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THE POTENTIAL FOR WATER YIELD AUGMENTATION FROM FOREST MANAGEMENT IN THE EASTERN UNITED STATES[1]

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ABSTRACT: Generally high rainfall and extensive forests in the East combine to produce excellent potential for managing forests for increased water yield. Models are presented that allow prediction of streamflow increase from hardwood and pine forests on a year-by-year basis. They are being routinely applied in land management planning on National Forests in the Southeast. A recent, independent test indicates that cumulative water yield increases can be predicted within about 14 percent of the actual value. However, because of the diverse land ownership patterns and the economic objectives of owners, realizing the potential will be difficult at best. The opportunity for realizing the full potential appears greatest where the land is publicly owned, but demand for water in the East has not reached the point where need for water dictates management prescriptions.
(KEY TERMS: water yield improvement; Eastern United States; forest management; vegetative effects; pine; hardwood.)

INTRODUCTION

When discussing processes as complex as the hydrologic cycle for an area as diverse as the Eastern United States, one is forced to deal to some degree in generalities. For example, the land mass east of the Mississippi River is nearly 600 million acres in size; half of it is forested, but the distribution of forests is highly variable. Woodlands comprise as little as 11 percent of Illinois and as much as 90 percent of Maine (U.S. Department of Agriculture, 1980). Annual rainfall varies from a low of 30 inches in Wisconsin and Michigan (Lull, 1968) to 50 inches or more throughout much of the South (U.S. Department of Agriculture, 1969). Potential evapotranspiration ranges from nearly 50 inches at the tip of Florida to about 18 inches annually at the Canadian border (Thornthwaite, *et al.*, 1958). Consequently, runoff also varies from 10 inches in sections of the North Central States to over 60 inches in places in the Blue Ridge Mountains. Because most drainage basins are in mixed land use, the effects of forests and their management on water yield augmentation are diluted and unclear. Nevertheless, the potential for water yield augmentation through management of eastern forests is excellent. In fact, if all timber in the East where mature and were harvested instantaneously, enough extra water would be yielded during the next year to equal half the annual flow of the Mississippi River.

As unbelievable as this theoretical increase seems, its magnitude can be defended by findings from forested experimental watersheds. The example is used to dramatize the enormous potential for augmenting yield although such a massive change in land use would be as physically undesirable as it would be impossible to achieve through purposeful management. Yield as used in this paper is the difference between precipitation and evapotranspiration; it is the sum of the water yielded as runoff plus water entering the water table.

THE CASE FOR MANAGEMENT

Water Yield Augmentation from Hardwoods

We know from scientific studies begun nearly 50 years ago that interruption of transpiration saves water, which is eventually released to ground water or streams. Hibbert (1967) summarized worldwide catchment studies and observed that deforestation increased and afforestation decreased water yield. He concluded that the response was highly variable and, for the most part, unpredictable. This might be expected when examining data from the great range of climates, vegetations, and geomorphic conditions which exist worldwide. Lull and Reinhart (1967) reviewed available information from forested catchment studies in the Northeastern United States looking for effects of partial or complete forest removal on yield response. They concluded that first year water yield increases were not highly sensitive to precipitation amount, that partial cuttings were not as efficient for augmenting water yield as were complete cuttings, and that water yield from well-stocked northeastern forests could be increased by from 4 to 12 inches the first year after complete cutting. By restricting their discussion to the humid Northeast, they felt more confident than did Hibbert (1967) in discussing the range in expected response, but they too were unable to offer a systematic method for estimating how water yield would

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change at specific sites after specific practices. They also could not offer convincing reasons for the large differences in yield response sometimes observed between two neighboring watersheds treated the same way.

Hibbert (1967) had pointed out the nearly threefold differences in yield response from clearcutting north- and south-facing watersheds at Coweeta (Figure 1). Although apparently associated with aspect, no clear explanation for the differences could be given. Scientists were uncertain if the aspect effect was real because it was only observed at Coweeta. Because managers interested in yield augmentation needed to know how much streamflow could be increased, the results from all watershed cutting experiments in the Appalachian Highland Physiographic Division (Figure 2) were examined to determine if estimates of yield changes could be improved (Douglass and Swank, 1972). A linear regression (Figure 3) was derived relating the first year yield increase after treatment to the percent basal area (or land area) cut.

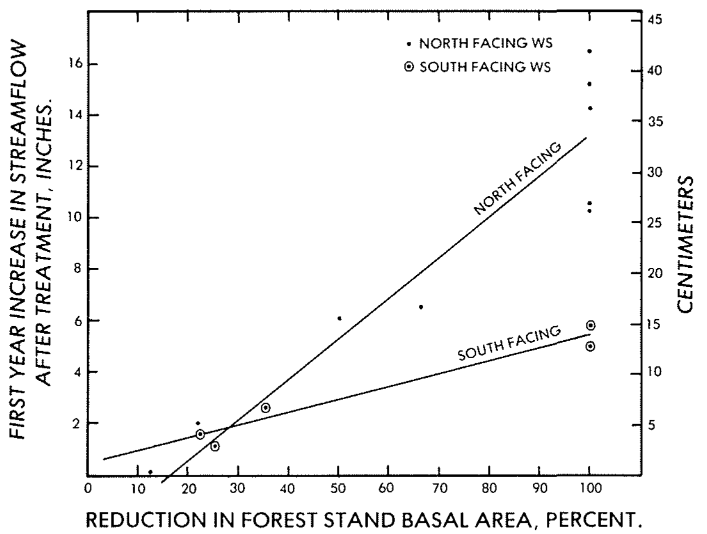

Figure 1. The Water Yield Increase Obtained After Harvesting North-Facing Watersheds at Coweeta Was About Two and One-Half Times Greater Than From South-Facing Watersheds. Increases from clearcutting north-facing watersheds varied about ± 30 percent of the mean.

Although a decided improvement, the wide scatter of points around the regression of first year yield increase versus basal area cut was disappointing. The response to clearcutting varied from 5 to 16 inches. Also, the model did not fit the belief by hydrologists that partial cuttings were less efficient at increasing streamflow than complete cuttings (Lull and Reinhart, 1967; Hornbeck and Federer, 1975; McMinn and Hewlett, 1975). It did not take into account aspect or latitudinal differences that might affect the level of response. An improved version of the first year yield increase model was derived (Figure 4); it included the energy theoretically received by watersheds of different slopes, aspects, and latitudes (Douglass and Swank, 1975). The energy function was termed the insolation index. This equation is curvilinear in form and it passes through the origin; thus, it is a more reasonable representation of the actual response to partial cuttings. Including insolation in the predicting equation accounted for another 10 percent of the variation in first year yield increase. Total variation explained was 89 percent.

As forests regrow, the initial increase declines logarithmically back to the base yield from a well-stocked forest (Figure 5; Kovner, 1956; Lull and Reinhart, 1967). This relationship provides the theoretical basis or model for predicting the yield increase for any year after harvest when the duration of the increase is known. The length of time increases lasted for Appalachian experimental watersheds depended on the size of the increase; the duration of the increase was 1.57 years for each inch of flow produced the first year after harvest (Douglass and Swank, 1972).

The final equations derived for estimating yield increases for hardwoods are:

$$Y_H = 0.00224 \left(\frac{BA}{PI}\right)^{1.4462} \quad (1)$$

$$D_H = 1.57 Y_{H_1} \quad (2)$$

$$Y_{Hi} = Y_H + b \log (i) \quad (3)$$

Y is the first year yield increase for hardwoods, BA is the percent basal area cut, PI is the annual potential insolation in langleys x 10^{-6} for the watershed calculated by the methods of Lee (1963) and Swift (1976), D is the duration of the increase in years, Y_{Hi} is the yield increase for the ith year after harvest, and b is a coefficient derived by solving Equation (3) for the year when i = D_H and Y_{Hi} = 0. The subscript H is for hardwoods.

The limitations on use of the equations are:

1. They were derived from experimental results obtained in the Appalachian Highland Physiographic Division, a humid region receiving 40 inches or more of annual precipitation reasonably well distributed through the year. Thus, the equations are applicable to 40 percent of the land mass of the East, a land base which is about 65 percent forested.

2. Equations were derived from experiments with deciduous forests and are not directly applicable to coniferous forests. Of the total forest area in the East, 65 percent is in hardwoods or mixed pine-hardwoods (U.S. Department of Agriculture, 1980).

3. The model was developed for energy conditions represented by insolation indices varying from 0.2 to 0.34. Applying the equation outside this range can lead to errors. For example, above 47°N latitude, roughly the Canadian border, very steep, north-facing slopes can have an insolation index of less than 0.2 and solving Equation (1) for a clearcutting may, in rare cases, estimate yield changes which exceed potential evapotranspiration. Obviously, any insolation index which

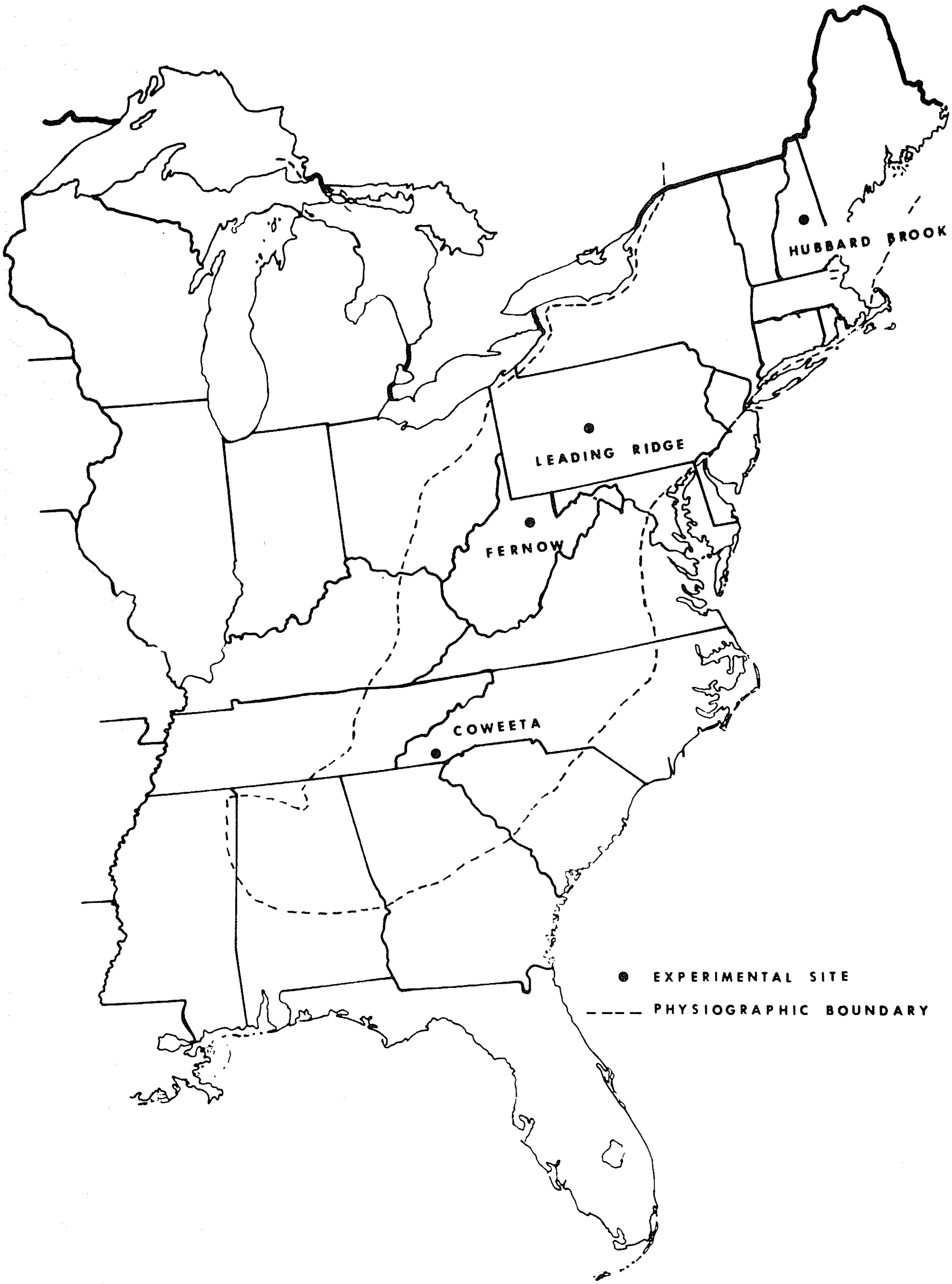

Figure 2. Data From Four Locations in the Appalachian Highland Physiographic Division Were Used to Develop Models for Estimating Water Yield Augmentation From Harvesting Hardwood Forests.

produces a greater first year yield increase than potential evapotranspiration should be rejected. The model was also derived where rainfall averaged over 40 inches annually. Although Lull and Reinhart (1967) minimized the effect of rainfall variations on yield increase, the amount of rainfall received does appear to affect the size of the increase even in the humid East (Hornbeck, *et al.,* 1970). The rainfall effect can be very large when precipitation is seasonal and comparatively low (Hibbert, *et al.,* 1974). This effect may be more pronounced in states like Michigan and Wisconsin with rainfall between 30 and 40 inches than in the East as a whole. That is, actual yield increases may be somewhat less than the amount predicted for hardwoods in areas receiving less than 40 inches of rainfall annually.

4. Equations were developed for well-stocked sawtimber aged forests that were using water at approximately the physiological maximum rate. Responses for understocked or young stands should be less than predicted from the equations.

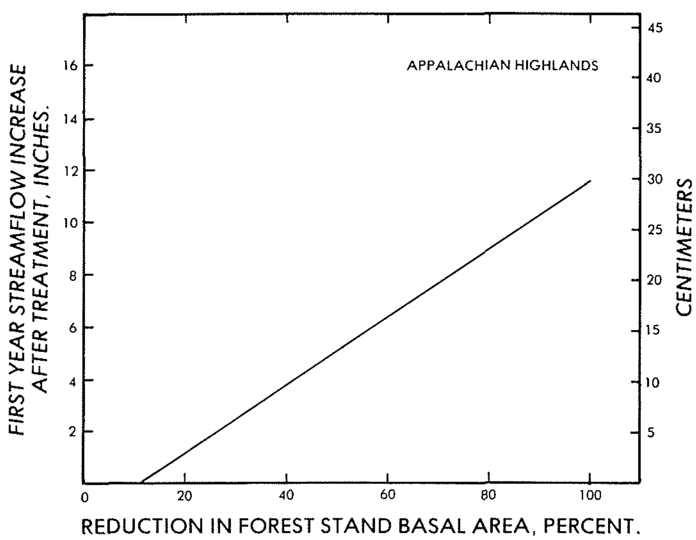

Figure 3. The First Year Increase in Streamflow for the Appalachian Highlands is Primarily Dependent Upon the Reduction in Basal Area During Harvest (Douglass and Swank, 1972).

Water Yield Augmentation from Conifers

Coniferous stands occupy 34 percent or about 102 million acres of forest land east of the Mississippi. Equations of the type developed for eastern hardwoods are needed for conifers, but not enough cutting data exist to develop the equations. However, if the physical processes of water use are similar for the two vegetative conditions, the hardwood model can be adjusted using existing data for conifers. Two adjustments are necessary – one for a difference in yield increase and one for a difference in duration of the increase.

The basis for adjusting the first year yield increase is the evapotranspiration difference between cover types, which causes a difference in yield when forests are harvested. Hewlett (1958) discussed theoretical concepts and experimental results which suggest that conifers might use more water than hardwoods. He described two experiments then underway at the Coweeta Hydrologic Laboratory to provide proof of any effects on water yield.

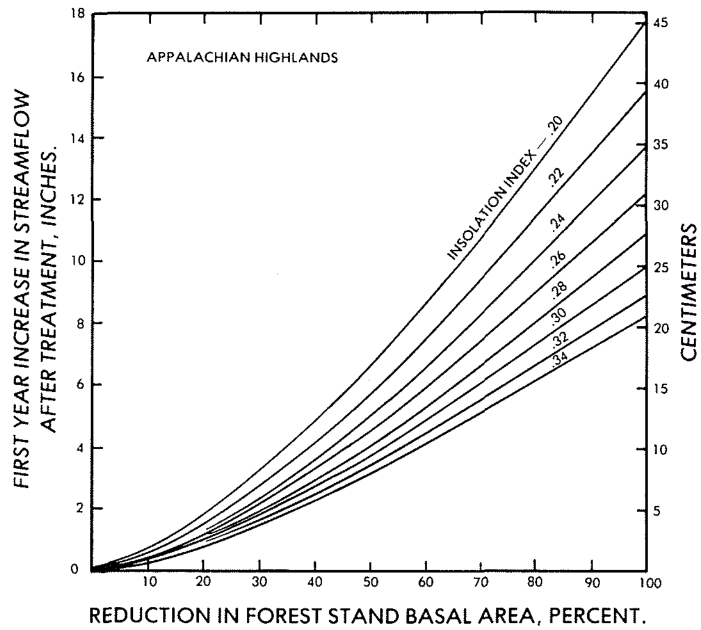

Figure 4. The First Year Increase in Streamflow After Harvesting Timber Varies with Percent Basal Area Cut and the Energy Received by the Watershed. Accounting for the insolation load on the watershed significantly improved predictive capability (after Douglass and Swank, 1975).

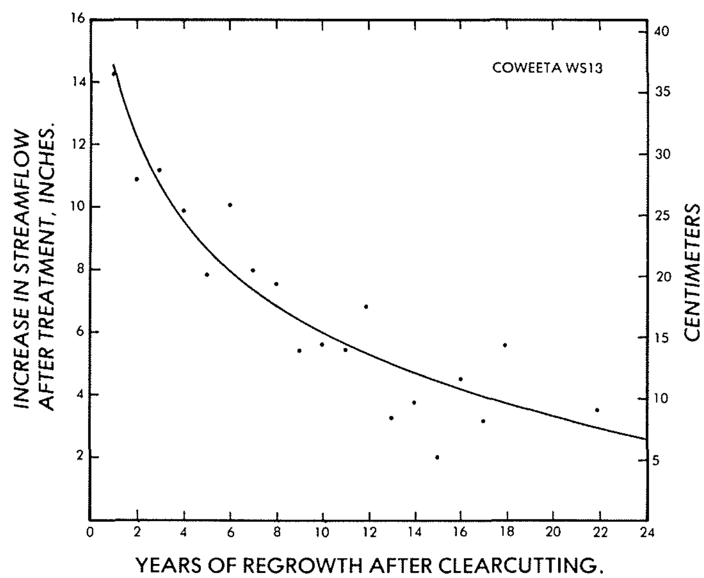

Figure 5. The Initial Increase in Streamflow Declines Logarithmetically with Time as a Forest Regrows. This time trend provides a basis for estimating yield augmentation during any year after timber harvest.

Because conifers retain their foliage year round and have greater leaf area, particularly in the winter, they intercept more water than hardwoods (Helvey, 1968, 1971). Because they retain their foliage, conifers can transpire water during warm periods in the winter when hardwoods are leafless or only leafing out. When the white-pine-covered watersheds described by Hewlett (1958) were only 10 years old, they were using as much water as the old-growth hardwoods they replaced; a few years later, they were using about 8 inches more water than hardwoods. The difference in use was attributed to both interception and transpiration (Helvey, 1968; Swank, 1968; Swank and Douglass, 1974; Swift, *et al.*, 1975).

Figure 6 supports the line of reasoning suggesting greater water use by conifers. Runoff equations were derived for high elevations (high precipitation and low insolation) and low elevations (lower precipitation and higher insolation) at Coweeta by plotting runoff over precipitation. For all practical purposes, these two lines bound the runoff response to rainfall of all hardwood-covered experimental watersheds in the Appalachian Highlands, where essentially all yield comes as runoff over the weir blade. Watersheds with intermittent flow and obvious leakage were excluded. A plotting for two pine-covered watersheds in the Coastal Plain near Charleston, South Carolina, is also shown; the relationship is similar to that of hardwoods but about 5 inches less. Swank (1968) estimates that interception differences alone could account for 3 to 4 inches of difference in yield between pine and hardwoods in the South Carolina Piedmont and Coastal Plain. Thus, the interpretation is that because pines evapotranspire more water than hardwoods, greater yield increases can be expected when pines are harvested. When viewed in the context of world experience, the yield response does appear greater from conifers (Bosch and Hewlett, 1982). The interception difference between conifers and hardwoods can be added to first year yield increase for hardwoods to provide an estimate of the first year increase that will result from harvesting conifers. Since this procedure only considers interception and not transpiration differences, the estimate should be conservative.

The second hardwood-model adjustment needed is for a difference in the duration of the yield increase. Again, the two conversion watersheds at Coweeta provide experimental data which indicate that the increases should end at about the time needle surface area reaches a maximum, or at about age 12 for white pine (Swank and Schreuder, 1973). Culmination of surface area increment of needles may vary with tree species and latitude, but lacking better site-specific information, one could assume a value of 12 years as the duration of increase for pine.

The derived equations for conifers become:

$$Y_C = Y_H + (I_C - I_H) \tag{4}$$

$$D_C = 12 \tag{5}$$

$$Y_{Ci} = Y_C + b \log (i) \tag{6}$$

$(I_C - I_H)$ is the interception difference between conifers and hardwoods with interception determined by Helvey's (1971) equations. Other parameters are as described above and the subscript C refers to conifers.

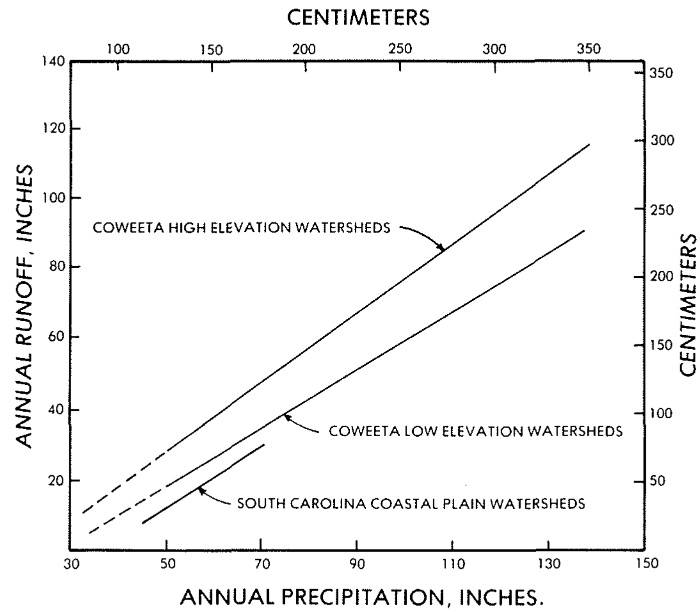

Figure 6. Annual Runoff from Undisturbed Hardwood Covered Watersheds at Coweeta Varies with Precipitation and Energy Received. The range in runoff response observed at Coweeta encompasses that observed for other hardwood covered watersheds in the Appalachian Mountains. Annual runoff is less for pine covered watersheds in coastal plains where evapotranspiration is greater.

Model Application

The validity of the equations for conifers and hardwoods can be judged by how well they perform when applied to other watersheds. In the first reported test (Douglass and Swank, 1976), the increase in yield was estimated for 10 years after about 65 percent of the basal area of a 356-acre watershed was harvested. The total yield increase predicted by the model for the 10 years was within 2 percent of the observed increase. The model also appeared to perform reasonably well on New Jersey watersheds that were defoliated by the gypsy moth or by herbicide. Recently, a 150-acre Coweeta watershed was clearcut and the yield increase for the first 4 years was within 14 percent of the model prediction (Swank, *et al.*, 1982). As indicated in Table 1, the deviation of model estimates and observed values during individual years was sometimes substantially greater than for the accumulated increase.

Large deviations for individual years probably result from three factors: (1) the first year yield increases used to develop Equation (1) are themselves estimates rather than absolute increases determined without error. The first year yield increases are average values representing the accumulated experience from many experiments conducted under different rainfall conditions. (2) The observed experimental increase also has an associated error because it is estimated from calibration regression. (3) Part of the difference observed for individual years may be due to rainfall peculiarities of the particular year, i.e., either wet, dry, or unevenly distributed. Therefore, the most reasonable performance expected from this sample model is over the long run. The hardwood equations appear to perform well over the life of the cutting. There are no tests of the performance of the equations for pine.

TABLE 1. Comparison of the Annual Increase in Yield with the Increase Estimated from the Model for Coweeta Watershed 7.

Year After Clearcutting	Annual by Model (inches)	Increase Observed (inches)	Deviation from Model (percent)
1	9.97	9.66	− 3.2
2	6.61	9.01	+26.6
3	4.64	7.18	+35.4
4	3.25	2.52	−29.0
	24.47	28.37	+13.7

With these equations, the augmentation in water yield from forest management can be estimated for specific cover types and locations in the East. The equations can be easily modified for local conditions if experience indicates a need. For example, if the duration of an increase from conifers is species dependent, or if it is shorter at southern than at northern latitudes, adjustments can be made as experience data become available. The equations can be incorporated in computer models such as DYNAST-TM (Boyce, 1978) to evaluate effects of alternative timber management practices on water under stable management as was done for a 6400-acre watershed in North Carolina (Douglass, 1980). A similar adaptation by the Forest Service is in general use in land management planning on southern National Forests and was described at the Atlanta meeting of AWRA last year (paper presented by Richard Burns).

YIELD AUGMENTATION BY DESIGN

The preceding discussion has demonstrated the potential for water yield augmentation from managing well-stocked eastern forests that are using water at their normal rate. This base condition exists on many millions of acres of pulpwood, small sawtimber, and old-growth forests. Other forests, which support seedlings and saplings or are understocked, may be yielding more water than the "base" stand forests. Thus, opportunities to augment yield (or perhaps reduce it in the case of conversion to conifers) are site specific, depending upon current stand conditions and the intensity of management applied to those stands. The important point is that we have the tools to assess yield for timber stand conditions that exist on specific watersheds and to evaluate the yield increase that can be attained on those watersheds through management of the forest.

From a practical standpoint, management of eastern forests to augment water yield is an attainable goal when two conditions exist:

1. Forests cover a significant part of the total watershed.
2. Water yield augmentation is more important than any losses associated with removal of trees.

Although the potential exists for increasing streamflow from every acre of forest, the volume of extra water that can be produced is highly variable from state to state, depending mainly on the proportion of the watershed area in forest. In agricultural states like Illinois, Indiana, and Ohio, with less than 25 percent of the land in forest (Table 1), the volume of extra water that can be produced is obviously less than in states such as Maine, which is 90 percent forested. In general, Southern and Northeastern States are heavily forested (Table 2). These states meet the first prerequisite and have greatest potential for water yield augmentation.

TABLE 2. Land Ownership Patterns in the East (from U.S. Department of Agriculture, 1980).

State	Total Land Area (acres x 10^3)	Forested (percent)	Forest Land Federally Owned (percent)
Connecticut	3,081.7	60	0.13
Delaware	1,232.5	32	1.28
Maine	19,729.2	90	1.29
Maryland	6,289.2	42	5.84
Massachusetts	5,006.6	59	2.03
New Hampshire	5,731.3	87	13.89
New Jersey	4,775.4	40	4.85
New York	30,356.6	57	1.16
Pennsylvania	28,592.2	59	3.31
Rhode Island	664.4	61	1.73
Vermont	5,906.9	76	6.09
West Virginia	15,334.8	76	8.57
Illinois	35,441.7	11	8.93
Indiana	22,951.1	17	9.24
Michigan	36,172.5	53	17.47
Ohio	26,121.0	24	3.35
Wisconsin	34,616.0	43	11.01
Florida	33,993.6	50	13.61
Georgia	36,795.7	69	5.93
North Carolina	30,955.7	65	9.11
South Carolina	19,143.0	64	7.32
Virginia	25,286.2	65	12.68
Alabama	32,231.1	66	3.93
Kentucky	25,282.0	48	7.69
Mississippi	29,929.7	56	7.77
Tennessee	26,289.9	50	8.06

The second factor important in managing forests for water yield improvement is control over management prescriptions. Herein lies a major obstacle to management to improve water yield. Eastern forests are predominantly privately owned and watersheds are characteristically made up of many small tracts of timber. Even large industrial holdings are often intermixed with small private tracts. With either type of private owner, economic return from harvesting timber is the basis for prescriptions, not the need for water at some point downstream. Any coherent plan to increase and stabilize water yield from lands owned by several private landowners is almost surely doomed from the start. There is no incentive to expend money to increase production of a product (water) that the landowner cannot sell.

Federal ownership offers the greatest potential for stable management, but Federal ownership varies from as little as 1 percent in Connecticut to between 10 and 17 percent in New Hampshire, Michigan, Wisconsin, Virginia, and Florida. Also, not all Federal land is open to timber-water management and, despite periodic droughts and water shortages, the demand for water has not yet reached the point where water dictates timber cutting practices on public, much less private, land.

The greatest opportunity for water yield augmentation from forests is on municipal watersheds, which were established to supply water to cities. About 4 to 5 percent of the land base in the Northeast and the South is in municipal watersheds. Most municipal watersheds are less than 5 square miles in size and many are heavily forested (Dissmeyer and Swank, 1976; Dissmeyer, *et al.*, 1975). Municipal managers were surveyed in the mid-1970's and over half of them were concerned about either timing of yield or total yield. But only 29 percent of municipal watersheds in the Northeast are actually owned or controlled by municipalities, Federal, or state agencies; in the South only 27 percent are publicly controlled. In the East, municipal watershed managers make management decisions on less than 2 percent of the total area. Even on municipally owned land, it is the revenue returned by timber sales rather than sale of the extra water produced that often dictates management prescriptions. Managers of some large northeastern municipal and some private watersheds freely admit that management for improving water yield is not a primary concern at this time (Hartley, 1975; Anspach, 1975; Hart, 1975; Bergey, 1975; Heagy, 1975). In the South, where two-thirds of the municipalities surveyed tap streams for their water, quality and seasonal distribution of yield are the major concerns of municipal watershed managers. However, there are situations today where water supply is critically short and municipal managers and the public are vitally concerned with and are augmenting yield by managing the forest.

In the Eastern United States today, we are in an unusual situation. We know how to manage forests to improve water yield and the potential for increasing the water supply is enormous. But the current demand to exercise the knowledge is limited. Today's concerns are chiefly with water quality, and water yield is augmented primarily as a byproduct of managing the forest for timber or other uses. While predicting the future is always chancy, all projections for the next 40 years indicate a diminishing water supply because of consumptive use and much greater demand for water. More reservoirs are part of the answer, but even expansion of storage has practical limits; eventually evaporation from reservoirs will negate any potential benefit from flow regulation. When that point is reached, water yield augmentation, water harvesting, and possibly cloud seeding will be viable options and may come into their own. When the gap between available supply and demand becomes critical, rights of private ownership may change when viewed from the perspective of public good, and managing forests to increase water supply may become the primary objective of management. Foresters and hydrologists can then feel a sense of pride in being able to provide the information needed to manage forests for water yield as well as for other resources and uses of the forest.

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