

Evapotranspiration and Water Yields Following Forest Cutting and Natural Regrowth

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CLIMATIC FACTORS operate through vegetation to transfer large quantities of water from the earth back to the atmosphere. The process is generally referred to as evapotranspiration.¹ It would appear, therefore, that the amount of evapotranspiration from a natural area would depend to some extent on the nature and condition of the vegetation. Unfortunately, it has been difficult to uncover the facts in regard to this relationship. Controlled experiments with small watersheds where the vegetation on the area has been drastically altered to the point of complete elimination have not produced clear-cut answers, viz., the Wagon Wheel Gap Study (2). Watershed studies by Ayer (1) and the Tennessee Valley Authority (7) did not show a change in water yield with reforestation and regrowth.

With our present limited knowledge of this subject, hydrologists are inclined to dismiss differences among

vegetation cover types as of little importance in the overall estimate of a situation. For example, differences in streamflow between neighboring watersheds within a regional forest type with about the same precipitation, soils, geology, topography, and aspect, would not be attributed to differences in the forest stands, which are known, however, to include a wide range of cover conditions due to a past history of exploitation. Along the same line, attention is called to the fact that the mathematical theory of evaporation has only been developed for a free liquid surface or a permanently saturated solid surface. The extension to drying of solids as in the case of the removal of water from the soil has not been too successful. It is therefore impossible to find answers to this problem using a theoretical approach.

Forest-streamflow relations are being studied at the Coweeta Hydrologic

Laboratory as described and summarized by Hursh (4). This field laboratory is located in the 80-inch high-rainfall belt of the southern Appalachian Mountains in western North Carolina. It was selected only after a careful search to find an area that would meet the rigid specifications of hydrologists, engineers, and foresters. Experiments there have been eminently successful in showing that a change in cover can markedly alter evapotranspiration from a given watershed. This basic principle, which in recent years is finding wider acceptance, may have a very practical application in watershed management aimed at increasing water supplies.

The purpose of this paper is to present the results of a 17-year watershed experiment at Coweeta and to show what happens to water yield when the forest stand is cut down and then allowed to grow back undisturbed. The results are of interest in watershed management since regrowth would tend to offset any changes in evapotranspiration or streamflow brought about by the initial cutting. Thus, it is a key experiment in showing that streamflow definitely responded to growth increments of the vegetation.

The cutting took place on a 39.8-acre watershed having predominantly an oak-hickory cover (27.7 acres), the balance being in cove hardwood on 3.8 acres, and yellow pine-hardwood on 8.3 acres. It was a second-growth stand with a scattering of old-growth saw timber. There was a good dominant canopy on 80 percent of the area, with a heavy understory vegetation on the remaining 20 percent. In other words, the combination of high and low vegetation afforded a complete canopy over the whole area and effectively shaded the ground. Basal

TABLE 1.—ESTIMATED ANNUAL INCREASES IN STREAMFLOW FOR PERIOD MAY 1-APRIL 30, WITH PRECIPITATION AND TIME SINCE TREATMENT

Year	Years since treatment	Annual precipitation	Estimated increases in streamflow		
			Observed minus normal runoff	By regression on time	± 95 percent confidence limit
	(1)	(2) Inches	(3) Inches	(4) Inches	(5) Inches
1940-41	1	54.56	14.45	14.68	2.36
1941-42	2	61.35	10.89	12.04	1.81
1942-43	3	80.99	10.94	10.50	1.55
1943-44	4	76.97	9.76	9.41	1.41
1944-45	5	63.44	7.88	8.56	1.35
1945-46	6	75.22	9.93	7.87	1.31
1946-47	7	66.68	7.93	7.28	1.30
1947-48	8	73.37	7.30	6.78	1.31
1948-49	9	89.91	5.19	6.33	1.33
1949-50	10	84.99	5.17	5.93	1.36
1950-51	11	72.75	5.59	5.57	1.39
1951-52	12	83.70	5.78	5.24	1.42
1952-53	13	64.98	4.99	4.93	1.45
Average		72.99	8.14	8.09	1.49

¹Includes interception.

area averaged 111 square-feet per acre.

The experimental watershed (No. 13) was calibrated for streamflow observations over a 3-year period against a nearby 31-acre control watershed (No. 18).

All the woody vegetation was then cut down between September 1939 and January 1940, and left in place with minimum disturbance to soil. Continuing protection was also provided by the prompt establishment of a heavy sprout and brush cover during the first growing season of 1940. For all practical purposes, the infiltration capacity of the soil was not affected by the treatment.

Hydrologic Results

The overall effect of the treatment on streamflow, in terms of annual values, is summarized in Table 1.

The estimated increases—observed minus normal runoff—decrease from 14.45 inches in the first year after treatment to 4.99 inches in the thirteenth year, for a net change of 9.46 inches. The increases are independent of the annual precipitation, as may be surmised by comparing the increases and amounts of precipitation, as listed in column 2, over a period of several years. The data are impressive in bringing out a condition where progressive changes in the streamflow regimen have been brought about by manipulating vegetation only on a watershed.

Regression analysis leads to an expression of the increases as a linear function of the logarithm of the time in years since treatment; that is, the rate of decline of the additional water yields has become smaller each year. Rates of growth of forest stands are known to produce the same characteristic. The regression is highly significant and the estimates with time trend are shown in column 4. These are all significant as shown by the 95-percent confidence limits in column 5.

In Figure 1 the behavior of the streamflow gains is shown for the year. It is rather surprising that the largest absolute change in streamflow occurs in the dormant season, January-April. This must result mainly from reductions in evapotranspiration occurring during the growing season, and evidently there is a marked lag relationship within a 12-month period between evapotranspiration and streamflow acting through soil reservoir storage. The curves have been extrapolated to arrive at an estimate of the duration of the treatment effect. Apparently, increases in streamflow will be negligible after the 35th year.

Ninety percent of the annual streamflow on Watershed 13 comes from groundwater; the balance consists of stormflow. Hence, practically all water appearing as streamflow is routed through the soil profile, so that soil-moisture deficits created by vegetation have maximum opportunity to become satisfied. It is extremely important to keep in mind this characteristic of the hydrology of the Coweeta watershed. It explains in part, for example, the large increases in streamflow noted previously for the dormant season. There was no evidence of any change in maximum stormflow.

Independent and direct estimates of annual amounts of evapotranspiration can be obtained from the water-balance equation

$$E_e = P - RO \pm \Delta S$$

where

E_e = Evapotranspiration including interception

P = Precipitation

RO = Streamflow

ΔS = Difference between groundwater storage at beginning and end of year

Soil moisture or retention storage is usually at or very close to field capacity on April 30 of each year. Therefore, the total change (ΔS) is approximately equal to the change in groundwater storage. This quantity may be estimated from a derived streamflow-storage relationship.

Table 2 shows annual evapotranspiration values calculated from the water-balance equation. Based on observations for pretreatment period

and similar data from the control watershed for the entire period of study, the annual evapotranspiration before cutting averaged 38.0 inches. The difference between this amount and the annual values during the treatment period are estimates of the annual reductions in evapotranspiration.

A comparison of the estimates obtained by regression analysis and water-balance method is shown in Table 3. The agreement is reasonably good, as is to be expected.

Changes in Vegetation

Some data on vegetation are available from the results of periodic timber cruises on permanent strips 1 chain wide and 10 chains long. Tables 4 and 5 compare the original forest stand with the stand after 12 years of regrowth following clearcutting.

In the 12 years since cutting in 1940, the forest on Watershed 13 increased in total basal area per acre from zero to 51.6 square feet, or slightly less than half the original basal area of 110.9 square feet per acre. Of course, the diameter distribution was not uniformly affected, and Table 4 shows that the stands are actually more divergent than the total figures indicate. The original forest, with a wide distribution of diameter classes, was replaced after 12 years by an even-aged young coppice stand with a 12-inch diameter limit, having 97 percent of the basal area in the 1- to 6-inch d.b.h. class.

A major shift in species composition was the loss of chestnut (*Castanea*

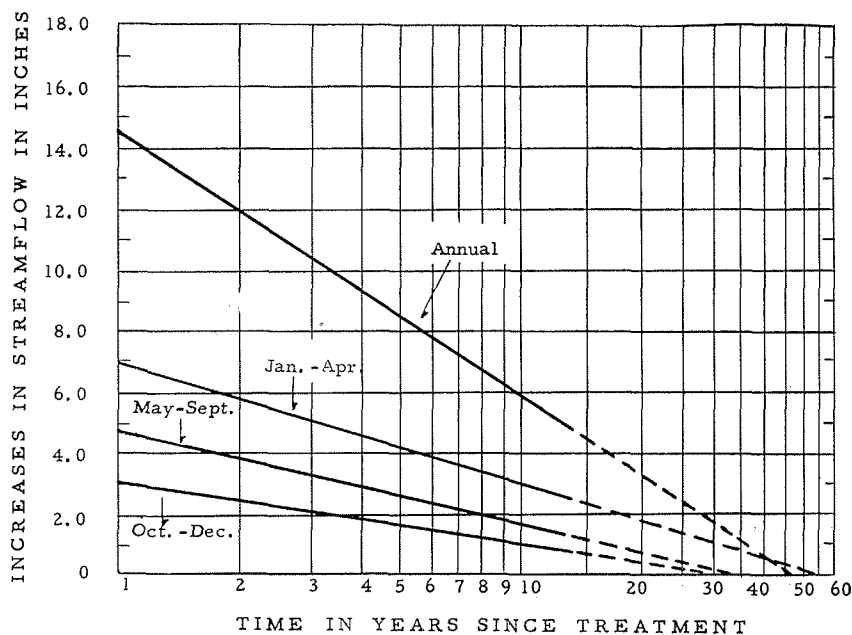


Fig. 1.—Increases in streamflow by year and season with extrapolated estimates.

dentata (Marsh.) Borkh.) as a result of the blight (*Endothia parasitica*). In 1934 the species constituted 33 percent of the basal area, but by 1952 its absence was almost complete.

Evapotranspiration opportunity is usually related to extent of cover on an area rather than to its character. In order to get some idea of the relative cover after treatment including all vegetation on the area, annual production of foliage was measured by collecting leaf fall throughout the year

in 36-inch square trays set close to the ground. These were located at random in both the treated and control watersheds. The oven-dry weight is presumed to be representative of leaf area with only a proportionality factor involved. In 1953-54 the oven-dry weight of annual leaf fall on a per-acre basis was 1.412 tons on Watershed 13 and 1.453 tons on control Watershed 18, with standard errors of 0.078 and 0.061 ton, respectively. Since leaf-weight data were not taken in the calibration

period, it will be assumed that the control may be used as a standard for reference. The difference between weights is not significant and the present cover on the area appears, therefore, to be equal to the original cover. This hypothesis is supported by field observation that there is a full cover on the area.

Figure 1 indicates that under normal conditions the streamflow increase will be zero at the end of 50 years. At that time the basal area per acre will be close to 100 square feet, on a basis of growth performance for older cut-over areas at Coweeta. The streamflow and growth data are combined in Figure 2 to establish an approximate rela-

TABLE 2.—WATER-BALANCE ESTIMATES OF ANNUAL EVAPOTRANSPIRATION FROM MAY 1-APRIL 30

Year	Precipitation (P)	Runoff (RO)	Change in ground-water storage (ΔS)	Evapo- transpiration (Ev)
	Inches	Inches	Inches	Inches
PRETREATMENT				
1936-37	75.88	35.87	-1.25	41.26
1937-38	60.97	24.22	-1.57	38.32
1938-39	84.41	45.56	+2.04	36.81
3-year average				38.80
TREATMENT				
² 1939-40	48.77	19.54	-1.58	30.81
1940-41	54.56	36.33	-1.44	19.67
1941-42	61.35	34.54	+1.63	25.18
1942-43	80.99	48.94	+2.43	29.62
1943-44	76.97	48.02	+1.29	27.66
1944-45	63.44	33.03	-0.37	30.78
1945-46	75.22	46.86	-1.41	29.77
1946-47	66.16	39.42	-1.03	27.77
1947-48	73.89	42.33	+0.87	30.69
1948-49	85.33	51.03	-0.70	35.00
1949-50	89.57	58.55	-0.95	31.97
1950-51	72.75	38.36	+1.34	33.05
1951-52	83.70	50.78	+0.55	32.37
1952-53	62.78	31.82	-2.96	33.92
13-year average				29.80

¹Adjusted from April 30 to nearest day without stormflow.

²Not included in average; cutting treatment September to March.

TABLE 3.—COMPARISON OF CHANGES IN STREAMFLOW AND EVAPOTRANSPIRATION

Year May 1-April 30	Years since treatment	Increases in streamflow ¹	Reduction in evapotranspiration
		Inches	Inches
1940-41	1	14.45	18.33
1941-42	2	10.89	12.82
1942-43	3	10.94	8.38
1943-44	4	9.76	10.34
1944-45	5	7.88	7.22
1945-46	6	9.93	8.23
1946-47	7	7.93	10.23
1947-48	8	7.30	7.31
1948-49	9	5.19	3.00
1949-50	10	5.17	6.03
1950-51	11	5.59	4.95
1951-52	12	5.78	5.63
1952-53	13	4.99	4.08
Average		8.14	8.20

¹From Table 1, column 3.

TABLE 4.—BASAL AREA PER ACRE BY DIAMETER CLASS IN 1934 AND 1952, WATERSHED 13

Diameter class	Year of cruise	
	1934	1952
Inches	Sq. ft.	Sq. ft.
1-3	18.38	33.42
4	4.04	9.85
5	5.04	4.51
6	5.34	2.05
7	4.82	0.87
8	5.32	0.46
9	4.99	0.19
10	5.46	0.12
11	5.74	0.14
12-20	36.78	—
21-32	15.01	—
Total	110.92	51.61

TABLE 5.—BASAL AREA PER ACRE BY SPECIES IN 1934 AND 1952, WATERSHED 13

Species	Year of cruise	
	1934	1952
	Sq. ft.	Sq. ft.
Chestnut	36.79	0.32
Red oaks	15.86	9.98
White oaks	15.28	9.84
Pitch pine	15.68	3.29
Hickory	5.91	3.20
Black gum	3.46	1.31
Dogwood	3.48	5.43
Red maple	3.80	5.86
Black locust	2.28	2.62
Chinquapin	2.91	0.33
Sourwood	2.00	2.05
Yellow-poplar	1.65	3.96
Sassafras	0.69	0.52
White ash	0.11	0.08
Serviceberry	0.13	0.22
Witch-hazel	0.63	1.60
Black birch	0.02	0.42
Miscellaneous	0.24	0.58
Total	110.92	51.61

tionship between increases in streamflow and basal area per acre for this particular experiment. For the first 13 years, the average rate of decrease of the streamflow is 0.19 inch per square foot of basal area per acre, while from the 14th to the 50th year the rate is 0.10 inch.

Discussion

There can be little doubt that the observed streamflow behavior must be due to regrowth of the vegetation on the watershed. In the experiment reported by Hoover (3), where forest vegetation was cut down exactly as in this experiment but regrowth was subsequently kept down by annual mowing, increases in streamflow were held within a narrow range to about 10.5 inches annually. Since quantitative growth information was lacking, a time variable was included in the treatment period in order to introduce the net effect of the growth.

The experiment has shown that under conditions at Coweeta evapotranspiration is very sensitive to changes in vegetative cover. Therefore, to obtain increases in streamflow at a prescribed level, it is necessary to stabilize the vegetation in a condition which will produce those increases. Otherwise, regrowth will tend to diminish the gains at a rate which will depend on the rate of regrowth. With cover stabilized, we have the important advantage that the gains will hold in years of low rainfall when additional supplies of water are most needed.

In some cases, stability of the new vegetation may be achieved as in conversion from forest to grass or vice versa. On areas where timber and water management are integrated, the control of regrowth to provide sustained increases in water yield may be very difficult.

Penman (6) was disturbed because his calculations of evapotranspiration from a Coweeta watershed based on meteorological elements did not agree with water-balance estimates. Obviously, when empirical formulas for estimating evapotranspiration such as those devised by Thornthwaite (8) and Penman (5) for large land areas with all kinds of cover are applied to specific forested watersheds, there is no certainty that the estimates will be in substantial agreement with those based on actual measurement of water-balance elements as presented in this paper.

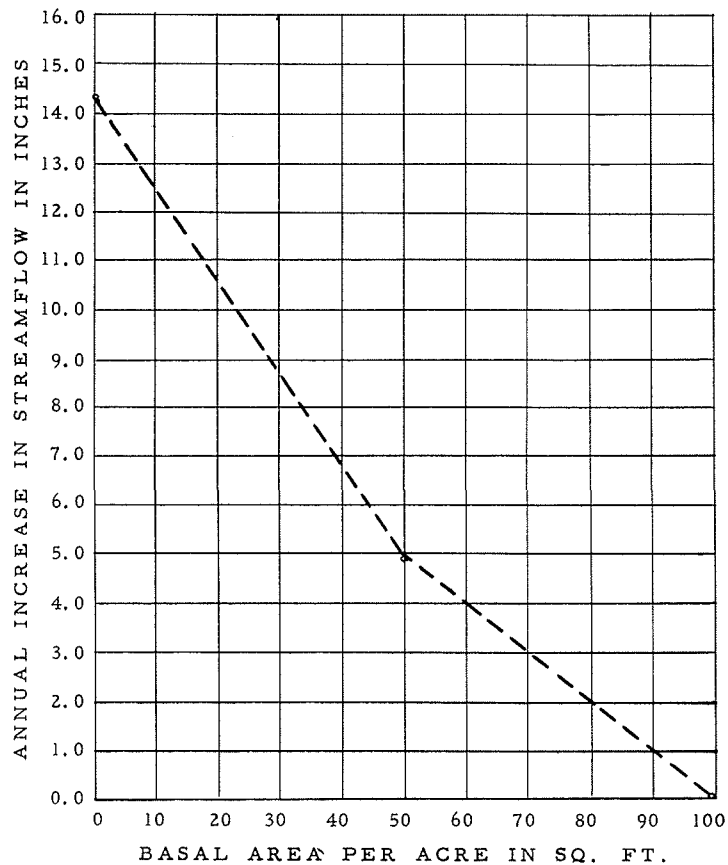


FIG. 2.—Periodic relationship between annual increases in streamflow and basal area per acre.

Summary of Results

The experiment has shown that in the high-rainfall belt of the southern Appalachians cutting down all vegetation on a well-forested watershed produced very large increases in streamflow. These increases accompanying regrowth of the forest stand following clearcutting were remarkably well defined and showed dynamic relationship between vegetation and streamflow, which could be expressed as a linear function of the logarithm of the time variable. Practically all the increase in streamflow came from base flow or groundwater.

The results obtained using paired watersheds were verified by use of the water-balance equation for the treated watershed. The increase in streamflow each year was due to a corresponding real decrease in the amount of evapotranspiration. Annual losses to the atmosphere are quite constant for the Coweeta watersheds because of the high rainfall. This accounts for the fact that the increases in streamflow were statistically independent of the annual precipitation for the range ex-

perienced—from 56 to 89 inches. It should be noted in this connection that the rainfall was not low for a series of years.

Heavy sprout and herbaceous growth sprang up and re-covered the area with surprising speed. Tests show that in the 13th year total annual foliage production, by oven-dry weight, was not significantly different from that of the control watershed. At the end of the 12th year the basal area per acre was 51.6 square feet, or approximately 50 percent of the projected normal stand. The original relatively all-aged stand was replaced by an even-aged stand with essentially a 6-inch diameter limit.

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