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22. Streamflow Changes Associated with Forest Cuttin Species Conversions, and Natural Disturbances

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An original research objective in the establishment of Coweeta was to measure ; evaluate the effects of man's use of the forest on the quantity and timing of streamfl Over the past 50 years at least 40 publications and numerous presentations h addressed this topic. Fifteen individual watershed-scale experiments have been c ducted in the basin, involving various intensities of forest cutting and harvest and c versions of hardwood forest to white pine or grass. A description of the treatment summarized in Chapter 1. The purpose of this chapter is to provide a synthesis of fi ings on (1) responses in annual and monthly streamflow quantities following cutti species conversions, and natural disturbance; (2) changes in storm hydrograph chaı teristics that accompany clearcutting; and (3) the application of results to wa resources planning on forested watersheds.

Changes in Annual and Monthly Streamflow

Hibbert's (1966) survey of catchment experiments throughout the world indicated t deforestation increased and afforestation decreased streamflow, but the magnitude response was highly variable and unpredictable. In that analysis he also pointed out nearly threefold increase in first year responses after clearcutting between north- south-facing watersheds at Coweeta. In an attempt to improve the relationship betw first year water yield increases as a function of basal area cut, Douglass and Sw (1972) expanded the data base to 22 forest cutting experiments in the Appalach Highlands Physiographic Division (Figure 22.1).

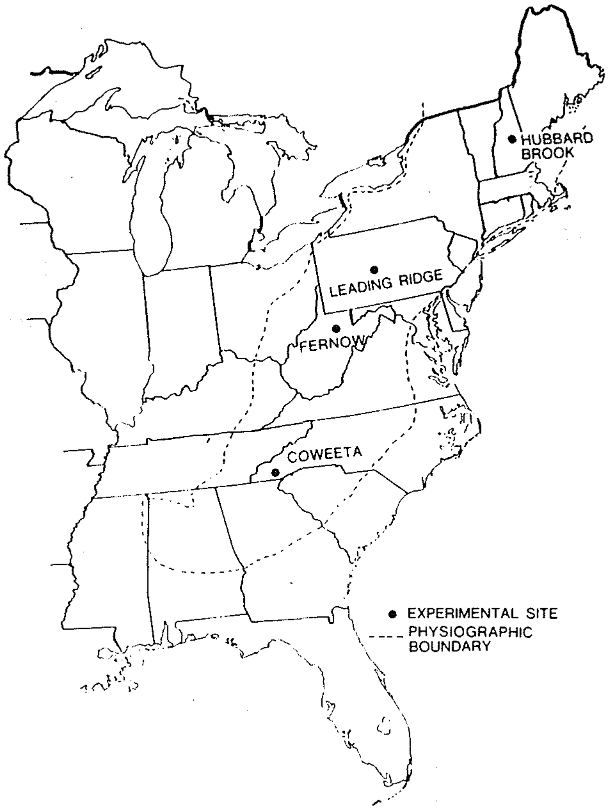

Figure 22.1. Location of the Appalachian Highlands Physiographic Division and experin sites.

Although the relationship between increases and percent basal area reduction improved, there was still a wide scatter of points about the regression; in fact, for c cutting (100% reduction in basal area), Coweeta responses bracketed all o experimental results and ranged from 13 cm to 41 cm. An improved version of the year increase model was derived by Douglass and Swank (1975) by adding an er variable (insolation index), which represents energy theoretically receive watersheds of different slopes, aspects, and latitudes (Figure 22.2). The rational adding the insolation index as a variable was based on Swift's (1960) findings that radiation theoretically available for evapotranspiration is greater on south- tha north-facing slopes in the dormant season, with little difference in the growing se Additional studies of total and net radiation patterns supported the theory (Swift 1 and it was hypothesized that streamflow response to cutting was inversely proport to solar energy input. The curvilinear relationship provides a reasonable represent of the actual response to partial cuttings. The final equation derived for estim first-year yield increases for hardwoods is:

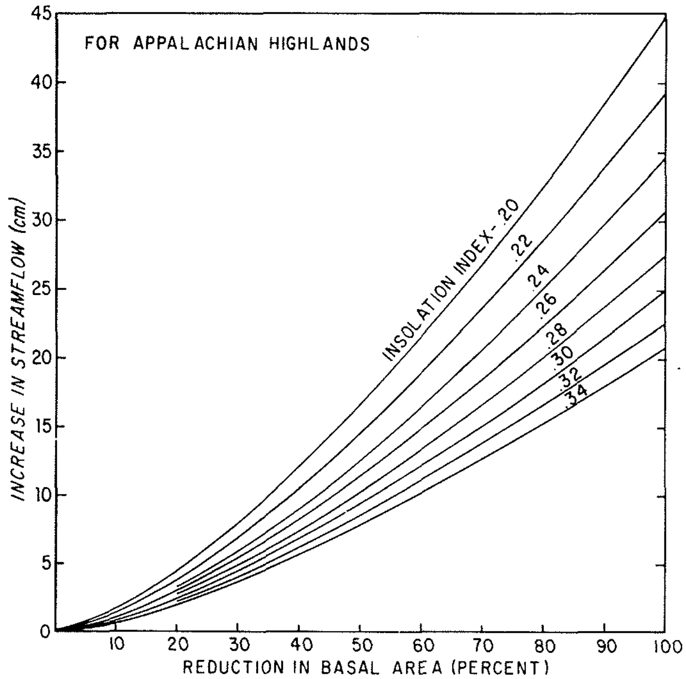

Figure 22.2. First year increases in streamflow after cutting mature, mixed hardwood f(based on the precent reduction in stand basal area and watershed insolation index.

$$\Delta Q = 0.00569\ (\text{BA/PI})^{1.4462}$$

where ΔQ is the first year increase in centimeters for hardwoods, BA is the pe: basal area cut, and PI is the annual potential insolation in langleys $\times\ 10^{-6}$ calcu by methods given by Swift (1976). Total variation explained by the two vari; was 89%.

As the forest regrows and the evaporating surface area (hence *Et*) increases, str flow increases decline as a function of the logarithm of time (see examples, this c ter). This relation provides a model for predicting the yield for any year after ha if the duration of measurable increases is known. An estimate of mean duration derived by Douglass and Swank (1972) as 0.62/year for each cm of first-year increase. The declining log equation for flow increase in any year (ΔQy) is

$$\Delta Qy = \Delta Q - b \log y$$

where y is the number of years after harvest and the coefficient b is derived by sol Eq. 2 at the point when $\Delta Qy = 0.0$:

$$b = \Delta Q / \log\ (0.62\ \Delta Q)$$

The limitations on the use of these equations have been given by Douglass (1ʕ An application of the equations to the most recent clearcut at Coweeta is give

Table 22.1. Comparison of Annual Predicted vs. Observed Increase in Water Yield Following Clearcutting on Coweeta WS 7

Year After Clearcutting	Predicted Increase by Model (cm)	Observed Increase[a] (cm)
1	25	26
2	17	20
3	12	17
4	8	12
5	6	4
6	3	4
Total	71	83

[a] Observed increase based on annual calibration regression.

Table 22.1 for Watershed 7 (WS 7), a 59 ha south-facing catchment. In the first y after cutting, streamflow increased about 25 cm and the model predicted 25 cm. In ensuing 2 years, observed increases were substantially above values predicted from equations, and these years coincided with the wettest and second driest years in past 50 years. Fourth and fifth year predictions were in closer agreement with obser values, and the total change predicted for the entire 6-year period was 71 cm compa to 85 cm observed. We would expect the most reasonable performance of the equati over several years rather than for individual years. Large deviations for indivic years could be expected for exceptionally wet or dry years and, of course, b observed and predicted values have an error term. Actual use of these equation forest management planning in the East has been documented (Douglass 1983) later in this chapter we will provide another example of potential application.

The effects of clearcutting on mean monthly flows are illustrated by results on WS during the 7 years when regrowth was cut annually (Figure 22.3). The timing monthly increases are representative of other clearcutting experiments in the ba Clearcutting has little effect on flow during later winter and early spring when moisture beneath undisturbed forests is fully recharged. With the onset of the grow season, increased flow from reduced *Et* begins to appear and increases in magnitud the growing season advances. In the lowest flow months of September, October, November, average monthly streamflow is about 100% greater from the clearcut t uncut forest. This is the period when water demands are greatest and flow fi undisturbed forests is lowest. Large increases continue into December and then be tapering off as storage differences between cut and uncut forests diminish. On ca ments with less soil water storage, recharge occurs more rapidly and increases are delayed as late into the winter.

Streamflow Responses to Regrowth

Long-term effects of clearcutting on water yield are important in both water reso planning and evaluation of nutrient export from forest ecosystems. Four experim

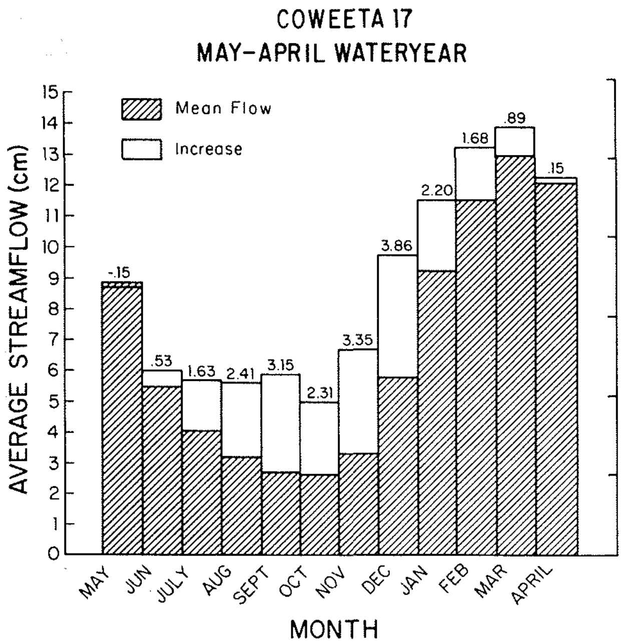

Figure 22.3. Mean monthly flow on Coweeta WS 17 during preclearcutting years and m monthly increases during a 7-year period of annual recutting.

on three experimental catchments totaling 304 ha of land, almost 200 years of strea flow records, an equivalent number of precipitation records, and detailed vegetat measurements, provide a unique documentation of flow recovery and major variab that affect responses. These experiments were previously summarized by Swift a Swank (1981) and most details will be omitted here. The longest record available is WS 13, which has been clearcut twice, first in 1940 and again in 1963 without remo of forest products and with natural regrowth allowed. Changes in flow as estima from differences between measured flow and flow predicted from the control cat ment are shown in Figure 22.4 for both cuttings along with trend lines fitted to th changes. Thirteen years after the first cutting, Kovner (1956) proposed the follow trend model: flow increase = $a + b$ (log of years since cutting) and the trend line v still valid when the stand was 23 years old. The initial response of the second cutt was nearly identical to that of the first cut, but the shape of trend curves of the t differ substantially in the early years. The estimated termination of yield increa based on data in Figure 22.4 is about 18 years earlier for the second cutting.

Swank and Helvey (1970) partially attributed the more rapid decline in water yi of the second cutting to a more rapid recovery of stand density and perhaps leaf a (Table 22.2), and, hence, evapotranspiration after the second cutting. Seven years af cutting, stem density was 2000 stems ha^{-1} greater after the second treatment. T higher stem density was attributed to greater sprouting potential of the even-aged sta with numerous small stems that were present prior to the second cutting. Leaf biom

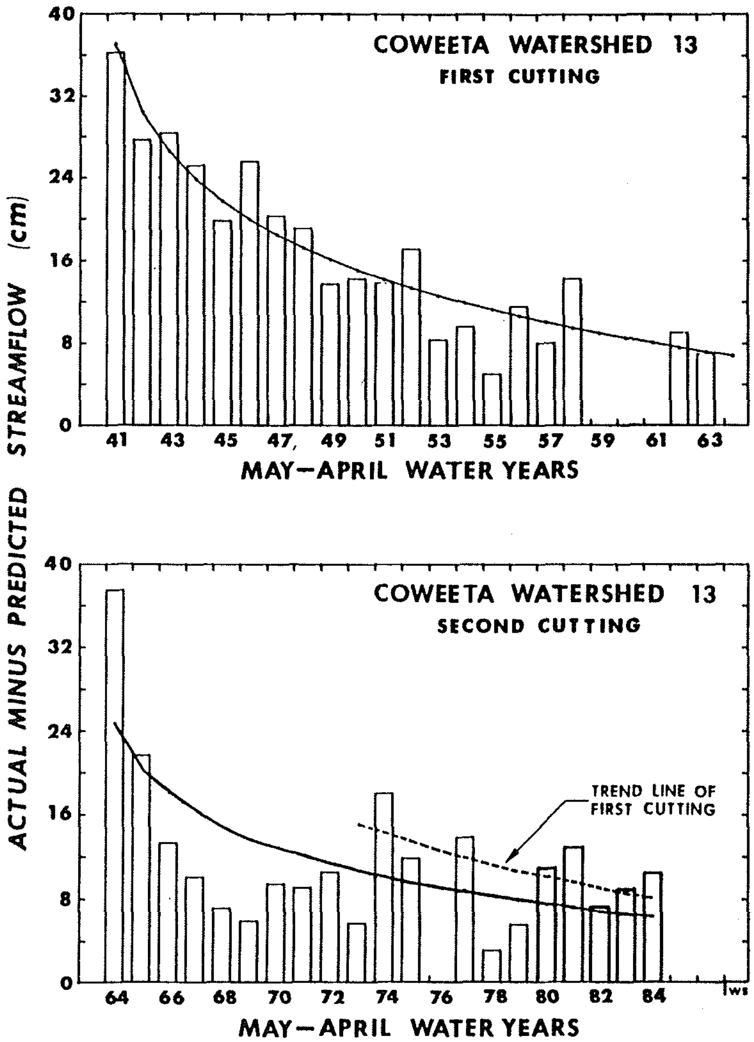

Figure 22.4. Streamflow increases following two clearcutting experiments on the mixed wood covered Coweeta WS 13. Streamflow was not measured in water years 1959, 1960, and 1976.

and surface area also recovered rapidly during the first 7 years after the second c (Table 22.2). At age 7, leaf biomass was nearly equal to leaf production at age 14 the first cutting, and leaf area index (LAI) was similar to values expected for m forests. In the next 2 years, leaf surface area and biomass declined sharply due mortality from competition in the dense stand, and this was associated with h streamflow increases during the same period. Fifteen years after the second cu LAI was 6.0 and streamflow was near pretreatment levels. These long-term ex ments illustrate the strong relationship between the temporal variations of the qu

Table 22.2. Characteristics of Forest Vegetation at Different Stand Ages for Coweeta WS

Water Year and Phase of Treatment	Stand Age (Years)	Stand Density (Stems ha^{-1})	Leaf Biomass (g m^{-2})	Leaf A Inde (m^2 m
1934	Mature, uneven-aged	2596	N/A	N/A
1940, First clearcut	Cut	0	N/A	N/A
Regrowth years	8	7630	N/A	N/A
Regrowth years	12	5322	N/A	N/A
Regrowth years	14	N/A	316	N/A
1962	22, even-aged	4196	N/A	N/A
1963, Second clearcut	Cut	0	N/A	N/A
Regrowth years	7	9659	268	5.2
Regrowth years	8	N/A	192	3.7
Regrowth years	9	N/A	191	3.8
Regrowth years	15	7338	309	6.0

N/A, not available.

of evaporating surface, evapotranspiration, and water yield. However, Swift ε Swank (1981) found that the addition of a rainfall variable improved the fit of the tre line in the second cutting.

Logarithmic trend lines were fitted to two additional cutting and regrowth expe ments (Figure 22.5). Streamflow increases on WS 37 temporarily returned to pretre ment levels during the fourth and sixth years after cutting. During the next 5 yea there was a general streamflow increase and then a second return to baseline response pattern similar to WS 13. Detailed discussion of the temporal trends streamflow and regrowth characteristics of WS 13 compared to WS 37 is given by Sv and Swank (1981). On WS 28, the multiple-use demonstration experiment, 51% of basin was clearcut, 22% was thinned, and 27% was left uncut. The recovery trend cu is not different in either slope or level from that of WS 37, but the level of fl increases for both experiments is different (less) than WS 13. Both watersheds higher in elevation, with steeper slopes, generally shallower soils, and shorter grow seasons than WS 13. Hence, we postulate that *Et* is less and changes in flow due to c ting are lower on these watersheds.

Effects of Cutting on Storm Hydrograph Characteristics

Of the cutting experiments conducted at Coweeta, only three have received rat thorough analysis of changes in storm hydrograph characteristics. Differences in extent and type of watershed disturbance, the period of record included in pc treatment assessment, inherent watershed hydrologic response factors, and the mag tude and frequency of storms following treatment complicate summary evaluations storm hydrograph responses. Nevertheless, the percent increases in four import storm hydrograph parameters calculated for the mean storm over the period of analy are summarized in Table 22.3. Increases in quickflow volumes for cutting experime with minimal disturbance to the forest floor (WS 7 and 37) are similar during the f

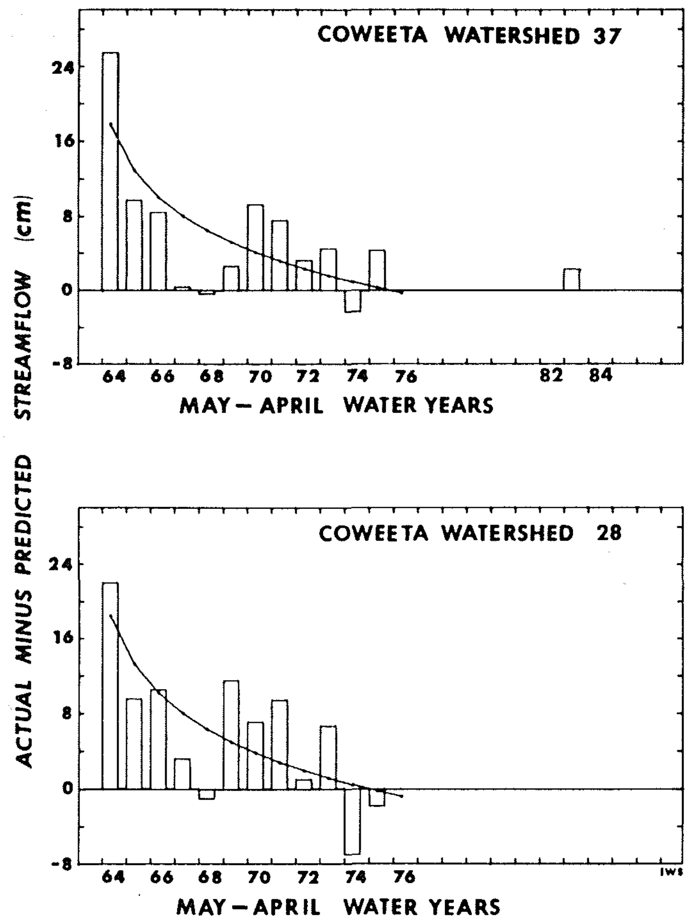

Figure 22.5. Changes in streamflow following cutting the mixed hardwood forest o Coweeta watersheds. Streamflow measurements were discontinued in 1975.

3 to 4 years after treatment, with a mean increase of about 10%. Commercial cle ting with cable logging and some road construction (WS 7) produced peak flow about double (15% vs. 7%) the mean increases from clearfelling alone (WS 37). I flow rates and recession time were also increased 10 to 14% on WS 7. The l changes occurred on WS 28, where commercial logging involved tractor skiddin a high road density. Quickflow increases averaged over the 9-year post-treat period increased 17%; mean peak flow rates increased 30% the first 2 years after ment and declined in subsequent years. It appears that the absence, or low densi carefully constructed roads, combined with little disturbance to the forest floor d harvest, produced the smallest changes in stormflow responses. More specifi detailed interpretations have been reported by Swank et al. (1982) for WS 7, Dou and Swank (1976) for WS 28, and Hewlett and Helvey (1970) for WS 37.

Table 22.3. Summary of Storm Hydrograph Responses to Clearcutting

Watershed Number	Size (ha)	Response Factor Mean Stormflow Volume ÷ Mean Precipitation	Treatment	Inclusive Years After Treatment	Mean Storm Increases for Selected Hydrograph Parameters: Total Quickflow Volume (%)	Peak Flow Rate (%)	Initial Flow Rate (%)	Recession Time (%)
7	58.7	0.04	Clearcutting, cable logging, product removal and minimal road density	3	10	15	14	10
28	144.1	0.09	77 ha clearcut, 39 ha thinned, 28 ha no cutting; products removed; high road density	9, 2[a]	17	30	N/A	N/A
37	43.7	0.19	Clearcut, no products removed	4	11	7	NS	NS

N/A, not available; NS, not significant.
[a] Inclusive years after treatment used for total quickflow and peak flow rates, respectively.

Natural Disturbance

The partial defoliation on WS 27 by fall cankerworms from 1969 to 1977 was of cient magnitude and duration to detect effects on streamflow during part of eacl Using WS 36 as a control for WS 27, preinfestation calibration regressions derived for annual, monthly, and a variety of combined monthly periods. No s cant changes in flow were detected in annual flow, individual monthly yields, o combined monthly analyses. However, significant (0.05 level) flow reductions f November through January period were observed in most years of infestation 22.4). Reductions varied from 5 to 15 cm or 7 to 18% below expected flow level 1978, which coincided with the decline of cankerworm populations. These responses are attributed to stimulation of leaf production by defoliation. Inst litter production of about 230 g m^{-2} and a leaf area index (LAI) of 3.1 typical fo elevation Coweeta forests, leaf production during most years of infestation exc 425 g m^{-2} with a LAI of at least 6.0. The elevated LAI apparently produced l evapotranspiration during the summer months, but streamflow reductions we observed at the weir until the winter period. This lag in timing between evapo changes within the watershed and measured effects at the weir agree with experimental results at Coweeta. Anticipated increases in flow during the : months were not detectable, possibly because of the brief period of defoliatio time of relatively low evaporative demand. To our knowledge, this is the documented evidence where an insect infestation has been shown to increase a reduce streamflow.

Species Conversions

Two major long-term studies of the effects on water yield of converting mixed woods to different vegetative covers have been conducted at Coweeta. One replacement of hardwoods with white pine, and the second a conversion to gra

Table 22.4. Reductions in Flow During the November–January Period by Year Due to Hardwood Defoliation by Fall Cankerworm

Year	Change in Flow (November-January) cm	%
1969	−6	11
1970	−9*	14
1971	−7	9
1972	−9*	11
1973	−15*	16
1974	−8*	15
1975	−5*	7
1976	−8*	18
1977	−15*	16
1978	+2	4

*Significant at 0.05 level.

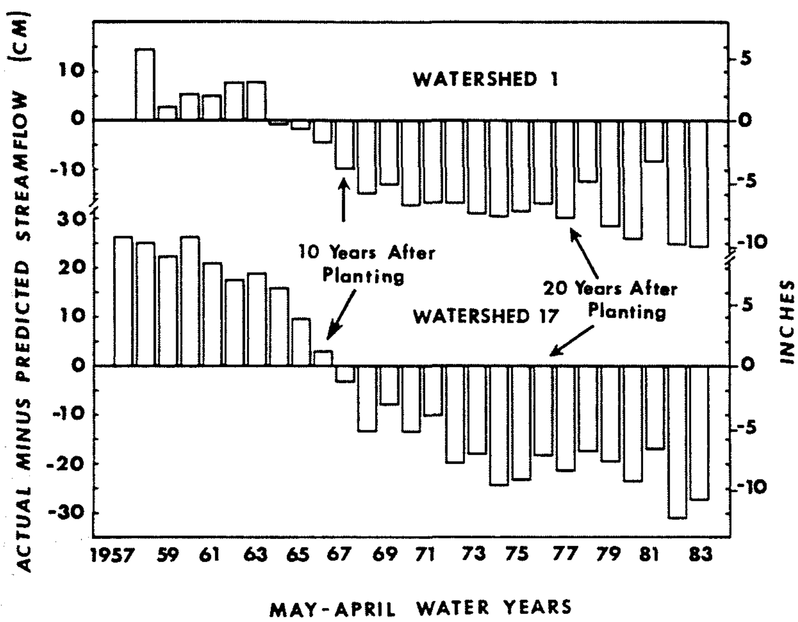

Figure 22.6. Annual changes in flow on two Coweeta watersheds following conversion fı
mixed hardwood to white pine.

lowed by succession. Both of these conversions have produced dramatic change: streamflow, which are of importance to forest managers, hydrologists, and ecologi

The white pine experiments were conducted on both north-facing and south-fac watersheds. For about 6 years after planting of white pine, streamflow increa remained relatively constant and near those expected for clearcut hardwoods (Fig 22.6). Thereafter, as the pine stands developed and hardwood competition reduced, streamflow increases declined at a rate of 2 to 5 cm per year until about 19 About 10 years after planting, streamflow was below levels expected from mature hε woods and, by age 15, water yield reductions were about 20 cm (20%) less tl expected for a hardwood cover. In the ensuing 9 years, annual reductions in flow fluc ated between 10 and 20 cm, depending upon annual precipitation. For example, dur an exceptionally wet year such as 1980, pine evapotranspiration was much higher t hardwoods, but in the following year (1981), precipitation was quite low and sn streamflow reductions were observed. Flow decreases during the more normal rain years of 1982 and 1983 exceeded 25 cm on both watersheds.

Reasons for greater evaporative losses from young pine than from mature hardwo have been given in several papers (Swank and Miner 1968; Swank and Douglass 19 Swift et al. 1975). Interception and subsequent evaporation of rainfall is greater pine than hardwoods, particularly during the dormant season. Interception loss va with LAI, and in the dormant season, LAI for hardwoods is less than 1 compared tc for white pine. Thus, less precipitation reaches the soil under closed pine stands the result is lower streamflow. Simulation of evaporation for pine and hardwoods u: the PROSPER model (Swift et al. 1975) shows greater dormant season transpirat

Table 22.5. Simulated Interception and Transpiration Totals for Oak-Hickory and Whit Forests During the Growing and Dormant Seasons

Year and Vegetation Type	Interception (cm)			Transpiration (cm)	
	May–October	November–April	Total	May–October	November–April
1972–1973					
Oak-hickory	13.83	9.01	22.84	56.05	9.98
White pine	18.28	13.64	31.92	54.68	21.84

After Swift et al. Water Resourc. Res. 11:667–673, 1975. Copyright by the American Geophysical

losses from pine (Table 22.5). On an annual basis, simulations indicate that int(tion and transpiration are equally important from a quantitative viewpoint.

The influence of precipitation quantities on annual responses can be normaliz expressing reductions in flow for any given year as a percent of flow expected watershed had not been treated (Figure 22.7). Flow reductions appear to culmin about age 12 and tend to remain rather constant until ages 25 and 26, when deci are 35 to 45% below hardwood levels. The original hypothesis in 1968 was th rapid streamflow reduction resulting from hardwood to pine conversion would t(level off when LAI culminated and thereafter gradually decline as the total plar face area (including stem and branch area) slowly increased with stand age. appeared plausible, because surface area is a structural characteristic closely rela the major evaporative processes of interception and transpiration. The culminat LAI development shown in the lower part of Figure 22.7 does, in fact, correspc the leveling off of streamflow reductions and the total surface area index has cont

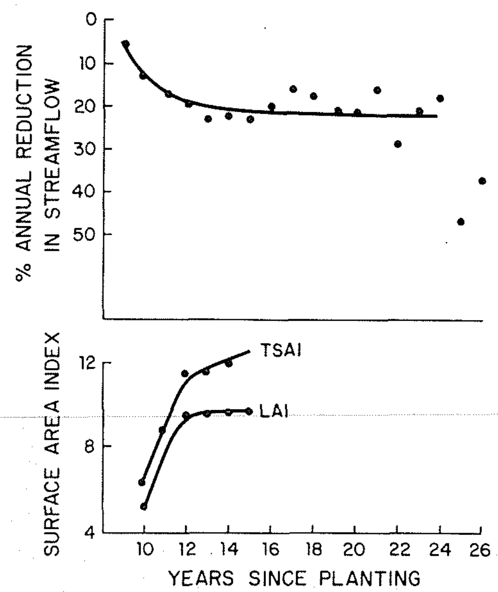

Figure 22.7. Percent reduction in ε flow after the planting of white pi Coweeta WS 1 in relation to the de' ment of plantation leaf area index and total surface area index (TSAI) i ing foliage, branches, and boles.

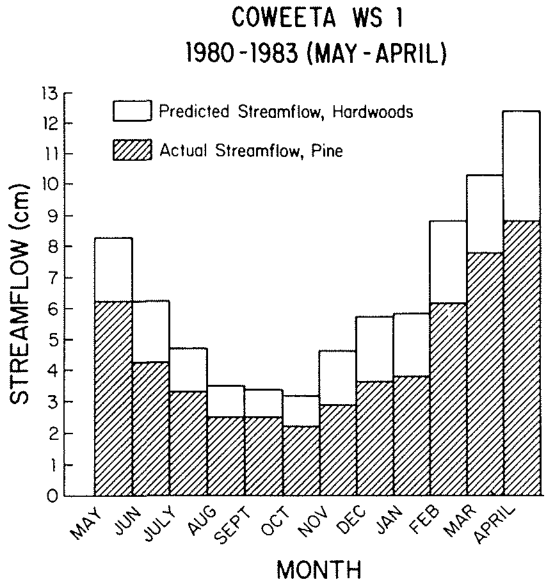

Figure 22.8. Mean monthly flows predicted for a mature hardwood forest on Coweeta WS 1 and actual flows measured from a white pine plantation on the watershed during a 4 year period (1980–1983).

to increase. The surface area graph is incomplete; the population has been sample for both biomass and surface area in subsequent years, but estimates are unavailat at this time. Some very large and sudden increases in pine evapotranspiration are indicated by reduced flow in both 1982 and 1983; the stand will be resampled aga to identify current changes in structural characteristics.

The average monthly flows for pine compared to hardwoods on WS 1 for 1980– are shown in Figure 22.8. Significant reductions occur in every month. Large reductions of 2 to 3 cm occur in March, April, and May when flows are highest, and at a time before and during hardwood leafout when evaporative demands can high. In the low flow months of August, September, and October, reductions average about 1 cm or 40% below levels expected for hardwoods.

The conversion from hardwood to grass, followed by deadening with herbicides and then succession, also significantly altered annual streamflow (Figure 22.9). Merchantable timber was harvested and a seedbed was prepared for planting Kentucky 31 fescue grass. At the time of seeding, lime and fertilizer were applied. In the first year after conversion, grass production was very high, with 7.85 t ha^{-1} of dry matter (3.5 ton $acre^{-1}$), and there was no significant change in streamflow. In the ensuing years, water yield increased and at the end of the fifth year was about 14 cm above the flow expected for the original hardwood forest. During the same period, grass production declined to 4.04 t ha^{-1} (1.8 ton $acre^{-1}$). To further test th inverse relation between change in streamflow and grass productivity, the grass w again fertilized in 1965; productivity increased to 7.85 t ha^{-1} (3.5 ton $acre^{-1}$) and streamflow again dropped to the level expected for hardwoods. A more detailed analysis of the early phases of this experiment is described by Hibbert (1969). Th results further demonstrate that both type and amount of vegetation have a major influence on *Et* and streamflow.

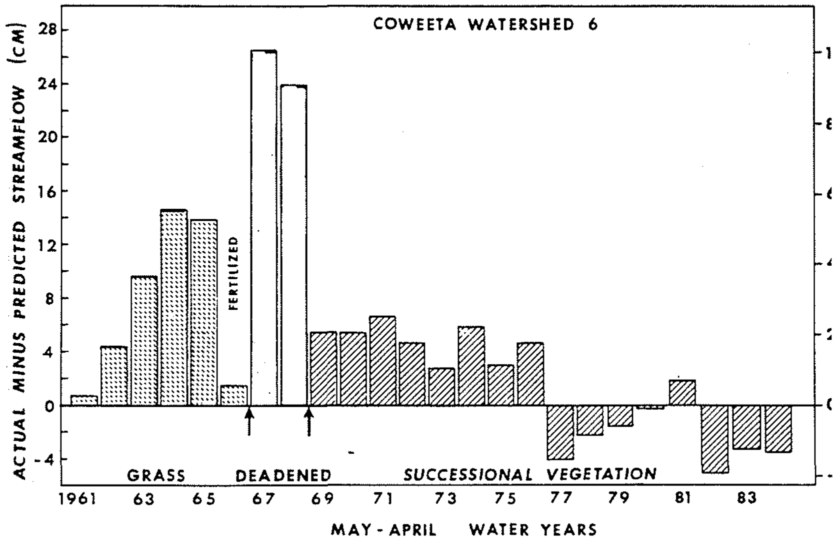

Figure 22.9. Annual changes in streamflow on Coweeta WS 6 during a 6 year period afte version from hardwood to grass, followed by 2 years of herbicide applications to deaden th and the ensuing 16 years of succession.

In 1967 and 1968, the grass was herbicided and flow increased about 25 response similar to that expected from clearcutting (Figure 22.9). During the firs of succession, the watershed was dominated by a thick, lush cover of herbaceou cies, and streamflow increases rapidly declined to only about 6 cm above harc levels. This level of increase continued for the next 7 years and then returned to expected for hardwoods. Thus, *Et* from a mixture of young hardwoods dominat black locust in association with blackberries, herbaceous species, and some gı equivalent to a mature mixed hardwood forest.

Special Case Application

The hydrologic principles derived from Coweeta studies of water yield and timing been utilized in a variety of ways by resource managers, administrators, and scie A simple example will serve to further illustrate how results can be utilized to ev alternative silvicultural prescriptions in the real world (Figure 22.10). In this ill tion, we demonstrate the effects of hardwood even-aged management vs. white plantation management on long-term water yield. The prescription conditions taken from current guidelines for the Nantahala National Forest management p North Carolina.

We begin by clearcutting a mature mixed hardwood forest with a solar inso index of 0.27, mean annual precipitation of 180 cm, and a mean annual flow of 9

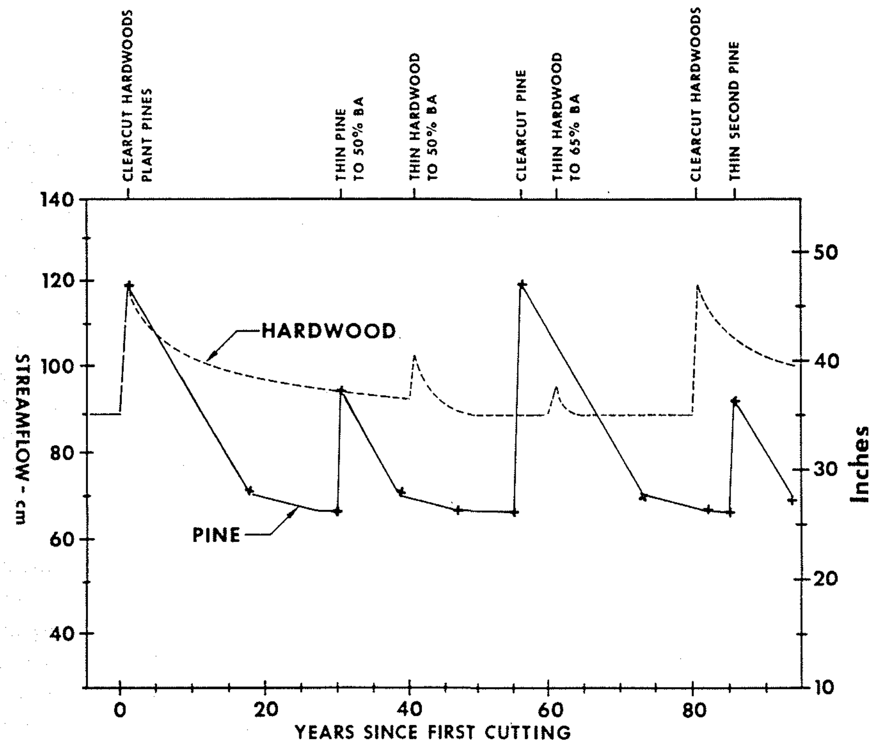

Figure 22.10. Estimates of long-term streamflow responses to hardwood even-aged manment and white pine plantation management based on experimental results for Coweeta clim conditions.

In one case, hardwoods regenerated from sprouts and seeds, and in the other ca white pine were planted. During the rotation, commercial thinning of hardwood applied at ages 40 and 60 years with removal of 50% and 35% of the basal area, resp tively. The stand is then again clearcut at age 80 years. The prescription for pine commercial thinning at age 30 years with 50% of the basal area removed and a final h vest by clearcutting at age 55, and replanting with white pine followed again by thinn at age 30 (Figure 22.10). For the 80 year period depicted, the average annual strea flow under hardwood even-aged management is 95 cm, and for pine the average fl is 81 cm. The cumulative difference in flow between the two prescriptions is 1120 (441 inches). If we assume the treated watershed is 10 ha (25 acres), the total differe is 1.12×10^6 m^3 (919 acre-feet) of water in 80 years.

This illustration shows that alternative silvicultural prescriptions can have a subst tial and very real effect on water yield. Although a variety of prescription scenar could be selected, the point is that functional relationships are available to make de sions about silviculture and water yield.

Conclusions

Long-term streamflow records for control and experimental forested watershe Coweeta provide a solid foundation for evaluating hydrologic responses to veget management. Results from these experiments and those elsewhere in the Appalac Highlands provide equations for predicting changes in annual water yield follo cutting and regrowth of hardwood forests. Only two parameters, proportion o stand basal area cut and potential insolation of the watershed are needed to solve t equations. Increases are produced in most months, with about a 100% increase dı the low flow months when water demands are usually high. The recovery of strean to preharvest levels associated with hardwood regrowth shows the interactions bet *Et*, stand dynamics, and watershed physical characteristics. Experiments indicate commercial clearcutting, with carefully located and designed roads, produce small and acceptable (about 15%) increases in mean stormflow volumes and peak rates. Natural alteration of vegetation such as insect defoliation can also inflı water yield by stimulating leaf production and increasing evapotranspiration, reducing winter streamflow by 7 to 18%.

Other long-term experiments show the striking dependence of streamflow volun type of vegetative cover. Within 25 years, hardwood to white pine conversion re annual flow by 25 cm and produces significant reductions in every month of the Greater *Et* for pine is due to a higher LAI for pine compared to hardwoods, h greater interception and transpiration by pine. Hardwood to grass conversion alters streamflow depending upon grass productivity. There is no significant char flow with a vigorous grass cover, but as grass productivity declines strean increases. Evapotranspiration from a luxuriant herbaceous cover is slightly lower in mature hardwoods, but later in succession with a mixture of hardwoods, grass herbs, *Et* is equivalent to hardwoods. In conclusion, forest managers should reco that silvicultural prescriptions influence evapotranspiration, and hence stream and that hydrologic changes are either a cost of doing business or an added benefit management decisions.