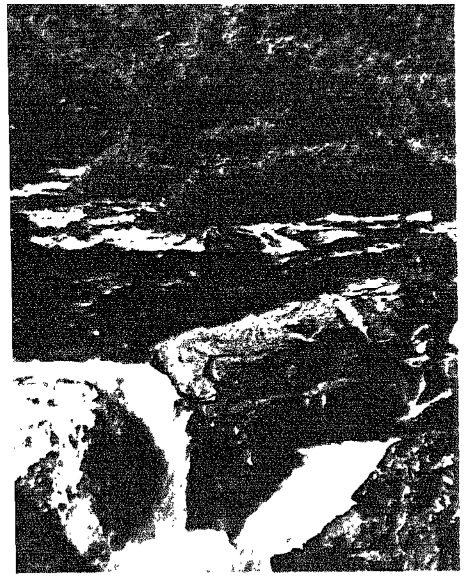

Increasing WATER YIELD in the Northeast by management of forested watersheds

by Howard W. Lull
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Preface

THIS research paper is designed to answer some of the questions of forest watershed managers interested in possibilities of increasing water yield through management and removal of forest cover. Water shortages from the recent drought and the growing interest in the subject of forest water-yield management, as evidenced in the Municipal Watershed Management Symposium held at the University of Massachusetts in 1965, make this paper timely.

To take advantage of the moment we have utilized and extrapolated what information we have so we can set forth management possibilities. Common knowledge for years has held that forest cover and water yield are inseparably connected. Here we suggest how forest cover may be employed to increase water yields. We do not have all the answers for management. In a few years current research programs will provide many of them. Meanwhile, though we see through our glass darkly, we see enough to make a beginning.

MORE WATER BY CUTTING TREES

INCREASING demands on water resources from all elements of population and industry in the Northeast and forecasts of even greater demands in the future, plus concern over the drought of the past 4 years, have stimulated a search for additional water sources. Sea water, cloud-seeding, and long-distance piping of water from areas of surplus to areas of shortage have been suggested and are being tried or studied. This paper describes the possibilities of increasing water yield in the Northeast by a method that has received little attention—by cutting trees.

Most kinds of vegetation use large amounts of water, but trees use the most. Canopies of mature hardwoods and conifers extending 40 to 80 feet or more into the air intercept rainfall and snow and draw moisture from the soil. The canopy's leaf surface may be as much as five times the land area occupied by the tree. Each square inch of the underside of leaves may possess a few hundred thousand stomates through which water vapor emerges into the atmosphere. Powering this movement is radiant energy: shortwave radiation received and not reflected from the leaf surface, and longwave radiation from cloud and ground. As long as the soil is wet, evaporation of moisture from the stomates into the atmosphere is the first use to which the energy is put.

Snow presents a special situation. Trees affect snow accumulation, evaporation, and melting. Of particular importance are the functions of conifer canopies that serve to intercept snow, to shade the snow below, and to slow its melting.

Thus, in the forests of the Northeast, 40 to 60 percent of all precipitation that falls is returned to the atmosphere by evaporation or transpiration and never reaches the stream or groundwater.

This presents an opportunity and a challenge: Can we reduce the amount evaporated to the atmosphere and thus increase the yields available for domestic, industrial, and other uses? Research results from all over the world, including some from the Northeast, indicate that we can. Removal of all or part of the forest, by cutting or use of herbicides, can accomplish this. The amount and duration of the increase depend on the kind of treatment, the ground cover that develops, and upon soil, weather, and other factors.

When trees are cut or killed, the principal mechanism for moisture movement from soil to atmosphere is destroyed. Evaporation from slash, litter, and the soil surface and transpiration from a shallow-rooted ground cover become the only means for moisture movement skyward; the upward movement of water through the soil is slowed. As a result, less water is lost and the soil remains moist; a smaller amount of subsequent rainfall is required to recharge the soil and a larger proportion finds its way to the stream.

Forest regeneration can rapidly re-establish conditions that prevailed before cutting. Sprout growth, utilizing previously developed root systems, and invasion of herbaceous vegetation can in a matter of 2 to 3 years re-establish transpiration and sharply curtail the yield increase (Kovner 1956; Reinhart et al. 1963).

The Northeastern United States (fig. 1)—Maine to West Virginia—offers perhaps more opportunities for forest water-yield management than any other region. It has a tremendous concentration of population and a sizable forest area. The Northeast has 6 percent of the total area of the United States, 28 percent of its total population, and 15 percent of its total commercial forested area. It has about 400 municipal watersheds and reservoir forests

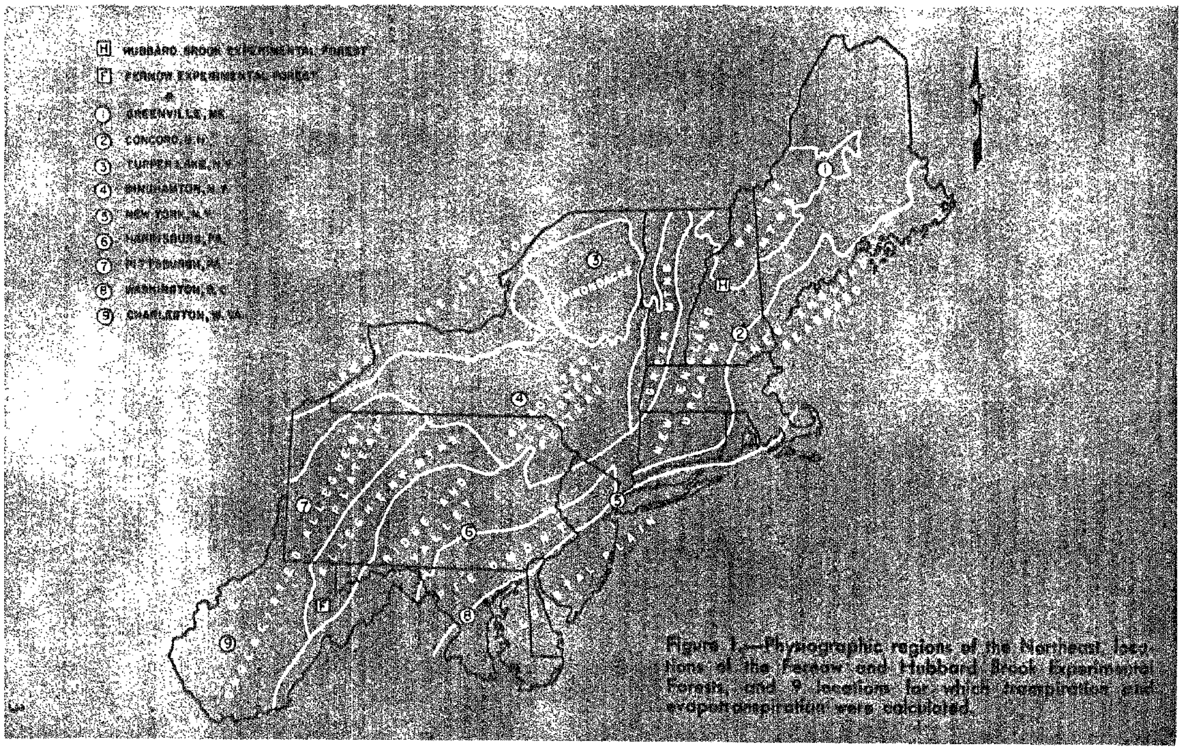

Figure 1.—Physiographic regions of the Northeast, locations of the Fernow and Hubbard Brook Experimental Forests, and 9 locations for which transpiration and evapotranspiration were calculated.

(well over 1,000,000 acres of forest land) that serve about one-third of the region's population. Because it has sufficient precipitation and solar radiation, evapotranspiration from the forest is great enough to permit sizable increases in water yield from forest cutting.

Highly populated and industrialized, the Northeast has great water demands, and they will very likely increase as population rises and as the water supply and labor force continue to attract industry. These increasing demands may yet turn municipal bureaus of water supply to cutting forested watersheds for additional water.

On a per-capita basis the Northeast has about one-fifth of the precipitation and one-third of the runoff of the 11 Western States, which are generally considered to be the water-short region of the country. Western runoff averages about 5.5 inches annually (Munns 1952) compared to 18 inches in the Northeast (Lull 1966); in the West the population density is about 23 water-users per square mile; in the Northeast, 251. In the Northeast used water may be re-used; whereas in the West about 90 percent of the water is used in irrigation and about two-thirds of this is lost to the atmosphere.

The purpose of this research paper is to present some of the methods by which water yields can be increased from forested watersheds and to discuss the effectiveness of these methods under different conditions. Methods discussed include clearcutting, partial cutting, and use of herbicides. Effectivness during drought is considered. Effects on water yield of reforestation, forest protection, and forest fire and other destructive agencies are discussed. And, finally, safeguards for water quality are considered.

Cutting trees on a watershed to increase water yield, as advocated here, is not so much a departure from time-honored concepts of the protective role of the forest in regard to streamflow and erosion as it is a recognition of the growing stature of the multiple-use concept that forest land is useful and can be managed for water, wildlife, and recreation, as well as for timber. To still incipient alarm as to possible flood and erosion damages from the procedures set forth, or destruction of scenic values, the authors would like to stress initially that: (1) forest cutting for water-yield increases must be followed by development of sufficient ground cover to protect the site: (2) water management on an intensive basis, involving clearcutting to obtain maximum water yields, would be limited in area and practiced only by some municipalities, those requiring additional water supplies; and (3) extensive water management through practice of a sustained-yield program of forest management is possible and productive both in timber and water. We believe that the forests of the Northeast, extensive in area and well-distributed throughout the region offer, in certain situations and selected areas, possibilities for management to increase water supplies.

TOTAL FOREST REMOVAL

Here we are concerned solely with means of obtaining a maximum increase in water yield from total forest removal (clearcutting or other methods of killing all vegetation). In the next major section, on partial forest removal, we discuss the possibilities of increasing water yield under a sustained-yield program of forest management.

Amount of Increase

Removal of all vegetation on a well-stocked forested watershed in the Northeast will increase annual water yield the first year after treatment by about 4 to 12 inches. Justification of this estimate rests on: (1) a first-year increase of 5 inches[1] at the Fernow Experimental Forest in West Virginia after removal of 80 percent of the basal area (Reinhart et al. 1963) and, more recently, an increase of 12 inches after total clearcutting and herbicide spraying; (2) increases of 5 to 16 inches at the Coweeta Hydrologic Laboratory in North Carolina after clearcutting mature hardwoods (Hewlett and Hibbert 1961); (3) and the following conservative estimates of the effects of clearcutting, in inches of water increase per year, for a number of points across the Northeast (fig. 1):

[1] 1 inch = 27,154 gallons per acre.

Location	Water increase (inches)	Location	Water increase (inches)
Greenville, Me.	4	Harrisburg, Pa.	11
Concord, N.H.	8	Pittsburgh, Pa.	12
Tupper Lake, N.Y.	5	Washington, D.C.	13
Binghamton, N.Y.	10	Charleston, W. Va.	13
New York, N.Y.	12		

These values are estimates of annual forest transpiration based on calculations of potential evapotranspiration from annual temperature and precipitation, followed by estimates of actual evapotranspiration and its division into evaporation and transpiration (Holdridge 1962). Forest removal eliminates forest transpiration, reduces interception, and increases evaporation from the soil, the net result giving a conservative cast to the above estimates of water-yield increases from transpiration-only savings. As is evident, these estimates are strongly related to latitude and temperature. The effect of total forest removal obviously must depend on the kind of forest present before cutting. Maximum results should be expected only when the forest fully occupies the site; where regrowth before treatment has not yet filled voids from earlier cuttings or from fire, insects, or diseases, less than maximum increases can be expected.

Four of the five inches of annual increase from commercial clearcutting at the Fernow Forest came in June, July and August (precipitation after treatment was far above average: the 3-month total was 27.6 inches). In the case of the 12-inch increase from a recent total clearcutting, 39 percent came in June, July, and August (the 3-month precipitation was 13.4 inches); 72 percent of the 12 inches came in the period June through November. This relatively quick response to reduction of evapotranspiration in the growing season is, we believe, in keeping with the shallow soils (2 to 5 feet deep) of the area. At Coweeta, where the soils are much deeper, more of the increase from clearcutting was delayed until the winter months.

Forested mountains of the Northeast (the White Mountains, Green Mountains, Adirondacks, Allegheny Plateau and Mountains, and the Ridge and Valley Province [fig. 1]) make up 57 percent of the region and have shallow soils of depths similar to the Fernow watershed. Much of the glaciated New England Upland also has shallow soils. Deep-soil areas are confined mostly to the Piedmont and Coastal Plain, the Connecticut Valley, and the Great Lakes Section in New York State, the major non-forest areas of the region.

Accordingly, we believe that in much of the Northeast any increases in water yield due to clearcutting will probably appear mostly in summer or early fall. In areas of accumulated snowpack (northern New York, Vermont, New Hampshire, and Maine) increases from reduced snow interception would appear in spring runoff.

Below- and Above-Normal Precipitation

Clearcutting a forested watershed during a drought will provide little relief. The upland soil is already dry; transpiration is at a minimum; and existing low streamflow comes from groundwater. Tree-cutting in this situation would cut off the low rate of transpiration, but would not provide greater water supplies for streamflow.

However, as soon as rainfall or snowmelt had recharged the soil (with an amount of water that will not necessarily break the drought), clearcutting would become effective, providing opportunity for greater proportions of subsequent rainfall to go into streamflow. Thus during a drought summer removal of the upland forest would not increase water yield, but the recharginng of the soil by winter precipitation and snowmelt (when, because of low evaporation, below-normal amounts of precipitation may be sufficient for recharge) would create the opportunity for greater water yield from spring and early summer rainfalls.

An exception to this is the cutting of riparian areas where even in drought trees with their roots tapping groundwater supplies may be transpiring heavily. Cutting these trees would effectively increase water yield, the amount depending on the proportion of the watershed occupied by riparian vegetation. Generally, in the Northeast, riparian areas occupy only a small part of forest-covered watersheds.

The drought of the past 4 years has raised the question whether periods of drought could be predicted with sufficient accuracy to permit forest harvesting just before or during dry cycles to produce water-yield increases when they are most valuable. Possibilities of predicting dry periods from sunspot activity have been studied for many years. Sunspots reach a maximum, on the average, every 11.3 years; some cycles are as short as 7 years and some as long as 17 (Tannehill 1955). Recent studies have shown that, though the energy received from the sun does not change to any extent during a sunspot cycle, these cycles appear to be related in some unknown way to the large-scale circulation of the atmosphere. This in turn is responsible for changes in local weather (MacDonald 1959). No generally accepted method of predicting solar variations has been developed that would permit forecasting droughts. Expected frequency and severity of droughts may be calculated from past records of precipitation and streamflow (nationwide, droughts have occurred about every 5 or 6 years) but exactly when and where droughts will occur cannot yet be predicted with any accuracy.

Below- or above-normal annual precipitation after forest removal will not have a pronounced effect on water-yield increases in the humid East. For instance, the greatest first-year increase experienced, the 16-inch increase from Coweeta's watershed 17, came during a period of below-normal precipitation—55 inches as compared with the normal annual of 74 inches. In the other direction, the 5-inch increase from the commercial-clearcut watershed at the Fernow, certainly not an exorbitant amount, came during a year of greater-than-normal rainfall—63 inches compared to the normal annual of 58 inches. However, in both of these high-rainfall areas, potential and actual evapotranspiration are very close and the below-normal precipitation still produced the continual soil wetness necessary for actual evapotranspiration to approach closely the potential.

The effects of normal and above- and below-normal growing season precipitation on water-yield increases due to clearcutting were estimated from the Fernow data by Lull and Sopper (1966c), using the Thornthwaite and Mather (1957) procedure.

Monthly water surpluses were computed from a daily water balance based on an estimated reduced potential evapotranspiration after clearcutting. Actual daily rainfall values were used for highest, lowest, and mean records, and the mean record was adjusted to give mean monthly totals. Water surpluses were given as follows:

	Rainfall (inches)	*Water surplus (inches)*
Highest (1958)	37.71	4.95
Lowest (1952)	20.81	3.34
Mean (1959)	28.44	3.03
Adjusted (1959)	29.88	4.39

The greatest surplus, 4.95 inches, the first year after cutting was associated with the highest rainfall of record. The effect of rainfall distribution is brought out in surpluses of 3.03 and 4.39 inches for mean rainfalls with different distributions. Note that the surplus from the lowest rainfall of record was 0.31 inches greater than that for the mean rainfall, again the result of different distribution of daily rainfall. Examination of these values suggest that differences in amounts of rainfall up to 17 inches during the growing season may produce differences in water surpluses of 1 to 2 inches.

Methods of Treatment

The total forest can be removed by timber cutting, use of herbicides, burning and bulldozing, or combining these treatments in various ways. After removal of trees and understory woody vegetation and before the protective forest floor deteriorates, growth of ground cover should be encouraged to maintain the stability of the site.

Timber cutting.—The most direct and common method of forest removal is by cutting the trees. Usually this can be accomplished by a logging operation that produces sawlogs, pulpwood, or other products whose sales more than covers the cost of the operation. However, for total forest removal there is usually some material to cut that is unmerchantable because of size or quality. This involves an out-of-pocket cost. When such material is cut, it is usually left on the ground.

Complete removal can be accomplished by cutting, but herbicides may be more practical for killing small woody stems and useful for preventing or reducing sprouting of hardwoods.

Cost of clearcutting varies widely depending upon the volume of timber cut and the methods used. Recently at the Hubbard Brook Experimental Forest in New Hampshire an unmerchantable stand of northern hardwoods (averaging 75 square feet of basal area per acre) was contract-cut for $170 per acre. Trees were felled and left lying. Slash was lopped off to a height of 3 feet or less. The operation required 4 man-days per acre; cutters who furnished their own power saws earned $4 per hour.[2] In 1962-63 at the Coweeta Hydrologic Laboratory in western North Carolina, two oak-hickory watersheds were clearcut, without removal of the felled trees, at per-acre expenditures of $112 and $128 and 8.8 and 10.3 man-days.[3] Details are given in the appendix.

Clearcutting after removal of merchantable material naturally is less expensive. In western North Carolina it has cost from $47 to $65 per acre (4.5 man-days per acre for the latter figure) and $37 to $60 per acre when clearing with a specially designed tractor-mounted blade. In another instance an intensive cleaning in an 11-year-old hardwood stand required 7.3 man-days per acre.[4] Further details are given in the appendix.

Herbicides.—There is a considerable backlog of experience on the use of herbicides in forest stands. However, herbicides have been used mostly for silvicultural reasons—usually to kill individual undesirable trees or some undesirable component of the stand. Their use to kill vegetation for water-management purposes has so far been limited mainly to experimental areas; thus methods of application have been considerably different and costs much higher than would be expected in routine applications.

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[2] Communication of February 23, 1966, from R. S. Pierce, project leader, watershed management research, Northeastern Forest Experiment Station, Durham, N. H.

[3] Communication of February 21, 1966, from James E. Douglass, project leader, watershed management research, Southeastern Forest Experiment Station, Franklin, N. C.

[4] Communications of February 28, 1966, from Richard F. Harlow, wildlife research biologist, Southeastern Forest Experiment Station, Asheville, N. C., and of March 4, 1966, from Charles E. McGee, project leader, U. S. Forest Service, Asheville, N. C.

Early tests have shown that very little, if any, of the herbicide applied to watersheds reaches the water supply (see pages 32 and 33). However, as a necessary precaution, their use should be governed by recommendations of state authorities responsible for coordinating use of these chemicals. These officials are usually associated with state agricultural experiment stations.

The current rate of development of new herbicides and methods for their use is almost phenomenal; prospects for increased efficiency and lower cost are good.

Killing individual trees.—Frill girdling, with application of 2,4,5-T or ammate to the frill, and stem injection appear to be the most economical methods for treating individual trees. Costs for killing all trees may range from $0.003 to $0.010 per inch of diameter or about $10 to $30 per acre. A review of several studies is given in the appendix.

Foliar sprays.—Peevy (1960) found that foliar spraying from the ground cost $22 per acre with ammate and $12 with 2,4,5-T. Labor costs were $1.25 per hour; 2,4,5-T cost $8.50 per gallon, and ammate $0.24 per pound. MacConnell (1962) reported costs of $6.17 to $10.73 per acre depending on concentration of the herbicide. The shoulder-mounted mistblowers used had effective ranges of 30 feet in quiet air. Oak was most susceptible and resprouting was abundant only from aspen and red maple. For total kill of vegetation within reach of a mistblower, costs of $15 to $20 seem logical when 2,4,5-T is used. Little and Mohr (1964) estimated that a combination of mistblowing and subsequent injector treatment of surviving hardwoods would cost about $15 and $18 per acre respectively.

Aircraft spraying is the least expensive method. For fixed-wing aircraft Peevy (1960) reported costs of $7.50 to $9.00 per acre using 2 pounds of 2,4,5-T, and Butler et al. (1963) reported a cost of $4.96 per acre for application of 1 pound of 2,4,5-T. Helicopter costs may depend largely on the proximity of the job to the machine headquarters. For instance, a recent aerial spraying of hardwoods on a relatively isolated area on the Monongahela National Forest in West Virginia cost $23 per acre, of which

$19.50 was the cost of the helicopter; whereas spraying easily reached New Jersey woodlands cost $9.10 per acre, of which about one-half was for the helicopter. In a 600-acre test in Tennessee, helicopter spraying of 2,4,5-T killed 85 percent of the low-grade hardwoods larger than 2.9 inches d.b.h. at a total cost of $8.85 per acre (Russell 1961).

Aerial treatments are mostly effective on overstory vegetation and must be supplemented by tree injection or mistblowing or both if all vegetation is to be killed.

Soil sterilants.—A number of chemicals have recently been introduced that eliminate vegetation for one to several years by their sterilizing effect upon the soil. They may be sprayed on the soil surface or broadcast as pellets, and they become effective when sufficient rainfall carries the chemicals to the root zone. Pelletized chemicals are more readily applied than the sprayed solutions, particularly in rough terrain, and will not drift and damage neighboring vegetation. Greater rates of application are required for deeper rooted vegetation. Possibilities of overland flow and erosion after protective vegetation is killed strongly suggest that sterilants be used with caution and at first only on an experimental basis.

Other methods.—Controlled burning using hot summer fires provides, in some situations, an inexpensive way of killing worthless hardwoods. In the New Jersey pine region Little and Moore (1953) found that, on medium wet and dry lowlands, hot summer fires killed or killed back all hardwoods and a large proportion of pine. Their control required 1 to 5 man-hours per acre. Light summer and winter fires were not as effective. Light summer fires killed 63 to 100 percent of the hardwoods and 40 percent of the pines. In one study, controlled winter burning killed all hardwoods below 0.6 inch in diameter but only 12, 2, and 1 percent of the 1-, 2-, and 3-inch trees respectively, and nothing any larger (Little et al. 1948). Fire used after logging to kill residual non-commercial material may be particularly effective because of fuel added by logging slash. One of the problems with hot summer fires is the necessity of always being ready to take advantage of infrequent periods of suitable fuel and weather conditions.

Bulldozing has little to recommend it. Costs are high, $35 to $60 per acre; and on sloping lands erosion can result, particularly from dormant-season operations (Carvell and Goodspeed 1962; Little and Mohr 1964). Sprouting may be so abundant that further treatment, burning or herbicidal treatment, is required.

Generally, burning and bulldozing, if used, should be confined to sites on the Coastal Plain where topography and soils limit overland flow and erosion.

Cutting and herbicides.—A combination of cutting and herbicides may be most practicable to achieve total forest removal. At the Fernow Experimental Forest, two watersheds were cleared in four steps: (1) before a commercial clearcutting, all trees above 1 inch d.b.h. were basal-sprayed with 2,4,5-T in diesel oil; (2) sawlogs and pulpwood were removed; (3) all remaining trees over 20 feet in height were felled; and (4) foliage was sprayed, using a backpack mistblower, in early summer and in late summer with 2,4,5-T in diesel oil and water (Reinhart 1965). Man-days per acre for the various operations (except the commercial clearcutting) were as follows:

1. Basal spray before logging	1.7
2. Cutting residuals	.5
3. Foliage spray	1.0
	3.2

With an 8-hour day and labor costs of $2 per hour, this would amount to $51 per acre. Herbicides and oil cost about $15 per acre. Because this operation had a research objective of determining water-yield increases after removal of *all* vegetation, the costs were higher than those expected when the operation is in practical application.

Total cost of obtaining increased yields will depend not only upon costs of initial treatment and maintaining the treatment, but also on the loss of income from timber growth. Cost estimates calculated for the commercial clearcutting on the Fernow provide an example. For this type of cutting no costs need be assessed for the initial treatment. Maintenance cost for application of herbicides every 5 years to kill small trees and low vegetation was estimated at $1.80 per acre per year. Timber income foregone was estimated at $4 per acre per year. For an estimated average annual increase in water yield of 144,000 gallons per acre (5.3 area-inches), the total cost per thousand gallons would be $0.04 (Trimble et al. 1963). Subsequent experience with vegetation regrowth indicates that these may be optimistic estimates for amount of increase as related to costs. Even so, this treatment is probably competitive with costs of other methods of increasing water supply.

Summary of costs.—Experience in forest removal, both by use of herbicides and by other methods, has been of limited scope and applicability, gained mostly from a few timber-management operations or watershed experiments. Thus the cost picture is not very clear. Better cost estimates must await pilot-scale tests of actual water-yield treatments. Even then, costs may vary widely with local conditions.

Present estimates of per-acre costs of removing fully stocked non-commercial stands show a wide range, about as follows:

Clearcutting	$100-$200
Herbicidal treatment:	
Frilling and poisoning	$10-$30
Tree injection	$10-$20
Foliar sprays, ground	$15-$20
Foliar spray, aerial	$5-$25
Controlled burning	$2-$10
Bulldozing	$35-$60

These treatments may not be completely effective. Often two or more may have to be used in combination, or re-treatments must be made. Two or more foliar sprayings may be required to kill all sprout growth from clearcutting; controlled burning may not kill the larger trees so that additional frilling and poisoning may be necessary. When the proper combination of treatments is used most of the vegetation, perhaps 75 percent, should be effectively killed by the initial application.

A commercial clearcut may have to be followed by cutting residuals. Costs can range from $35 to $65 per acre; frill-girdling or stem injection plus mist-spraying smaller material may cost about $30 per acre.

Maintaining Maximum Yields

Regrowth begins soon after timber is removed, or during its removal, depending on the season of the year. Regrowth can rapidly reduce water-yield gains experienced the first year as shown in the estimated regression of annual water yields in inches during the 10 years after clearcutting watershed 1 at the Fernow and watershed 13 (north-facing) at Coweeta (Kovner 1956; Lull and Reinhart 1966).

Years after cutting	*Fernow (inches)*	*Coweeta (inches)*
1	5.1	14.7
2	4.0	12.0
3	3.0	10.5
4	2.4	9.4
5	1.8	8.6
6	1.4	7.9
7	1.1	7.3
8	.8	6.8
9	.6	6.3
10	.5	5.9

This reduction in yield may be expressed in terms of the height of the vegetation, assuming full stocking of sprouts and seedlings. For the Fernow, the average annual height of forest regrowth the 7 years after cutting, and concurrent reductions in water yield, are given in table 1. Similar data are given for Coweeta watershed 13, based on Kovner's (1956) analysis of recession in water yields after regrowth and a height-growth curve for upland oak with a site index of 70 (Schnurr 1937).

In the 7 years a height growth of 18 feet at the Fernow was related to a reduction in increased yield of 78 percent. At Coweeta the same percentage reduction was equivalent to a height growth of 36 feet in 20 years. Thus at Coweeta it took about three times longer and twice the height growth to reduce yield proportionately to the Fernow reductions. Soil moisture-storage between field capacity and wilting point in the Fernow watersheds is about 4.5 inches (Reinhart 1964a), or an average soil depth of 30 inches dried to wilting point; soil depth to bedrock ranges from 2 to 5

Table 1.—*Average height of forest vegetation after clearcutting, and concurrent increase in water yield*

Fernow Experimental Forest			Coweeta Hydrologic Laboratory		
Year after clearcutting	Height of vegetation	Increase in water yield	Year after clearcutting	Height of vegetation	Increase in water yield
	Feet	*Inches*		*Feet*	*Inches*
1	4	5.1	1	4	14.7
2	8	4.0	2	8	12.0
3	11	3.0	3	11	10.4
4	13	2.4	4	13	9.4
5	15	1.8	5	15	8.6
6	17	1.4	—	—	—
7	18	1.1	—	—	—
—	—	—	10	21	5.9
—	—	—	15	29	4.5
—	—	—	20	36	3.3
—	—	—	25	42	2.4
—	—	—	30	48	1.8
—	—	—	35	54	1.0
—	—	—	40	60	.6
—	—	—	45	65	.2
—	—	—	50	70	.0

feet. At Coweeta roots are located mostly in the top 4 or 5 feet of soil, but occasional roots have been observed as deep as 20 feet (Hewlett and Hibbert 1961). Because of this greater depth, it takes longer than at the Fernow for roots to reoccupy the soil mass, and this may be one reason why increased water yield is prolonged.

A foliar spray would probably be the most efficient way of maintaining maximum yields. Data in table 1 suggest that mist-blowing would be necessary annually or every other year at the Fernow and perhaps every third year at Coweeta. The percent of the maximum increase obtainable from killing of vegetation at 1- to 5-year intervals would be as follows:

Year	*Fernow (percent)*	*Coweeta (percent)*
1	100	100
2	89	91
3	79	84
4	71	79
5	64	75

The cost of spraying woody regrowth would depend on its size and density. Little information of this kind is now available. As already noted, it cost $66 per acre for basal spraying, cutting of residuals, and foliar spraying with a backpack mistblower for the initial treatment on two Fernow clearcut watersheds. The next growing season, foliage spray was applied to considerable regrowth, including a volunteer growth of herbs and grasses, at a cost of $40 per acre ($19 for labor at $2 per hour and $21 for chemical). Such a thorough and expensive job would probably be too costly for practical water management. A more realistic estimate is the $5 to $25 per acre cost of foliar spraying given previously.

Maintaining a non-forest raises questions of site deterioration and water-quality effects. Annual regrowth cut clearly for 15 years on watershed 17 at Coweeta gradually produced a closed cover of herbaceous and low shrubby growth over the soil. Storm peaks and sedimentation were not increased at all (Dils 1957). Herbicidal treatment of annual growth with 2,4,5-T or 2,4-D would have a more drastic effect but moderated to the extent that the area would be invaded by grasses that are not susceptible to these chemicals. Periodic application of soil sterilants to keep a watershed entirely free from vegetation would be undesirable, for it would ultimately result in decay and disappearance of the forest floor with consequent exposure to rainfall impact, soil compaction, overland flow, and erosion.

To prevent erosion and maintain high water quality, some type of ground cover must be allowed to develop after total forest removal. Recent experience at the Fernow has indicated that clearcutting and herbicidal treatment of the understory is followed by a rapid invasion of herbaceous vegetation. We know very little about natural invasion of a ground cover, its rate, species, water-use, and soil-holding properties. Possibilities of seeding clearcut and herbicide-treated areas to get desirable cover must be investigated. For purposes of water use, shallow-rooted vegetation — preferably low-growing and with a short growing season—would be best. For watershed managers an evaluation of water use of herbaceous vegetation would be helpful.

Management of Reservoir Shorelines

On most municipal reservoirs the forest cover extends to the shoreline though there are instances where shoreline forest has been cut to reduce transpiration losses or to facilitate detection of trespass. Many shoreline areas have been planted to conifers as a screen to prevent hardwood leaves from blowing into the reservoirs and discoloring the water.

The amount of water transpired by forest vegetation growing along shorelines has never been determined. Obviously however, within the area in which the roots reach the groundwater extending from the reservoir, transpiration must be at a maximum. The difference in evapotranspiration from reservoir shorelines and from the upland forest above the shorelines may be estimated as the difference between potential evapotranspiration (not limited by deficiences in soil-moisture) and actual evapotranspiration (with occasional deficiences in soil-moisture) as can be approximated by the procedure developed by Holdridge (1962). Approximate annual evapotranspiration values for selected points in the Northeast are as follows:

Location	*Potential (inches)*	*Actual (inches)*	*Difference (inches)*
Greenville, Me.	10.04	8.63	1.41
Concord, N. H.	16.50	15.34	1.16
Tupper Lake, N. Y.	12.01	10.93	1.08
Binghamton, N. Y.	21.65	19.27	2.38
New York, N. Y.	27.60	23.74	3.86
Harrisburg, Pa.	27.09	22.20	4.89
Pittsburgh, Pa.	28.73	22.87	5.86
Washington, D. C.	31.97	25.90	6.07
Charleston, W. Va.	30.67	26.06	4.61

On a per-acre basis these differences range in equivalent water volumes from 38,287 gallons for Greenville, Me., to 164,825 gallons for Washington, D.C. As to magnitude of shoreline forests: a square-shaped reservoir with a water surface of 10 acres and a perimeter of 2,640 feet with a shoreline forest 200 feet in depth would have 12 acres of forest.

To reduce excessive water losses along shorelines, the forest cover should be cut back to a line perhaps 10 to 15 feet above the water table, and a herbaceous ground cover should be allowed to develop. The distance will depend on the slope of the water table and the slope of the land. Thus, if the water table slopes 5 percent to the reservoir, and the land surface slopes 10 percent, a line 10 feet above the water table would be 200 feet back of the shoreline. Cutting the forested shoreline may not be entirely advantageous. Tree removal will reduce shading of the shallow water at the lake margin and increase windflow over the lake, which will often bring in advected heat and facilitate turbulent exchange of water vapor. The extent of these effects is not known.

Water Harvesting

It is conceivable that the ultimate stage of water-yield management after forest removal would be water harvesting by treating the soil to increase rainfall runoff. By constructing an impermeable surface, almost all rainfall can be realized as runoff. Forest watersheds in the Northeast yield as runoff from 40 to 60 percent of the precipitation. Clearcut they may yield 70 percent; with a soil treatment perhaps 90 percent.

With 40 inches of annual precipitation and 90 percent recovery, each square foot of impermeable surface can produce 22.4 gallons of water; each acre can produce 977,486 gallons, and each square mile 625,600,000 gallons, a volume sufficient to provide 100 gallons daily for 17,000 people. On this basis the Pequannock watershed of Newark, N. J., 36,000 acres of forest land, if treated for water harvesting could meet the water needs of 964,000 people if ample storage could be provided.

Current research suggests that treatments can be developed to waterproof and stabilize the soil surface for an annual cost of 2 cents per square yard. Clearing, smoothing, and rolling the site preparatory to treatment costs 5 cents per square yard (Myers 1963). Recovering 90 percent of 40 inches of annual rainfall at a treatment cost of 7 cents per square yard the first year, 4.5 cents the first 2 years, 3.7 cents the first 3 years, and 2.5 cents the first 10 years, would be equivalent to a water cost of 35, 22, 18, and 12 cents per 1,000 gallons, respectively. Stabilizing the channel from the collection site to the reservoir would be a necessary additional cost.

The least expensive treatment developed to date, according to Myers (1963), is an asphalt spray that should have an annual cost of $0.03 per square yard or less. Other materials are considerably more expensive. One-mil aluminum foil can be bonded to the soil with an asphaltic emulsion for about $0.25 per square yard. Thirty-mil butyl rubber sheeting costs about $1.60 per square yard and has an expected life of over 10 years. Vinyl and polyethylene plastic sheeting have proved unsatisfactory.

According to Myers (1963), wide-scale application of water-harvesting principles seems certain to develop within the next decade. Certainly, the costs seem to be competitive with other methods. Water harvesting probably would not be feasible on the steep and rocky slopes that comprise much of the forest land in the Northeast. The requirement of clearing, smoothing, and rolling preparatory to spraying the impermeable surface suggests that gently sloping pasture or cropland close to reservoir storage would be more suitable. Water harvesting is still in an experimental stage regarding soil-sealing methods, their costs and duration, and the maintenance of site and channel stability.

PARTIAL FOREST REMOVAL

Here we are concerned with increase in water yield that may be achieved from timber management under a sustained-yield program in which only part of the timber on a watershed is removed. In this situation we must consider both timber and water together. Timber management and water-yield effects cannot be considered separately, for the harvesting of forest products will, to some degree, reduce interception and transpiration and thereby affect water yield.

The magnitude of the effect, under a sustained-yield program, depends largely on whether all-aged management or even-aged management is employed. All-aged management that involves harvesting of mature trees by individual selection will have a small effect on water yield, as we will show. Even-aged management that involves clearcutting of selected areas will have a greater effect, its magnitude depending on the proportion of the watershed area cut and the size of individual clearings. Thinnings and improvement cuttings will, like selection cuttings, generally have a minor effect. In some instances, herbicides may be used to improve a stand by treating certain components or areas.

All-Aged Management

The only examples of the effects of all-aged management on water yield in the Northeast come from the Fernow Experimental Forest where in 1958-59 three experimental watersheds were partially cut. In one, subjected to a diameter-limit cutting, every merchantable tree of long-lived species above 17.0 inches d.b.h. and every tree of short-lived species larger than 7.0 inches were cut and culls above 17.0 inches d.b.h. were killed. In a second watershed, under extensive selection, harvesting and killing of culls were limited to marked trees larger than 11.0 inches d.b.h. In the third, under intensive selection, cutting and cultural work were limited to selected trees above 5.0 inches d.b.h. (Reinhart et al. 1963). These last two practices employed individual-tree selection.

The severity of the cutting and the size of the increases in annual and seasonal yield are given in table 2. Annual increases were related to the amount of timber cut and culled and came mostly during growing seasons. They were but fractions of the annual increase of 5.1 inches from the commercial clearcut watershed on the same experimental forest. First-year annual increases were 10.0, 2.4, and 1.3 percent of predicted annual runoff from the diameter-limit, extensive, and intensive treatments respectively (as compared to 19.2 percent for the commercial clearcut); and growing-season increases amounted to 52.9, 33.3, and 8.8 percent. In volumes of water, annual increases were equivalent to 68, 19, and 8 thousand gallons per acre. These increases persisted for barely more than a year.

First-year increases from partial cuttings at the Fernow Experimental Forest correspond roughly to first-year increases from six watersheds of southerly aspect at Coweeta (Hewlett and Hibbert 1961). Five of these six had ratios of increased annual yield in inches to percent of basal area cut of 0.03 to 0.07 (the sixth had 0.00); two of the four treated Fernow watersheds had ratios of

Table 2.—*Cutting and water-yield changes in three watersheds at the Fernow Experimental Forest*

Watershed treatment	Gross timber volumes[1]			Water yield changes					
	Original	Cut and culled	Residual	1st year		2nd year		3rd year	
				GS[2]	DS[2]	GS	DS	GS	DS
	M bd. ft.	*M bd. ft.*	*M bd. ft.*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
Diameter-limit	7.1	4.2	2.9	1.8*	0.8	0.7*	0.8	—0.2	0.5
Extensive selection	12.0	3.7	8.3	1.4*	—.6	—.3	.3	.0	—.7
Intensive selection	8.3	1.7	6.6	.3	.0	.4	.9	—.1	.4

[1] Gross volumes in thousands of board feet per acre to 8-inch top, including volume in cull trees.
[2] GS = growing season (May to October); DS = dormant season (November-April).
* Increase statistically significant at the 5 percent level.

0.06 to 0.07 and two had ratios of 0.02 and 0.03. Ratios for northerly aspect watersheds at Coweeta averaged 0.15; the difference is under study.

Increases in water yield at the Fernow Experimental Forest from partial cuttings, like the increases from clearcutting, are probably close to the maximum for the region. Increases in the Adirondacks and northern New England may be one-third to one-half those in West Virginia (see tabulation, p. 6). Region-wide, partial cutting under all-aged management can have only a small and short-lived effect on water yield.

Even-Aged Management

In even-aged management the situation is quite different because harvest cuts under this system are essentially clearcuttings. In upland hardwood stands, for instance, Roach and Gingrich (1962) recommend cutting all stems larger than 2 inches d.b.h. Harvest cuttings under even-aged management are even more complete than commercial clearcuttings in that unmerchantable trees are killed. In some forest types, supplemental measures such as mistblowing or prescribed burning are also used to reduce or eliminate woody understories that hinder the establishment or growth of desired reproduction.

Increases in water yield from clearcutting have already been discussed. The evidence we will rely upon in this discussion is the 5.1-inch increase from the commercial-clearcut watershed on the Fernow Experimental Forest; 4 years later this increase had dropped to 2.2 inches.

To assess quantitatively the effects of even-aged management on water, a hypothetical situation may be useful for illustrative purposes. Take for example a 4,000-acre municipal watershed with an upland hardwood forest. The management objective is 24- to 28-inch sawtimber on an 80-year rotation. And the forester-in-charge plans to clearcut 500 acres every 10 years. The question is: what would be the increase in water yield for the 10-year period in respect to the clearcut area and to the entire watershed?

If, as the Fernow and Coweeta experience seems to indicate, the diminishing of increased yield over several years follows a straight line on semilog paper, and if we consider that the increase would be 5.1 inches the first year and about 0.5 inches after 10 years, annual increases from clearcutting 500 acres in terms of the increase from the total area of 4,000 acres would range from 0.64 to 0.06 inches (3.2 to 0.3 percent of an estimated average annual yield of 20 inches) (table 3).

Regularity in annual increases in water yield, by annual clearcutting of 50 acres, would produce, by the end of the 10-year cycle, an increased average annual water yield of 0.26 inches over the 4,000-acre watershed equivalent to a 1.3-percent increase or 28 million gallons annually. With adequate reservoir storage this would meet the annual water needs of 774 people (at 100 gallons per day), or irrigate 173 acres with 6 inches of water, or fill each year 3,146 swimming pools 10 x 30 x 4 feet in dimension. Thus, though the percent increase is small, the actual increase in volume of water is substantial. The size of the increase is noteworthy when we remember that it stems from a practice for which the main objective is increased timber income, not increased water yield.

However, the increase would be reduced to the extent that the forest bordering the clearcutting is drawing soil-moisture from it

Table 3.—*Predicted annual increase in water yield from clearcutting 500 acres of mature hardwoods per year*

Year	Increase in runoff			
	Clearcut area	Total area (4,000 acres)		
	Inches	*Inches*	*Millions of gallons*	*Percent*
1	5.1	0.64	69	3.2[1]
2	4.0	.50	54	2.5
3	3.0	.38	41	1.9
4	2.4	.30	33	1.5
5	1.8	.22	24	1.1
6	1.4	.18	19	.9
7	1.1	.14	15	.7
8	.8	.10	11	.5
9	.6	.08	8	.4
10	.5	.06	7	.3

[1] Based on average annual runoff of 20 inches.

and thereby reducing the possibilities of increasing water yield. The extent of this influence depends on the perimeter of the bordering forest, which in turn depends on the size of the areas clearcut. The smaller the areas cut, the greater their perimeter. In 1-acre cuttings, as much as 64 percent of the 500 acres clearcut would be influenced by a forest border of the largest trees. This would drop to 39 percent if the border contained a range of tree sizes. For 25-acre cuttings the percentages would drop to 15 and 9 percent, respectively.

The effect of thinnings on water yield may be similar to the effects of selection harvesting. Therefore, if 20 to 30 percent of the basal area of an even-aged stand were removed to increase the growth rate of the remainder, the first-year effect might be an increase in yield of about 1-inch, with no significant increase the second year.

All-Aged vs. Even-Aged Management

As we have noted, the effects of partial cuttings in extensive and intensive selection treatments are small, whereas partial cuttings through even-aged management can give substantial increases in water yield. Returning to our example of even-aged management, suppose equal volumes of timber had been removed in an extensive selection cut as in the clearcutting, what increase in yield would have been expected?

The clearcutting removed 86 percent of the timber volume for an increase of 5.1 inches or 138 thousand gallons per acre; the extensive selection removed 31 percent for 0.7 inch or 19 thousand gallons. Extensive selection on 2.77 acres would result in a volume of cut equal to 1 acre of clearcutting. It would provide an increased yield of 2.77 times 19 or 53 thousand gallons. This 53 thousand gallons is but 38 percent of the increased yield on 1 acre of clearcutting. Thus for purposes of water yield, for equal volumes of timber cut, extensive selection is 38 percent as effective as clearcutting. The Fernow intensive selection removed 20 percent of the timber volume for an increase of only 0.3 inch. This treatment applied to 4.3 acres would provide a timber cut equal to 1 acre of clearcutting; it would however yield an increase of only 35 thousand gallons; it may be considered 25 percent as efficient as clearcutting.

We can add to these estimates the observation that increases in flow were less persistent from the selection cuttings compared to the clearcutting. As a result, for equal volumes removed, a selection cutting would provide no more than one-fourth of the increase resulting from clearcutting. Obviously, removing a tree here and a tree there in a selection cutting will make more moisture available to the remaining vegetation and it will also provide more energy per unit of vegetation to consume the moisture. Therefore the effects on evapotranspiration and yield could only be small.

Fire, Insects, Diseases, and Hurricanes

The principles responsible for the effects of forest removal and partial cuttings on water yield pertain also to the effects of fire, insects, diseases, and hurricanes. Roughly, their effect on any one watershed would be related to the proportion of timber killed in the burned or infested area or the blowdown, and the proportion of that area to the watershed area.

Diseases are responsible for the greatest mortality of live sawtimber and growing stock in the Northeast, followed by other causes (weather, animals, suppression), insects, and fire. Estimated mortality for 1952 was as follows (U.S. Forest Service 1958):

Cause	*Growing stock (million cu. ft.)*	*Live sawtimber (million bd. ft.)*
Diseases	257	582
Other causes	231	323
Insects	31	77
Fire	12	17
	531	999

If confined to one area, these totals would be equivalent to perhaps 300,000 acres of forest destroyed. An estimated 8-inch increase in annual water yield over this supposedly plague-stricken area would be equivalent to an increase of 65 billion gallons of water. The fact that damages are scattered throughout the entire region and that in any one affected area mortality may be confined to a single disease or insect-ridden species tends to make water-yield effects small and very likely comparable to those from selection cuttings. Also, to a certain extent the damages occur from year to year over all areas and their effect is incorporated into what we might consider normal discharge for an area.

As we have mentioned, hot summer fires are necessary to get a significant kill of hardwoods: winter fires may do little damage. Generally, conditions necessary for hot summer fires are not common in the Northeast. For instance, on an average there are only 9 to 11 days annually in New Jersey and Pennsylvania when the burning index is 60 or more, a condition that accounts for more than half of the total acreage burned.[5]

Outside of the Coastal Plain, the Northeast is among the most fireproof regions in the country. The area burned in the period 1959-63 amounted to 1.3 percent of the protected state and private forest lands as compared to 3.3 percent for the six Central States, and 2.6 percent for the eight Southern States. Major fires in the Northeast have been associated with unusual periods of dryness and (outside of the Coastal Plain) unusual accumulations of slash or down timber.

The effects of diseases and insects on water yield are somewhat different from the effects of fire because they tend to be more selective. For instance, the effects of any one attack may be limited to one or two host species. Thus in forests composed of a number of different species, it is doubtful if a disease or insect attack can have a significant effect on water yield. Although chestnut blight reduced the productive capacity of the hardwood forest north of Maryland by 15 to 50 percent (Boyce 1938), it occurred in mixed stands and is a progressive disease, requiring 1 to 10 years to kill a tree, so that other species very likely were able to grow and maintain evapotranspiration rates. Water yield under these conditions would be little affected.

Spruce budworm, heartrots, and birch dieback are responsible for the greatest losses of timber in the Northeast. The 1910-20

[5] Unpublished reviews of the forest fire situation in Pennsylvania and New Jersey by Wayne Banks, 1964. Northeastern Forest Experiment Station, Upper Darby, Pa.

epidemic of the budworm resulted in an estimated killing of about 8 billion board feet in New England, and a second outbreak occurred in the 1950's. Heartrot, which occurs in all tree species, accounts for one-third to one-half of the mortality from disease. Birch dieback since 1930 has destroyed much of the yellow and paper birch in New England. By 1958 almost 500 million board feet of sawtimber had been killed by this disease. Again, these infestations are active over a period of several years and over substantial areas and are therefore judged to have a negligible effect on water yield.

Among the damaging agents, catastrophic winds or fire are very likely the only events that would effectively increase water yield. The efficient forest fire protection organizations in the Northeastern States would seemingly reduce the chance for a holocaust. Hurricanes, like the one in 1938, which destroyed about half the merchantable timber in a swath 80 miles wide extending from Rhode Island and eastern Connecticut to the White Mountains (Barrett 1962), would doubtless tend to increase water yield to the extent that felled timber was killed. Eschner[6] has shown how extensive blowdown in the Adirondacks from a storm in 1950 interrupted a 39-year trend in which annual water yield from a protected forest watershed had gradually declined. Continuing mortality of storm-weakened trees during the next several years resulted in increased water yield.

REFORESTATION AND FOREST PROTECTION

The effect of regrowth after forest removal by clearcutting has already been discussed. Reforestation and the increasing of stand density through forest protection can similarly reduce water yield. For instance, planting 71 percent of an experimental watershed at Coshocton, Ohio, to locust and pine reduced annual water yield after 19 years by 5.3 inches (Brakensiek and Amerman 1964).

[6] Eschner, Arthur R. FOREST PROTECTION AND STREAMFLOW FROM AN ADIRONDACK WATERSHED. Ph.D. Diss., Syracuse Univ. Coll. Forestry, Syracuse, N. Y. 1965.

Partially planting (47, 58, and 35 percent) three New York State watersheds to red pine and Norway spruce reduced November to April runoff, over a 23-year period, by 4.2, 5.1, and 6.8 inches. These dormant-season reductions were attributed largely to interception of snow by the evergreens. From 13 to 16 percent of the area was in open land and the remainder forested (Schneider and Ayer 1961). For the same area Muller[7] estimated that growing-season potential evapotranspiration on the Allegheny Plateau amounts to 2.6 inches more for hardwoods and 3.2 inches more for conifers than in open and overgrown lands. This was based on an estimated albedo of 0.19 for openland, 0.10 for second-growth hardwoods, and 0.08 for conifer plantations, and an estimate that one-half of the additional energy absorption by hardwoods and conifers is used in evapotranspiration. His water-balance calculations for all seasons indicated that replacement of agricultural land by conifer plantations results in an approximate 25-percent reduction in water yield.

Increased transpiration with growth of the stand suggests that if a watershed, consisting of forest land in various stages of growth and abandoned land reverting to forest, is protected from cutting and fire, transpiration over a period of years should increase and water yield should decrease. This was illustrated recently in a study by Eschner[6] to determine the effects of long-time protection on water yield in the Adirondack Forest Preserve.

Analyzing streamflow records of the 491-square-mile Sacandaga watershed, Eschner found that a slow one-directional change in land use and increase in forest cover was correlated with a decrease in annual, dormant-season, and April runoff over the 39-year period 1912-50. In 1912 the total forest stand density and the density of conifers were at a minimum after logging, insect attacks, and a series of fires. As forest density increased under protection, streamflow decreased: there was a reduction over the 39-year period of 7.7 inches or 23 percent of the 1912 annual runoff. Most of this, 5.2 inches, was a reduction in October-to-

[7] Muller, Robert Albert. The EFFECTS OF FARM ABANDONMENT AND REFORESTATION ON WATER YIELD ON THE ALLEGHENY PLATEAU, NEW YORK. Ph.D. Diss., Syracuse Univ. Coll. Forestry, Syracuse, N. Y. 1962.

April runoff that may have been due to increased interception from the increasing amount of coniferous cover. An increase in the amount of soil-moisture recharge (because of increased transpiration the preceding growing season) also may have been a factor.

PRECAUTIONS AND SAFEGUARDS

The possibility of undesirable effects after treatment to increase water yields cannot be ignored. However, appreciable damage can be avoided if proper safeguards are taken. Most important, in all cutting and herbicidal treatments the forest floor should be disturbed as little as possible to maintain its characteristic high infiltration capacity. Roads and skidtrails should be kept to a minimum. In special cases where the area is kept in a low cover, the herbaceous vegetation can be relied upon to maintain high infiltration. These areas should not be grazed.

Flood Damages

Management of forested watersheds to increase water yield is not expected to produce damaging peak flows although this factor must be taken into consideration. On Coweeta watershed 17, where all trees were cut and left on the ground, a record first-year increase of 16 inches was obtained; however, no overland flow occurred and maximum peak-discharges were not significantly changed (Hoover 1944). Instantaneous peaks following the Fernow commercial clearcutting increased an average of 21 percent in the growing season and a negligible amount in the dormant season. Perhaps even more significant is that the larger percentage increases came with the smaller storms; the effect apparently diminishes as storm size increases. Also of importance, the major causative factor was antecedent soil moisture and not overland flow (Reinhart 1964b). Timber harvest on the Fernow by individual-tree selection had no determinable effect on peaks.

If only one-eighth of the Fernow watershed had been clearcut and regrowth permitted, as in our previous example of even-aged management, the increase in peak flows would very likely be of no practical significance.

Not only are the effects on the cutover watersheds minor; it is also probable that regionally only limited areas would be clearcut and they would be interspersed in areas largely uncut. Areas more intensively managed for water production, by methods like repeated spraying to keep vegetation at an erosion-prevention minimum, would be even more limited in size. Therefore we cannot conceive of a major effect on peak flows or possibilities of appreciable flood damages from water-yield management.

Where impervious surfaces are applied for the purpose of water harvesting, runoff will be most rapid. However, there appears to be no likelihood that large enough areas will be treated this way to cause a serious problem. Most of the water harvested would be channelled into reservoir or groundwater storage.

Water Quality

Erosion and sediment.—High water quality can be maintained in forest water-yield management by following rather simple, common-sense procedures. Studies at Coweeta and Fernow have shown, for instance, that clearcut areas with intact forest floor are not sources of overland flow (Reinhart 1964b) and do not erode (Hoover 1944). The qualifier here, of course, is the phrase "with intact forest floors". What is surprising is the considerable extent of forest floor that may remain intact even after clearcutting.

The forester's principal concern, then, is to see that the forest floor is subjected to minimum disturbance. How? By careful location and construction of truckroads and skidroads and necessary maintenance. A haphazardly built transport system may disturb as much as 20 percent of the surface: a well-planned system need not occupy more than 10 percent of the land area (Haussman 1960). Clearcutting, as compared to selection cutting, would require perhaps more careful attention to erosion control to offset the greater soil compaction associated with the greater volume of timber removed.

Basic safeguards to protect water quality have been set forth by Trimble (1959):

- Locate roads and trails away from stream courses except where a stream crossing cannot be avoided. The distance between stream and road should be 50 feet plus 4 feet for each 1 percent of slope between them. Thus on a 20-percent slope the road should be kept about 130 feet away from the stream.
- Keep logging operations away from the stream to prevent soil disturbance near the stream and to keep slash from plugging the channel and causing bank-cutting.
- Truckroads should cross all water courses, even ephemeral ones, on closed culverts or bridges.
- Except for very short stretches, the maximum grade on truckroads and heavily used skidtrails should be less than 10 percent.
- For adequate road drainage the intervals in feet between cross drainages can be calculated from 1,000/percentage of grade.
- As far as possible, build roads and skidtrails in dry weather. Wet-weather operations increase erosion.
- The sooner the logging job is finished, the shorter will be the period of greatest erosion hazard.
- After the logging job is finished, remove temporary bridges and open-top culverts and seed problem areas with grasses.
- Close supervision is required to insure the safeguarding of water quality.

Herbicides.—Arguments in recent years over the use of pesticides are known to all. Generally herbicides are much less toxic to humans and animals than insecticides. With many herbicides, objectionable taste and odor levels are much lower than levels of toxicity. Even so, wherever domestic water supplies are involved, herbicides must be applied with caution; and odor should be taken as a warning of possible toxicity. However, in three pertinent studies, little or no contamination was reported.

Streamside vegetation on two small headwater streams at Newfoundland, N. J., and two near State College, Pa., were sprayed with 2,4,5-T in an oil-water emulsion and 2,4,5-T diluted in water only (Reigner et al. 1964). In each watershed the operator mist-sprayed swaths 20 feet each side of the stream for a distance of about 1,000 feet. Water samples were taken below the treated stretch and 1 mile downstream immediately after treatment, 4 hours after treatment, at daily intervals, after the first rainstorm following treatment, and after the first storm of 1.0 inch precipitation or more.

Contamination was found in samples taken below the treated area within 4 hours after treatment, and in one watershed after the first rain of 1 inch or more. Concentrations of the herbicide in the samples were estimated to be 40 p.p.b. (parts per billion) immediately after spraying, 20 p.p.b. 4 hours later, and 10 to 20 p.p.b. after the first large storm (1,000 p.p.b. are considered toxic). No contamination was found downstream. Since very little contamination occurred it was concluded that with normal precautions phenoxy herbicides can be used on municipal watersheds.

At the Fernow Experimental Forest in West Virginia, basal spraying, stump treatments, and foliage spraying with 2,4,5-T during the course of a clearcutting operation resulted in no detectable contamination of streamflow (Reinhart 1965).

In southern California, spraying vegetation in a strip 100 to 400 feet wide along 1.3 miles of canyon bottom with a mixture of 2,4-D and of 2,4,5-T resulted in no herbicide contamination of water samples taken within a few days after spraying. Small traces of oil used in the spray mixture, ranging from 2 to 30 parts per million, were detected (Rowe 1963).

DISCUSSION AND CONCLUSIONS

To date no one in the Northeast has taken advantage of the possibilities for increasing water yield by cutting trees. The cities of Baltimore and Newark have been interested sufficiently to institute research programs on their own watersheds (Lull 1960). Interest of other Northeastern municipalities is attested to by the recent Municipal Watershed Management Symposium at Amherst, Mass. (Noyes 1967). Outside this region, the major action program for water-yield increase is in Arizona (Arizona Water Resources Committee 1959), where climatic conditions are not nearly as suitable for increasing water yield as in the Northeast.

An efficient program for increasing water yield depends on provision of sufficient reservoir storage to contain the increases. In some cases, increase in summer yield may be necessary because of insufficient reservoir storage for winter and spring runoff. The decision about the necessity of forest water-yield management under these circumstances will depend on alternative costs of increasing reservoir storage.

Before anyone embarks on a program of forest water-yield management, we suggest a degree of conservatism. First, alternative possibilities for increasing water yield—and their costs—should be investigated. Second, the feasibility of forest water-yield management should be judged in light of the physical geography of the area concerned, and forest watershed managers of some experience should be consulted. No two watersheds are alike, and though the forces that govern delivery of streamflow are the same at all watersheds, the physical conditions under which these forces operate may be quite different.

With these qualifications in mind, the following conclusions are offered:

- Removal of all vegetation on a well-stocked forested watershed in the Northeast will increase annual water yield the first year after treatment by about 4 to 12 inches.

- Water-yield increases from forest removal will probably appear mostly in the late summer months.

- Costs of forest removal range from $2 to $10 per acre for controlled burning, $5 to $25 for herbicidal treatment, and $100 to $200 for clearcutting. A combination of a commercial clearcutting and herbicidal treatment may cost in the neighborhood of $30 per acre.

- Regrowth 5 years after forest removal can lower the water-yield increase by two-thirds, and after 10 years most of the increase will have disappeared.

- Foliar sprays, annually or every other year, are probably the most efficient way of maintaining high increased yields. Annual or biennial spraying will be necessary until most of the vegetation is killed. The spraying will cost $5 to $25 per acre.

- Maintenance of high increased yields must be accompanied by encouragement and maintenance of a protective ground cover.

- Partial cutting under all-aged management can have only a minor effect on water yield.

- Partial cutting under even-aged management as done in a sustained-timber-yield program can yield a small percentage increase in annual water yield but a somewhat substantial increase in terms of water volume. The magnitude of the increase will depend on the proportion of the watershed area cut, the size of individual clearings, and the condition (and water use) of the forest stand before cutting.

- Thinnings may have only a negligible effect on water yield.

- Planting abandoned agricultural land to conifers can in time reduce annual water yield as much as 25 percent where snowfall is abundant.

- Long-term protection of forest land from fire and cutting will tend to reduce annual water yield. The reduction will depend on how thoroughly the original stand occupied the site.

- Clearcutting upland areas of a forested watershed during a drought will not provide relief until after rainfall or snowmelt has recharged the soil. Clearcutting riparian areas can increase water yields.

- Below- or above-normal annual precipitation after forest removal may not have a pronounced effect on water-yield increases.

- In general, damage caused by fire, insects, and diseases will have a negligible effect on water yield.

- Forest cover along reservoir shorelines can use an estimated 1 to 6 area-inches more water annually than upland forest cover.

To reduce these losses, the shoreline forest should be cut back to a line 10 to 15 feet above the water table.

- Waterproofing the soil surface can produce water yields equivalent to about 90 percent of annual rainfall at costs competitive with other methods of increasing water supplies.
- Management of forested watersheds to increase water yield is not expected to produce peak flows of damaging consequence.
- High water quality can be maintained in forest water-yield management by following basic safeguards in location, use, and maintenance of logging roads and skidtrails. How restrictive these safeguards must be depends upon local conditions.
- Little contamination has been reported from limited experimental use of herbicides in treatments to increase water yield.

These conclusions provide a basis for an action program to increase water yields. In considering the possibilities, the watershed manager should study carefully:

1. Nearby streamflow records of the U.S. Geological Survey that can provide some understanding of annual and seasonal discharges that may be expected locally from forested watersheds, and their relation to variation in annual and seasonal precipitation.

2. Regional atlases that depict mean precipitation, streamflow, and evapotranspiration (Knox and Nordensen 1955; Schneider et al. 1965).

3. Regional studies of streamflow, its variation, and factors that influence it (Sopper and Lull 1965; Lull and Sopper 1966a, 1966b).

4. Results of forest-watershed-management research as to the effects of forest cutting on water yield (Reinhart et al. 1963; Hewlett and Hibbert 1961).

Additional information can be obtained in the Northeast at the following locations where forest watershed research is now under way:

Watershed Management Research Project
Northeastern Forest Experiment Station
Durham, New Hampshire 03824

Watershed Management Research Project
Northeastern Forest Experiment Station
Upper Darby, Pennsylvania 19082

Watershed Management Research Project
Northeastern Forest Experiment Station
Parsons, West Virginia 26287

New York State University College of Forestry
at Syracuse University
Syracuse, New York 13210

School of Forest Resources
The Pennsylvania State University
University Park, Pennsylvania 16802

If time permits, the watershed manager may wish to calibrate and clearcut small experimental watersheds (20 to 60 acres) to determine for his area the maximum possibilities for increasing yield. Such a program requires a minimum of 10 years, the construction of two or more gaging stations (for construction details see Reinhart and Pierce 1964), and the operation of a climatic station. Research of this kind is now under way at Newark, N.J., and Baltimore, Md., watersheds in cooperation with the Northeastern Forest Experiment Station (Lull 1960). Shorter-term soil-moisture studies of the kind recently reported by Mader et al. (1967) and Hunt (1967) for Boston's Quabbin Reservoir watershed may give an indication of treatment results.

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APPENDIX A

Clearcutting Costs

Costs and related information for clearcutting oak-hickory forest at the Coweeta Hydrologic Laboratory in 1962-63 were as shown in the table below.

Watershed area, slope, and forest cover

Watershed No.	Area	Average slope	Forest cover	
			Basal area*	Stems
	Acres	*Percent*	*Sq. ft./acre*	*No./acre*
13	40	26	74	2,364
28	86	31	—	—
37	108	27	118	1,637

Cost of Treatment

Watershed No.	Labor	Cost in dollars per acre		
		Labor	Operation**	Total
	Man-days per acre			
13	10.3	$108	$20	$128
28	8.8	94	18	112
37	8.8	—	—	—

* Basal area in stems 1 inch and larger.

** Operation costs include vehicle mileage, repairs, and 100 percent depreciation of power saws, axes, etc.

Hourly wage rates changed periodically but were about $1.87 for work leaders, $1.70 for power-tool operators, and $1.35 for laborers. The most efficient crew organization consisted of a foreman, 3 crew leaders, and about 8 two-man power-saw teams using 5-horsepower direct-drive chain saws. Chain-saw crews were more effective than combined chain-saw and ax crews. Clearcutting residual material after a commercial clearcutting and timber-sale operation on watershed 28 required 2.45 man-days per acre, a 70 percent reduction in labor costs over clearcutting.[3]

On the Pisgah National Forest in western North Carolina, an area clearcut was given an intensive cleaning in the winter of 1959-60. In cleaning, all woody stems except selected crop trees were cut. Before cleaning, the 11-year-old stand averaged 3,214 saplings per acre of stems over 4.5 feet tall; after cleaning, spacing was just under 9 x 9 feet. The mountain slopes averaged 42 percent in steepness and ranged from 18 to 72 percent.

Cleaning time averaged 7.3 man-days per acre for two 3-man crews equipped with one chain saw and two axes per crew. The men were experienced browse cutters employed by the North Carolina Wildlife Resources Commission. The cleaning required as few as 6.1 man-days per acre and as many as 11.1 man-days. Slope steepness, and especially shrubby growth (*Kalmia latifolia* and *Rhododendron maximum)* and vines (*Vitis* spp. and *Smilax* spp.) increased the cleaning time considerably.[8]

Cutting noncommercial material in 1949 after a commercial clearcutting of 70 acres on the Pisgah National Forest cost $43 per acre (Ripley and Campbell 1960).

In 1964 a 50-acre tract was clearcut on the upper Long Branch drainage of the Bent Creek Experimental Forest. The area was very steep with slopes generally over 50 percent. About 400,000 board feet of overmature timber, including pulpwod, was removed by commercial loggers. All remaining trees under pulpwood size and over 4.5 feet tall were cut by a contractor for $35 per acre. About 8 acres contained dense stands of laurel and rhododendron, which increased the cost somewhat. On similar areas without laurel and rhododendron a complete removal job will cost about $25.[8]

APPENDIX B

Costs of Frilling and Tree Injection

Costs of frilling and poisoning hardwoods at the Duke Forest in North Carolina in relation to tree diameters were as follows:

Inches d.b.h.

4	6	8	10	12	14	16	18
4.8¢	5.8¢	6.9¢	8.0¢	9.0¢	10.0¢	11.1¢	12.2¢

Costs were based on an hourly wage of $0.95 and $0.22 per pound for ammate (Carvell 1956). In an even-aged stand of 500 trees per acre with an average d.b.h. of 6 inches, this treatment would cost $29.00 per acre; for 240 ten-inch trees, $19.20. Cost of treatment per inch of diameter ranges from $0.012 for the 4-inch trees to $0.007 for the 12-inch trees.

A number of studies show that frilling and poisoning hardwood culls with 2,4,5-T costs from $0.005 to $0.011 per diameter-inch. In Maryland, Little and Mohr (1956) found that treatment of 385 trees per acre with an average diameter of 6 inches cost $13 to $15 (0.006 per diameter-inch). In Ohio, Ryker and Minckler (1962) reported that their treatment cost $0.011 per tree diameter-inch. Peevy (1960) reported a cost of $0.005 for poisoning southern weed trees. MacConnell and Babeu (1964) reported per diameter-inch costs of $0.007 for frilling hardwoods

[8] Communication of March 4, 1966, from Charles E. McGee, project leader, U. S. Forest Service, Asheville, N. C.

in Massachusetts and costs of $0.009 for killing 4- to 12-inch trees and $0.016 for killing 13- to 25-inch trees.

At the Fernow Experimental Forest in West Virginia, Yawney (1961) found that frilling and ammate treatment of 6 to 15 cull trees per acre cost $1.32 to $3.61, with an average cost per inch of tree diameter of $0.017. This was based on a labor cost of $1.20 per hour and ammate at $0.24 per pound. An average of 108 tree-diameter inches was treated per man-hour and 44 inches treated per pound of ammate.

Tree injection costs are somewhat lower. Peevy (1960) reported a cost of $0.003 per diameter-inch for tree injection of southern weed trees, and MacConnell and Baben (1964) treated Massachusetts hardwoods for $0.007, and reported killing costs of $0.007 for 4- to 12-inch trees and $0.014 for 13- to 25-inch trees using the amine form of 2,4,5-T. In 1966 Little and Cramner found that labor ($2 per hour) and chemical costs for treating a thousand diameter-inches with six commonly-used chemicals ranged from $4.89 to $6.31.[9]

[9] Unpublished data, Northeastern Forest Experiment Station.