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EFFECTS OF MANAGEMENT PRACTICES ON WATER QUALITY AND QUANTITY: COWEETA HYDROLOGIC LABORATORY, NORTH CAROLINA

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ABSTRACT. Results from nearly 40 years of watershed experiments at Coweeta are summarized. An equation is presented to predict the annual increase in streamflow from the percent basal area cut and from the theoretical extra-terrestrial radiation load for the watershed. Timing of the increased flow from watershed experiments depends on the magnitude of the increase, but results consistently show that much of the increase appears in the low-flow season. Two watershed experiments indicate that conversion of hardwoods to white pine substantially reduces monthly and annual streamflow. Conversion of a hardwood-covered watershed to grass produces up to 5.8 inches of increased flow per year. Although some increase in nutrient export occurs from forest cuttings and species conversions, the increase is well within drinking-water standards.

SINCE THE 4,000-acre Coweeta Experimental Forest was established in 1933, the research effort there has been to determine the effects of man's use of the forest on the quality, quantity, and timing of streamflow. About 20 controlled watershed experiments and many plot and laboratory studies have taken place. The results provide useful information to the municipal watershed manager interested in improving water supplies. These results, when combined with those from the other sites in the Appalachian Highlands, provide the most complete and detailed information available anywhere on the response of streams to management by man.

DESCRIPTION OF THE BASIN

Climate

The marine climate of the basin and surrounding area is characterized by cool summers and mild winters. Maritime tropical air masses which develop over the Gulf of Mexico, Caribbean Sea, and Atlantic Ocean are the primary source of precipitation. Rainfall occurs from frontal, convection, and orographic and occasionally from cyclonic storms.

Precipitation for the basin averages 80 inches annually and is relatively uniform throughout the year. The lowest and highest rainfall months are October with about 4.5 inches and March with nearly 8 inches. Rainfall extremes of over 10 inches can occur during any month, but rainfall is less than 2 inches per month only 5 percent of the time. Precipitation varies widely over short distances because topographic features modify wind patterns and rainfall distribution. Also, an orographic effect causes an approximate 13-inch difference in rainfall between low and high elevation watersheds.

The maximum and minimum air temperatures on record are 98 and —15°F. Annual maximums may occur anytime between June and the end of September, and minimums can occur between November and March. The average maximum and minimums are 92° and 1°F, respectively; and the mean annual temperature is 54.7°F. Pan evaporation averages 35 inches and has varied from 31 to 39 inches ± a standard error of 0.35 inch. Less than 1 inch of pan evaporation is common in December and January; and between May and October, pan evaporation ranges from about 3 to 5 inches per month.

Geology, Physiography, Soils

The laboratory is in the Nantahala range of the Blue Ridge Mountains. Underlying rock is classified as Carolina gneiss from the Precambrian era. Granite gneiss, mica gneiss, and mica schists are all represented and have undergone complex folding.

Topography is steep, and elevations range from 2,220 to 5,223 feet. Average slope of the basin (max.-min. elevation/distance) is 19 percent, but individual watersheds are considerably steeper. Slopes in places exceed 100 percent, and some rock outcrops are found on steep slopes at high elevations.

Soils vary because of differences in parent material, topography, and elevation. At lower elevations, soil horizon development is complete, but immature soils are found on higher, cooler sites. Soils are highly permeable; infiltration rates frequently exceed 50 inches per hour, and runoff over the soil surface is virtually unknown on undisturbed sites. The regolith is deep; drilling has shown that porous material is sometimes over 70 feet deep and averages perhaps 20 feet deep.

Vegetation

Basin vegetation was originally dominated by American chestnut, oak, and hickory. In 1909, several small logging operations began and continued intermittently until 1918, when the land was acquired and timber rights reserved by the Forest Service. Logging continued until 1923, but no trees smaller than 15 inches diameter on the stump were cut. Cruises made in 1933 showed that basal area at mid and upper elevations often exceeded 150 square feet/acre. Between 1930 and 1945, chestnut was blight-killed, and basal area was reduced on all watersheds.

Currently, about 60 species of hardwoods are indigenous in the basin; and hemlock, pitch pine, and eastern red cedar are the native conifers. The type groups, as described by the Society of American Foresters, are oak-hickory, pitch pine-oak, northern red oak, and yellow-poplar. The abundant understory is composed of hardwood saplings, mountain laurel, rhododendron, blueberry and huckleberry, azalea, and less numerous trees and shrubs. Ground cover consists of grasses, anemones, asters, bedstraw, ferns, trilliums, violets, mayapples, and mosses.

TREATMENT EFFECTS ON WATER YIELD

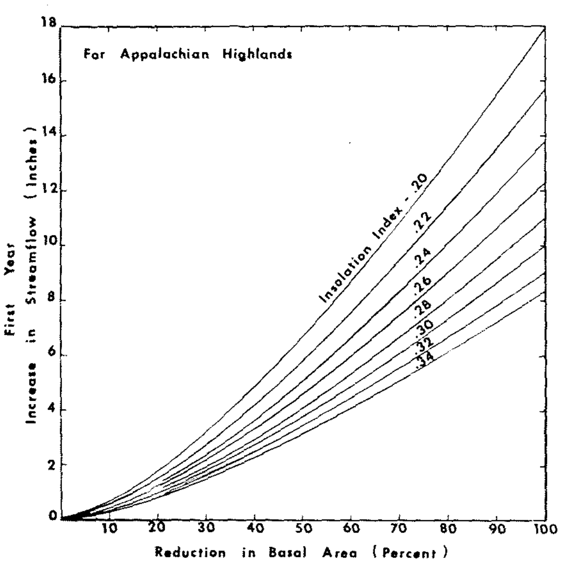
Water yields have been measured at Coweeta after cutting or deadening part or all of the vegetation and after conversion from hardwood to another cover type.

In his survey paper, Hibbert *(1966)*

concluded that the increase in streamflow after removal of hardwood cover at Coweeta was proportional to the amount of cover removed. He also noted that the streamflow increase was much greater for north- than for south-facing watersheds. Prediction of the increase in flow after cutting or deadening the forest can be improved simply by grouping watersheds by aspect.

To explain the difference in streamflow observed when north- and south-facing watersheds are cut, Swift *(1960)* studied the theoretical solar energy available for evapotranspiration. He found little difference in incoming extraterrestrial radiation during the growing season but considerably more radiation on south- than north-facing watersheds during the dormant season. Total and net radiation patterns were found to be similar in form to theoretical patterns *(Swift 1972)*, and we hypothesized that streamflow response to cutting was inversely proportional to solar energy input.

Figure 1.—First-year increase in streamflow determined from the percent reduction in forest stand basal area and the insolation index of the watershed.



Using data on basal area cut and potential insolation from Coweeta, Hubbard Brook, Fernow, and Pennsylvania State University watersheds, a prediction equation was derived for the first-year streamflow increase after cutting hardwood forests. Potential insolation on a map area basis was calculated by the methods of Lee *(1963)* and Swift *(1973)*.

The model for predicting the first-year change in yield is:

$$\triangle Q = a \left(\frac{X_1}{X_2}\right)^b$$

where $\triangle Q$ is the first-year increase in streamflow in inches, X_1 is the percent basal area cut, X_2 is potential annual insolation in langleys (insolation index), and a and b are coefficients. For convenience, the insolation index for each watershed was coded by multiplying by 10^{-6}. Regression analysis yielded the equation

$$\triangle Q = .00224 \left(\frac{X_1}{X_2}\right)^{1.4462}$$

This equation whose r^2 is 0.89, is graphically represented in figure 1.

To predict the increase in streamflow for any year after silvicultural practices are applied, the first-year increase, the duration of the increase, and a model for describing the time-duration relationship of the increases in streamflow are required. Douglass and Swank *(1972)* presented the time-duration model for a regrowing forest as:

$$\triangle Qi = a + b(\log Ti)$$

where $\triangle Qi$ is the increase in flow in year i, a is the first-year increase, Ti is the ith year after treatment, and b is a coefficient. The total duration of an increase in streamflow with regrowth allowed is estimated from the relationship between the first-year streamflow increase and duration of increased flow observed on experimental watersheds. The duration of the increase is approximately equal to 1.57 times the first-year yield increase.

To illustrate the use of these equations, consider a hardwood forest, a 50-percent basal area cut, and a potential insolation of 260,000 calories/square centimeter. Using Equation 1, the first-year yield increase is

$$\triangle Q = .00224 \left(\frac{50}{.26} \right)^{1.4462}$$

$$\triangle Q = 4.49 \text{ inches}$$

The duration of the increase is estimated to be

$$T = 1.57 \text{ (first-year increase)}$$
$$T = 1.57 \ (4.49)$$
$$T = 7.04 \text{ rounded to 7 years}$$

The estimating equation for a yield increase in any year i is obtained by solving Equation 2 for b when $T = 7$ and $\triangle Q_7 = 0$. Thus,

$$\triangle Q_7 = a + b(\log Ti)$$
$$0 = 4.49 + b(\log 7)$$
$$b = -5.31$$

and the final equation becomes

$$\triangle Qi = 4.49 - 5.31(\log Ti).$$

The expected yearly increases in streamflow are

Year after cutting	*Increase, in inches*
1	4.49
2	2.89
3	1.96
4	1.29
5	.78
6	.36
Total	11.77

Now consider the second type of experiment. Conversions of vegetative types at Coweeta have produced dramatic changes in streamflow, which should be of interest to managers of municipal watersheds.

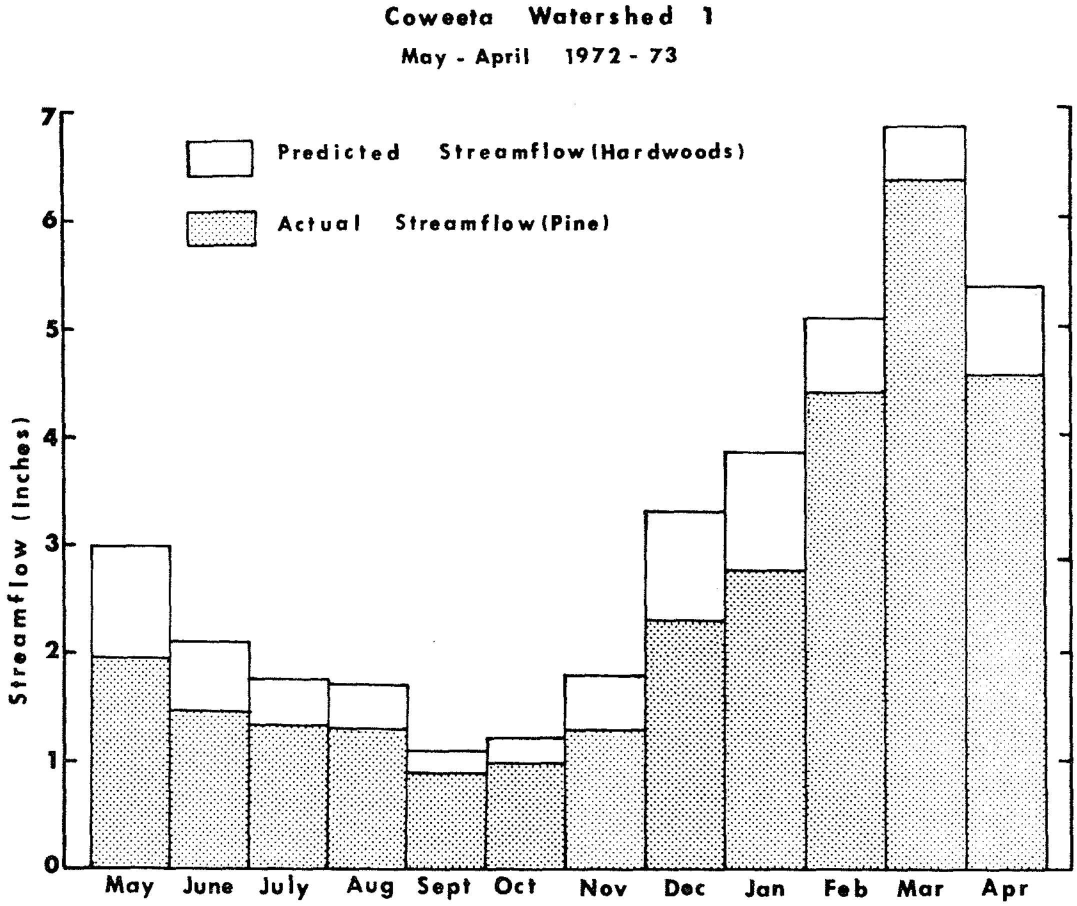
In two experiments, conversion of hardwoods to white pine on a north- and south-facing watershed greatly reduced streamflow. For the first 6 years, the streamflow increases were about as expected for clearcut hardwood forests. Then, streamflow on both watersheds declined at a rate of 1 to 2 inches per year for the next 3 years. By age 10 years, the white pine was using more water than the original hardwood cover *(Swank and Miner 1968)*.

Over the last 4 years, the rate of streamflow reductions has tended to level off; but in 1973, when the pines were about 16 years old, flow was approximately 8 inches (25 percent) less than the flow expected if the watersheds had remained in a hardwood cover.

On a south-facing watershed, monthly streamflow reductions of 0.5 to 1.1 inch were observed during the dormant and early growing season (November through June) of 1972-73 (fig. 2). Streamflow was reduced about 0.4 inch in July and August, and reductions in flow tapered off to about 0.2 inch in September and October. Although reductions appear to be small in August through October, streamflow is normally lowest during these months. These reductions represent a 16- to 30-percent decrease in monthly flow from the previous hardwood cover. Similar reductions in streamflow were observed for the north-facing white pine-covered watershed.

The greater evaporative losses from pine than from hardwoods are due to greater interception and transpiration losses. Experimental data derived from Helvey's studies *(1967)* showed that interception and subsequent evaporation of rainfall is greater for pine than hardwoods during the dormant season. Interception loss is a function of the plant

Figure 2.—Changes in streamflow after a south-facing hardwood-covered watershed was converted to white pine in 1957.

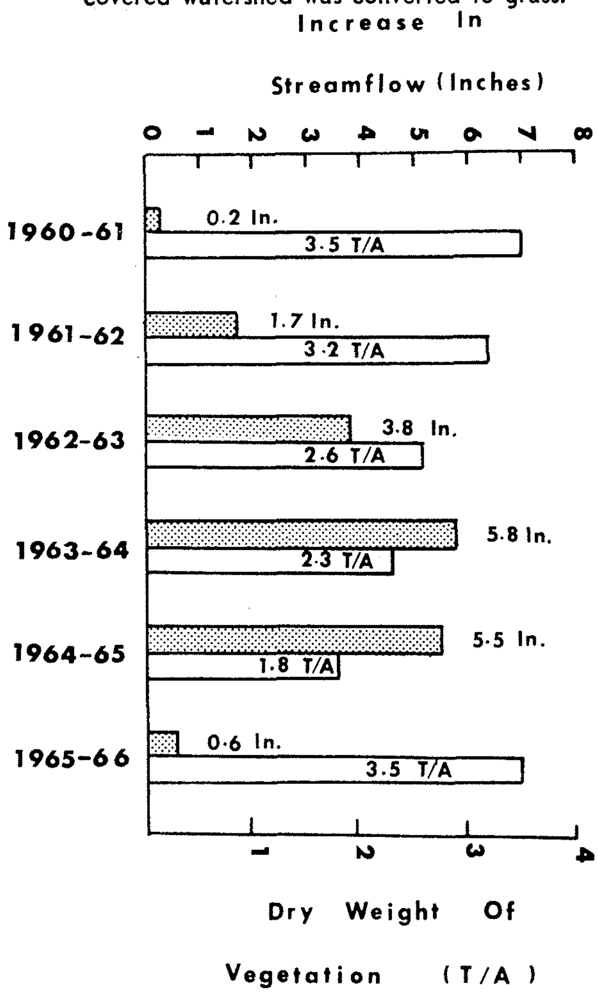


surface area, and the surface area in a hardwood stand is drastically reduced by leaf fall. Thus, in the dormant season, the ratio of leaf surface area to ground area (leaf area index or LAI) for hardwoods is less than 1, whereas Swank and Schreuder *(1973)* estimated that the LAI was 9.9 for the white pine on Watershed 1 in the winter of 1972. Consequently, less precipitation reaching the soil under pine caused lower streamflow during the dormant season. A further reduction in streamflow is attributed to greater transpiration within the pine canopy, at least during certain months.

In spring and summer, atmospheric conditions favor high evaporation. In April and May, when pine is in full leaf and hardwoods are leafing out, combined interception and transpiration losses are much greater from pine. Even after hardwoods are in full leaf, maximum LAI is only about 6 *(Whittaker and Woodwell 1967)* compared to a peak LAI of 17.8 for the pine on Watershed 1 *(Swank and Schreuder 1973)*. Although Raber *(1937)* concluded that the summer transpiration rate of hardwoods per unit of leaf area is greater than for conifers, transpiration per stand may be greater for pine because of the larger transpiring surface. Greater transpiration and greater interception losses cause streamflow from white pine forests to be lower than from hardwood forest throughout the year. The conclusion is inescapable: If maximum water yield is desired, conifers are a poor choice for a watershed cover.

Conversion from hardwood to grass also significantly alters streamflow. Hibbert *(1969)* removed merchantable timber from a 22-acre hardwood forest, prepared a seedbed by burning, grubbing, and harrowing, applied 3 tons of lime and 1 ton of 2-12-20 fertilizer per acre, and seeded Kentucky 31 fescue at a rate of 20 pounds per acre. An increase in water yield was expected, but it did not appear in the first year after treatment. Grass productivity was very high — 3.5 tons of dry matter per acre — but it declined to 1.8 tons per acre by the end of the 5th growing season. As grass productivity declined, streamflow increased. During the 4th and 5th year under grass, the watershed yielded over 5 inches of extra water each year (fig. 3). To verify the inverse relation between change in streamflow and grass productivity, the grass was refertilized in 1965; productivity increased to 3.5 tons per acre, and streamflow again dropped back to that expected from a hardwood cover. Grass also appeared to evaporate more water in the spring and less water in the late summer than the original forest cover. Thus, a grass cover of low vigor can significantly increase streamflow.

Figure 3.—Annual yield change and gross dry-matter weight per acre after a hardwood-covered watershed was converted to grass.

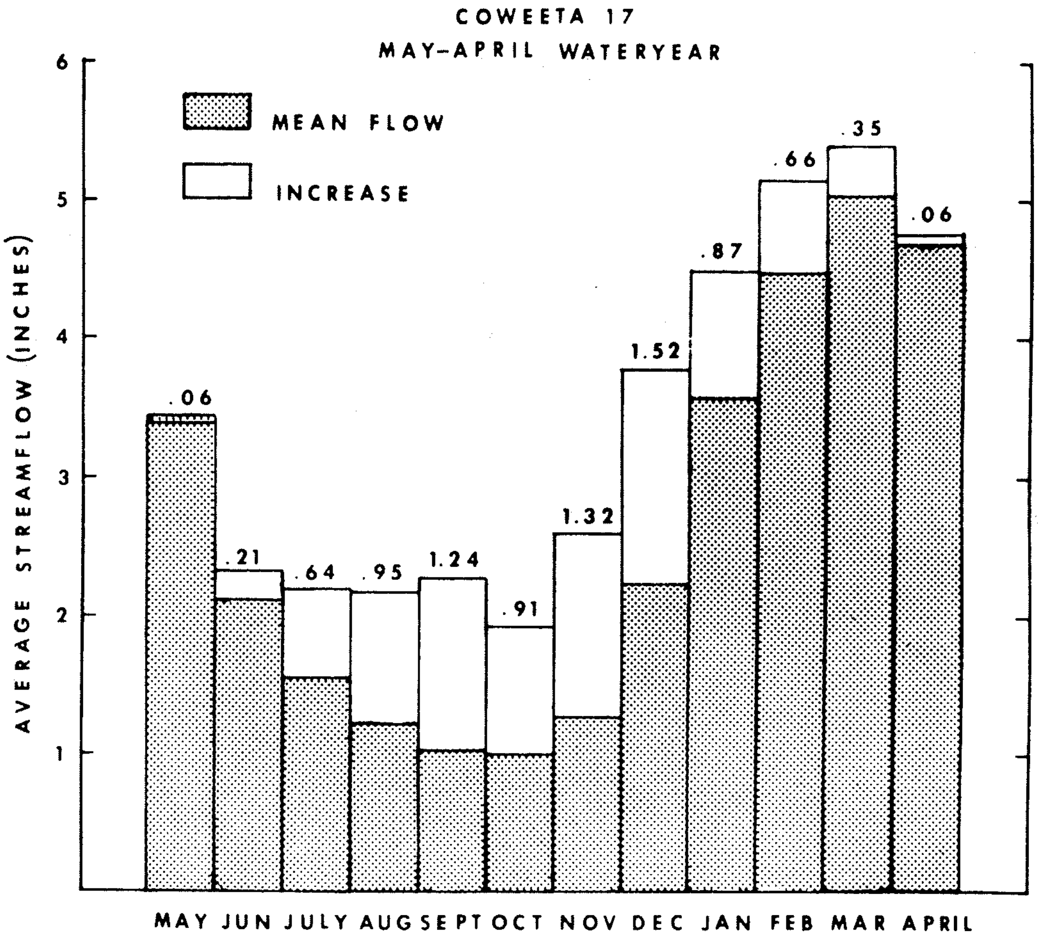


TREATMENT EFFECTS ON DISTRIBUTION OF FLOW

Douglass and Swank *(1972)* presented data on average monthly flow rates before trees were cut and during 7 years when sprouts were cut annually from Watershed 17 (fig. 4). These data are representative of other experiments at Coweeta. A forest cover had no measurable effect on monthly flow when soil storage space was charged with moisture (season of high flows). Before and after clearcutting, the watershed contained nearly equal volumes of water during late winter and early spring, and the hydrologic response was about the same.

As the growing season progressed, however, the difference in moisture storage between the cut and forested conditions progressively increased. Drainage reaching the stream shortly after a rain was proportional to the moisture storage difference between the forest and clearcut conditions. Streamflow increases began in about June and increased in magnitude as the growing season advanced. In September, October, and November,

Figure 4.—Average monthly streamflow and the increase in flow during 7 years of annual recutting on Watershed 17.



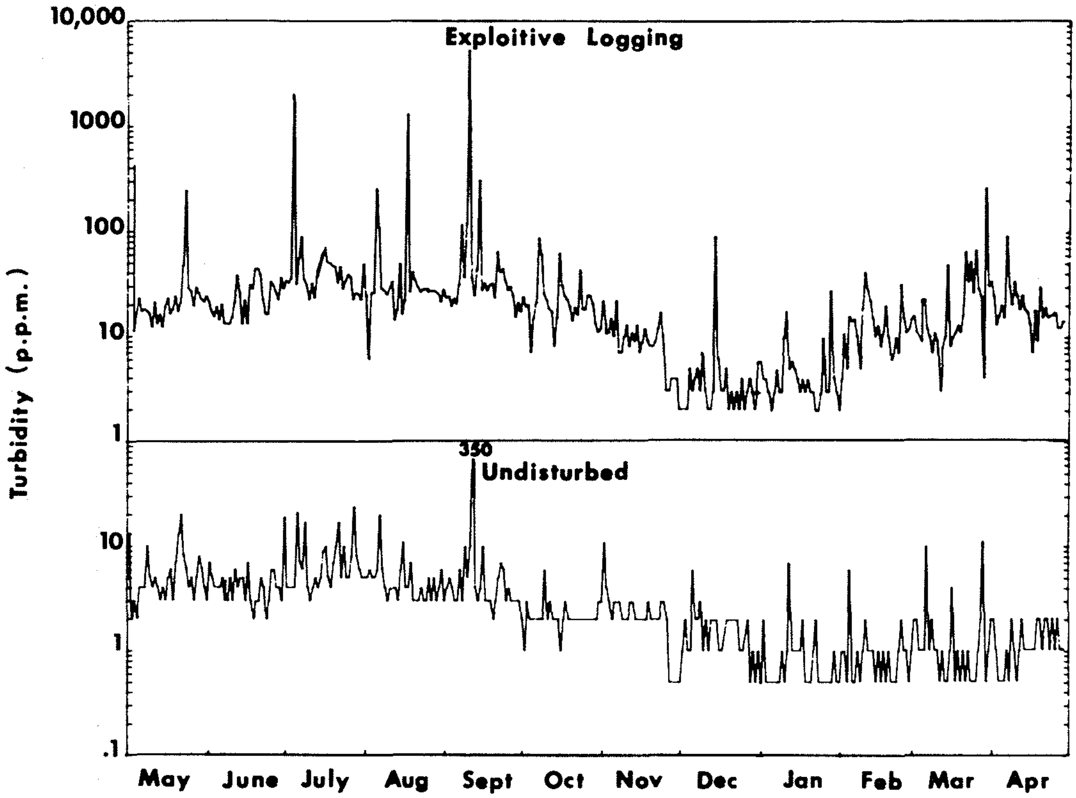
streamflow was increased by 100 percent. This is precisely the season when demand for water is greatest and unregulated flow is lowest. Large increases continued until December and then declined as the difference in moisture storage between clearcut and forested conditions declined. For treatments which produce less drastic storage differences, recharge occurs more quickly and increases are not delayed as late into the winter.

Timing of flow can be improved or degraded by treating the vegetation. Those practices which increase total annual flow produce large quantities of extra water during the low-flow periods. Conversely, streamflow during low-flow months is reduced by practices which decrease annual streamflow. Conversion to pine reduces flows during all months primarily because of interception and transpiration differences between pine and hardwoods at that stand age.

TREATMENT EFFECTS ON WATER QUALITY

The criteria of water quality vary with the intended use of the water. At Coweeta, turbidity, temperature, and mineral content of water have been measured.

Figure 5.—Comparison of turbidity from an exploitive logging and an undisturbed hardwood-covered watershed from May 1947 through April 1948.



Between 1942 and 1954, a 212-acre watershed was clearcut, and the logger selected road sites and logging technique. Roads were poorly constructed, often traversing steep grades without proper drainage, water bars, or grass cover. Between storms, turbidity on the logged watershed was much greater than from an undisturbed control watershed; and during storms, turbidity on the logged watershed was 10 to 20 times greater (fig. 5). Maximum turbidity recorded for the year was 5,700 ppm, but measurements were usually taken at about the same time each day and it is probable that maximum turbidity was often much greater. On a watershed that was logged properly from well-designed roads, turbidity increased only slightly. Cutting where soils were not disturbed by roads or skidding and converting from hardwood to pine did not discernibly increase turbidity. In general, we at Coweeta have concluded, as did Packer *(1966)*, that poorly designed and poorly located roads are the main cause of deterioration in water quality.

A 23-acre forested watershed at Coweeta was cut in 1940; and 6 acres were planted to corn, 7 acres were put into pasture, and 10 acres were allowed to grow back to hardwood coppice. Before treatment, soil losses averaged 156 pounds per acre. Dils *(1953, 1957)* found that soil losses varied from about 400 to over 18,000 pounds per acre during the 13 years of farming. Since eroded soil came from the corn field, pasture, and stream channel, losses cannot be assigned to any single source. After the pasture and corn field were planted to grass and later to white pine and yellow-poplar, soil losses for the next 15 years averaged only 128 pounds per acre annually compared to 2,047 pounds per acre for the farming period.

Manipulation of the forest can also change water chemistry.[1] Mineral cycling in four contrasting ecosystems has been studied intensively at Coweeta since 1968. Annual budgets and seasonal fluctuations of Ca^{++}, Mg^{++}, K^{+}, and Na^{+} for watersheds with a hardwood, a grass-to-forest succession, a hardwood coppice, and an eastern white pine cover were reported by Johnson and Swank *(1973)*. Cation budgets varied by watershed, but drastic alterations of the forest ecosystem have not caused a long-term loss of cations by erosion or drainage waters.

Relatively minor changes in mean annual concentrations of cations and anions on Coweeta watersheds treated in a variety of ways support these findings (table 1). Of the cations studied, only calcium concentrations from two watersheds to which lime had been applied were appreciably higher than would be expected from undisturbed watersheds. Of the anions studied, only NO_3-N increased in concentrations after treatment. Mean annual concentration of NO_3-N on treated watersheds was from about 4 to 150 times that on undisturbed watersheds, but the maximum concentration observed (grass-to-forest succession) was only 1.23 ppm. The next-to-highest concentration of 0.25 ppm was observed after hardwood-to-white pine conversion, compared with 0.002 to 0.013 ppm for undisturbed watersheds.

The concentrations of all cations and anions on treated watersheds are quite low, and the increased export of nutrients is insufficient to create pollution problems for drinking water or to degrade fertility. Similar observations on other, more recent clearcuttings in western North Carolina appear to support the findings at Coweeta, but data collection is not complete.

Herbicides and pesticides used in forestry operations can pollute water. On a grass-covered watershed, the grass cover was killed with atrazine and paraquat in May 1966 and re-treated with atrazine and 2,4-D in July of the same year *(Douglass et al. 1969)*. During the first spraying, grass hanging directly over the stream was treated, and low concentrations of atrazine and paraquat were detected in streamflow. Concentrations of atrazine were highest (20 to 40 ppb) during rains immediately after spraying, when intercepted water carried herbicides directly into the stream. After 30 days, concentrations of atrazine were always less than 10 ppb, and paraquat could no longer be detected.

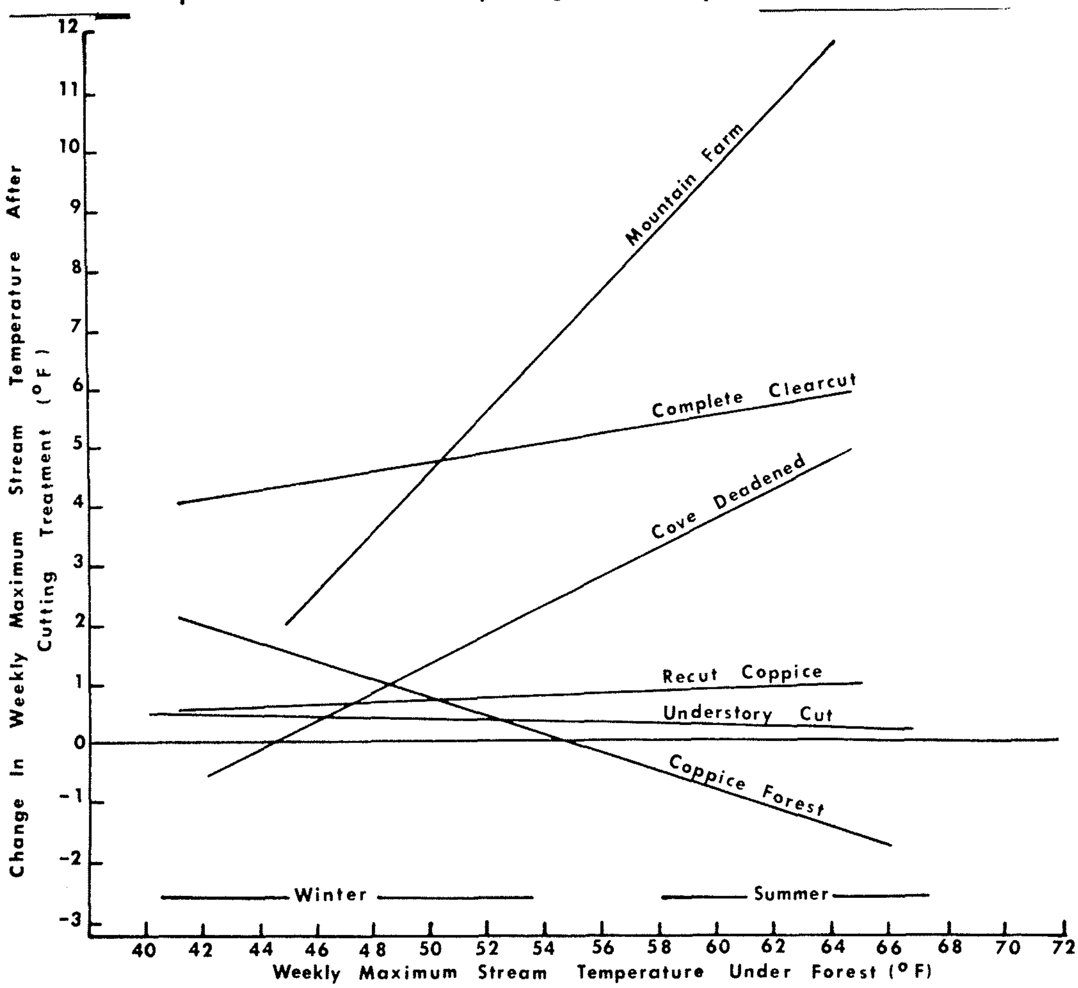
During the second spraying, a 10-foot strip on either side of the channel was left unsprayed. No increase in atrazine and no trace of 2,4-D was detected after the second treatment. Similarly, Grzenda et al. *(1964)* observed that when entire watersheds were broadcast-sprayed from fixed-wing aircraft to control elm spanworm, low levels of DDT were detected in streams. But when spraying was restricted mainly to ridges and slopes away from streams, DDT was not detected in the streams. Since most water reaches the streams at Coweeta through the soil rather than as overland flow, water quality is adequately pro-

[1]Water chemistry analyses supported in part by the Southeastern Forest Experiment Station, Forest Service, United States Department of Agriculture, and in part by the University of Georgia, Eastern Deciduous Forest Biome, US-IBP, funded by the National Science Foundation under Interagency Agreement AG 199, 40-193-69 with the Atomic Energy Commission —Oak Ridge National Laboratory.

Table 1.—pH and concentration of selected ions, in ppm, May 1972 through April 1973.

WS No.	Treatment	pH			NO_3-N			NH_4-N			PO_4-P			Cl			K			Na			Ca			Mg		
		Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
1	15-yr-old white pine	6.71	4.90	7.40	.029	.001	.077	.003	.001	.020	.006	.001	.022	.660	.560	.920	.580	.187	1.189	1.111	.929	1.748	.731	.620	1.125	.368	.200	.523
3	7.4 acres in 16-yr-old poplar 5.4 acres in 16-yr-old white pine 10 acres in 32-yr-old coppice (old mountain farm)	6.87	5.40	7.50	.015	.001	.038	.004	.001	.033	.006	.001	.022	.568	.480	.970	.441	.177	.935	1.046	.741	1.575	6.057	4.820	7.317	.485	.379	.680
6	Grass-to-forest succession	6.73	5.00	7.30	.619	.230	1.230	.004	.001	.010	.007	.001	.030	1.381	1.060	2.490	.588	.203	1.909	1.140	.896	1.374	1.118	.971	1.493	.640	.292	.820
13	10-yr-old coppice	6.63	6.00	7.40	.044	.003	.084	.003	.001	.014	.004	.001	.013	.491	.408	.672	.426	.177	.922	.698	.534	1.220	.501	.368	.849	.285	.189	.617
17	16-yr-old white pine	6.72	5.65	7.40	.154	.030	.249	.004	.001	.012	.012	.001	.336	.485	.400	.675	.446	.183	.946	.835	.663	1.338	.577	.388	.827	.247	.145	.374
28	180 acres clearcut, 80 acres thinned, 96 acres undisturbed	6.66	6.05	7.40	.094	.010	.208	.003	.001	.017	.004	.001	.020	.493	.390	.890	.465	.200	1.051	.901	.655	1.692	1.021	.684	1.319	.454	.275	.675
37	10-yr-old coppice	6.58	5.75	7.35	.149	.072	.246	.004	.001	.038	.006	.001	.095	.442	.300	.783	.424	.174	.975	.667	.500	1.231	.742	.256	1.128	.312	.203	.637
2	Undisturbed hardwoods	6.91	5.90	7.85	.004	.001	.017	.002	.001	.020	.006	.001	.020	.673	.490	.922	.589	.257	1.368	1.351	1.060	1.676	.713	.488	1.036	.359	.233	.552
14	Undisturbed hardwoods	6.76	5.50	7.30	.004	.001	.024	.004	.001	.031	.005	.001	.017	.544	.450	.738	.369	.161	.817	.772	.603	1.087	.513	.196	1.186	.292	.196	.416
18	Undisturbed hardwoods	6.77	5.60	7.35	.003	.001	.014	.004	.001	.022	.005	.001	.018	.554	.460	.880	.479	.206	1.022	.930	.674	1.424	.685	.448	.891	.317	.156	.457
21	Undisturbed hardwoods	6.55	5.08	7.35	.003	.001	.016	.004	.001	.024	.004	.001	.029	.490	.428	.800	.381	.163	.735	.717	.551	1.097	.530	.326	.864	.228	.157	.364
27	Undisturbed hardwoods	6.60	5.65	7.60	.013	.001	.050	.005	.001	.024	.004	.001	.018	.499	.425	.675	.243	.106	.511	.529	.400	.841	.384	.255	.662	.209	.163	.307
32	Undisturbed hardwoods	6.45	5.05	7.45	.003	.001	.015	.003	.001	.013	.004	.001	.013	.491	.430	.722	.322	.137	.843	.665	.541	.940	.550	.304	.815	.295	.220	.381
34	Undisturbed hardwoods	6.76	5.35	7.50	.002	.001	.019	.003	.001	.024	.006	.001	.019	.556	.425	.775	.429	.198	1.065	.931	.692	1.322	.749	.591	.922	.353	.262	.453
35	Undisturbed hardwoods	6.77	5.00	7.30	.008	.001	.030	.003	.001	.030	.004	.001	.014	.545	.438	.778	.342	.146	.740	.824	.500	1.352	.670	.421	1.244	.277	.203	.348

Figure 6.—Effect of six cutting treatments on weekly maximum stream temperature at the Coweeta Hydrologic Laboratory.



tected by the simple precaution of not spraying streamside vegetation where throughfall or stemflow can flush chemicals directly into streams or ditchlines.

Increased stream temperature can adversely affect or even kill trout. Swift and Messer *(1971)* summarized the effects of 6 watershed treatments at Coweeta on stream temperature (fig. 6). Where forest types and all understory vegetation were completely cut, maximum stream temperatures increased from the normal 66°F to 73°F or more. Mountain farming raised summer maximum temperatures over 12°F above normal. In other treatments where streambank vegetation was not cut or had regrown, summer maximum temperatures were unchanged or even lowered slightly. Swift and Baker *(1973)* found that if a buffer strip is retained to shade the water surface, temperatures of streams are not adversely affected by treatment of the rest of the watershed.

SUMMARY

The watershed experiments at Coweeta provide numerous detailed conclusions that are useful to watershed managers. Some of the most significant are:

1. Cutting the mixed hardwood cover in the southern Appalachians increases annual streamflow in proportion to the amount of cover removed.
2. The streamflow increase after cutting is approximately twice as great from north-facing watersheds as from south-facing watersheds. Equations for predicting changes in water yield after cutting are based on the proportion of the stand basal area cut and the potential insolation of the watershed.
3. Converting Coweeta watersheds from hardwoods to white pine greatly reduces streamflow.
4. Converting a hardwood to a low grass cover can significantly increase streamflow.
5. Timing of streamflow can be improved or degraded by treating vegetation. When annual flow is increased, extra water is produced during low-flow periods; those practices that decrease annual flow reduce streamflow during the low-flow months.
6. Poorly designed and poorly located logging roads are the main source of high turbidities connected with logging operations. Road specifications that minimize turbidity are available for mountainous terrain.
7. Water pollution from sprayed herbicides and pesticides can usually be prevented by not spraying streamside vegetation.
8. Stream temperatures are not increased by forest cuttings if a buffer strip is retained to shade the stream.
9. Water chemistry studies to date provide no evidence that forest cuttings in the mountains of North Carolina have rendered streamflow less fit for human use or degraded soil fertility.

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