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Long term responses of streamflow following clearcutting and regrowth

LLOYD W. SWIFT, JR & WAYNE T. SWANK
USDA Forest Service, Southeastern Forest Experiment Station, Coweeta Hydrologic Laboratory, Otto, North Carolina 28763, USA

ABSTRACT Long term changes in streamflow following forest cutting are presented for three experimental basins at Coweeta Hydrologic Laboratory, North Carolina, USA. Previous analyses have shown that, following forest cutting, streamflow increases and then declines with the logarithm of time as the forest regrows. Recent data indicate that the streamflow decline following cutting is related to vegetation regrowth, but the relationship is not a consistent function of simple stand measurements. The mixed hardwood forest of one basin was clearcut twice in the past 40 years. During the second regrowth period, streamflow increases after the first year were about one-half the increases at the same points in time after the first treatment. Concurrent with the second cutting, two other basins were cut whose mid-elevations are 400 m higher. The increases for the upper basins were similar, even though basal area was reduced by only 65% on one. Both streamflow increases were less than for either cutting on the lower basin. Variability of flow increases for the three concurrent treatments is similar and appears partly related to precipitation.

Réactions à long terme du débit des cours d'eau après coupe et repeuplement

RESUME Les changements à long terme dans le débit des cours d'eau après la coupe des arbres sont présentés dans trois bassins expérimentaux du Laboratoire Hydrologique de Coweeta en Caroline du Nord, Etats-Unis. Des analyses antérieures ont montré qu'à la suite d'une coupe, l'accroissement dans le débit annuel baisse, à mesure que la forêt repousse, en relation avec le logarithme négatif du temps écoulé depuis la coupe. Des résultats récents indiquent que bien que la réaction de l'écoulement après la coupe soit une fonction de la végétation, ce n'est pas une fonction constante des simples mesures de futaie. Une forêt mixte de plusieurs sortes d'arbres dans un bassin a été coupée deux fois dans les 40 dernières années. Pendant la seconde période de repeuplement, l'augmentation du débit après un an était de 50% a peu près du niveau enrégistré à la même époque après le premier traitement. A l'époque de la seconde coupe, on a procédé également à des coupes dans deux autres bassins dont l'altitude moyenne était de 400 m plus élevée. Les augmentations pour les bassins plus élevés étaient du même ordre bien que la surface de base n'était réduite que de 65% pour l'un d'entre eux. Les augmentations du débit étaient moindres que celles des deux autres coupes dans le bassin inférieur. La variabilité de l'augmentation du débit pour les trois traitements simultanés est à peu près la même et semble se rapporter, en partie, aux précipitations.

INTRODUCTION

This report updates early results for three experimental basins at Coweeta Hydrologic Laboratory in western North Carolina, USA (Douglass & Swank, 1976; Swank & Helvey, 1970). Two basins were totally clearcut without removal of forest products - one of them twice - while the third was a forest management demonstration and received a mix of thinning, clearcutting, and noncutting (Hewlett & Douglass, 1968). Clearcutting is defined here as the cutting of all living vegetation, a practice which aids the regeneration of a new forest. In each case, indigenous forest vegetation was allowed to regrow. All three basins are in the same valley, within 4 km of each other, and three of the treatments were imposed at the same time. With this unique set of experiments, streamflow responses have been observed for: (a) two recovery periods on the same basin 23 years apart, (b) concurrent recovery periods for two clearcut basins at different elevations, and (c) concurrent recovery periods on two high-elevation basins - one partially cut and the other clearcut. Changes in streamflow immediately after cutting and as the forest regrew are reported and related to variations in vegetation, climate and basin elevation.

METHODS AND EXPERIMENTAL BASINS

The experimental basins are in a 1640-ha, bowl-shaped valley in the southern Appalachian Mountains of western North Carolina, USA. They are part of a long term research site of the USDA Forest Service devoted to the study of the effects of forest management on mountain streams (Douglass & Swank, 1975). The experimental basins are characterized by deep, permeable soils formed on steep slopes from folded gneiss. Precipitation typically exceeds 80 mm for all months, and about 95% of the 2000 mm of mean annual precipitation is rain. Continuous documentation of streamflow, climate and vegetation began in 1934. The native forest is dominated by oak, hickory, yellow poplar, red maple, and a variety of associated species. Treatment histories of the three experimental basins were presented by Douglass & Swank (1976) and Swank & Helvey (1970). Hydrological characteristics are summarized in Table 1. All three basins face east to east-northeast.

The paired or control basin analysis is used to assess treatment effects. Annual changes in streamflow (May-to-April water year) are estimated as measured streamflow minus predicted flow. Predicted flow is based upon a regression of flows on each treated

Table 1 Characteristics of experimental basins

Characteristics	WS 13: clearcut water years 1940 and 1963	WS 37: clearcut water year 1964	WS28: partly logged water year 1964
Area (ha)	16	44	144
Land slope* (%)	49	71	52
Mid-area elevation (m)	810	1300	1200
Mean annual precipitation (mm)	1900	2220	2320
Mean annual streamflow for calibration period (mm)	889	1604	1534
Standard deviation about the calibration regression (mm)	18	21	39
Calibration period (years)	3	16	12

*Mean slope of a sample of transects within a basin by the intersection-line method (Horton, 1932).

basin against an adjacent control basin and is an estimate of what flow would have been in the absence of any treatment. The length of each calibration period and standard deviations of the calibration equations are given in Table 1. The May-to-April water year is used because soils are recharged by winter precipitation and the carryover effects of evapotranspiration from the previous growing season are minimized. Trend lines were fitted to each set of estimated increases using the model proposed by Kovner (1956):

flow increase = a + b (log of years since cutting)

Trend lines were tested for similarity of slope and level by the method given by Freese (1967).

Basal areas and stand densities for the woody vegetation on the basins were derived from plots systematically distributed over the landscape (Swank & Helvey, 1970; Douglass & Swank, 1976). Leaf biomass was sampled with randomly located litter trays, and leaf area index was estimated for each species from regressions of leaf area vs. leaf biomass (Gist & Swank, 1974).

Clearcut and coppice forest repeated, WS 13

After the forest on Watershed 13 (WS 13) was clearcut in 1940, streamflow increased 362 mm, 65% above predicted flow. Seedlings and coppice were allowed to regrow for 23 years and then the forest was recut. The second time, streamflow increased 375 mm, 40% above predicted flow. After each cutting, streamflow declined from the initial large increase as the forest regrew. The time trend obtained for the full 23 years of the first treatment exactly matches Kovner's (1956) model, which was derived with only 13 years of data. Streamflow increases and the fitted time trends for the increases which followed both cuttings on WS 13 are shown in Fig.1. The initial responses to cutting were virtually identical, and the probability for the slopes of the two time trends to be different

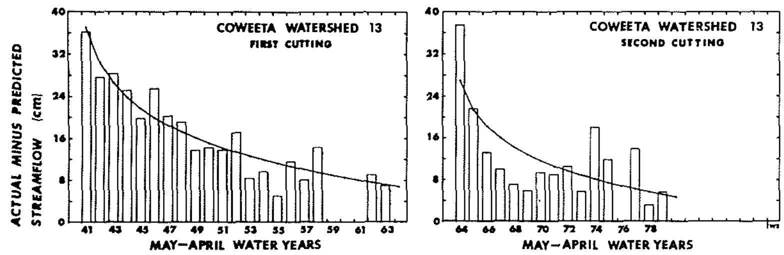

Fig. 1 Streamflow increases following two cuttings of deciduous forest on Watershed 13, Coweeta Hydrologic Laboratory. Streamflow was not measured in water years 1959, 1960, 1961, and 1976.

is less than 0.6. However, the levels of the two curves differ by about 68 mm of flow per year, and the estimated termination of treatment effect is about 18 years earlier for the second cutting (31 vs. 49 years).

Swank & Helvey (1970) reported a very rapid decline in response based upon the first 6 years of data following the second cutting. Indeed, Fig.1 shows that flow increases for 1966-1969 were substantially below the time trend defined using all 15 years of data. However, flow increases for 1974-1977 were greater than in the preceding and following years and were similar in magnitude to the trend line in the eleventh-fourteenth years after the first cutting. An explanation was sought for these erratic responses.

The irregular pattern of increases after the second cutting suggests that vegetation regrowth differed from that after the first cutting or that precipitation or some other climatic factor had an effect. February-May rainfall, expressed as a deviation from the 4-month mean, was fitted as a second variable in a new trend line equation for the second cutting. The correlation coefficient was improved 18% over the equation fit to logarithm of years alone. Kovner (1956) reported that streamflow increases after the first cutting were independent of annual precipitation. However, predicted increases, calculated from the trend line equation with spring rainfall, display irregularities similar in sign and magnitude to the irregularities of the streamflow increases. Many other expressions for a precipitation variable exist, and the same variable may not be appropriate for all basins or for the entire duration of an experiment. For example, in the first 4 years after cutting, flow increases appear to be inversely related to precipitation; thereafter, streamflow increases seem directly related to precipitation amount. Although the streamflow increases were notably different between the two regrowth periods, the mean precipitation amounts for the two periods were quite similar. An exhaustive study of all possible precipitation functions is beyond the scope of this paper. The purpose here is to note that opportunities for useful precipitation functions do exist.

Swank & Helvey (1970) partially attributed the smaller water yields in the early years of the second regrowth period to a more rapid recovery of vegetation after the second cutting, as indicated by increased stand density and greater leaf areas. Basal areas of the two regrowth forests were comparable at similar successional ages.

Table 2 *Forest vegetation parameters at different stand ages for Coweeta Watershed 13*

Water year	Stand age (years)	Stand density (stems ha^{-1})	Basal area (m^2 ha^{-1})
1934	Mature, uneven-aged	2596	25.46
1940	Cut	0	0.00
1948	8	7630	9.41
1952	12	5322	11.84
1962	22, even-aged	4196	18.47
1963	Cut	0	0.00
1969	7	9659	6.99
1977	15	7338	12.66

Water year	Stand age (years)	Leaf biomass (g m^{-2})	Leaf area index (m^2 m^{-2})
1954	14	316	N/A
1970	7	268	5.2
1971	8	192	3.7
1972	9	191	3.8
1978	15	309	6.0

Prior to the first cutting, WS 13 contained 25 m^2 ha^{-1} of basal area, which is typical of mature hardwood forests of the southern Appalachians. Hardwood regeneration by stump and root sprouting was rapid and, after only 8 years of regrowth, basal area had recovered to 9 m^2 ha^{-1}. By 1962, when the stand was 22 years old, basal area was 73% of that for the original forest (Table 2). Similar rapid regrowth was observed after the second cutting with nearly equivalent basal areas at comparable stand ages of 7 and 15 years.

Changes in species composition during this experiment have resulted from both natural causes and from clearcutting. American chestnut, initially the dominant tree species, was eliminated from the overstory by the fungus *Endothia parasitica* in the late 1930s (Table 3). Clearcutting favours species which readily sprout and thus, was instrumental in the shift of species composition (Table

Table 3 Basal area of major tree species on Watershed 13 during the experimental history of the basin

	Basal area (m^2 ha^{-1}) in water year:					
Species	1934	1948	1952	1962	1969	1977
White oak group (*Quercus* spp.)	3.51	1.73	2.26	3.97	1.34	2.60
Red oak group (*Quercus* spp.)	3.64	1.34	2.29	3.73	1.23	1.69
Red maple (*Acer rubrum* L.)	0.87	1.09	1.34	1.76	0.71	1.74
Yellow poplar (*Liriodendron tulipifira* L.)	0.38	0.48	0.91	2.23	0.85	2.47
American chestnut (*Castanea dentata* (Marsh.) Borkh.)	8.44	0.95	0.07	0.02	0.15	0.04
Hickory (*Carya* spp.)	1.36	0.75	0.73	0.92	0.46	0.50
Pitch pine (*Pinus rigida* Mill.)	3.60	0.09	0.75	1.01	0.00	0.00
Black locust (*Robinia pseudoacacia* L.)	0.52	1.10	0.60	0.60	0.42	0.64
Dogwood (*Cornus florida* L.)	0.80	0.70	1.25	1.86	0.80	0.84
Miscellaneous	2.34	1.18	1.64	2.37	1.03	2.14
Total	25.46	9.41	11.84	18.47	6.99	12.66

3). Each cutting has produced substantial basal area increases in yellow poplar, red maple, and dogwood, and a reduction in pitch pine. However, any transpiration differences between hardwood tree species and their possible effect upon streamflow are thought to be small (Federer & Lash, 1978).

In addition to these shifts in species composition, each cutting increased stand density, as demonstrated by the stems-per-hectare data in Table 2. Before the first cutting, the uneven-aged stand contained 2600 stems ha^{-1}, with many larger than 20 cm in diameter. Seedlings and sprouts were plentiful after clearcutting, and 7630 stems ha^{-1} remained alive in the eighth year. By age 22, immediately before the second cutting, the coppice forest still contained 1600 more stems ha^{-1} than did the mature forest of 1934; 95% of these stems were less than 4 cm in diameter. This heavier stocking of small-diameter trees favoured even more prolific sprouting after the second cutting, producing densities consistently 2000 stems ha^{-1} above the densities observed after the first cutting.

Leaf biomass and surface area recovered rapidly after the second treatment (Table 2). At age 7, leaf biomass was 268 g m^{-2}, nearly equal to leaf production in 1954 when the stand was 14 years old. Streamflow increases were about 95 mm in both 1954 and 1970. Leaf area index (LAI) in the seventh year was equivalent to LAI estimates of 5.0 - 6.0 for mature, mixed hardwood forests at Coweeta. However, leaf biomass and surface area declined markedly in the next 2 years, due to high sprout mortality within the dense coppice stand. This decline in leaf area is associated with 3 years of slightly greater streamflow increases (Fig.1). By 1978, 15 years after the second cutting, leaf biomass had recovered from earlier sprout mortality, LAI was 6.0, and streamflow was near pretreatment levels.

Clearcut and coppice forest, WS 37

A second experimental basin, WS 37, was clearcut in the summer of 1963, shortly after the second cutting of WS 13. Details of the calibration and treatment were given by Swank & Helvey (1970). Watershed 37 is at a higher elevation, is steeper, and yields a greater percentage of precipitation to streamflow than the other two basins listed in Table 1. Streamflow increased 255 mm the first year, 15% above predicted flow, then increases fell to zero during the fourth to sixth years (Swank & Helvey, 1970). As found with WS 13, data for the next 6 years show a general increase and thus a later return to pretreatment levels for WS 37 than indicated by the early results (Fig.2). Trend lines for WS 37 and the second

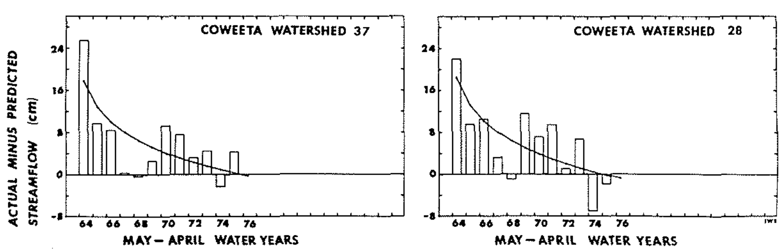

Fig. 2 Streamflow increases following the cutting of the deciduous forest on two basins at Coweeta Hydrologic Laboratory. Streamflows were not measured after 1975.

cut of WS 13 were compared statistically; slopes were the same (probability of difference only 0.25), but the level of estimated streamflow increases was 79 mm $year^{-1}$ lower for WS 37. Because the treatment periods coincided, the year-to-year departures from the trend lines for these two basins could be compared for similarity, and with climatic and vegetational measurements.

The common response pattern for WS 13 and WS 37, showing smaller flow increases for the 3 years, 1967-1969, compared with the next 2 years, suggests a common external influence upon water use by vegetation. Climatic records were searched for data which changed over these same years. In August-October, rainfall was greater and mean air temperatures were lower for years with the smaller streamflow increases.

The difference in level of the trend lines suggests differences in basin hydrology or vegetation. The higher elevation, steeper slopes, and generally shallower soils of WS 37 are known to affect streamflow (Hewlett & Hibbert, 1966), and may also affect changes in flow due to cutting. Also, the growing season at WS 37 is approximately 6 weeks shorter than at the lower elevation.

The contrasts in vegetation are also striking and bear a relationship to size of flow increases. Prior to cutting, the hardwood forest on WS 37 contained 21 m^2 ha^{-1} of basal area, only slightly less than on WS 13 prior to its first cutting. However, stand density was only about half that on WS 13. Eight growing seasons after clearcutting, the coppice stand on WS 37 contained 7.9 m^2 ha^{-1} basal area distributed over 2910 stems ha^{-1}. Again, basal area was similar, but the stand density was only about 30% of the stocking found on WS 13. Leaf biomass of the 8-year-old coppice stand on WS 37 was 104 g m^{-2}, with a LAI of 1.8 - about one-half the production on WS 13 at the same time. Similarly, leaf production for mature forests at Coweeta decreases with increasing elevation. For example, the control basin adjacent to WS 37 had a leaf area of 3.1 and a biomass of 230 g m^{-2} in 1970. Both values are less than those for the lower elevation WS 13 in the same year (Table 2). The LAI values and the reductions in flow with regrowth were comparable for the two basins; i.e. on both basins, streamflow increases had fallen about 70% by the eighth year, whereas leaf area indices were 60% of mature forest values.

Forest management demonstration, WS 28

A large, upper-elevation basin, WS 28 (Table 1), was developed as a multiple-use management demonstration at the same time WS 13 and WS 37 were clearcut. Hewlett & Douglass (1968) describe the logging pattern where 51% of the basin was clearcut; 22% was thinned, reducing basal area to one-third on the better sites; and 27% was left uncut on the steep, upper slopes and ridges. Unlike the treatments of the other two basins, 7.5 km of roads were constructed and logs were removed from WS 28. The streamflow and vegetation responses to this treatment were summarized by Douglass & Swank (1976).

With a 65% mean reduction in basal area over the entire basin, first-year streamflow increased 220 mm, 15% above expected flow (Fig.2). The trend curve for WS 28 is not different in either slope or level from that of WS 37, the other upper-elevation basin shown in Fig.2. The probability of a difference in either parameter was less than 0.15. In addition, the irregularities of flow increases for WS 28, WS 37, and WS 13 closely correspond. The notable exception occurs in 1974 when WS 13 shows a large 181 mm increase and WS 28 and WS 37 show decreases. This exception may be related to the high precipitation during water years 1973 and 1974 (wettest and third wettest on record at the Laboratory, respectively). The resulting high streamflows were outside the range of calibration data in 4 months of water year 1974. Precipitation was greater for all basins, but the gradient with elevation was also greater. Growing season rainfall at WS 37 normally averages 10-15% above that at WS 13. However, the upper-elevation gauge caught 26% more rain during the May-October growing season of water year 1974.

Basal area on WS 28 averaged 28 m^2 ha^{-1} before cutting. The combination of thinning and clearcutting removed 65% of the total basal area, most of it from the moist sites near the stream and from the lower slopes. In the sixth year, basal area in the clear-cut was 7.1-8.2 m^2 ha^{-1} (Table 4), similar to values for other

Table 4 Treatment, area, and basal area of compartments on forest management demonstration, Coweeta Watershed 28

			Basal area (m^2 ha^{-1}) in water years:			
Compartment	Treatment	Area (ha)	1962	1964	1970	1975
Bottomland and lower slopes	Thinned	32	28	10	16	35
Lower slopes	Clearcut	16	27	0	8	15
Upper slopes and ridges	Clearcut	57	28	0	7	11
Upper slopes and ridges	Uncut	39	28	28	28	28
Entire basin		144	28	10	15	22

Stand age in cut compartments was mature, uneven-aged in 1962; newly cut in 1964; 6 years in 1970; and 11 years in 1975.

clearcuts at this age. By 1975, when changes in streamflow had become negligible, the basal area was 77% of pre-cutting levels. As with the other experiments, stand density in the clearcut compartments was high, 16 000-20 000 stems ha^{-1} 2 years after cutting and 7000-9000 stems ha^{-1} in the eleventh year. This stocking within the clearcut compartments resembled that on WS 13, but was greater than that on the other upper-elevation basin, WS 37.

DISCUSSION

The results from these four experiments clearly show that streamflow from mountain basins increases when the forest is cut and that these increases decline as the vegetation regrows. Furthermore, the data allow closer examination of the factors influencing the trend line equations fitted to streamflow increases. Those factors which may establish the slope and the level of the equations and the deviations of individual increases away from a smooth line are now considered.

Vegetation regrowth is the dominant change occurring after the forest is cut on a basin and thus is the prime determinant of the trend lines for the Coweeta experiments. The most significant finding is that the slopes of the trend lines were essentially identical for all cases, despite these experiments involving different sets of years, different degrees of cutting, and basins with distinctly different physiography and elevation. The general equation for the trend line, combining data for all four experiments is:

$$\text{flow increase} = a - 190.7 \log (\text{years since cutting})$$

where a is the level parameter or increase in the first year. The common slope of the trend lines from these four experiments, -190.7 mm (log year)$^{-1}$, may be an improved expression to use with the first year predictive equation given and refined by Douglass & Swank (1972, 1975). In Fig.2, the trend lines for WS 28 and WS 37 are shown to cross the zero-increase level instead of being asymptotic to zero. If zero increases had been measured in 1976 or later years, the trend lines would not be altered enough to change the conclusion of common slopes. These experiments were terminated in 1975 and cannot reveal if these young regrowing forests consistently caused streamflow decreases.

In the experiments, measures of forest regrowth included basal area, stand density, leaf area, and leaf biomass. However, sampling was not frequent enough to fully characterize the changes in these measures over time or to define completely the link of vegetation to the declining streamflow increases. Nevertheless, some inferences may be drawn. Per cent reduction in basal area is an effective predictor of streamflow increase the first year after cutting (Douglass & Swank, 1972). Basal area accumulation over time was similar for these four experiments: 7-9 m^2 ha^{-1} in the sixth-eighth year after clearcutting and 11-15 m^2 ha^{-1} for three treatments sampled at 11-15 years after cutting. The common slope of trend lines fitted to increases in streamflow may be due to the similar rates of basal area accumulation during regrowth.

The individual logarithmic trend line equations for the four experiments differ only in the level parameter. The two responses to repeated cutting of WS 13 provide an opportunity to consider the effect of vegetation where basin and mean climatic variables were unchanged. Although basal area values were nearly equivalent for similar aged forests, the stand density was 27% greater in the second regrowth stand while the level of flow increase was 38% less. In three studies, the higher levels of trend lines seemed to be associated with lower stand density. When ranked in order of increasing stand density in the eleventh to fifteenth years, all experiments except WS 37 fall in a sequence of decreasing level of the trend line equation; i.e. WS 13 first cut, WS 13 second cut, WS 28 clearcuts. In distinct contrast, however, stand density on WS 37 was less than on the other basins throughout the study and the level of the trend line was also lower. Stand density in an early regrowth period has a direct bearing on leaf area, a parameter more closely related to evapotranspiration processes. Hence, smaller flow increases in the early years after the second cutting of WS 13 appear to be a response to a large leaf area and a rapid recovery of evapotranspiration. Leaf area (and biomass) data are not available to compare all four experiments but leaf area can be related to changing streamflow on WS 37. Although initial stand conditions differed substantially between WS 13 and WS 37, the 60% recovery of LAI is proportional to the 70% recovery of streamflow for both basins in 1971. This proportionality of streamflow trends to amount of vegetation is consistent with Hibbert's (1969) findings on a grassed basin where a strong relationship was shown between streamflow increases and grass biomass.

The levels of flow increases for WS 28 and WS 37 were very similar, even though WS 28 was only partially cut. Other differences between the basins include a greater precut basal area on WS 28 and the physiographic contrasts of a smaller basin, steeper slopes, less complex drainage pattern, and shallower soils on WS 37. The initial rapid decline of streamflow increases for WS 37, relative to WS 13, were attributed to shallow soils on the upper elevation basin (Swank & Helvey, 1970). Because WS 37 yields a greater percentage of precipitation to streamflow, responses to changes in vegetation may be less dramatic than on other basins at Coweeta.

In addition to demonstrating long term effects of vegetation and basin variables upon streamflow increases, these data show year-to-year variation of flow response which may be attributed to tree mortality, precipitation pattern, and other climatic variables. The relative importance of these variables may change with time, the vegetation being paramount in the early years after cutting and climate being relatively more significant as the annual change in vegetative structure becomes less.

For three reasons, climatic variation was the most likely cause for departures of streamflow increases from the smooth trend line. First, the irregular patterns of individual streamflow increases for each of the three concurrent treatments were remarkably similar. Second, all basins were subject to the same general climatic conditions. And third, vegetation should not be expected to have changed drastically at the same time on all three basins, except as weather influenced tree growth and water use.

In two ways, precipitation was found to correlate with irregularities of streamflow increases for all three basins. After the first 4 years, relatively larger streamflow increases occurred in those years with high spring rainfall. In the earlier years this relationship appeared to be reversed. Fitting a trend line to WS 13 data using a reversible rainfall function as a second variable reduced the standard deviation of the regression 26% below that when using logarithm of years alone. This precipitation relation may be an interaction with stand structure dynamics. For Coweeta coppice forests, this time period coincides with the vegetation transition from a discontinuous low form to a more distinct and continuous three-dimensional structure.

In 1974, the low elevation basin had a large positive streamflow increase whereas the two high-elevation basins showed small decreases. A steeper gradient of precipitation with increasing elevation occurred in this high precipitation year. Rarely have precipitation data been required to explain streamflow experiments at Coweeta. These new implied relationships underscore a need to apply adequate climatic data to questions of streamflow response, even in humid regions.

The resources used in these four experiments include 304 ha of land, over 188 gauge years of streamflow records (counting both treated and control basins), equivalent numbers of precipitation records, and repeated vegetation measurements. While this investment has yielded results that are significant, invaluable, and the most precise evaluation available for streamflow response to forest regrowth, they do not fully explain why the measured responses occurred. However, these integrated basin responses and the extensive data will provide an ideal opportunity to utilize process oriented evapotranspiration models (Swift *et al.*, 1975) to further increase our understanding of the forest hydrological cycle.

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