SILVICULTURE FOR WATER YIELD

James E. Douglass

Principal Hydrologist, Coweeta Hydrologic Laboratory,

U.S. Forest Service, Franklin, North Carolina

In an article on the folklore and bromides in watershed management, Sartz (1969) recounted many popular misconceptions, but he omitted perhaps the greatest of them all--the belief that forests cannot be managed to improve water yield. When I first heard this view expressed, I assumed the speaker was "pulling my leg." However, through the years, I have come to realize that these opinions were sincere; many foresters, engineers, and, yes, even some hydrologists still believe that management of the forest for improved water yield is not practical, despite 40 years of evidence to the contrary. In fact, my own research has been referenced to conclude that no measurable increases in yield can be expected from typical modes of multiple-benefit management (Boyce 1977). The reference was to the conclusion that a certain percentage of the basal area of a watershed must be cut to produce an increase in flow large enough to be statistically significant.

This conclusion was drawn from watersheds where cuttings varied from partial cuts to complete clearcuts. If 1 percent of the basal area on a watershed is removed in a partial cut, the increase in streamflow from the watershed is impossible to detect experimentally. If, on the other hand, 1 percent of the watershed is clearcut, the increase from the clearcut is substantial and easy to detect, whereas the increase for the watershed as a whole still could not be detected. This is more than just a play on words; failure to grasp this distinction creates confusion.

Also, individuals often fail to realize that the effect of a forest cutting lasts for a number of years. The total effect on water yield is not just from last year's cutting; it is the cumulative yield increase of all previous cuttings that are still producing extra water. In the above example, an increase of 10 inches on the treated area from the 1 percent complete clearcut would theoretically yield only 0.1 inch of extra water from the watershed as a whole. In a regulated forest on a 100-year rotation, an additional 0.4 inch accrues because of yield increases from cuttings made in previous years. Thus, the increase in yield from eastern hardwoods would be about 0.5 inch per year.

A 0.5-inch increase would be difficult to detect on a large watershed. Measurements of daily flows on large watersheds are commonly accurate to $\pm$ 10 percent or more. Annual flows are probably accurate to a similar percentage. Thus, the true flow from a watershed with a measured flow of 20 inches would be between 18 and 22 inches. A real increase of 0.5 inch could not be detected experimentally. It does not follow, however, that increases which cannot be measured do not exist.

Even when we hydrologists are able to report detectable increases in water yield, forest managers often do not seem to be interested. One explanation may be the units in which we report the increases--depth per unit area. A yield increase of 0.5 inch, or of 0.04 acre-feet, just doesn't sound like much. Maybe we would get more attention if we reported our benefits in cubic feet, as timber managers do. By that convention, the increase just mentioned would be 1,815 cubic feet of water per acre per year. Now there's a number you can get your teeth into.

Another belief that discourages consideration of water yield in management plans is the notion that mixtures of ownership and of land uses on a large watershed preclude effective action to improve water yields. On a watershed that is only 50-percent forested, the effects of forest treatments on the watershed as a whole are only half those on a completely forested watershed. And when ownership of the forested portion of the watershed is mixed and some owners are unwilling to cooperate in a watershed management plan, the possibilities for improving water yields are further reduced. These difficulties led Bethlahmy (1974a) to conclude that little could be gained from managing large, complex watersheds for the specific purpose of increasing water yield. Although the problems he cited are real, I do not agree with his conclusion. Whenever a timber stand is treated in an appropriate manner, the increase in water yield from that stand is real. Size and complexity of the watershed do not preclude the benefits; they only preclude the detection and measurement of benefits.

Contrary to popular belief, forested watersheds are being managed for water yield, either inadvertently or by design. Silvicultural activities increase or decrease evapotranspirational loss. The magnitude of the effect depends upon prevailing climatic conditions; in particular, on the heat load on the watershed, the amount and distribution of rainfall, and the amount of vegetation killed, converted, or cut.

EVAPOTRANSPIRATION AND WATER YIELD INCREASES

If we define water yield to include streamflow, increments to groundwater, and changes in soil water storage, the water balance equation simplifies to:

$$\text{Precipitation} - \frac{\text{Evapotranspiration}}{\text{Loss}} = \text{Water Yield}$$

It is clear that any reduction in evapotranspiration will produce an increase in water yield. This has been demonstrated countless times on experimental watersheds when part or all of the forest was cut or deadened, or when forests were converted from one cover type to another or to grass (Hibbert 1967). This change in yield occurs not because of some mystique associated with silviculture, but because the evapotranspiration loss from the watershed has been changed in some way. Indeed, catastrophic events, such as insect infestations (Bethlahmy 1974a, 1975; Corbett and Heilman 1975; Love 1955), hurricanes (Patric 1974), blow downs (Eschner and Satterlund 1966), and wildfire (Helvey 1972) have all produced increases in water yield. Several of these documented incidents produced increases in flow large enough to be detected on watersheds hundreds of square miles in size.

Conversely, any increase in evapotranspiration by reforestation or afforestation will reduce water yield (Eschner and Satterlund 1966; Hibbert 1967; Hill 1960; McGuinness and Harold 1971; Satterlund and Eschner 1965; Schneider and Ayer 1961; Stephens et al. 1972; Swank and Douglass 1974; TVA 1961, 1962). Again, some reductions in water yield with forest regrowth have been reported on both small, experimental watersheds and on quite large watersheds. These results demonstrate that small, experimental watersheds are not unique; that large reductions in evapotranspiration will appear as water yield increases from both large and small watersheds.

CLIMATE AND WATER YIELD INCREASES

In humid regions, the solar energy load received by the watershed has a pronounced effect on the magnitude of the increase in water yield (Cline et al. 1977; Douglass and Swank 1975). A high energy load results in large evapotranspiration losses and large soil-moisture deficits which must be satisfied before excess rainfall appears as runoff. Conversely, a low energy load creates smaller soil-moisture deficits. Experimental data has shown that the removal of forest vegetation from watersheds with a low moisture deficit; i.e., a low energy load, produces a larger streamflow increase than a similar treatment on a high energy load watershed. These data from hardwood-covered watersheds of the Appalachians are the basis for figure 1. The figure

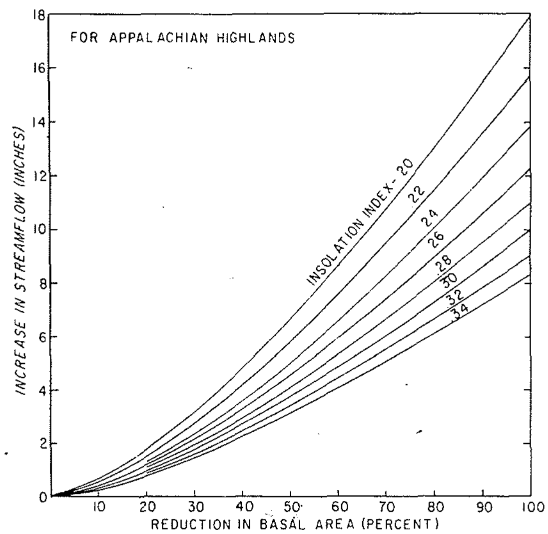

Figure 1. The first year increase in streamflow determined from the percent reduction in forest stand basal area and the insolation index (total langleys per year x 10^{-6}) of the watershed.

shows that the greater the energy load, the less the yield increase will be for a given percentage of the forest cut. Because we do not know the nature of the relationship beyond the indices shown, the relationships should not be extrapolated. However, the figure covers the range of radiation load that will be experienced on most forests in the East.

The data used to derive figure 1 was too limited to allow the effects of amount and seasonal distribution of rainfall on yield increase to be determined. However, amount of rainfall has a decided effect (Hornbeck et al. 1970; Hibbert et al. 1974; Verry 1976). Figure 2 illustrates the preliminary relationship between rainfall amount and the yield increase obtained from cutting or deadening chaparral in the Southwest.

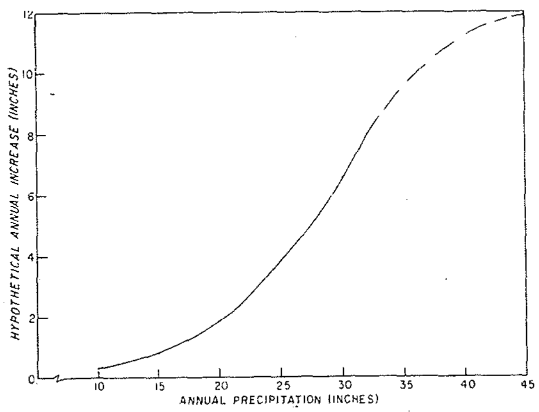

Figure 2. Yearly increase in streamflow in relation to annual precipitation for five watersheds in Arizona. The dashed line is an extrapolation of data from Hibbert et al. (1974).

Because rainfall is seasonally distributed there, the ET-induced difference in soil-moisture between chaparral and cleared watersheds is an estimate of the potential yield increase to be expected. If the watershed is only partially recharged by winter rains, only part of the potential increase is realized. Progressively greater rainfall allows more of the potential increase to be realized. The dashed line is an extrapolation from data presented by Hibbert et al. (1974). It indicates that, if rainfall exceeds 35 to 40 inches, water yield increases approach those produced in the humid East. The level at which the yield increase plateaus, and the rainfall necessary to produce this maximum, are probably variable, depending on local conditions, such as soil depth, vegetative density, etc.

These two examples illustrate the dependence of yield increase on energy load and rainfall amount and distribution. Although the interaction of these factors is poorly understood, the energy load received by the watershed appears to be the dominant climatic factor in the East, and the relationships depicted in figure 1 allow the yield increase to be estimated reasonably well.

SILVICULTURE AND WATER YIELD INCREASES

Silviculture is defined as the art of producing and tending a forest (Smith 1962). Practices that vary from killing vegetation with herbicides through all forms of cuttings from single tree selection to clearcutting, reduce vegetation surfaces and, therefore, alter hydrologic processes, including evaporative loss. Because silvicultural practices influence evapotranspiration, these practices increase or decrease water yield. Species conversions change the composition, density, function, and persistence of vegetative surfaces. For example, changing hardwood or chaparral cover to grass generally increases water yield, and conversion of hardwoods to pine reduces water yield.

Maximum increases in water yield are produced by complete removal of the forest. Partial cuttings, thinnings, and herbicide treatments are not as "efficient" as clearcutting in producing water. Lull and Reinhart (1967) concluded that an all-age selection cutting in West Virginia was only 38 percent as effective as a clearcutting. However, the relationship is not a constant. In the Southern Appalachian Mountains, partial cuts become progressively less efficient as the size of the opening or basal area removed during the cutting become smaller (fig. 1). Hibbert et al. (1974) reached a similar conclusion for chaparral shrub removal in the Southwest. They related percent shrub removal to the hypothetical increase in streamflow as percent of maximum yield (fig. 3) and

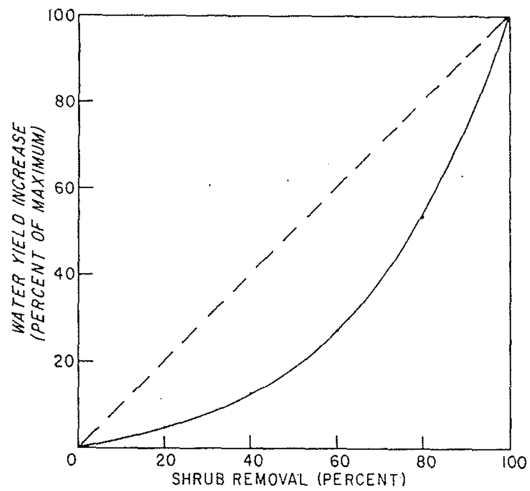

Figure 3. Hypothetical water yield increase as a function of chaparral removal. After Hibbert et al. (1974).

produced a curve similar in shape to figure 1. Removing part of the stand may give little or no increase because water use by residual vegetation increases and approaches a maximum rate when physiological factors become more limiting than soil moisture. As water supply becomes more available, the curve trends toward the 1:1 line. To reach this line, water would have to always be available--a situation that rarely, if ever, exists, even in marine climates. Although the exact shape of the curve can vary with many factors, the conclusion for the arid Southwest and humid East is the same. Substantial yield increases require removal of a large part of the transpiring surface area.

In regions where most precipitation comes in the winter, the efficiency of partial cuts should be lowest because the residual stand can utilize most or all available water during the long, dry summer. The physical arrangement of partial cuttings also affects water yield increases. The shape and orientation of patch and strip cuttings determines snow accumulation and melt rates. Also, when cuts are made on the contour, and soil moisture flows downslope from the cut through uncut patches or strips of forest, soil moisture is subjected to repeated evaporative stresses, if it passes through the rooting zone.

EVALUATING POTENTIALS FOR INCREASING WATER YIELD

In the introduction, some reasons were given for the widespread belief that forests could not be managed for water yield. Another possibility is that the tools needed for examining the effects of management do not exist or are difficult for most practicing foresters to use. Consequently, assessments of the potential for increasing water yield have been made by hydrologists who have spent their careers studying the relationship between forests and water, rather than by land use planners and practicing foresters (Berndt and Swank 1970; Douglass and Swank 1975; Harr 1976; Hibbert et al. 1974; Norton and Campbell 1974; Rich and Thompson 1974; USDA 1969). Although these state-of-the-art papers are quite useful, the information they contain is difficult to apply in a management context because watershed size, ownership, land use, and other factors vary within the watershed.

It is important that hydrologists progress to the next step, that of combining the salient relationships for a region into models that can be used to portray the effects of management on water yield. The work of Brown et al. (1974) is a notable example because of the emphasis that they placed on developing relationships which could be used by resource managers. They have also presented their water yield relationships in a multiple-use context, although emphasis was on water.

Boyce (1977, 1978) presented a simple model for evaluating the potential of eastern hardwood forests for supplying timber and other benefits. A major advantage of the model is that it enables the land use planner to compare responses of a number of resources which are subjected to alternative silvicultural practices. One can use the model to compare resource outputs on a relative scale, where 1 is a maximum for the resource, or to compare quantitative outputs, such as inches of runoff. The input data required for the model is an expression of the relationship between forest benefits and types of forest communities. Community type is the area in seedlings, saplings, pole, mature, and old growth stands. These data are available in the latest Forest Survey reports. Fortunately, the model can be used by planners, even though the land is in mixed ownership and part of the land base is in nonforest use.

I proposed earlier that silviculture has an impact on the water yield from a watershed. I will demonstrate the effects of length of rotation and size of opening on water yield using Boyce's (1978) DYNAST-TM model and his example area, the 6,396 acre Big Ivey watershed in Buncombe County, North Carolina. This data base is used in order to compare water yield outputs with outputs reported by Boyce for timber, aesthetics, and several species of wildlife. Boyce outlined, in great detail, the theoretical concepts and mechanics of programming. Using similar techniques and some relationships presented earlier (Douglass and Swank 1975), Boyce's model was modified to predict the increase in water yield for several management options (fig. 4). The basic equations predict the first year increase for each opening and the decline and duration of the increase. The increase at any point in time is the sum of increases from all newly cut openings plus the sums of increases from all 1-year-old, 2-year-old, etc., openings. Two parameters, rotation length and opening size, specify the management options and produce the family of curves in figure 4. After a steady state is reached, the number of acres cut in any one year is the total acres in Big Ivey divided by rotation length in years. Therefore, the number of openings cut in a year is the acres cut divided by the opening size in acres.

It is clear from this figure, that rotation length and size of individual openings or clearcuttings significantly influence water yielded from this watershed. The apparent anomaly of the existing forest producing 200 acre-feet of extra

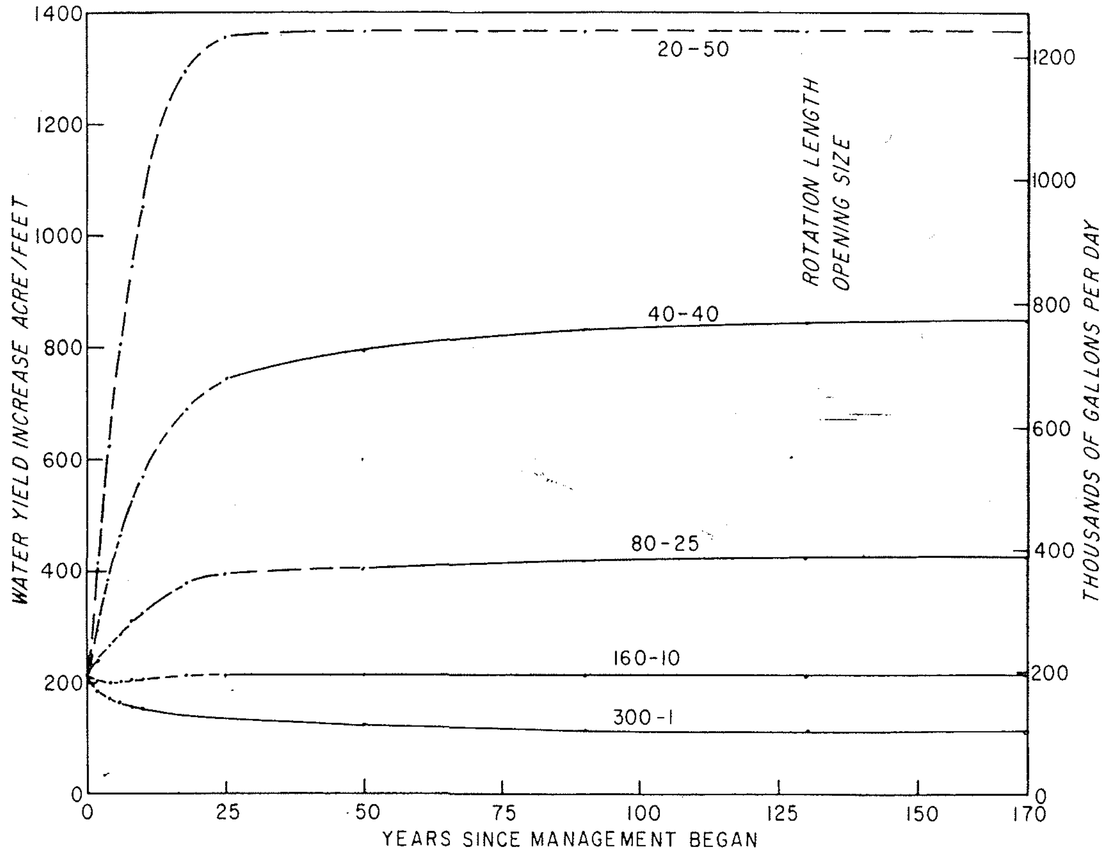

Figure 4. The increase in streamflow expected from managing the timber stand on a Southern Appalachian watershed under different rotation lengths in years and with different size openings. Each opening represents a clearcutting of the acreage specified.

water raises the question "More than what"? The answer is "more water than an old-growth forest." Because of the actual distribution of age classes on Big Ivey, some stands are producing extra water today. This is why the curve for the 300-year rotation shows an initial decrease in water yield as the young stands are allowed to mature. The 80-year rotation with 25-acre openings is fairly typical of Forest Service management in the Southern Appalachians, except where intermediate cuts are made. This 80-year, 25-acre option would produce about 200,000 gallons more water than is being obtained from Big Ivey today, or enough extra water to supply another 2000 to 3000 people.

The effects of a 20-year rotation are dramatic and the responses stabilize over a short period. A 20-year rotation may be too brief for eastern hardwoods, but a fuel wood rotation might easily be this short. As rotation length increases, less water is produced, but other benefits may be increased. When rotation length equals 160 years, some, but very little, extra water is produced, compared to current conditions. Any longer rotation and smaller (or no man-made) openings reduce water yield to that which might be expected from wilderness management.

On a watershed with excellent gaging installations, the 1,364 acre-foot increase from a 20-year rotation with 50-acre clearcuts would probably be detected. The yield increase from a 40-year or longer rotation probably would not be detected experimentally, even with excellent measurement techniques. Regardless of whether the increase can be shown statistically, it is the expected response to management and is no less real simply because it can't be seen or measured.

The illustration chosen shows that silviculture can produce positive and very real increases in water yield. It would also have been possible to illustrate negative effects of silviculture by developing algorithms for reforestation and conversion from hardwood to pine types. Indeed, the only way to ascertain whether the effect of management on water yield will be positive or negative is to calculate the changes based on algorithms describing the functional relationships which exist between silviculture and water yield.

Silviculture and water yield are only part of the story. For a given rotation and size of opening, outputs of other benefits should also be examined (Boyce 1978). That is the utility of the DYNAST-TM model; it can be used to portray the responses of a variety of resources to alternative silvicultural practices. It is, therefore, an appropriate way to reexamine multiple use, which is one of the objectives of this annual meeting.

The intent of this paper is to present persuasive evidence that managing forests for improved water yield is an appropriate goal of forest management. Streamflow will either increase or decrease when management of the forest changes evaporation from its vegetated surfaces. In the example, I chose practices that increase streamflow, but could have shown, as well, that yield decreases after afforestation or conversion of hardwoods to pine. Indeed, the only way to be certain whether the effect of management will be positive or negative is to calculate the changes based on algorithms describing the functional relationships which exist between silviculture and water yield. Foresters must recognize that, because silviculture does influence evaporation and does change yield of water from the landscape, they do manage water yield. They should recognize that these changes in water yield are either a cost of doing business or an added value gained from managing the timber.

LITERATURE CITED

Berndt, H.W., and G.W. Swank. 1970. Forest land use and streamflow in central Oregon. USDA For. Serv. Res. Pap. PNW-93, 15 p. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

Bethlahmy, N. 1974a. More streamflow after a barb beetle epidemic. J. Hydrol. 23:185-189.

Bethlahmy, N. 1974b. Water supply as affected by micro- and macro-watershed management decisions on forest lands. Northwest Sci. 48:1-8.

Bethlahmy, N. 1975. A Colorado episode: beetle epidemic, ghost forests, more streamflow. Northwest Sci. 49:95-105.

Boyce, S.G. 1977. Management of Eastern hardwood forests for multiple benefits (DYNAST-MB). USDA For. Serv. Res. Pap. SE-168, 116 p. Southeast. For. Exp. Stn., Asheville, N.C.

Boyce, S.G. 1978. Management of forests for timber and related benefits (DYNAST-TM). USDA For. Serv. Res. Pap. SE-184, 140 p. Southeast. For. Exp. Stn., Asheville, N.C.

Cline, R.G., H.F. Haupt, and G.S. Campbell. 1977. Potential water yield response following clearcut harvesting on north and south slopes in northern Idaho. USDA For. Serv. Res. Pap. INT-191, 16 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Corbett, E.S., and J.M. Heilman. 1975. Effects of management practices on water quality and quantity: The Newark, New Jersey, Municipal Watersheds, p. 47-57. In Municipal watershed management symposium proceedings 1973. USDA For. Serv. Gen. Tech. Rep. NE-13, Upper Darby, Pa.

Douglass, J.E., and W.T. Swank. 1975. Effects of management practices on water quality and quantity: Coweeta Hydrologic Laboratory, N.C., p. 1-13. In Municipal watershed management symposium proceedings 1973. USDA For. Serv. Gen. Tech. Rep. NE-13, Upper Darby, Pa.

Eschner, A.R., and D.R. Satterlund. 1966. Forest protection and streamflow from an Adirondack watershed. Water Resour. Res. 2:765-783.

Harr, D.R. 1976. Forest practices and streamflow in western Oregon. USDA For. Serv. Gen. Tech. Rep. PNW-49, 18 p. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

Helvey, J.D. 1972. First-year effects of wildfire on water yield and stream temperature in north-central Washington. p. 308-312. In Proc. Natl. Symp. on Watersheds in Transition. Colo. State Univ., Fort Collins.

Hibbert, A.R. 1967. Forest treatment effects on water yield. Natl. Sci. Found. Adv. Sci. Semin. Int. Symp. For. Hydrol. Proc. 1965: 527-543.

Hibbert, A.R., E.A. Davis, and D.G. Scholl. 1974. Chaparral conversion potential in Arizona. Part I. Water yield response and and effects on other resources. USDA For. Serv. Res. Pap. RM-126, 36 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Hill, L.W. 1960. Forest plantation development influences streamflow. Proc. Soc. Am. For. 1960:168-171.

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

Love, L.D. 1955. The effect on streamflow of the killing of spruce and pine by the Engelmann spruce beetle. Trans. Am. Geophys. Union 36:113-118.

Lull, H.W., and K.G. Reinhart. 1967. Increasing water yield in the Northeast by management of forested watersheds. USDA For. Serv. Res. Pap. NE-66, 45 p. Northeast. For. Exp. Stn., Broomall, Pa.

McGuinness, J.L., and L.L. Harold. 1971. Reforestation influences on small watershed streamflow. Water Resour. Res. 7:845-852.

Norton, J.S., and C.J. Campbell. 1974. Management of phreatophyte and riparian vegetation for maximum multiple use values. USDA For. Serv. Res. Pap. RM-117, 23 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Patric, J.H. 1974. River flow increases in central New England after the hurricane of 1938. J. For. 72:21-25.

Rich. L.R., and J.R. Thompson. 1974. Watershed management forests: The status of our knowledge. USDA For. Serv. Res. Pap. RM-130, 15 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Sartz, R.S. 1969. Folklore and bromides in watershed management. J. For. 67:366-371.

Satterlund, D.R., and A.R. Eschner. 1965. Land use, snow, and streamflow regimen in central New York. Water Resour. Res. 1:397-405.

Schneider, W.J., and G.R. Ayer. 1961. Effect of reforestation on streamflow in central New York. U.S. Geol. Surv. Water Supply Pap. 1602, 61 p.

Smith, D.M. 1962. The practice of silviculture, 7th ed. John Wiley & Sons, Inc., New York. 578 p.

Stephens, G.R., N.C. Turner, and H.C. De Roo. 1972. Some effects of defoliation by gypsy moth (Porthetria disper L.) and elm spanworm (Ennomos subsignarius Hbn.) on water balance and growth of deciduous forest trees. For. Sci. 18:326-330.

Swank, W.T., and J.E. Douglass. 1974. Streamflow greatly reduced by converting deciduous hardwoods to pine. Science 185:857-859.

Tennessee Valley Authority. 1961. Forest cover improvement influences upon hydrologic characters of White Hollow Watershed 1935-58. Div. Water Control Plann. Hydraul. Data Branch. 104 p.

Tennessee Valley Authority. 1962. Reforestation and erosion control influence upon the hydrology of Pine Tree Branch Watershed 1941 to 1960. Div. Water Control Plann. Hydraul. Data Branch. 98 p.

Verry, E.S. 1976. Estimating water yield differences between hardwood and pine forests: An application of net precipitation data. USDA For. Serv. Res. Pap. NC-128, 12 p. North Cent. For. Exp. Stn., St. Paul, Minn.

U.S. Department of Agriculture, Forest Service. 1969. Water yield improvement potentials on National Forest lands tributary to Ochoco Reservoir, 52 p. USDA For. Serv., Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.