USDA Forest Service Research Paper SE-94 May 1972

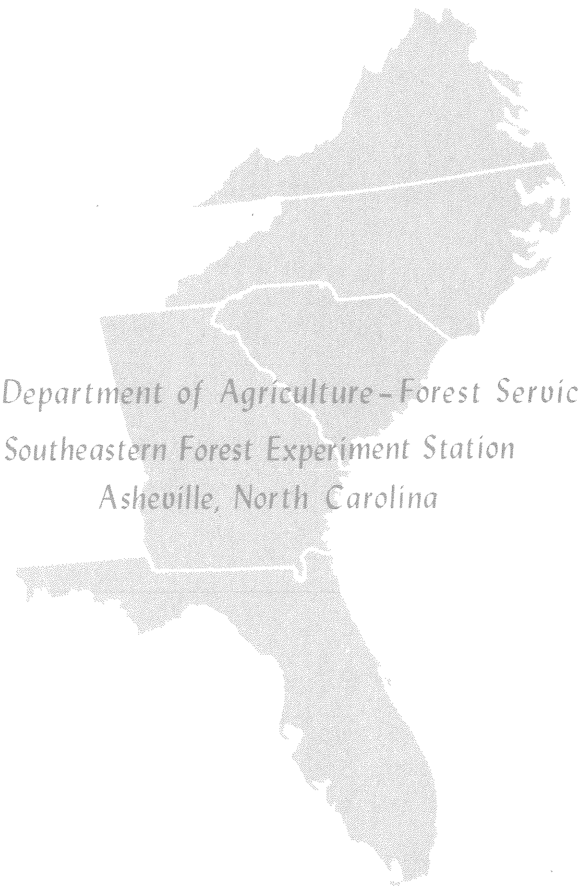
Streamflow Modification Through Management of Eastern Forests

by

James E. Douglass

and

Wayne T. Swank



U.S. Department of Agriculture-Forest Service

Southeastern Forest Experiment Station

Asheville, North Carolina

Streamflow Modification Through Management of Eastern Forests

by

James E. Douglass, Principal Hydrologist

and

Wayne T. Swank, Principal Plant Ecologist

Coweeta Hydrologic Laboratory
Franklin, North Carolina

INTRODUCTION

Protection of the water resource was a primary objective in establishing the National Forest System in America, and improving quantity, quality, and timing of streamflow is an important objective of forest management in certain regions of the United States. Effective management of the forest for increased streamflow presupposes that impact of various management practices on water yield can be predicted, but prediction equations do not exist for most regions.

Because the difference between precipitation input and vapor loss represents the quantity of water available for man's use, the watershed manager seeks to reduce the total vapor loss from forest vegetation in order to increase the flow of streams. Estimating the evaporative loss is possible by using energy balance and water balance methods. Although promising, the energy balance method has not been developed to the point where it is a useful tool for guiding water management activities. The water balance approach derives vapor loss indirectly; its accuracy is usually limited by errors in measuring rainfall and runoff, and unmeasured leakage can be particularly troublesome.

Using paired control and treatment watersheds, the change in yield produced by vegetative changes can be precisely measured and the effect of errors minimized. If leakage occurs, the estimate of change in yield is conservative (5) and represents the minimum effect expected from similar experiments. Thus, the catchment study has been the most definitive method for describing the response of water yield to vegetative manipulation. Although many watershed treatments have been conducted, they have generally been regarded as case studies for different soils, geology, and climate. Hibbert's (6) worldwide survey of catchment studies has been the only attempt to consolidate the results of watershed experiments. He concluded that "...results of individual treatments vary widely and for the most part are unpredictable." Consequently, little information has been available to guide management of forest lands for increased production of water.

This Paper reports on a recently devised, preliminary method for predicting water yield changes which result from cutting hardwood forests of the Appalachians. Predicted yield increases were compared with actual yield increases obtained from a logged watershed in continuing efforts to translate results from catchment studies into practical guides for managing water resources. This Paper also discusses the effects of forest cuttings on other characteristics of streamflow.

EXPERIMENTAL SITES AND WATERSHEDS

The boundary of the Appalachian Highlands Physiographic Division (10) and the four sites[1] of catchment studies are shown in figure 1. Latitudes vary from about 35 degrees to 44 degrees north and precipitation varies from more than 80 inches at Coweeta Hydrologic Laboratory in North Carolina to 48 inches at Hubbard Brook Experimental Forest in New Hampshire. Annual snowfall (not accumulation) averages about 10 inches at Coweeta, 30-40 inches at the Fernow Experimental Forest in West Virginia, 40-60 inches at the Leading Ridge watershed in Pennsylvania, and 60-80 inches at Hubbard Brook. Annual runoff is lowest (15 inches) at Leading Ridge and highest (35-60 inches) at Coweeta (14). Soils range from residual ones 20 feet or deeper at Coweeta to shallow glaciated soils averaging about 5 feet deep at Hubbard Brook. The common characteristic of all sites is a mixed deciduous hardwood forest cover, although species composition varies between sites. Timber resources in the experimental areas are typical of millions of acres of forest land in the Appalachian Highlands.

Table 1 lists the cutting experiments by location and describes features of each experiment. Of the 23 experiments, 13 were conducted at Coweeta, 8 at Fernow, and 1 each at Leading Ridge and Hubbard Brook. Treated catchments ranged in size from 22 to 356 acres, and most major topographic aspects were represented. The type of cutting depended upon study objectives; for example, treatments included cutting all vegetation over part or all of the catchment and cutting or deadening a portion of the vegetation over part or all of the catchment. Individual treatments were applied with and without removal of forest products and, in some instances, with subsequent herbicide control of regrowth.

[1] The Coweeta Hydrologic Laboratory, Fernow Experimental Forest, and Hubbard Brook Experimental Forest are field research installations operated by the Forest Service, USDA. The Leading Ridge watershed is a field research installation operated by the School of Forest Resources, Pennsylvania State University.

We acknowledge the cooperation of W. E. Sopper, Pennsylvania State University, and R. S. Pierce and J. H. Patric, Northeastern Forest Experiment Station, for supplying data for this study.

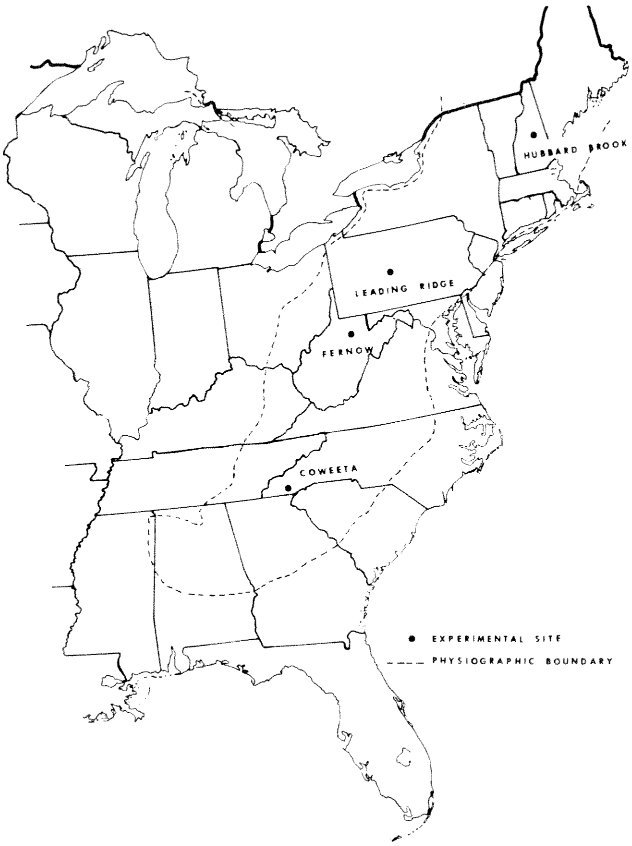


Figure 1.--Location of the four experimental watershed study sites within the Appalachian Highlands.

PREDICTION METHOD

Results from 22 cutting experiments conducted in the Appalachian Highlands are plotted in figure 2. The ordinate is the first-year streamflow increase (the deviation of measured flow the first year after cutting from the expected flow if the vegetation had not been cut). The abscissa is the percentage reduction in forest stand basal area achieved by cutting. In a few cases, the plotted value is a nonsignificant increase judged by the calibration regression error term, but these points are plotted as the best estimate of the increase. Nonsignificant increases occurred only when cuttings removed a small percentage of the total basal area of the stand.

Streamflow response the first year after cutting is quite variable, even between catchments in the same drainage basin and for catchments having relatively similar treatments. The scatter of data results because of differences in slope and aspect of watersheds, climate, vegetative conditions, and because ordinate values are estimated from regression. Nevertheless, figure 2 leaves no doubt that substantial volumes of extra water can be produced by cutting eastern hardwood forests. Cutting part of the timber gives proportionately smaller increases, and there is a lower limit of basal area below which cutting will produce no measurable extra water. When a light partial cut is made, the residual stand may be

Table 1.--Location and description of experimental catchment studies in the Appalachian Highlands

Watershed number	Area	Aspect	Mean flow from forest	Treatment	Basal area treated (cut or deadened)	First-year water yield increase
	Acres		Inches/year		Percent	Inches
COWEETA HYDROLOGIC LABORATORY, FRANKLIN, N. C.						
1	40	S	31	Cove vegetation deadened by chemicals.	25	1.2
				All trees and shrubs cut on entire catchment, no products removed, partially burned.	100	5.8
6	22	NW	33	All trees and shrubs within zone along stream cut, no products removed.	12	0
				Hardwood forest converted to grass, then all vegetation deadened with herbicides except narrow strip alongside stream.	100	10.5
13	40	NE	34	All trees and shrubs cut on entire watershed, no products removed.	100	14.2
				Treatment repeated 23 years later.	100	15.0
17	33	NW	27	All trees and shrubs cut on entire watershed, no products removed.	100	16.3
19	70	NW	48	Laurel (*Kalmia latifolia* L.) and rhododendron (*Rhododendron maximum* L.) understory cut, no products removed.	22	2.0
22	85	N	50	All trees and shrubs within alternate 33-foot strips deadened by chemicals, no products removed.	50	6.1
[1]28	356	NE	60	All trees and shrubs cut on 190 acres, cove forest of 97 acres thinned, no cutting on remaining 69 acres; products removed.	66	6.5
37	108	NE	60	All trees and shrubs cut on entire catchment, no products removed.	100	10.2
40	50	SE	39	Commercial logging with selection cut, products removed.	22	1.7
41	71	SE	54	Commercial logging with selection cut, products removed.	35	2.7
FERNOW EXPERIMENTAL FOREST, PARSONS, W. VA.						
1	74	NE	23	Merchantable trees cut and removed on entire catchment.	85	5.1
2	38	S	26	All merchantable trees 17 inches d.b.h. and above cut and removed.	36	2.5
3	85	S	25	Selected trees above 5 inches d.b.h. cut, products removed.	14	0.3
5	90	NE	30	Selected trees above 11 inches d.b.h. cut, products removed.	22	0.7
6	54	SE	19	All trees and shrubs cut on lower half of catchment, products removed, sprouting controlled with herbicides.	51	6.5
				Remainder (49 percent of basal area) of trees and shrubs cut, products removed.	100	10.2
7	59	E	24	All trees and shrubs cut on upper half of catchment, products removed, sprouting controlled with herbicides.	49	6.1
				Remainder (51 percent of basal area) of trees and shrubs cut, products removed.	100	9.9
LEADING RIDGE, STATE COLLEGE, PA.						
2	106	SE	14	All trees and shrubs cut from 21 acres on lower portion of catchment, products removed, sprouting controlled with herbicides.	29	2.7
HUBBARD BROOK EXPERIMENTAL FOREST, WEST THORNTON, N. H.						
2	39	SE	27	All trees and shrubs cut on entire catchment, products not removed, sprouting controlled with herbicides.	100	13.5

[1] This example watershed was not used to derive figure 2.

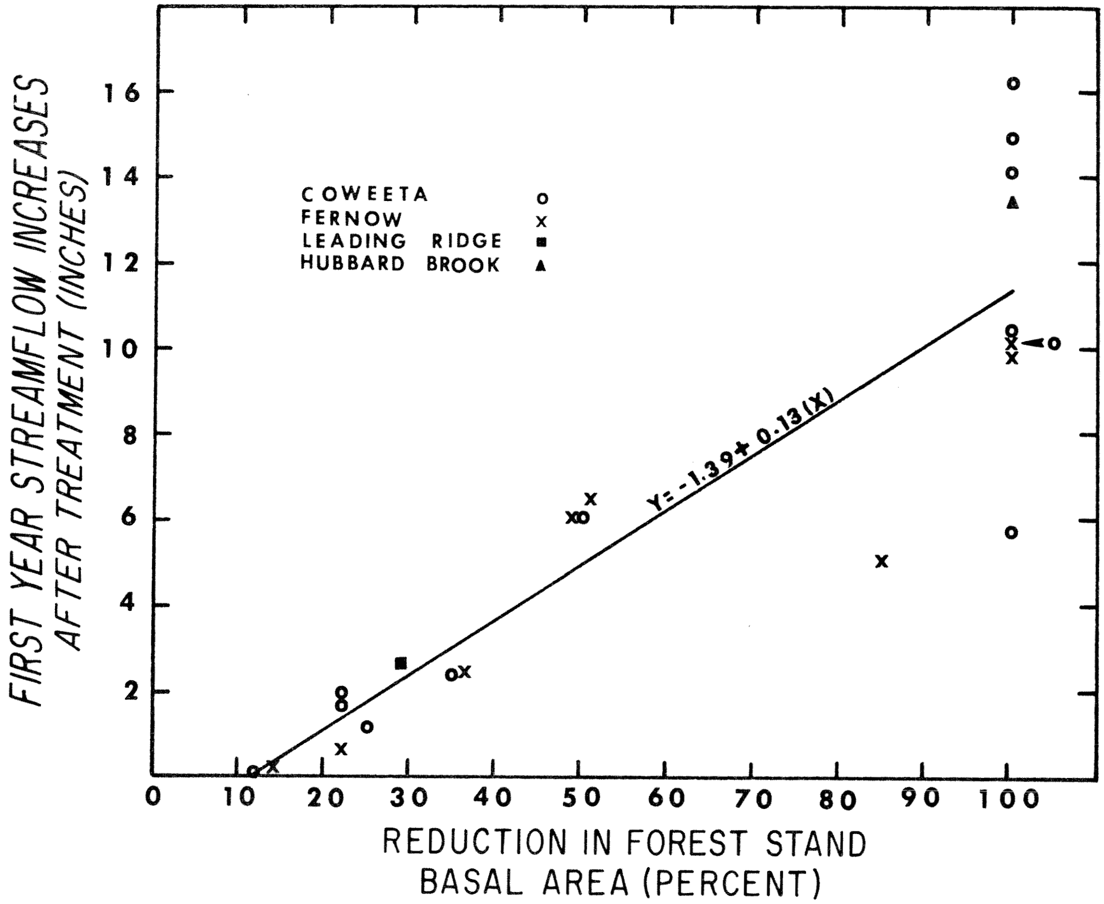


Figure 2.--Relationship between streamflow increase the first year after forest removal and the percentage reduction in forest stand.

capable of evaporating some of the extra water made available by the cutting, and the streamflow increase will be small. Even with the degree of accuracy afforded by the control watershed approach, a small increase in flow may not be detectable because of experimental error.

Catchment experiments have shown that treatment effects are largest the first year after treatment. In subsequent years, as the forest regrows, the evaporating surface area increases and streamflow increases diminish. In figure 3, the duration of streamflow increase has been related to the initial treatment response. The wide scatter of data is largely the result of differences in type of treatment and subsequent rates of regrowth; nevertheless, the depicted relationship indicates proportionality between variables.

If we can estimate the initial streamflow increase from figure 2 and the duration of the increase from figure 3, the total volume of water which accrues from cutting can be approximated from the time trend of treatment effect. Kovner (11) and Hewlett and Hibbert (4) found that initial increase in streamflow declines with the logarithm of time. This trend is defined by the model:

$$Y_i = a + b \log T \qquad (1)$$

where Y_i is the streamflow increase (inches) during the ith year after treatment, T is time (years) after treatment, and a and b are coefficients to be determined. This equation can be solved with figures 2 and 3: knowing the percentage of basal area cut, the initial streamflow increase, a, is defined. Having obtained a, figure 2 is used to estimate duration of the increase, T, at which time streamflow has returned to precutting levels (the yield increase equals zero). Thus figure 2, figure 3, and Equation 1 completely define the streamflow increase obtained by cutting Appalachian hardwood forests.

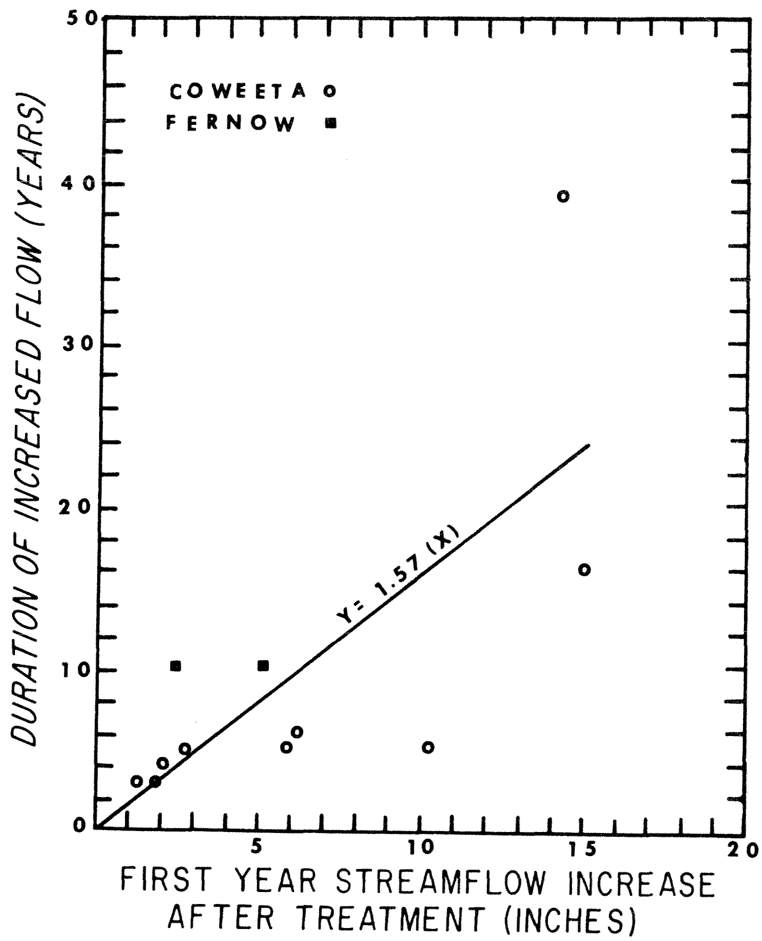


Figure 3.--Relationship between the duration of increase in streamflow and the first-year increase in flow after forest removal.

A PRACTICAL EXAMPLE

High-elevation, hardwood-covered Watershed 28 at Coweeta is 356 acres in size. This watershed was used to demonstrate intensive multiresource management of timber, water, and wildlife resources and recreational opportunity. Description of vegetation, soils, road system, and cutting prescriptions have been published (2). For this example, it is sufficient to state that 190 acres were clearcut and another 80 acres were given a combination thinning and understory cut. An overall 66-percent reduction in forest stand basal area was achieved over 20 months.

From figure 2, a 7.2-inch initial increase in streamflow is expected from the cutting, and from figure 3 the increases in flow are expected to persist until the 11th year. The prediction equation for the increase in annual streamflow for years Y_1, Y_2, Y_i is:

$$Y_i = 7.2 - 6.9 \log T \tag{2}$$

The predicted and measured yield increases for each year since treatment are shown in table 2.

Table 2.--Comparison of predicted and measured streamflow increase for forest cutting on Watershed 28, Coweeta Hydrologic Laboratory, Franklin, N. C.

Year	Predicted increase	Measured increase	Difference in predicted-measured increase
		Inches	
1	7.2	6.5	-0.7
2	5.1	4.0	-1.1
3	3.9	3.1	-0.8
4	3.0	0.9	-2.1
5	2.4	1.1	-1.3
6	1.8	3.2	+1.4
7	1.4	4.1	+2.7
Total	24.8	22.9	-1.9

In this practical example, the predicted first-year streamflow increase was 0.7 inch more than the measured increase. The overestimate was expected because the first-year increase was calculated for the basal area removed over the 20-month period. During the first year of study, the actual basal area removed was somewhat less than this amount. The first-year yield increase determines, to a large extent, subsequent annual increases. As in this case, an overestimate of the first-year increase will usually result in an overestimate of subsequent yearly increases and duration of the cutting effect (an underestimate of the first-year yield increase would have the opposite effect). Nevertheless, for the 7 years of record after cutting, the measured streamflow increase was only 1.9 inches less than was predicted (an underestimate of less than 10 percent). Considering the error in measured first-year increase and the scatter in figures 2 and 3, the agreement between predicted and measured streamflow increase in this example is sufficiently accurate for many purposes.

Reasonable agreement might be expected because Watershed 28 is located at Coweeta, one of the four sites of catchment studies; however, data from this watershed were not used to derive figures 2 and 3. To arrive at the final equations for predicting the first-year yield increase and the duration of the increase, we combined the data from Watershed 28 and the other 22 watersheds. The final equations are:

$$\text{First-Year Yield Increase} = -1.41 + .13\ (\text{Percentage Basal Area Reduction}) \tag{3}$$

$$\text{Duration of Yield Increase} = 1.55\ (\text{First-Year Yield Increase}) \tag{4}$$

YIELD DECREASES

If cutting a forest increases streamflow, then conversely the establishment and growth of a forest stand or reforestation can be expected to reduce streamflow. Fewer experimental data are available on the decrease in water yield associated with regrowth of a forest than are available on the increase in yield from forest cutting. But, Hibbert (6) indicates that streamflow declines by approximately .084 inch for every 1 percent of an area afforested or reforested, and this rate of reduction is smaller than the rate of increase in flow due to deforestation. Hibbert pointed out that this apparent lack of compatibility may not be real but simply may result from an insufficient range in experimental observations. When hardwoods are cut and the site is reforested with hardwoods, streamflow is expected to return to precutting levels when the forest matures. But, if agricultural cropland or grassland is afforested, the subsequent reduction in water yield will be proportional to the evapotranspiration difference between the original cover and that of the forest which replaces it.

Swank and Miner (18) showed conclusively that converting a mixed hardwood stand to eastern white pine substantially reduced streamflow of a southern Appalachian watershed because of interception and transpiration differences between the two forest types. Their information suggests that water supplies could be improved by favoring hardwoods over pine as a cover type for the catchment. In another experiment, Hibbert (7) found that after converting a hardwood-covered catchment to grass, Kentucky 31 Fescue, annual streamflow increased in proportion to the declining productivity of the grass. He found no difference in water yield from the two cover types when productivity of the grass was maintained at a high level by fertilization, but streamflow increased by about 5 inches annually as the productivity of the grass declined over a period of 5 years. These studies illustrate the need for careful evaluation of vegetative alternatives in the management of water resources.

TIMING OF YIELDS

One objective of water resource development is to make water available when it is needed and in sufficient quantities so that withdrawals by man will not damage or destroy the aquatic environment. Augmentation of streamflow is often required during periods of low flow, and the engineer accomplishes this by controlled discharge of impounded water. Resource managers should also be aware of the opportunities for regulating the time distribution of flow afforded by vegetative manipulation.

The seasonal distribution of an increase (or decrease) in annual flow resulting from forest cutting varies somewhat throughout the Appalachian Highlands. At Coweeta, Watershed 17 was clearcut and maintained in a low coppice-herb condition by annual recutting for 7 years. Figure 4 shows the average monthly flow under a hardwood cover and the average monthly increase in flow during the recutting period. About 60 percent of the 8-inch increase in annual flow came in the period July through November, and the remainder came during the winter months. During the months of low flow (August, September, October), flow was increased by nearly 100 percent. Other experiments at Coweeta confirm this seasonal response to cutting.

In West Virginia where soils are shallower, almost all significant streamflow increases appeared from June through November (17). More important, deforestation of half a watershed in West Virginia changed the flow characteristic from intermittent to perennial (15). In Pennsylvania (13) and New Hampshire (9) significant increases in flow began in March because snow melted earlier than normal. Starting in June and lasting through October or November, large increases in streamflow resulting from decreased evapotranspiration were observed. Thus, experimental results consistently show that largest increases in flow obtained by cutting forests appear mostly in the growing and early dormant seasons when demand for water is greatest and flows are normally least.

The forest hydrologist is limited in exercising control over the flow regime--he cannot "turn on or turn off the tap" at will. Precipitation distribution and the melting of snow are important factors in determining when the extra water will be delivered. Hewlett (1) observed that monthly increases are strongly correlated with monthly rainfall at Coweeta where "it takes water to fetch water." When monthly rainfall is below some threshold amount, no increase in flow occurs, and base flow is derived mostly from water stored deep in the soil mantle. Rainfall above this threshold value will trigger the release of some of the accumulated evapotranspiration savings stored in the soil profile. Because of the large storage capacity of soils at Coweeta, some savings do not appear until January or February. At Fernow and Hubbard Brook, where soils are shallower, the accumulated reduction in evapotranspiration is recovered by December at the latest.

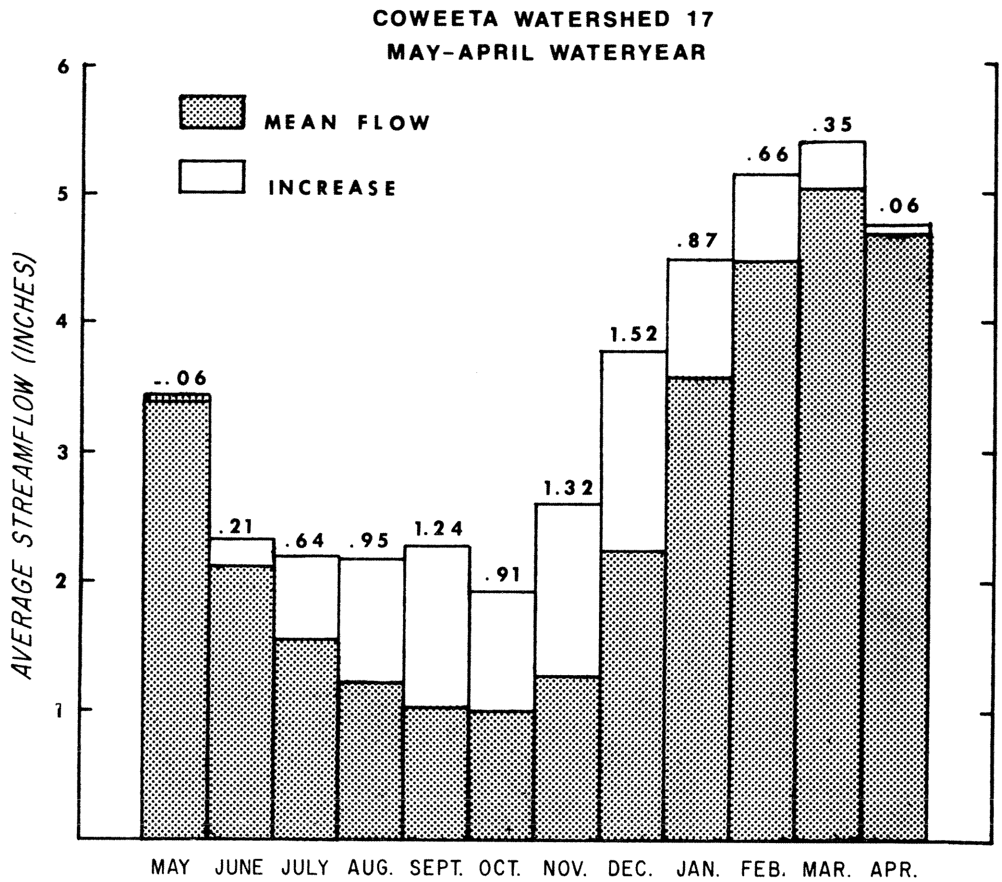


Figure 4.--Timing of mean flow before treatment and the average increase in flow produced by a Coweeta watershed which was clearcut and recut annually for 7 years.

STORMFLOW PEAKS AND VOLUMES

Experimental treatments which were specifically designed to document maximum sustained streamflow increases have shown that appreciable increases in peak discharge and stormflow volumes can occur. At Fernow, the lower half of one watershed and the upper half of a different watershed were deforested (15), and herbicides were used to control regrowth. Although no changes in dormant-season peak flows occurred on either treated catchment, peak discharge was significantly increased during the growing season on the watershed which had the lower half deforested. In an experiment at Hubbard Brook (9), all timber on a watershed was cut, no products were removed, and the watershed was maintained free from vegetation by herbicide treatment. The researchers found that growing season storm peaks larger than 20 cubic feet per second per square mile (c. s. m.) increased 22 to 246 percent and stormflow volumes increased 115 to 300 percent. However, the total stormflow volume in excess of 20 c. s. m., the primary contributor to downstream flooding, was less than 1 area-inch for the first 3 years after treatment.

An experiment at Coweeta indicates what may be a lower level of the stormflow response to clear-felling timber than that obtained farther north. In the experiment all vegetation was cut, but no forest products were removed and no roads were constructed on the watershed. Hewlett and Helvey (3) found that stormflow volume was increased by 11 percent overall (significant at .001 level) and peak discharge was increased by 7 percent (.05 level) but other hydrograph flow characteristics were not changed significantly. Individual stormflow increases attributed to deforestation ranged from 0 for small storms to 1.9 inches (a 22-percent increase) during a regional record storm lasting 7 days.

The response of peaks and stormflow volumes to commercial clear-felling may fall between these treatment extremes, and the response to partial cuts will be less than from clear-felling.

At Fernow, where a commercial clearcutting was done "loggers choice"--without stringent controls on road construction and logging methods--both peak discharge and stormflow volumes were increased somewhat (16). On the Leading Ridge catchment, where the lower 20 percent of a watershed was clearcut and logged, peak flows increased during the growing season when antecedent soil moisture content and rainfall intensity were high (13). No significant increase in peaks was observed for storms during the dormant season.

WATER QUALITY

Numerous measures of water quality are possible, depending upon the intended use of water resources. In forest watershed experiments, only temperature and turbidity have been measured with any consistency. Swift and Messer (19) measured effects of various types of vegetative management on weekly maximum stream temperatures at Coweeta. The greatest increase occurred when a hardwood forest was converted to a mountain farm--normal summer maximum temperatures of 67° F. were raised by 9 to 12 degrees. When hardwood trees in a cove site were deadened, summer maximum temperatures increased by 4 to 5 degrees, and winter maximums were only slightly affected. Subsequent clearcutting of the deadened timber raised summer maximums 5 to 6 degrees and winter maximums 4 degrees above the temperatures expected of streams flowing from undisturbed forests. An understory cut had little effect on summer or winter maximums, and after one clearcut watershed was revegetated by a dense coppice stand, summer maximum temperatures were slightly reduced. Studies have generally shown that forestry practices which open up the stream channel to direct insolation are the only practices which increase stream temperatures (13, 15).

Cutting trees, per se, does not influence stream siltation and turbidity, but improper road construction and removal of forest products have adverse effects. Hoover (8) reports turbidities of 7,000 p.p.m. during large storms at places logging methods and roads were not subject to controls, compared with 80 p.p.m. from an undisturbed watershed. Reinhart et al. (16) report storm period turbidities as high as

56,000 p.p.m. on a commercial clearcut where roads and logging methods were loggers choice, while maximum turbidity from a nearby undisturbed forested watershed was only 15 p.p.m. These high turbidities demonstrate the potential damage which can occur without controls to protect the water resource. On the other hand, when proper logging methods and road location and construction procedures are followed, only small and temporary increases in turbidity occur (1, 12, 13, 16). There is no longer any question that increases in both temperature and turbidity can be held within tolerable limits by exercising reasonable care in managing forested watersheds.

The impact of forest manipulations on water chemistry has seldom been documented. The most complete study in the East has been at Hubbard Brook where a catchment was clearcut, no products were removed, and herbicides prevented vegetative growth for three successive summers. Likens et al. (12) found in stream water large increases in concentrations of most ions studied and nitrate concentrations exceeded, almost continuously, the maximum levels for drinking water for the first 2 years after treatment. But this was an experimental cutting and not a recommended forest management practice because the watershed was intentionally maintained free from vegetation. Contrary to findings at Hubbard Brook, the results of experimental treatments at Coweeta have not shown an accelerated loss of ions to the streams.[2] Further study is needed to provide adequate information on the interrelationships between common management practices and water chemistry.

DISCUSSION AND CONCLUSIONS

In the past, forest hydrologists have been reluctant to extend results from experimental watersheds to other forested areas. The reluctance is understandable for two reasons. First, results derived in one region have sometimes been indiscriminately applied in another geographic area where similar responses could not be expected. In this report, the area for which the relationships were developed is delineated in figure 1. The reader should be aware, however, that in limestone formations the increase may not appear in the basin in which the cutting is made. Part of the increase may leave through underground channels to reappear at some point farther downstream. Also, the yield increase obtained from cutting pine will be greater than from cutting hardwoods (17, 18); therefore, Equation 3 is valid only for forests comprised primarily of mature hardwoods and will underestimate streamflow increases from coniferous forests.

A second reason for reluctance to extend catchment results is the large difference in streamflow increase which is sometimes observed after two watersheds are treated in a similar manner. This is apparent

[2] Swank, W. T., and Elwood, J. W. The seasonal and annual flux of cations for forested ecosystems in the Appalachian Highlands. (Paper presented at Second Natl. Biol. Congr., Miami Beach, Fla., Oct. 23-26, 1971.)

from data for the 100-percent cuts (fig. 2). We know that much of the observed scatter of data occurs because the watersheds differed in slope, aspect, vegetative density, rainfall, and perhaps other factors; thus, the scatter was to be expected. We concede that a high degree of accuracy may not be obtained for an individual watershed which varies appreciably from the "average" watershed represented by Equations 3 and 4. To dwell on this point, however, is to miss the significance of the information presented: The ability to predict changes in water yield makes it possible, for the first time, to consider vegetative management in protecting and developing water resources for large areas. Because a large watershed contains a variety of slopes, aspects, soils, and vegetative conditions, Equations 3 and 4 should provide a reasonably good estimate of the average streamflow response to forest cuttings.

We can conclude from the experimental watershed evidence in the Appalachian Highlands that cutting forest vegetation has a favorable impact on the water resource by supplementing man's supply of fresh water when consumptive demands are most critical. And, the amount of extra water produced can be predicted with a degree of accuracy which is sufficient for many purposes. Although heavy forest cuttings will usually increase some stormflow characteristics on that portion of the watershed cut over, regulated cutting on upstream forest land will not produce serious flood problems downstream. Studies have also demonstrated the adequate methods that will hold water temperature and turbidity increases within tolerable limits--usually it is a question of applying existing knowledge in the management of the watershed. Much less is known about the influence of forest cutting on the chemical composition of water.

As studies of cause and effect relationships between vegetation, soils, climate, and streamflow produce new information, improved models will be developed for predicting the effects of various forest management practices on the quality, quantity, and timing of streamflow. Meanwhile, the summary data from these 23 watershed experiments provide the best information available on how cutting hardwood forests in eastern United States modifies streamflow.

LITERATURE CITED

(1) Hewlett, J. D.
1967. Will water demand dominate forest management in the East? Soc. Am. For. Proc. 1966: 154-159.

(2) ________ and Douglass, J. E.
1968. Blending forest uses. Southeast. Forest Exp. Stn., U.S.D.A. Forest Serv. Res. Pap. SE-37, 15 pp.

(3) ________ and Helvey, J. D.
1970. Effects of forest clear-felling on the storm hydrograph. Water Resour. Res. 6: 768-782.

(4) ________ and Hibbert, A. R.
1961. Increases in water yield after several types of forest cutting. Int. Assoc. Sci. Hydrol. Bull. 6(3): 5-17.

(5) ________ Lull, H. W., and Reinhart, K. G.
1969. In defense of experimental watersheds. Water Resour. Res. 5: 306-316.

(6) Hibbert, A. R.
1966. Forest treatment effects on water yield, pp. 527-543. In W. E. Sopper and H. W. Lull [ed.], International symposium on forest hydrology. Natl. Sci. Found. Adv. Sci. Semin. Proc. 1965.

(7) ________
1969. Water yield changes after converting a forested catchment to grass. Water Resour. Res. 5: 634-640.

(8) Hoover, M. D.
1952. Water and timber management. J. Soil & Water Conserv. 7: 75-78.

(9) Hornbeck, J. W., Pierce, R. S., and Federer, C. A.
1970. Streamflow changes after forest clearing in New England. Water Resour. Res. 6: 1124-1132.

(10) Hunt, C. B.
1967. Appalachian Highlands, pp. 166-204. In James Gilluly and A. O. Woodford [ed.], Physiography of the United States. San Francisco, Calif.: W. H. Freeman and Co.

(11) Kovner, J. L.
1957. Evapotranspiration and water yields following forest cutting and natural regrowth. Soc. Am. For. Proc. 1956: 106-110.

(12) Likens, G. E., Bormann, F. H., Johnson, N. M., and others
1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook Watershed Ecosystem. Ecol. Monogr. 40: 23-47.

(13) Lynch, J. A.
1969. Changes in streamflow following partial clearcutting on a forested watershed. M.S. Thesis, Pa. State Univ. Dep. For. & Wildl.

(14) Miller, D. W., Geraghty, J. J., and Collins, R. S.
1962. Water atlas of the United States. Water Inf. Cent., Inc., Port Washington, N.Y., 81 pp.

(15) Patric, J. H., and Reinhart, K. G.
1971. Hydrologic effects of deforesting two mountain watersheds in West Virginia. Water Resour. Res. 7: 1182-1188.

(16) Reinhart, K. G., Eschner, A. R., and Trimble, G. R., Jr.
1963. Effect on streamflow of four forest practices in the mountains of West Virgin a. Northeast. Forest Exp. Stn., U. S. Forest Serv. Res. Pap. NE-1, 79 pp.

(17) Rothacher, Jack
1970. Increases in water yield following clearcut logging in the Pacific Northwest. Water Resour. Res. 6: 653-658.

(18) Swank, W. T., and Miner, N. H.
1968. Conversion of hardwood-covered watersheds to white pine reduces water yield. Water Resour. Res. 4: 947-954.

(19) Swift, L. W., Jr., and Messer, J. B.
1971. Forest cuttings raise temperatures of small streams in the southern Appalachians. J. Soil & Water Conserv. 26: 111-116.

*U.S. GOVERNMENT PRINTING OFFICE: 1972-745-563/5042, Region No. 4

Douglass, James E., and Swank, Wayne T.
1972. Streamflow modification through management of eastern forests. Southeast. Forest Exp. Stn., USDA Forest Serv. Res. Pap. SE-94, 15 pp.

Equations for predicting the first-year yield increase, duration of the increase, and the total volume of water which occurs from cutting forests are presented. The equations are based on a summary of 22 experimental cuttings of hardwood forests in the Appalachian Highlands. Predicted yields are compared with actual yields obtained from a logged watershed. The paper also discusses the effects of forest cutting on the seasonal distribution of increased annual flow, stormflow peaks and volumes, and water quality characteristics.

Douglass, James E., and Swank, Wayne T.
1972. Streamflow modification through management of eastern forests. Southeast. Forest Exp. Stn., USDA Forest Serv. Res. Pap. SE-94, 15 pp.

Equations for predicting the first-year yield increase, duration of the increase, and the total volume of water which occurs from cutting forests are presented. The equations are based on a summary of 22 experimental cuttings of hardwood forests in the Appalachian Highlands. Predicted yields are compared with actual yields obtained from a logged watershed. The paper also discusses the effects of forest cutting on the seasonal distribution of increased annual flow, stormflow peaks and volumes, and water quality characteristics.

Douglass, James E., and Swank, Wayne T.
1972. Streamflow modification through management of eastern forests. Southeast. Forest Exp. Stn., USDA Forest Serv. Res. Pap. SE-94, 15 pp.

Equations for predicting the first-year yield increase, duration of the increase, and the total volume of water which occurs from cutting forests are presented. The equations are based on a summary of 22 experimental cuttings of hardwood forests in the Appalachian Highlands. Predicted yields are compared with actual yields obtained from a logged watershed. The paper also discusses the effects of forest cutting on the seasonal distribution of increased annual flow, stormflow peaks and volumes, and water quality characteristics.

Douglass, James E., and Swank, Wayne T.
1972. Streamflow modification through management of eastern forests. Southeast. Forest Exp. Stn., USDA Forest Serv. Res. Pap. SE-94, 15 pp.

Equations for predicting the first-year yield increase, duration of the increase, and the total volume of water which occurs from cutting forests are presented. The equations are based on a summary of 22 experimental cuttings of hardwood forests in the Appalachian Highlands. Predicted yields are compared with actual yields obtained from a logged watershed. The paper also discusses the effects of forest cutting on the seasonal distribution of increased annual flow, stormflow peaks and volumes, and water quality characteristics.