintained intact. In treatments where the forest floor is severely disturbed, results are likely to be much different, e.g., heavy surface runoff during storm periods and a decrease rather than an increase in discharge in low-flow periods.

cutting will result in an increase in streamflow, watershed foresters may wish to put these results into practice. However, knowledge is still too meager to prescribe a specific treatment for a watershed area and to confidently predict the amount and timing of the increase.

One reason for this is the wide variety of conditions on different watersheds that affect the results of treatment. These include amount and time distribution of precipitation, temperature, soil depths, soil-moisture storage capacities, vegetation, and the like. Also, even on the same watershed, weather varies from year to year and this has a bearing on any treatment effect obtained.

Another question with respect to putting results into practice is the more or less transitory effect of forest cutting. The Fernow studies are not far enough along to determine much about the duration of streamflow increases obtained; some of the Coweeta studies show more in this respect (Kovner, 1956). The shallow rooting of the volunteer herbaceous vegetation on the Fernow Clearcut Watershed helps to explain why increased streamflow is still measured after an almost complete vegetative cover has been reestablished.

Even with the present limited knowledge, however, the watershed forester should be able to recommend a treatment to influence water yields in many areas. And he should be able to predict the direction and general magnitude of resulting changes in streamflow. For a more or less permanent increase in flow, the recommended practice would probably be one of heavy cutting on relatively small portions of the watershed in successive increments spread over a number of years. A hypothetical example of such a treatment is given in the Appendix. Other possibilities include the conversion from forest to grass or other vegetation types.

Flood Flows

On the Fernow, the effect of heavy forest cutting on high flows was variable, depending upon presence or absence of snow, antecedent soil-moisture, and probably other factors.

It is clear, however, taking the Fernow results and reviewing other research, that building up or preserving fully-stocked stands will generally be a benefit to flood control in the growing season and in the fall recharge period.

In the dormant season, after completion of the fall recharge period, the effect is not usually very great. Under certain conditions heavy cutting may result in decreased flows, as has been described. Somewhat the same results were noted in the investigations at Fraser and in the Harz Mountains in Germany.

In the region where the Fernow Experimental Forest is located, flood occurrence is greater in the dormant season than in the growing season. At the gaging station on the Cheat River near Parsons, West Virginia, 4 miles from the Fernow Experimental watersheds, there have been 135 occurrences of discharge above a base of about 10,000 c.f.s. (14 c.s.m) since 1913. Of these, 102 occurred in the dormant season and only 33 in the growing season.[3]

Again, it must be pointed out that none of the Fernow treatments resulted in serious disturbance of the forest floor except on limited areas of skidroads. If the forest floor had been severely disturbed much greater changes in high flows could have been expected.

Timber Values

In the management of forest lands, many uses must be considered. In research on the Fernow, water and timber are the two main uses being studied. In recommending treatments to be applied to watershed lands, the impact upon values from timber growth and harvest cannot be ignored. Generally, heavy cuttings and low stand densities, while prescribed to obtain increases in water yield, might result in a decrease in timber growth and yields. And high stand densities, while prescribed for reduction of summer flood flows, probably would result in greater growth rates. However, to utilize this growth and at the same time maintain dense stands for maximum flood protection would necessitate light and frequent harvests. Such management is generally not very profitable under present cost-and-return conditions. Economic evaluations must be made for individual areas in the light of specific physical and economic conditions prevailing there.

When we look to the future and examine the four treatments in terms of returns from continued management, we envision a financial situation different from the one defined by cost-and-return data from the first cutting. To do this,

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[3] Data supplied by U.S. Geological Survey, Charleston, West Virginia.

we must draw upon our knowledge of stand development in relation to the management goals defined for each of the treatments.

We can expect the net return from the Extensive Selection Watershed to increase for several cuttings. Roads have been constructed and the most costly cultural work has been done. Considering the productivity of the sites in this watershed, the 10-year cutting should finally level off at an estimated 4 M b.m. per acre with a high proportion of the volume in desirable species and good quality logs.

Estimating future returns from the Diameter Limit Watershed is more of a problem. Growth of merchantable trees in this watershed is expected to be less than for Extensive Selection because mortality is higher with the 20-year cutting cycle and the lower level of cultural treatments leaves many small culls to occupy growing space. Also, the designation of a diameter limit for cutting allows no leeway to cut low-vigor trees below this limit or to leave high vigor ones above it. We can expect less consistent volumes in succeeding cuttings because the method used will not exercise control over spacing and size-distribution of the trees. The unit value of products from this watershed will probably be less than for the Extensive Selection Watershed because there is no opportunity, without marking of individual trees for cutting, to up-grade the stand by favoring trees of desirable species and high quality potential. As compared to Extensive Selection, forestry costs for cultural treatment and marking of trees, etc., will be lower. All things considered, it is likely that this practice will be financially feasible.

The Intensive Selection Watershed will show a future increase in volume harvested and a big increase in product value. However, costs of marking, cultural treatment, and probably logging will be higher than for the other areas. The higher cost of logging will be due to the following factors: the special care taken to protect water quality; the small volume cut per acre because of the short cutting cycle; and the higher cost per thousand of removing some trees below sawlog size. The 5-year cutting should eventually build up to about 2 M b.m. per acre which would make this a marginal operation under present market conditions when both forestry costs and logging costs are considered. Generally, returns are not likely to balance costs on many intensively-managed areas cut every 5 years unless the stands are very easily accessible and on very productive sites. There is little question that this management practice would be profitable if the cutting cycle were lengthened.

The Clearcut Watershed will not produce another cutting equal in value to the one just made for another 60 to 80 years. It is even doubtful if a small-products operation for materials such as pulpwood can be made on a break-even basis in less than 25 years.

In discussing the relative profitability of the different treatments, the assumption was made that site productivity, or site quality, is about the same on all the watersheds. Though not strictly true, they are close enough to make this generalization. In addition, the assumption was made that all areas are easily and equally accessible. Actually, the Clearcut Watershed is less accessible than the others.

Forest Game

Deer browse and deer use have been measured for 10 years on compartments managed like the watersheds.[4] While no firm comparisons can as yet be made between management programs in respect to these factors, a tentative pattern is emerging.

After cutting, all four practices produce browse and cover. The Clearcut produces more of each for about 10 to 15 years. After this period, both browse and cover become progressively more scarce on clearcut areas. As far as deer are concerned, the developing even-aged, large-sapling, and pole stands provide neither sufficient cover nor browse.

The Intensive Selection program, with the short cutting cycle, probably provides the most constant supply of deer browse and desirable cover. In the Diameter Limit the 20-year cycle between cuttings is so long that the young vegetation that follows treatment grows beyond the deer-utilization stage before the next cutting.

No studies have as yet been made on the Fernow on the effect of the management programs on other game. However, continuing discussions of game habitat with game technicians and knowledge of forestry environment developing under these programs enable us to make a surmise on the subject.

The Clearcutting eliminates such mast as acorns, hickory nuts, and beech nuts for a long time. Squirrels are practically

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[4] Cooperative study with the Division of Game and Fish, West Virginia Department of Natural Resources.

up to large sapling size, they provide cover for grouse. New clearcuts also provide berries as well as weed and shrub seeds, which grouse feed on. Apparently grouse, like deer, prefer new clearcuts but later on find them unattractive.

Both selection programs provide for maintaining a large part of their canopy in big vigorous trees. As a consequence, they further the production of large mast crops, which favor such mast-eating game as squirrel, turkeys, and bear, and to a lesser extent deer and grouse.

Future Research

The current studies on the Fernow Experimental Forest will be continued to: (1) measure changes in vegetation following the treatments, (2) measure the trend of treatment effects on streamflow quantity and quality, and (3) measure the effects of successive cuttings on the partially cut watersheds.

A large mass of data has been accumulated in this investigation. This report shows how that data was analyzed and interpreted. Much more knowledge about forest watershed hydrology doubtlessly can be gained from this data, and further opportunities for fruitful analysis of the data already collected will be explored.

In this experiment, and in other research, much has been learned about the effect of different forest treatments on streamflow. Much more research is needed to broaden our present knowledge and to improve management on watersheds where physical conditions vary widely and where objectives of management differ.

More basic research is needed to relate results to primary causes. To a considerable extent, results of this type of research are generally applicable and not limited to the region or locality in which the studies are conducted.

Much could be gained from a comprehensive study of the many investigations already completed in many regions of the United States and in other countries. Many data have been collected which should be subjected to intensive analysis. Correlation of various types of studies in various places should reveal the underlying reasons for differences in water quality results, differences in quantity and timing of water yield, and so on.

Fuller attainment of benefits from research already done and new research, both basic and applied, may be expected to greatly advance forest watershed management in the next decade or two. The forest manager should then be able to prescribe sound forest watershed management practices and predict results in quantitative as well as qualitative terms.

Summary

After a 6-year calibration, four watersheds on the Fernow Experimental Forest were logged in 1957-58. Treatments ranged from a commercial clearcutting with unplanned logger's choice skidroads to a light selection cutting with planned skidroads on moderate grades. For the most part, the treatments did not seriously disturb the forest floor.

Treatments resulted in an increase in annual flow, ranging up to 5 area-inches on the Clearcut Watershed the year after treatment. Flow increases fell into a logical pattern in relation to volume cut. Most of the flow increase came into the growing season. In the 6-month period from May to October 1959, for example, increases were 3.0, 1.8, 1.4, and 0.3 area-inches for per-acre cuttings of 8.5, 4.2, 3.7, and 1.7 M b.m., respectively.

Low flows were augmented, especially for the two heavily-cut watersheds. Effect on high flows was variable. On the Clearcut Watershed some storm-period discharges in the growing season were more than doubled as a result of treatment and some snowmelt flows were reduced.

Care in the logging operation was clearly reflected in water quality. Maximum turbidities ranged from 56,000 p.p.m. on the watershed with unplanned and undrained skidroads to 25 on the watershed with carefully planned skidroads. Even on the two watersheds with unplanned skidroads, turbidities were high only during and immediately after the logging operation.

Effects of treatment are diminishing with time. Measurements on the watersheds are continuing in an effort to determine the duration of changes due to treatment and the effect of succeeding harvests on the partially cut watersheds.

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Appendix

I. CLIMATIC DATA

Precipitation and temperature records for the experimental watersheds are shown in tables 14, 15, 16, by month, season, and year in the study period. Table 17 shows streamflow of the Control Watershed.

II. INSTRUMENTATION AND MEASUREMENT

Stream discharge.—The gaging stations on the five watersheds are 120-degree V-notch weirs with FW-1 water level recorders installed in concrete-block gage houses. In construction of the concrete weir cutoff walls every effort was made to extend the wall down to bedrock or impervious subsoil so that all flow from the watershed would be over the weir blade. The weir blades are constructed of 3½ x 3½ inch angle iron and are bolted to the concrete wall. The upper edge of each blade is bevelled to a knife edge at a 45-degree angle. The notch is 2 feet deep.

The recorder is attached by perforated tape to a float in the stilling well below the gage house. A pen arm is actuated by the tape and records a continuous tracing on a drum-chart driven by an 8-day clock. The pen arm shows height of water surface above the low point in the V-notch.

A rating table, showing quantity of flow corresponding to any stated depth, was prepared for each weir. The rating was based upon the formula determined by Hertzler (1938) for the prototype of these weirs.

The formula is: $Q=4.43H^{2.449}$, in which Q is discharge in c.f.s. and H is head (or height of water above low point in notch) in feet. For low flows, the discharge was collected over a measured time period and weighed or measured volumetrically. Based on these measurements, the rating table determined from the above formula was adjusted for the individual weir as necessary. Adjustments were made up to heads of about 0.2 foot for three weirs; the rating table was applicable without adjustment for the other two weirs.

From the charts and the rating tables, mean daily flow in c.s.m. was computed and tabulated. Then compilations were made of flows by month, season, and year in area inches. Other tabulations were made from the charts for special purposes, such as discharge during storm periods.

Precipitation.—At the start of the study, 15 standard precipitation gages and 3 weighing-recording gages were installed on the 5 watersheds. These were distributed more or less uniformly over the area and located to sample various topographic positions. After several years of operation, analyses were made to determine whether some gages could be dropped without appreciably affecting the amount of catch. As a result, the number of standard gages was reduced to nine.

Amount of catch is determined by the standard gages. The record of the recording gages is used to break down amounts measured in the standard gages by storm, by day, or for studies involving intensities.

Precipitation on each watershed was computed by storm or by month by weighting the catches in the individual gages by the Thiessen polygon

Table 14.—Precipitation on the Fernow watersheds, by month, season, and year, in inches

(Figures are averages for the five watersheds)

Month	Water-year									9-yea mean
	1951-52	1952-53	1953-54	1954-55	1955-56	1956-57	1957-58	1958-59	1959-60	
May	5.40	6.00	6.54	3.61	3.31	8.91	3.81	5.45	4.98	5.33
June	10.70	4.03	4.22	3.62	5.48	6.76	8.13	6.90	2.92	5.86
July	3.18	3.73	6.63	6.28	4.65	7.48	3.80	11.96	7.10	6.09
August	2.01	2.44	7.14	10.68	9.05	6.74	1.55	8.62	4.95	5.91
September	3.09	3.63	1.72	2.34	1.69	3.98	2.54	3.02	1.40	2.60
October	2.09	1.47	1.45	10.78	3.95	2.84	5.59	1.65	6.99	4.09
May-Oct total	26.47	21.30	27.70	37.31	28.13	36.71	25.42	37.60	28.34	29.89
November	4.93	2.90	2.08	2.74	3.65	2.70	2.28	3.58	5.33	3.35
December	7.21	4.18	4.62	5.57	2.60	7.02	6.51	1.85	5.59	5.02
January	8.85	6.68	5.29	4.04	5.32	6.72	4.70	6.18	5.69	5.94
February	1.30	4.17	3.10	5.78	8.16	7.69	4.70	3.59	5.06	4.84
March	4.76	6.13	6.55	7.34	7.35	3.04	4.54	4.55	4.04	5.37
April	5.20	5.15	3.29	3.42	3.94	4.97	6.65	5.36	4.27	4.69
Nov-Apr total	32.25	29.21	24.93	28.89	31.02	32.14	29.38	25.11	29.98	29.21
Total for year	58.72	50.51	52.63	66.20	59.15	68.85	54.80	62.71	58.32	59.10

Table 15.—Mean air temperature on the Fernow Experimental Forest by month, season, and year, in °F.

Month	Water-year									9-year mean
	1951 -52	1952 -53	1953 -54	1954 -55	1955 -56	1956 -57	1957 -58	1958 -59	1959 -60	
May	--	55	61	51	59	57	58	56	61	57*
June	--	67	65	63	59	62	65	60	63	63*
July	--	68	66	65	69	64	64	67	68	66*
August	64	65	63	64	67	62	62	63	70	64
September	58	57	58	60	59	54	60	58	65	59
October	53	45	53	50	48	53	45	48	53	50
Growing-season mean	--	60	61	59	60	59	59	59	63	60*
November	33	40	42	37	36	39	41	41	38	39
December	33	32	32	27	24	40	34	25	33	31
January	34	34	30	25	24	26	24	26	32	28
February	34	33	34	31	34	36	20	32	27	31
March	36	38	35	40	36	38	33	36	24	35
April	47	45	54	53	45	52	48	50	53	50
Dormant-season mean	36	37	38	36	33	38	33	35	34	36
Water-year mean	--	48	49	47	47	49	46	47	49	48*

*Mean of 8 years of record.

method (Linsley et al., 1949). Totals by season and year were then tabulated for each watershed.

Air temperature and humidity.—A weather shelter is maintained near the center of the experimental area. It houses a recording hygrothermograph and maximum and minimum thermometers. This installation was serviced weekly. Tabulations of maximum, minimum, and mean temperature were prepared by day, month, and year.

Water quality.—Water samples were obtained by hand sampling. The sample bottle or glass was dipped into the stream at the designated sampling point a short distance upstream from the weir. As the stream gradients were high and flow usually turbulent, this simple method provided a representative sample.

When the sample was clear (that is, 5 turbidity units or less), the record was made on the basis of observation. For turbidities between 5 and 25, the determination was made by reference to a series of standard suspensions in Nessler tubes prepared by the chemist of the West Virginia State Water Resources Commission. Turbidities above 25 were measured with a Jackson turbidimeter (Rainwater and Thatcher, 1960).

For some very turbid samples this method will not work; for these the

Table 16.—Mean maximum and mean minimum air temperatures on the Fernow Experimental Forest by month, season, and year, in °F.

Month	1951-52		1952-53		1953-54		1954-55		1955-56		1956-57		1957-58		1958-59		1959-60		9-year mea	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min
May	--	--	66	45	71	51	62	41	71	47	69	44	70	47	67	45	72	50	68*	46
June	--	--	76	57	75	55	73	53	68	49	70	53	72	57	70	50	74	53	72*	53
July	--	--	77	59	76	56	75	55	78	61	71	57	73	55	74	59	77	58	75*	58
August	72	55	74	55	72	55	71	58	74	59	69	55	71	53	72	55	81	60	73	56
September	66	49	68	46	69	48	68	52	67	50	62	46	68	53	66	49	78	51	68	49
October	64	42	57	33	66	41	58	41	57	39	61	45	53	37	58	38	64	42	60	40
Growing-season mean	--	--	70	49	72	51	68	50	69	51	67	50	68	50	68	49	74	52	69*	50
November	42	24	50	31	53	30	45	29	45	27	48	28	50	31	51	31	49	28	48	29
December	42	24	38	25	40	23	34	20	33	15	47	32	42	25	34	16	41	25	39	23
January	43	25	42	26	38	21	34	16	31	17	35	18	32	17	35	17	39	24	37	20
February	42	25	42	24	44	24	41	21	43	26	44	28	28	13	42	22	36	18	40	22
March	45	27	47	29	45	24	51	28	47	26	47	30	39	33	48	25	34	14	45	26
April	57	37	55	35	67	41	65	40	56	34	64	40	59	36	62	38	66	39	61	38
Dormant-season mean	45	27	46	28	48	27	45	26	42	24	48	29	42	26	45	25	44	25	45	26
Water-year mean	--	--	58	39	60	39	56	38	56	38	57	40	55	38	57	37	59	38	57*	38

*Mean of 8 years of record.

Table 17.—Streamflow of the Control Watershed by month, season, and year, in area-inches

Month	Water-year									9-year mean
	1951-52	1952-53	1953-54	1954-55	1955-56	1956-57	1957-58	1958-59	1959-60	
May	2.74	2.95	3.39	1.40	1.24	4.60	1.10	3.20	2.14	2.53
June	4.32	.24	.14	.17	.61	2.84	1.58	2.15	.35	1.38
July	.81	.04	1.19	.31	.34	1.50	.24	4.27	.21	.99
August	.03	.00	1.81	2.59	1.56	2.44	.00	4.10	.12	1.41
September	.02	.00	.00	.16	.03	.12	.00	.14	.01	.05
October	.00	.00	.00	4.00	.03	.17	.04	.03	.26	.50
May-Oct	7.91	3.24	6.54	8.64	3.82	11.65	2.95	13.90	3.09	6.86
November	.29	.01	.00	1.57	.36	.56	.07	.57	1.69	.57
December	3.75	.59	.29	3.91	1.27	4.72	3.07	1.07	4.18	2.54
January	6.53	3.93	3.03	1.62	2.53	5.31	2.18	4.38	4.40	3.77
February	1.05	3.16	1.76	5.54	7.11	5.68	2.08	2.35	1.53	3.36
March	3.09	3.69	4.48	5.58	5.41	2.28	4.46	2.94	4.61	4.06
April	3.32	3.41	1.83	1.87	2.47	3.29	5.72	3.01	3.60	3.17
Nov-Apr	18.03	14.78	11.40	20.09	19.15	21.84	17.57	14.33	20.00	17.47
Year[1]	25.95	18.02	17.93	28.74	22.97	33.49	20.53	28.22	23.09	24.33

[1] Yearly totals may differ from the sums of the semi-annual figures because of rounding.

solid matter in a sample of measured volume was filtered out, dried, and weighed to obtain suspended solids in parts per million.

For pH determination, the Hellige color comparator was used. With this instrument, indicator dyes are added to a sample of the water (Ellis et al., 1948) and the resulting color is compared to standard colors on labeled discs. This method is not the most accurate. However, it was considered adequate for the purposes of this study because the waters being all being made from one day's operation by one observer. In this way personnel differences were largely eliminated.

For phenolphthalein alkalinity (hydroxide and normal carbonate alkalinity), phenolphthalein indicator solution was added to the water samples (Ellis et al., 1948). With the Fernow samples, no color resulted in this test and phenolphthalein alkalinity was always recorded as zero.

Methyl orange alkalinity, or total alkalinity, was determined by adding methyl orange indicator to the solution and then titrating with N/50 sulfuric acid (Ellis et al., 1948). The alkalinity in p.p.m. was determined from the amount of acid added.

The specific conductance of water is a measure of its ability to carry an electric current; hence it is an indication of the ionic strength of the solution and a measure of the amount of dissolved minerals in the water. It is determined with a meter using the principle of the Wheatstone bridge and is recorded in micromhos per square centimeter.

III. CALIBRATION AND ANALYSIS

The control-watershed concept was used in this study to compensate as far as possible for climatic variation from year to year. One watershed (No. 4 in this instance) was used as a control for each of the other four watersheds.

Prediction equations, computed from data of the 6 calibration years, are in the form of straight-line regressions; in most instances, very high correlation coefficients were obtained, indicating that the straight-line regressions are appropriate. For example, correlation coefficients for annual flow of the watersheds to be treated and the Control were 0.996, 0.996, 0.998, and 0.998 for Watersheds 1, 2, 3, and 5, respectively.

In most analyses, the regressions were based on six observations (6 years); put in another way, N equals 6. This was true even for the analyses of flow by months; there were, for example, six Julys in the 6-year calibration period. For high flows, some analyses considered the quantity of high flow in the year or season with an N of 6. Others treated individual storm flows as separate observations and the N's were larger; for example, 48 calibration-period storms were used in several of the analyses.

Analyses of water quality were handled somewhat differently. In the case of turbidity, the effects of treatment—and the differences between treatments—were of such magnitude that statistical tests of significance were considered unnecessary. For chemical tests and water temperature, comparison of paired observations by simple "t" tests was used.

After treatment, the regression equations were used, along with measured values for the Control Watershed, to compute predicted values for the treated watershed. This prediction, of course, was the value that would be expected if the treatment were without effect. Measured and predicted values were then compared, the difference being an apparent treatment effect.

The difference between individual predicted and measured values was tested by computing the error of estimate for an individual value (Y) of the treated watershed (Snedecor, 1956). The example in table 18 shows how the prediction equation was computed and how an individual after-treatment value was tested for significance.

Table 18.—Sample computation: annual discharge-prediction equation for Clearcut Watershed and test for significance of increase in discharge in water-year 1958-59

Calibration data

Water -year	Annual discharge, in area-inches	
	Control Y	Clearcut X
1951-52	25.95	24.40
1952-53	18.02	16.77
1953-54	17.93	16.55
1954-55	28.74	25.91
1955-56	22.97	21.52
1956-57	33.49	32.20

Prediction for water-year 1958-59

Measured flow of Control = 28.22 area-inches.

Measured flow of Clearcut = 31.56 area-inches.

Predicted flow of Clearcut = 0.967 (28.22) - 0.82 = 26.47

Increase in flow of Clearcut = 31.56 - 26.47 = 5.09.

Prediction equation (straight-line regression)

$\hat{Y} = 0.967X - 0.82$

$\hat{Y}$ = Estimated flow of Clearcut Watershed, assuming no treatment.

X = Measured flow of Control.

$n = 6$

$\bar{x} = 24.52$

$\bar{y} = 22.89$

$S_x{}^2 = 188.3947$

$r = 0.996$

$s_{y.x}{}^2 = 0.398$

Test of significance

$x = X - \bar{x} = 28.22 - 24.52 = 3.70$ in which X is flow of Control in test year.

$x^2 = (3.70)^2 = 13.6900$

$s_Y^2 = s_{y.x}{}^2\ (1 + 1/n + x^2/S_x{}^2) = .398\ (1 + 1/n + [13.6900/188.3947])$
$= 0.4935$

$s_Y = \sqrt{0.4935} = 0.702$

$t = (Y - \hat{Y})/s_Y = 5.09/.702 = 7.25$

Determine probability by reference to graph of t over probability.

Probability = 0.001 (The probability that an increase of this magnitude occurred by chance alone. This is a test for increase, and area under one end only of the probability curve is considered.)

Reference: Snedecor, G. W. 1956. Statistical methods. 5th Ed., 534 pp. Iowa State College Press, Ames, Iowa.

In the example, the probability was computed as 0.001. In this study, the accepted level of significance was 0.05. Thus this analysis showed that there was a significant increase in annual flow in the 1958-59 water year on the Clearcut Watershed.

Analysis of covariance has not been relied upon so far in this study even though it is often recommended in experiments of this type. In most cases, too few after-treatment observations were available for covariance analysis. In analyzing for treatment effects on individual storm flows, sufficient observations were available but variances in the calibration and treatment period were not homogeneous. Homogeneity of variance in both periods is a prerequisite for covariance analysis by usual methods; therefore the stormflow data were not analyzed by covariance.

The fact that variances before and after treatment are not homogeneous is not surprising: the watersheds were as near identical as could be when selected and as a result correlations in the calibration period were naturally high; treatment purposely resulted in differences between each treated watershed and the Control and resulted in poorer correlation in this period.

When analyses were made at the close of the calibration period, it appeared that prediction equations for discharge by individual months were not precise enough to be used for determination of significance of treatment results. This was based upon an estimated 10 to 25 percent change in flow due to treatment. However, for many of the months after treatment, especially on the Commercial Clearcut Watershed, significant treatment effects were obtained. In many cases, the increase in flow resulting from treatment amounted to several hundred percent.

IV. TREATMENT EFFECTS

Water Quality

Tables 19 and 20 are given here as background information about the effects of treatment on certain chemical characteristics and on water temperature. The streams on the experimental watersheds are slightly acidic:

Table 19.—Mean pH, alkalinity, and specific conductance of water from experimental watershed, December 1957 to April 1960

Watershed	pH	Alkalinity (methyl orange) p.p.m. $CaCO_3$	Specific conductance Micromhos/cm^2
Commercial clearcut	6.4	9	38
Diameter limit	6.1	6	25
Extensive selection	6.2	6	24
Intensive selection	6.1	6	16
Control	6.1	6	17

Table 20—Maximum, minimum, and mean water temperatures on the Control Watershed by month, in °F.

Month	Water temperature[1]		
	Maximum	Minimum	Mean
May	54	47	50
Jun	58	50	54
Jul	63	54	58
Aug	62	55	58
Sep	64	52	58
Oct	58	46	52
Nov	50	42	46
Dec	45	38	42
Jan	44	38	41
Feb	44	38	41
Mar	44	35	40
Apr	53	44	48
Water-year	53	45	49

[1] Averages for two years of record; May 1958 through April 1960.

watershed mean pH values ranged from 6.1 to 6.4. Alkalinities are very low; the water is essentially unbuffered. Specific conductances are also very low, indicating that there is little mineral matter dissolved in the water. As for water temperatures, maximums measured were not very high: mean maximum for July was only 63° F. The month with the lowest mean minimum temperature was March, with 35° F. (both of these means were based on only 2 years of record).

Total Discharge

A graph was shown earlier to relate increase in flow, by seasons, to the amount of cut and cull in M b.m. per acre. Figure 22 shows a similar presentation based on basal area rather than M b.m. More complete tables showing effect of treatment on flow by individual months are presented here (tables 21 to 24).

Low Flow

Results of an analysis of number of days of low flow below 0.05 c.s.m. (approximating 50 gallons per acre per day) were presented earlier. Table 25 shows also the effect of treatment on number of days of flow below 0.075 c.s.m. and 0.10 c.s.m. (75 and 100 gallons per acre per day). This table also shows the probabilities associated with the decreases. All changes are decreases in number of days of low flow (indicating an increase in quantity of flow due to treatment) and most are significant at the 5-percent level.

Table 21.—Increase in flow on Commercial Clearcut Watershed after start of logging, by month, in area-inches

1957-58				1958-59				1959-60				1960-61			
Month	Discharge		Prob-ability[1]	Month	Discharge		Prob-ability	Month	Discharge		Prob-ability	Month	Discharge		Prob-ability
	Pre-dicted	In-crease			Pre-dicted	In-crease			Pre-dicted	In-crease			Pre-dicted	In-crease	
May	0.78	0.26	0.10	May	3.00	0.09	0.30	May	1.88	0.25	0.09	May	3.10	0.00	--
Jun	1.37	[2] -.02	--	Jun	1.85	1.27*	<.001	Jun	.32	.09	.31	Jun	1.05	.46*	0.02
Jul	.18	.48*	.01	Jul	3.99	1.60*	.003	Jul	.15	.58*	.004	Jul	.14	.22	.06
Aug	.03	.03	.43	Aug	3.83	1.14*	.003	Aug	.14	.53*	.02	Aug	.34	.29	.08
Sep	.00	.04	.15	Sep	.09	.46*	<.001	Sep	.01	.16*	.004	Sep	.35	.71*	.001
Oct	.06	.58*	<.001	Oct	.05	.16*	.001	Oct	.29	1.27*	<.001	Oct	.08	.16*	.002
Nov	.13	.27*	.01	Nov	.56	.64*	<.001	Nov	1.51	.86*	<.001	--	--	--	--
Dec	3.00	.54*	.02	Dec	1.10	-.18	--	Dec	4.05	-.30	--	--	--	--	--
Jan	1.98	.14	.22	Jan	4.26	-.11	--	Jan	4.28	-.16	--	--	--	--	--
Feb	1.83	.47*	.01	Feb	2.08	.22	.08	Feb	1.31	.20	.10	--	--	--	--
Mar	4.10	.27	.10	Mar	2.78	.08	.35	Mar	4.24	.12	.27	--	--	--	--
Apr	5.46	-.79	--	Apr	2.78	-.17	--	Apr	3.36	-.18	--	--	--	--	--

*Statistically significant at 5-percent level.

[1] The probability that an increase of the magnitude given could have occurred by chance alone.

[2] Negative value indicates an apparent decrease.

Table 22.—Increase in flow on Diameter Limit Watershed after start of logging, by month, in area-inches

1958-59				1959-60				1960-61			
Month	Discharge		Prob-ability[1]	Month	Discharge		Prob-ability	Month	Discharge		Prob-ability
	Predicted	Increase			Predicted	Increase			Predicted	Increase	
--	--	--	--	May	2.41	0.42*	0.01	May	3.72	0.17	0.10
Jun	2.22	0.27*	0.04	Jun	.34	.13	.18	Jun	1.24	.17	.12
Jul	4.30	.24	.24	Jul	.18	.44*	.01	Jul	.17	.21	.07
Aug	4.21	.47*	.01	Aug	.17	.30*	.02	Aug	.38	.07	.28
Sep	.11	.28*	<.001	Sep	.03	.10*	<.001	Sep	.39	.20*	<.001
Oct	.05	.12*	.01	Oct	.32	.40*	<.001	Oct	.08	.05	.08
Nov	.58	.31*	.03	Nov	1.85	.52*	.01	--	--	--	--
Dec	1.09	[2] -.03	--	Dec	4.65	-.38	--	--	--	--	--
Jan	4.95	-.01	--	Jan	4.98	-.22	--	--	--	--	--
Feb	2.47	.05	.35	Feb	1.62	.27	.052	--	--	--	--
Mar	3.06	.00	--	Mar	4.89	.37*	.01	--	--	--	--
Apr	3.17	.02	.46	Apr	3.79	-.20	--	--	--	--	--

*Statistically significant at 5-percent level.

[1] The probability that an increase of the magnitude given could have occurred by chance alone.

[2] Negative value indicates an apparent decrease.

Table 23.—Increase in flow on Extensive Selection Watershed after start of logging, by month, in area-inches

1958-59				1959-60				1960-61			
Month	Discharge		Probability[1]	Month	Discharge		Probability	Month	Discharge		Probability
	Predicted	Increase			Predicted	Increase			Predicted	Increase	
--	--	--	--	May	2.56	0.50	0.06	May	3.89	-0.04	--
--	--	--	--	Jun	.50	.00	--	Jun	1.45	-.12	--
--	--	--	--	Jul	.37	.18	.16	Jul	.36	-.01	--
Aug	5.43	[2] -0.37	--	Aug	.23	.21	.15	Aug	.50	.14	0.23
Sep	.21	.06*	0.03	Sep	.05	.06*	.02	Sep	.70	.04	.28
Oct	.11	.02	.41	Oct	.40	.58*	.001	Oct	.15	.04	.33
Nov	.91	.16	.18	Nov	2.36	.50*	.04	--	--	--	--
Dec	1.61	-.25	--	Dec	5.35	-.57	--	--	--	--	--
Jan	5.54	-.18	--	Jan	5.56	-.27	--	--	--	--	--
Feb	2.85	.12	.31	Feb	1.87	-.03	--	--	--	--	--
Mar	3.61	-.05	--	Mar	5.58	-.27	--	--	--	--	--
Apr	3.73	.05	.34	Apr	4.44	-.21	--	--	--	--	--

*Increase is statistically significant at the 5-percent level.

[1] The probability that an increase of the magnitude given could have occurred by chance alone.

[2] Negative value indicates an apparent decrease.

Table 24.—Increase in flow on Intensive Selection Watershed after start of logging, by month, in area-inches

1958-59				1959-60				1960-61			
Month	Discharge		Probability[1]	Month	Discharge		Probability	Month	Discharge		Probability
	Predicted	Increase			Predicted	Increase			Predicted	Increase	
--	--	--	--	May	2.32	0.06	0.36	May	3.45	0.15	.20
--	--	--	--	Jun	.44	.01	.45	Jun	1.27	.14*	.049
--	--	--	--	Jul	.24	.03	.41	Jul	.23	.06	.32
--	--	--	--	Aug	.18	.03	.41	Aug	.39	[2] -.08	--
--	--	--	--	Sep	.04	.00	--	Sep	.65	-.02	--
Oct	0.06	0.03	0.051	Oct	.29	.07*	.005	Oct	.09	.06*	.01
Nov	.61	-.07	--	Nov	1.79	-.04	--	--	--	--	--
Dec	1.06	.10	.21	Dec	4.21	-.23	--	--	--	--	--
Jan	4.37	.00	--	Jan	4.39	-.11	--	--	--	--	--
Feb	2.31	.12	.25	Feb	1.53	.09	.30	--	--	--	--
Mar	2.93	-.06	--	Mar	4.40	.16	.08	--	--	--	--
Apr	3.04	.03	.14	Apr	3.59	-.02	--	--	--	--	--

*Statistically significant at 5-percent level.

[1] The probability that an increase of the magnitude given could have occurred by chance alone.

[2] Negative value indicates an apparent decrease.

Table 25.—Effect of treatment on number of days of low flow in calendar year

Watershed	Year	Days below 0.05 c.s.m.			Days below 0.075 c.s.m.			Days below 0.10 c.s.m.		
		Pre-dicted	De-crease	Prob-ability	Pre-dicted	De-crease	Prob-ability	Pre-dicted	De-crease	Prob-ability
Commercial clearcut	1957	124	72*	<0.001	130	66*	<0.001	140	66*	0.001
	1958	38	38*	.002	55	53*	.001	68	59*	.002
	1959	99	63*	<.001	111	63*	<.001	118	55*	.002
	1960	46	39*	.002	64	46*	.001	79	46*	.003
Diameter limit	1958	22	22*	.02	39	35*	<.001	54	40*	<.001
	1959	74	47*	.001	94	52*	<.001	105	54*	<.001
	1960	29	27*	.01	49	34*	<.001	66	37*	.001
Extensive selection	1959	58	21*	.005	70	19*	.01	76	12	.08
	1960	17	14*	.02	27	9	.09	38	3	.35
Intensive selection	1959	65	5	.19	77	7	.15	89	8	.11
	1960	20	13*	.04	34	16*	.03	52	25*	.006

*Statistically significant at 5-percent level.

High Flow (or Storm Flow)

As already stated, analysis of high-flow data was more complicated than in the case of the other characteristics studied. Of the many analyses made on data for the Clearcut Watershed (the major analysis effort), four are presented here. Features common to all four analyses:

1. Prediction equations (straight-line regressions) were developed based upon calibration-period data to relate high flow of the watershed to be clearcut (No. 1) to the Control (No. 4).

2. Precipitation in the storms causing the high flow was analyzed. When weighted precipitation of No. 1 was more than 10 percent above or below that for No. 4, the resulting high flow was not analyzed in either calibration or treatment periods.

3. High flows measured after treatment were compared with predicted flows and the amount of change determined. The probability that a change of this magnitude could have occurred by chance alone was then computed. This was done by using Student's "t" test and took into account the area in both tails of the probability curve (a two-tailed test).

Special features of each analysis:

Analysis I: Instantaneous peaks. The basic data in this analysis were the maximum instantaneous discharges in c.s.m.; flows were included when discharges on the Control Watershed exceeded 10 c.s.m.

Analysis II: Storm period discharge. The basic data in this analysis were the volumes of discharge in the period between the time runoff began (SRB) and the time when the hydrograph receded to a stage midway between that at SRB and the peak. This time interval was determined on the Control. Discharge was computed for the Clearcut Watershed for the same time period.

Analysis III: Volume of discharge above 10 c.s.m. by storms. For each period of high flow, the volume of discharge above 10 c.s.m. was determined. This is equivalent to drawing a horizontal line through the hydrograph at 10 c.s.m. and determining the discharge represented by the area above the line and below the hydrograph tracing. High flows were included when discharge on either or both the Clearcut and Control Watersheds exceeded 10 c.s.m.

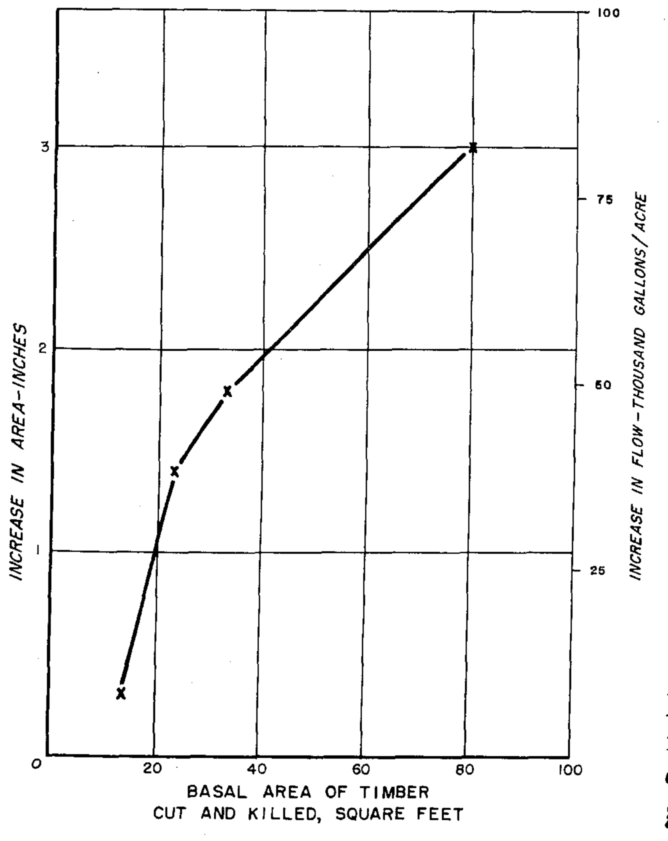


Figure 22.—Increase in flow related to basal area cut and culled, 1959 growing season.

This analysis was based upon tabulations of mean daily flow in c.s.m. For each day of flow above 10 c.s.m., the amount in excess of 10 c.s.m. was tabulated. Totals were computed for growing season, dormant season, and year; then they were converted to area-inches. Separate prediction equations were developed for the two seasons and for the year. Days of high flow were included when mean daily discharge of either or both the Clearcut and Control Watersheds exceeded 10 c.s.m.

Comparison of the four methods.—In considering high flows, use of instantaneous peaks (Analysis I) is the most logical and easiest to explain. However, correlation studies between watersheds are not too valuable because minor differences in intensity and timing of precipitation may cause sizable differences in peaks. Also, measurement of maximum instantaneous flow is generally of little practical importance except at points of flood damage.

Storm period discharge (Analysis II) provides an arbitrary method of comparing high flows before and after treatment, with results that are suitable for statistical analysis.

One shortcoming of both these analyses resulted from the poorer correlation of high flows on the treated watershed and the Control after treatment as compared to before treatment. High flows when discharge on the Control exceeded 10 c.s.m. but that on the treated watershed was less than 10 c.s.m. were included in the analysis. When the reverse was true, data were excluded from analysis. This tended to underestimate any effect of treatment on increasing high flows.

The analysis of discharge above 10 c.s.m. (Analyses III and IV) avoided this difficulty. Of these two analyses, Analysis III (by storms) had the advantage of a larger number of observations. Analysis IV (by season or year) had fewer observations. However, particular pains were taken with these observations to reduce the variability and to increase the scientific reliability. Analysis IV was also based upon tabulations of mean daily flow which had been previously prepared and were much easier to use than determination of volumes of flow from study of the hydrograph.

Tables 26 to 29 give the results of these four analyses. They all show similar results.

The following tabulation, prepared from season and year totals in tables 26 to 29, shows the percent change in high flows resulting from the Clearcut treatment:

Period	*I Instantaneous peaks*	*II Storm-period discharge*	*III Discharge over 10 c.s.m. (by storm)*	*IV Discharge over 10 c.s.m. (by season & year)*
Growing season	+ 21	+ 24	+ 75	+ 42
Dormant season	— 4	+ 2	0	— 1
Year	+ 4	+ 7	+ 13	+ 11

In all analyses, there is a considerable increase for the growing season. The dormant season shows small changes, either increases or decreases. The annual changes are increases, but these are small when compared to those in the growing season.

Table 26.—High-flow analysis I: effect of treatment on instantaneous peaks, Clearcut Watershed

Date of storm	Peak flow			Change as percentage of predicted peak
	Predicted $\hat{Y}$ in c.s.m.	Change		
		$Y - \hat{Y}$ in c.s.m.	Probability	
		GROWING SEASON (7 storms)		
5/5/58	21.9	+ 0.5	0.91	--
6/14/58	11.9	+19.2*	<.001	--
6/22/58	17.7	+ .5	.91	--
7/21/58	39.4	+ 3.6	.41	--
8/1/58	26.3	- .3	.94	--
8/4/58	19.5	+ .3	.94	--
8/8/58	39.9	+13.2*	.004	--
Growing-season total	176.6	+37.0	--	21.0
Growing-season mean	25.2	+ 5.3	--	--
		DORMANT SEASON (13 storms)		
12/7/57	19.2	+15.7*	<0.001	--
12/26/57	17.9	0	1.00	--
1/22/58	10.0	+ 2.3	.60	--
4/28/58	66.4	- 8.1	.075	--
1/15/59	14.6	- 1.1	.80	--
1/22/59	76.5	+ 2.2	.63	--
2/15/59	10.7	+ 1.1	.80	--
11/28/59	17.1	+ 1.7	.70	--
12/12/59	41.3	- 9.4*	.035	--
1/3/60	22.3	+ 1.1	.80	--
1/15/60	18.3	- .1	.98	--
3/30/60	59.5	-21.4*	<.001	--
4/4/60	21.9	- .2	.96	--
Dormant-season total	395.7	-16.2	--	-4.1
Dormant-season mean	30.4	- 1.2	--	--
Total	572.3	+20.8	--	3.6
Mean	28.6	+ 1.0	--	--

*Significant at 5-percent level.

Explanatory Notes

Observations not included in analysis if measured precipitation on Watershed 1 was 10 percent more or less than that on No. 4 (Control).

Prediction Equation

$\hat{Y} = 1.220X - 2.34$

(X is peak flow of control in c.s.m.)

$n = 48$

$\bar{x} = 24.30$

$Sx^2 = 18,600.78$

$s_{y.x} = 4.28$

on storm-period discharge of Clearcut Watershed

Date of peak	Storm period discharge			Change as percentage of predicted value
	Predicted $\hat{Y}$ in area-inches	Change		
		$Y - \hat{Y}$ in area-inches	Probability	
		GROWING SEASON (6 storms)[1]		
5/5/58	1.26	+0.10	0.34	--
6/14/58	.66	+ .46*	<.001	--
6/22/58	.58	+ .07	.51	--
8/1/58	.84	+ .16	.13	--
8/4/58	.60	+ .03	.78	--
8/8/58	.80	+ .30*	.006	--
Growing-season total	4.74	+1.12	--	23.6
Growing-season mean	.79	+ .19	--	--
		DORMANT SEASON (13 storms)		
12/7/57	1.15	+0.45*	<0.001	--
12/26/57	.70	+ .02	.85	--
1/22/58	.50	+ .06	.57	--
4/28/58	1.56	- .01	.93	--
1/15/59	1.04	- .10	.34	--
1/22/59	1.52	+ .18	.10	--
2/15/59	.78	+ .02	.85	--
11/28/59	.62	+ .07	.50	--
12/12/59	1.17	- .13	.22	--
1/3/60	.68	+ .03	.77	--
1/15/60	1.17	+ .03	.77	--
3/30/60	3.86	- .21	.17	--
4/4/60	1.03	- .01	.92	--
Dormant-season total	15.78	+ .40	--	2.5
Dormant-season mean	1.21	+ .03	--	--
Total	20.52	+1.52	--	7.4
Mean	1.08	+ .08	--	--

[1] One of storms in Analysis I was not used here in Analysis II because clock on Control recorder failed after the peak and part of hydrograph had to be estimated.

*Significant at 5-percent level.

Explanatory Notes

Basic data: For each storm when flow on Control exceeded 10 c.s.m., storm-period discharge is the discharge between the time when storm runoff began to the time when the stage receded to a point midway between the peak stage and the stage when runoff began. Storms with non-uniform precipitation were excluded as in Analysis I.

Prediction Equation

$\hat{Y} = 0.981X + 0.01$

(X is storm period discharge of the Control in area-inches)

$n = 48$

$\bar{x} = 0.92$

$Sx^2 = 7.7170$

$s_{y.x} = 0.103$

Table 28.—High-flow analysis III: effect of treatment on storm-period discharge above 10 c.s.m.

Date of peak	Discharge above 10 c.s.m.			Change as percentage of predicted value
	Predicted	Change		
	$\hat{Y}$ in area-inches	$Y - \hat{Y}$ in area-inches	Probability	
	GROWING SEASON (8 storms)[1]			
5/5/58	0.219	+0.032	0.69	--
6/14/58	.028	+ .273*	.001	--
6/22/58	.138	+ .044	.59	--
8/1/58	.284	+ .033	.68	--
8/4/58	.170	+ .008	.92	--
8/8/58	.445	+ .257*	.003	--
7/25/59	.010	+ .043	.60	--
10/23/59	.010	+ .292*	.001	--
Growing-season total	1.304	+ .982	--	75.3
Growing-season mean	.163	+ .123	--	--
	DORMANT SEASON (13 storms)			
12/7/57	0.260	+0.390*	<0.001	--
12/26/57	.137	+ .019	.81	--
1/22/58	.010	+ .014	.86	--
4/28/58	.943	- .087	.30	--
1/15/59	.144	- .036	.66	--
1/22/59	.925	+ .113	.18	--
2/15/59	.014	+ .003	.97	--
11/28/59	.109	+ .045	.58	--
12/12/59	.628	- .149	.07	--
1/3/60	.210	+ .028	.73	--
1/15/60	.162	+ .006	.94	--
3/30/60	2.463	- .344*	.002	--
4/4/60	.261	- .016	.84	--
Dormant-season total	6.266	- .014	--	-0.2
Dormant-season mean	.482	- .001	--	--
Total	7.570	+ .968	--	12.8
Mean	.360	+ .046	--	--

---

[1] One of storms in Analysis I excluded here for same reason as in Analysis II. Two additional storms were used in this analysis (July 25, 1959 and Oct. 23, 1959). In these storms, flow of 10 c.s.m. was exceeded on the Clearcut Watershed but not on the Control. This distinction was also followed in analysis of calibration data.

Explanatory Notes

Basic data: For each storm, the amount of discharge above 10 c.s.m. was computed. This is equivalent to drawing a line across the chart at 10 c.s.m. and determining the discharge represented by the area between this line and the hydrograph tracing when the latter is above the line.

Storms with non-uniform precipitation were excluded as in Analysis I.

Prediction Equation

$\hat{Y} = 0.991X = 0.01$

(X is discharge above 10 c.s.m. on the Control)

$n = 48$

$\bar{x} = 0.311$

$Sx^2 = 6.946460$

$s_{y.x} = 0.080$

by season and year on discharge above 10 c.s.m. on Clearcut Watershed

Water year	Discharge above 10 c.s.m.			Change as percentage of predicted value
	Predicted $\hat{Y}$ in area-inches	Change		
		$Y - \hat{Y}$ in area-inches	Probability	
	GROWING SEASON			
1957-58	0	0	--	--
1958-59	1.73	+0.51*	0.048	--
1959-60	0	+ .22	.23	--
Growing-season total	1.73	+ .73	--	42.2
Growing-season mean	.58	+ .24	--	--
	DORMANT SEASON			
1957-58	1.16	+0.47*	0.01	--
1958-59	1.00	+ .06	.01	--
1959-60	3.72	- .61*	.01	--
Dormant-season total	5.88	- .08	--	-1.4
Dormant-season mean	1.96	- .03	--	--
	YEAR[1]			
1957-58	1.09	+0.54*	<0.01	--
1958-59	2.64	+ .66*	<.01	--
1959-60	3.74	- .41*	.02	--
Total for year	7.47	+ .79	--	+10.6
Mean for year	2.49	+ .26	--	--

[1] Values for seasons do not sum up exactly to values for year because different prediction equations were used.

*Significant at 5-percent level.

Explanatory Notes

Basic data: Using tabulations of mean daily flow, the amount of flow above 10 c.s.m. was accumulated for each watershed (Clearcut and Control) by seasons and years. For each day of high flow, 10 c.s.m. was deducted from the mean daily value. Flows were converted to area-inches.

Prediction Equations

Growing season	Dormant season	Year
$\hat{Y} = 1.083X - 0.09$	$\hat{Y} = 0.988X + 0.01$	$\hat{Y} = 1.019X - 0.086$
$n = 6$	$n = 6$	$n = 6$
$\bar{x} = 0.62$ area-inch	$\bar{x} = 1.57$ area-inch	$\bar{x} = 2.19$ area-inch
$Sx^2 = 1.4938$	$Sx^2 = 8.0841$	$Sx^2 = 11.0537$
$s_{y.x} = 0.130$ area-inch	$s_{y.x} = 0.099$ area-inch	$s_{y.x} = 0.094$ area-inch
$r = 0.981$	$r = 0.9975$	$r = 0.998$

Due to the characteristic of the analysis, it is to be expected that percent change will be higher when the volume of discharge over 10 c.s.m. is analyzed instead of the whole storm-period flow.

Inspection of data for individual storms shows that changes in the growing season are almost universally increases—some small and some large. Changes in the dormant season may be either increases or decreases.

Discussion of dormant season variability.—General observation in the watersheds and a study of the records indicate that changes in dormant-season flow are largely the result of treatment effect on rate of snowmelt. The treatment resulted in increased insolation and more melt and streamflow on cool, sunny days. Thus less snow remained to contribute to streamflow during succeeding relatively warmer periods during which rain sometimes occurred. Snowmelt from insolation seldom results in extremely high flow. It is most effective for only a small part of the day and, because of varying aspects, on only part of the watershed area. On occasion, high flow from snowmelt occurred on the Control when a considerable portion of the Clearcut Watershed was bare of snow.

Other treatments.—So far, effect of treatment on high flows has been given for the Clearcut Watershed only. Table 30 shows a comparison with the other three treatments for area-inch increase in volume of flow over 10 c.s.m. The comparison is for the 1959-60 water-year, the only year when all four treatments were in effect.

The considerable treatment effect on the two selection-cut watersheds as compared to the other two watersheds is surprising. One reason perhaps is that the Clearcut Watershed was logged more than a year before the others and regrowth had occurred.

The 1959 growing season did not provide any large storms (flows over 10 c.s.m.) on any of the five watersheds except the Clearcut. Hence, there was no good test of storm effects. All watersheds show decreases for the 1959-60 water-year; if it had not been for the snowmelt runoff in the period March 19-29, 1960, the change for the year would have been an increase.

Table 30.—High-flow analysis: effect of treatments by season and year on discharge above 10 c.s.m. in water-year 1959-60

Item	Change in volume of discharge above 10 c.s.m., in area-inches[1]			
	Commercial clearcut	Diameter limit	Extensive selection	Intensive selection
Growing season	+0.22	0	-0.32	0
Dormant season	- .61*	- .81	- .68	-0.25*
Year	-0.41*	-1.10*	-0.99*	-0.30*

[1] Procedure of analysis same as in Analysis IV.

*Significant at 5-percent level.

flow characteristics. More study is needed—on these watersheds and on other areas—to get a clearer picture.

Flow Duration

Figure 23 is the flow-duration curve for the Control Watershed for the 3288 days in the study period (May 1, 1951 through April 30, 1960). It gives a general picture of streamflow on the undisturbed watersheds.

To derive the flow-duration curves to show the effect of treatment on the Clearcut Watershed in the growing season, data on mean daily flows were first tabulated showing, for Watershed 4 (the Control) and for No. 1 (Clearcut), the number of days in each growing season that flow exceeded 0.001, 0.005, 0.01, 0.05, 0.1, 0.5, 1, 5, 10, 20, 30, 40, and 50 c.s.m., respectively. This was done by electronic computer.

Using data for the six growing seasons in the calibration period, prediction equations (straight-line regressions) were computed for each of the rates of flow listed above. For each growing season in the treatment period, a prediction was made for the number of days each rate of flow would be equaled or exceeded. This was made using the equation and the measured number of days for the Control in each of the treatment years. For each rate of flow, the number of days was totaled for the four seasons in the treatment period and the appropriate percentage was determined by divid-

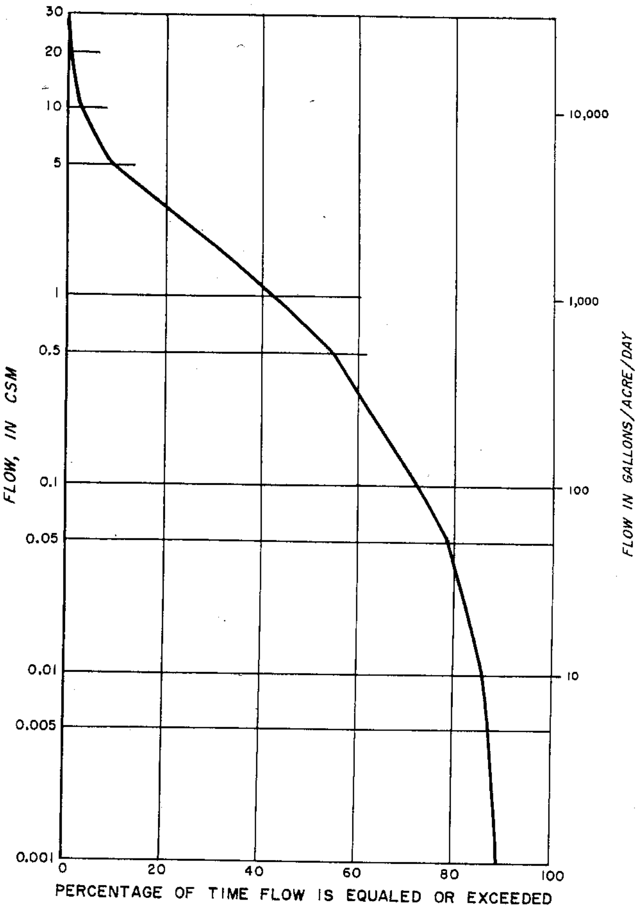


Figure 23.—Flow-duration curve of the Control Watershed in the 9 years of the study period.

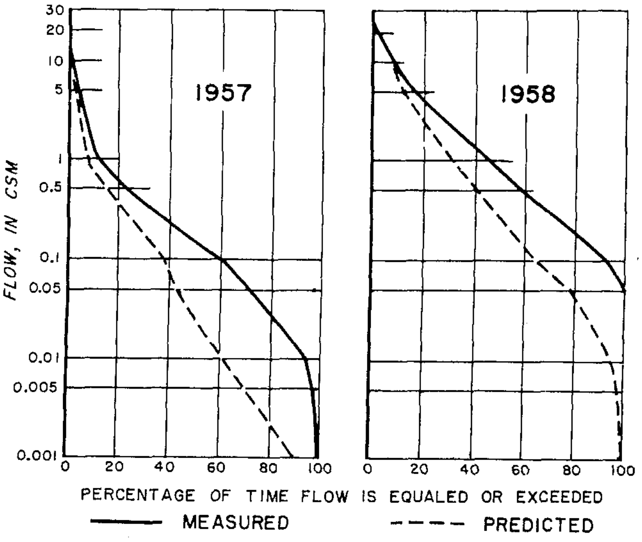


Figure 24.—Flow-duration curves for Clearcut Watershed for growing seasons in 1957 and 1958.

ing by 736, the total number of days in the four growing seasons. The resulting percentages were plotted on semi-log scale to form the *predicted* flow-duration curve.

Based on streamflow measurements on the Clearcut Watershed in the four seasons of the treatment period, the number of days and corresponding percentages were computed and plotted on the same graph to form the *measured* flow-duration curve.

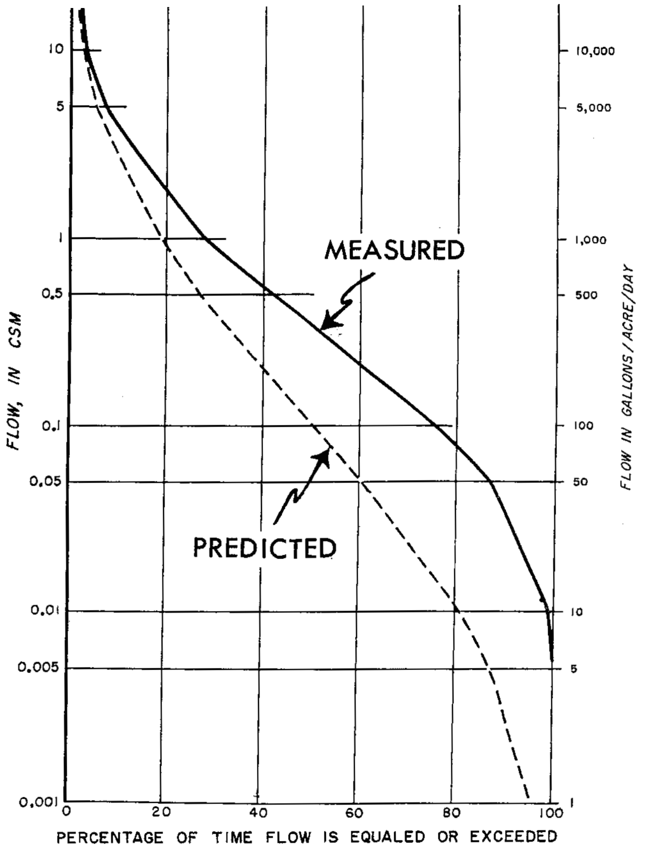
The growing-season curves for the Clearcut Watershed showed the average effect on flow duration in the four seasons after start of treatment. It is of more than passing interest to examine the situation in a *dry* year and in a *wet* year, especially since water-supply problems usually occur in abnormal years rather than in years having near-average conditions.

In the 1957 growing season, there were 75 days on the Control Watershed when flow was below 5 gallons per acre per day. In 1958, there were only 3 such days. Figure 24 shows flow-duration curves of the Clearcut Watershed for these two growing seasons. The displacement to the right of both 1958 curves, when compared with those for 1957, reflects the difference in the weather of the two seasons. However, the treatment resulted in substantial augmentation of low flows in both the *wet* and the *dry* year.

Figure 25 shows the average effect of the Clearcut treatment on the flow-duration curve for 3 water-years following the start of logging. In line with other analyses, the spread between the curve based on predicted flow and the one based on measured flow is not as pronounced as that for the growing-season curves; however, the difference between the two is readily apparent.

Effects of treatment on discharge were not very large in the dormant season on any of the watersheds; therefore, flow-duration curves are not given for this season.

An additional note should be added concerning this presentation of flow-duration curves. These curves are not intended to establish whether or not the treatments had a statistically significant effect upon discharge. As analyses by water-year, season, and month that have already been presented



tion curves for Clearcut Watershed in 3 water-years after start of logging, May 1957 through April 1960.

showed such increases in many cases, the flow-duration curves have been presented to indicate the relationship between increase and rate of discharge.

Runoff as a Percent of Precipitation

Effect of treatment on runoff as a percentage of precipitation has already been given for the Commercial Clearcut Watershed. Table 31 gives the same type of information for all four watersheds and shows the probabilities associated with the increases. As might be expected, the results are similar to those obtained in the analyses of quantity of streamflow by season and year. The results are impressive: this type of analysis appears to be a sensitive and fruitful approach to the problem of determining treatment effects.

V. DISCUSSION OF RESULTS

Following is a hypothetical example of how the research results might be used to obtain an approximation of the effect of a treatment made to increase water yield.

Assumptions:

1. Watershed under consideration is similar to Fernow watersheds in climate, soil, geology, topography, etc.
2. Effect of treatment will be the same as in Fernow experiments in 1959 and 1960.

Treatment.—Apply diameter-limit cutting practice[5] to 5 percent of watershed each year but construct skidroads to standards of the intensive-selection program. Insofar as practicable, choose each cutting area so that it includes a cross-section of aspects and slope positions.

Expected increase in discharge.—Table 32 gives the expected increase in water yield for the growing season and for two late-summer months. Any gain in flow that might occur more than 2 years after cutting is not included in the computations; this might be considered a safety factor. Increases are given in area-inches, in gallons per acre, and in terms of number of people that could be supplied.

Table 31.—Effect of treatment on runoff as a percentage of precipitation on the four treated watersheds

Period	Treatment	Year	Runoff as percent of precipitation		
			Predicted	Change	Probability
Growing season	Commercial clearcut	1957	11	+ 3*	0.04
		1958	34	+12*	.001
		1959	10	+10*	.001
	Diameter limit	1958	41	+ 1	.18
		1959	12	+ 6*	.001
	Extensive selection	1959	15	+ 5*	.009
	Intensive selection	1959	13	0	.50
Water-year	Commercial clearcut	1957-58	34	+ 4*	0.007
		1958-59	42	+ 8*	.001
		1959-60	36	+ 7*	.001
	Diameter limit	1958-59	50	0	.50
		1959-60	43	+ 4*	.01
	Extensive selection	1959-60	51	0	.50
	Intensive selection	1959-60	40	0	.50

*Statistically significant at 5-percent level.

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[5] Treatment considered here is a diameter-limit cutting because of availability of research results; a different cutting practice might be more desirable for either water or timber production.

Item	Discharge period		
	Growing season	August	September
Increase on area treated in first year after treatment .... area-inches ..	1.8	0.3	0.1
Increase on area treated in second year after treatment .... area-inches ..	.7	.1	.2
Mean increase on area treated .... area-inches ..	1.25	.20	.15
gallons/acre ..	33,942	5,431	4,073
Average increase distributed over whole watershed .... gallons/acre ..	3,394	543	407
Days in period .... number ..	184	31	30
Average increase for watershed ... gallons/acre/day ..	18	18	14
Assumed per-capita consumption .... gallons/day ..	50	50	50
Watershed area needed to supply one additional person from increase in flow .... acres ..	3	3	4

Note: This example is presented as an illustration only; wide variations from watershed to watershed prevent precise quantitative estimates of practical application of these research results.

VI. OTHER WATERSHED RESEARCH

Many investigations have been made at various times and places in an effort to determine the effect of forest cutting on streamflow. The results obtained have differed greatly because of the wide variety of conditions under which the studies were made, the various treatments applied, and different study methods used.

Forest Cutting on Watersheds Calibrated with a Control Watershed

Wagon Wheel Gap, Colorado.—The historic forest and streamflow experiment at Wagon Wheel Gap, Colorado, is well known (Bates and Henry, 1928). In this experiment, started in 1910, two watersheds of about 200 acres each were calibrated for 8 years. During the experiment, annual precipitation averaged 21 inches. After calibration, one of the watersheds was denuded by cutting, piling, and burning the vegetation of Douglas-fir, pine, spruce, and aspen. Within a year after cutting, a thin stand of aspen sprouts developed. Streamflow measurements continued for 7 years after treatment.

To facilitate comparison, the records of annual flow for the Wagon Wheel Gap Watersheds have been reanalyzed in the same way the Fernow data were analyzed. The following tabulation shows the increases in annual flow on the treated watershed at Wagon Wheel Gap:

Year	*Area-inches*	*As percent of predicted flow*	*Probability*[1]
Year of treatment	0.63*	8	0.018
First year after	1.35*	19	<.001
Second year after	1.86*	27	<.001
Third year after	0.98*	16	.002
Fourth year after	.85*	12	.004
Fifth year after	.53*	12	.029
Sixth year after	.52*	12	.031

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[1] The probability that an increase of the magnitude given could have occurred by chance alone.

*Statistically significant at the 5-percent level.

The pattern of seasonal increase is of interest: 80 percent of the increase in annual flow occurred during the spring melt period (March 1 to July 10). At Wagon Wheel Gap snowmelt provided most of the annual flow. Peak flow in the spring was increased about 50 percent as a result of treatment.

Fraser Experimental Forest, Colorado.—After a lengthy calibration period, about half the merchantable timber on 714-acre Fool Creek Watershed was harvested by strip clear-cutting in the period from summer 1954 to fall 1956 (Goodell, 1958). At Fraser, annual precipitation is about 30 inches; about three-fourths of this falls as snow in the October to June period. This treatment resulted in a definite increase in annual streamflow; in 1956 the increase was 4.2 area-inches or 37 percent of the expected flow; in 1957, 3.4 area-inches or 17 percent. In 1958, the increase was 2.1 inches (Rocky Mountain Forest and Range Experiment Station, 1959). The bulk of the increases occurred during spring freshets from snowmelt. However, streamflow was also slightly higher during summer and fall in 1956 and 1957.

The spring flood peak was increased the first year after cutting and decreased in comparison with the control in the second year. In 1958, the third year after cutting, peak flow was 30 percent higher than predicted. The interaction between spring weather and treatment seems to explain the difference in spring peaks.

Sediment yields since cutting have been low due to the considerable care taken in the logging operation. For example, no timber was cut within 90 feet of the main stream.

Roads were constructed in the watershed well ahead of logging (in 1950 and 1951). No effect on water yield could be detected as a result of the 35 acres of roadway clearing.

Coweeta Hydrologic Laboratory, North Carolina.—Because of similarities in climate, forest types, topography, and methods of study, research results from the Fernow Forest can perhaps be compared with those from Coweeta better than from anywhere else. Average annual precipitation at Coweeta is 80 inches, almost all of which occurs as rain (Dils, 1957).

On Coweeta Watershed 17, all vegetation was cut and left on the ground; this was followed by an annual slashing of regrowth. Since no logging was done, there was little disturbance of the forest floor. First-year increase in streamflow was 17 area-inches. In the second year, after regrowth was cut for the first time, many herbaceous plants began to invade the area. Under this cover, the increase in water yield leveled off at about 11 area-inches from the third to the thirteenth year. Dils states, "The maximum increases came in the November to February period, but significant increases also occurred in July, August, and September—the period when municipal and industrial water shortages are most likely. Maximum peak discharges during storm periods and the distribution of streamflow were not appreciably altered . . . There has been no measurable change in stream turbidity. Air temperatures near the forest floor have increased markedly."

Coweeta Watershed 13 was treated in the same manner as No. 17 except that forest growth was allowed to come back naturally. Streamflow increase in the first year was about 15 area-inches; the increase diminished with time but was still more than 4 inches 15 years after cutting. Here, also, the greater increase occurred in the winter period. As in the case of Watershed 17, there were no measurable changes in storm peaks, volume of stormflow, or distribution of storm runoff.

After a 6-year calibration period, 212-acre Coweeta Watershed 10 was logged: 50 percent of the basal area was removed over a 3-year period. Skidroads were "logger's choice" as on the Fernow Clearcut and Diameter Limit Watersheds; truck roads were also constructed in the watershed. Logging in this manner caused extensive erosion and consequently very high stream turbidities, even in small storms; maximum turbidity measured was 5,700 p.p.m. Even after logging stopped, the exposed clay subsoil continued to move into streams after every storm, thus impairing the water quality.

This study has been reported as a demonstration of effects of exploitive logging on water quality. Apparently the effects of treatment on quantity of discharge received little emphasis; a streamflow increase of 4.0 area-inches was measured the first year after logging (Southeastern Forest Experiment Station, 1961).

Other Coweeta experiments have been conducted and reported upon but do not compare so directly with the Fernow investigations as those listed above. Some additional watershed treatments at Coweeta, not yet fully reported in the literature, have resulted in streamflow increases that were small in relation to those described above. Watershed research must seek the causes for these differences in results that apparently are not explained by the amount cut nor proportion of the stand removed.

Sierra Ancha Experimental Forest, Arizona.—Three watersheds in the Workman Creek drainage in central Arizona have been studied since 1938. The forest stand is of the mixed conifer type (Rich, 1959). Average annual precipitation is 32 inches. A logging operation and timber-stand-improvement measures in 1953, 1954, and 1955 reduced the basal area by 36 percent. No significant change in water yields had, as of 1959, resulted from this treatment.

Kamabuti, Japan.—Many investigations of the effect of forest cover and forest cutting upon streamflow have been made in foreign countries. Unfortunately, many of these have not had adequate control, so definite conclusions cannot be drawn. One Japanese experiment is of particular interest (Maruyama and Inose, 1952). The control-watershed approach was used with a calibration period of 8 years. This experiment also gives an idea of treatment effects in an area of high average precipitation (99 inches annually) and high average streamflow (76 area-inches annually). After calibration, the mixed conifer-broadleaf stand was clearcut and the regrowth cut annually on the 6-acre treated watershed. Over a 3-year period, annual streamflow was increased by about 5 percent. Increases were significant in the summer season (June to November) but not in the winter season (December to May). Average peak runoff and increased runoff due to heavy rains for 6 examples rose more than 20 percent by cutting.

Other Investigations on Watersheds Relating Vegetation Differences to Streamflow

Sperbel and Rappen, Switzerland.—An early Swiss study, reported upon by Engler (1919) and Burger (1943) showed that streamflow from the fully forested Sperbel watershed was continuously less than streamflow from the lightly forested Rappen watershed.

Flow of Springs, California.—Biswell and Schultz (1958) report a prompt and measurable increase in flow of several springs in California following removal of vegetation by burning or cutting.

White River, Colorado.—The killing of spruce and pine by an insect epidemic affected streamflow of the White River in Colorado as reported by Love (1955). Average annual precipitation at Meeker, Colorado, is about 16 inches. In the period 1941 to 1946, the beetle killed most of the trees on 226 square miles, or 30 percent of the 762-square-mile watershed. Analysis, using nearby Elk River as a control, showed that annual flow of the White River was increased by 2.3 inches (or 22 percent) in the 1947 to 1951 period. Love estimates that an increased flow of 7.7 area-inches came from the 226-square-mile area of beetle-killed timber.

Harz Mountains, Germany.—A recent paper (Delfs et al., 1958), compared two watersheds, one forested and one clearcut, in the Harz Mountains of Germany. Annual water yield was slightly higher from the clearcut watershed; winter yield was slightly higher from the forested watershed. Flood peaks when rain followed a thaw were frequently higher from the forested area; during summer, peaks were generally higher from the clearcut area. Suspended sediment was higher from the clearcut area than the forested area.

Reforestation Experiments

This paper has dealt largely with effects of cutting, complete or partial, of the forest stand. Generally speaking, reforestation, afforestation, or the improvement of existing forest stands by protection from fire or other forest-management measures should have a corresponding effect in the opposite direction. Many studies have been conducted to determine such effects.

Coshocton, Ohio, in 1939 has resulted in a progressive decrease in annual streamflow of about 0.28 area-inch per year, amounting to about 5 inches by the 18th year of the plantation (Harrold et al., 1962). Average annual precipitation at Coshocton is about 38 inches. Decrease was divided between the growing and dormant seasons; about 70 percent of it occurred in the dormant season. This indicates that groundwater recharge has been affected to a considerable degree.

White Hollow Watershed, Tennessee.—On White Hollow Watershed in Tennessee, 588 acres out of a total 1,715 acres were reforested and other conservation methods were applied (Rothacher, 1953). No effect on annual discharge was noted. Summer peak flows were reduced 73 to 92 percent. Overland flow and soil erosion were practically eliminated.

Pine Tree Branch, Tennessee.—The Tennessee Valley Authority also investigated the effect of reforestation and other erosion-control measures upon the hydrology of 88-acre Pine Tree Branch Watershed (Tennessee Valley Authority, 1955). Watershed treatment was done largely in the period 1945 to 1948. Considering records to 1950, the report states, "There is some indication of a slow, progressive decrease in water yield, but whether or not this is significant remains to be determined by further measurements." Marked reductions in peak discharges and sediment production were measured; however, much of this is probably due to measures other than reforestation, such as contouring and check dams in stream channels and gullies.

Plot Studies

Many studies have been made of the effect of forest cutting upon soil moisture. It is logical to infer that under most conditions any treatment that results in maintaining a higher level of soil moisture will increase streamflow to some degree. Much of the information needed to corroborate and explain results determined on gaged watersheds will come from plot studies. Of the many experiments conducted, only a selected few will be mentioned here.

Crossett Experimental Forest, Arkansas.—Moyle and Zahner (1954) measured soil moisture on a number of plots at Crossett, Arkansas, during the summer of 1953. At Crossett, annual rainfall is about 50 inches and the normal for the May-September period is 18 inches. They found sizable soil-moisture differences related to stand conditions. For example, in August there was as much as 10 inches less water in the upper 4 feet of soil under an all-aged cull-hardwood stand than under a similar stand in which all hardwoods over 4 inches d.b.h. had recently been poisoned. Their summary states in part: "Where pine or hardwood stands with a stocking of 70 to 100 square feet of basal area were undisturbed, water was removed from the ground rapidly with the onset of hot dry weather. On plots where large cull hardwoods were deadened, and where all living vegetation was removed, soil water remained relatively high throughout the summer."

Fraser Experimental Forest, Colorado.—Wilm and Dunford (1948) reported on an intensive plot study conducted near Fraser, Colorado, to determine water available for streamflow from areas cut to varying residual volumes of timber. Approximating the amount of timber cut, the following tabulation shows the annual increase in water available for streamflow:

Volume of merchantable timber cut		*Average increase available over 4-year period*	
M b.m. /acre	*Percent of total volume*	*Area-inches*	*Percent of expected value*
6	50	1.0	10
8	67	2.0	19
10	83	2.1	20
12	100	3.2	31

These increases are attributed largely to the effects of treatment on snow interception and evaporation. Autumn soil-moisture deficits (a measure of evapotranspiration during the summer) showed "only a weak average effect" of treatment. The authors point out that this effect was much stronger in the one treatment year when above-average precipitation (5.9 inches) occurred in the July to September period. In that year the deficits were as much as 1.24 inches less on the treated plots.

College Station, Texas.—Koshi (1959) studied soil-moisture trends under varying densities of oak overstory near College Station, Texas. Normal annual precipitation for College Station is about 39 inches. Throughout the period of observation, soils of clearcut plots had more moisture than those of undisturbed plots, while soils of thinned plots had an intermediate amount. Differences for the upper 24 inches of soil between clearcut and undisturbed plots ranged up to about 3.5 inches. Differences tended to be greatest in periods of high soil moisture and least at times of drought. After one prolonged drought, there was little difference in residual moisture among the three treatments.

Calhoun Experimental Forest, South Carolina.—Metz and Douglass (1959) studied soil-moisture depletion under several cover types in the Piedmont of South Carolina. Average annual precipitation in the area is about 48 inches. For a drying period of 40 days, the authors report soil-moisture losses in a 60-inch soil layer of about 2.9, 4.0, and 5.8 inches from barren, broomsedge, and pine plots, respectively.

◆

Acknowledgment

THE evalution of treament effects in investigations of this kind depends as much upon the accuracy and dependability of daily measurements as upon the magnitude of the treatment effects themselves. For the decade of this study, Burley D. Fridley, forestry aide on the Fernow Experimental Forest, Parsons, West Virginia, maintained the instruments and installations and collected most of the basic records. Much of the success of this study can be attributed to his conscientious and efficient field work.