FOREST TREATMENT EFFECTS ON WATER YIELD

ALDEN R. HIBBERT

Coweeta Hydrologic Laboratory, Southeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture, Asheville, North Carolina

ABSTRACT

Results are reported for thirty-nine studies of the effect of altering forest cover on water yield. Taken collectively, these studies reveal that forest reduction increases water yield, and that reforestation decreases water yield. Results of individual treatments vary widely and for the most part are unpredictable. First-year response to complete forest reduction varies from 34 mm to more than 450 mm of increased streamflow. A practical upper limit of yield increase appears to be about 4.5 mm per year for each percent reduction in forest cover, but most treatments produce less than half this amount. There is strong evidence that in well-watered regions, at least, streamflow response is proportional to reduction in forest cover. As the forest regrows following treatment, increases in streamflow decline; the rate of decline varies between catchments, but appears to be related to the rate of forest recovery. Seasonal distribution of streamflow response to treatment is variable; response in streamflow may be almost immediate or considerably delayed, depending on climate, soils, topography, and other factors.

INTRODUCTION

For centuries man has made casual observations on the relationship between forests and water, but only recently has he become concerned with other than the engineering aspects of water control and transport. Scientific investigation into forest-water relations began around the turn of this century. In 1912 Raphael Zon attempted to enlighten the U.S. Congress and the public with his report, *Forests and Water in the Light of Scientific Investigation.* His aim was to "bring together impartially all the well-established scientific facts in regard to the relation of forest to water supply". In retrospect, we find that many of the tenets of only 50 years ago seem strange to us now. This is encouraging. We have made progress, and I believe the increased knowledge of how forests affect water is paying dividends today. But we still have much to learn if we are to meet mounting demands for clean, plentiful water and at the same time conserve our natural resources.

The objective of this paper is to review results from world wide studies of the effects of altering forest cover on water yield, and to discuss the significance of these results when considered collectively.

HISTORY OF EXPERIMENTS

In 1900 the Swiss began studies on two small catchments in the Emmenthal Mountains. One was almost completely forested, the other mostly pastureland. Measurements of streamflow, precipitation, and climate were made to determine the influence of the forest on the water economy. Despite attention to detail and the thoroughness of Engler's (1919) work, there was no way to be certain that differences in streamflow between the two catchments were caused solely by differences in forest cover.

The control watershed approach (comparing flow from two similar catchments during a period of "calibration", and then treating one while leaving the other untreated as a control) was first used in the Wagon Wheel Gap study of 1911 on two small forested catchments high in the Colorado Rockies. This was the second serious attempt to measure quantitatively the influence of

TABLE 1

Location, Description, and Results of

Catchment	Area	Mid-area elev.	Slope × 100 (Elev. Diff. / Length)	Aspect	Vegetation and soils	Mean annual precip.	Mean annual stream-flow
Coweeta, N.C.	*ha*	*m*	%			*mm*	*mm*
13	16.1	810	26	NE	Mixed hardwoods. Basal area about 24 m^2/ha. Granitic origin, deeply weathered sandy clay loam, up to 6 m deep, base rock tight.	1829	792
17	13.5	885	44	NW		1895	775
22	34.4	1035	35	N		2068	1275
19	28.2	960	32	NW		2001	1222
1	16.1	840	34	S		1725	739
3	9.2	825	32	SE		1814	607
10	85.8	975	24	SE		1854	1072
41	28.7	1065	46	SE		2029	1285
40	20.3	1035	42	SE		1946	1052
6	8.8	790	35	NW		1821	831
37	43.7	1280	47	NE		2244	1583
28	144.2	1200	31	NE		2270	1532
Fernow, W. Va.							
1	29.9	755	23	NE	Mixed hardwoods. Basal area about 24 m^2/ha. Sandstone and shale, stony silt loam, 1 to 1.5 m deep.	1524	584
2	15.4	780	15	S		1500	660
5	36.4	780	14	NE		1473	762
3	34.4	805	13	S		1500	635
7	24.2	800	13	NE		1469 (some snow)	788
H. J. Andrews, Oreg.							
1	95.9	700	28	NW	Coniferous. Volcanic tuffs and breccias, clay loams, shallow to deep.	2388	1372
3	101.2	760	32	NW		2388	1346
San Dimas, Calif.							
Monroe Canyon	354.1	840	17	S	Chaparral with woodland riparian vegetation along streams. Granitic, rocky sandy loam, generally shallow.	648	64
Bell 2	40.5	885	32	S			
Sierra Ancha, Ariz.							
North Fork, Workman Creek	100.4	2225	17	SW	Coniferous (ponderosa pine). Quartzite, clay loam up to 5 m deep.	813 (some snow)	86
South Fork, Workman Creek	128.7	2165	8	NW		813	87

Water-yield Experiments, with references

Description of treatment (percentage refers to portion of area treated unless otherwise stated)	Water yield increases by years following treatment					References
	1st	2nd	3rd	4th	5th	
			mm			
1940, 100% clearcut, no removal, regrowth.	370	283	279	247	203	Kovner (1956)
1962, experiment repeated.	371					
1941, 100% clearcut, no removal, regrowth cut annually except years 3, 4 and 5.	408	361	256	167	245	Johnson and Kovner (1954) Hoover (1944)
1955, 50% poisoned in alternate 10 m strips, no removal, regrowth restricted 4 years.	198	155	130	112	100	Hewlett and Hibbert (1961)
1949, 22% basal area cut (understory only), regrowth.	71	64	55	47	39	Johnson and Kovner (1956)
1954, 25% poisoned (cove hardwoods), regrowth restricted 3 years.	46	24	36			
1956–7, 100% clearcut, partly burned, pine planted, regrowth restricted.	152	48	46	50	38	
1940, 100% area cleared for agriculture.	127	95	59	113	80	
1942, to 1956, 30% basal area cut by uncontrolled logging, regrowth.	averaged 25 mm per year					
1955, 35% basal area cut by selective logging, regrowth.	averaged 55 mm per year					
1955, 27% basal area cut by selective logging, regrowth.	nonsignificant					
1942, (July), 12% clearcut (streambank vegetation), regrowth.	immediate small increases, nonsignificant on annual basis					Dunford and Fletcher (1947)
1963, 100% clearcut, no removal, regrowth.	286					
1962–4, 51% clearcut, timber removal, 26% thinned, regrowth.	200 (approximate)					
1957–8, 85% basal area removed by commercial clearcut, regrowth.	130	86	89			Reinhart *et al.* (1963)
1957–8, 36% basal area removed by diameter-limit cut, regrowth.	64	36				
1957–8, 22% basal area removed by extensive-selection cut, regrowth.	36					Reinhart and Trimble (1962)
1957–8, 14% basal area removed by intensive-selection cut, regrowth.	8 (nonsignificant)					
1964, 50% (upper half) area cut, timber removed, regrowth not permitted.	92 (growing season only)					
1962–3, 40% commercial clearcut.	small increase in low flow					Rothacher (1965)
1963–4, 40% additional commercial clearcut.	small increase in low flow					
1959, 8% area cleared for road construction.	small increase in low flow					
1962–3, 25% clearcut and burned.	small increase in low flow					
1958, 1.7% cut (riparian vegetation only), sprouts controlled, grasses encouraged.	May–December 6 mm, January–April 4 mm.					Rowe (1963)
1959, additional 2.6% cut (canyon bottom vegetation), sprouts controlled, grasses encouraged.	May–December 5 mm					
1959, 40% poisoned (chaparral on moist sites), repeated application of herbicide.	June–September 17 mm					Merriam (1961) Crouse (1961)
1953, <1% cut (riparian vegetation only), sprouts controlled.	nonsignificant					Rich *et al.* (1961)
1958, 32% cleared (moist site), grass seeded.	13	51	15	48	30	U.S. Forest Service (1964)
1953–5, 30% basal area cut by selective logging.	nonsignificant					
1956, 6% basal area cut by thinning.	nonsignificant					
1957, 9% basal area reduced by burning.	nonsignificant					

TABLE 1

Catchment	Area	Mid-area elev.	Slope × 100 $\left(\frac{\text{Elev. Diff.}}{\text{Length}}\right)$	Aspect	Vegetation and soils	Mean annual precip.	Mean annual stream-flow
	ha	*m*	%			*mm*	*mm*
Fraser, Colo.							
Fool Creek	289.0	3200	18	N	Coniferous (lodgepole pine, spruce-fir). Granitic, sandy loam > 2.5 m deep.	762 (75% snow)	283
Wagon Wheel Gap, Colo.							
B	81.1	3110	37	NE	84% forested (aspen and conifers). Augite, quartzite, rocky clay loam.	536 (50% snow)	157
Meeker, Colo.							
White River	197,400				Conifers (spruce).	265	
Kamabuti, Japan							
II	2.5	200	40	E	Conifer 60%, broadleaf 40%. Tuff, shale.	2616 (40% snow)	2075
Kenya, East Africa							
Kericho Sambret	688.0	2200	5	NW	High montane and bamboo. Phenolite lava, deep friable	1905	416*
Kimakia A	35.2	2440		S	clay.	2014	568*
Jonkershoek, South Africa							
Bosboukloof	208.0	520	30	SW	Sclerophyll scrub (chaparral		475
Biesievlei	32.0	365	30	SW	type).		490
Coshocton, Ohio							
172	17.6	350	14	SW	30% hardwoods in 1938. Sedimentary, silt loams.	970 (little snow)	300
Western Tennessee							
Pine Tree Branch	35.7	160	5	E	23% mixed hardwoods in 1941. Sandy silt loams.	1230	255
Eastern Tennessee							
White Hollow	694	410	6	SE	65% mixed hardwoods and pine in 1934. Limestone, cherty silt loams.	1184	460
Central New York							
Sage Brook	181	525	15	SE	Mixed hardwoods and conifers.	974	535
Cold Spring Brook	391	565	35	S	Shales and sandstones overlain	1030	616
Shackham Brook	808	520	5	S	by glacial till, silt loams up to 3 m deep.	1030	627
Adirondacks, New York							
Sacandaga River	127,200	575	1		Northern hardwoods with conifers. Glacial till, sandy loam < 1 m deep.	1143 (some snow)	770
Southwestern Washington							
Naselle River	14,245	275			Douglas-fir, western hemlock. Silty-clay loam and stony loam, 2 m deep.	3300	2690

* Three years during treatment,

—continued

Description of treatment (percentage refers to portion of area treated unless otherwise stated)	Water yield increases by years following treatment					References
	1st	2nd	3rd	4th	5th	
	mm					
1954–7, 40% commercially clearcut in strips, regrowth.	86	53	79	97	53	Goodell (1958) Martinelli (1964)
1919, 100% clearcut, some removal, slash burned, regrowth.	34	47	25	22	13	Bates and Henry (1928) Reinhart *et al.* (1963)
1941–6, insects killed up to 80% of timber on 30% of area.	58 (average for 5 years)					Love (1955)
1948, 100% cut, annual recut of sprouts.	110 (average for 3 years)					Maruyama and Inose (1952)
1959–60, 34% cleared for tea plantation, clearweeded.	103					Pereira (1962, 1964)
1956, 100% cleared, pine planted, cultivation of vegetables for 3 years.	457	229	178			
	Reduced water yield for given year					
1940, 53% afforested with pine.	104 (4-yr. mean) at 16–20 yrs.					Banks and Kromhout (1963)
1948, 98% afforested with pine.	142 (4-yr. mean) at 8–12 yrs.					Wicht (1940, 1943)
1938–9, 70% reforested, mostly pine.	135 (after 19 years)					Harrold *et al.* (1962)
1946, 75% reforested, mostly pine.	76 to 152 (after 16 years)					TVA (1962)
1934–42, 34% reforested, mostly pine.	no detectable change					TVA (1961)
1932, 47% reforested, conifers.	106 (after 26 years)					Schneider and Ayer (1961)
1934, 35% reforested, conifers.	172 (after 24 years)					
1931–9, 58% reforested, conifers.	130 (after 24 years)					
1912 to 1950, basal area increased from 17 to 28 m^2/ha.	196 (after 38 years)					Eschner (1965)
1916 to 1954, 64% area logged at rate of 2% per year, regrowth.	no detectable change					Martin and Tinney (1962)

treatment effects removed.

forests on streamflow. In the words of Bates and Henry (1928): "It is not enough to know whether forests influence streamflow; it is necessary to know how much, at what seasons, and under what conditions of climate, soil, and topography, and the variations between different kinds of forests, as well."

After eight years of calibration, one of the catchments was denuded and for seven additional years streamflow from the denuded area was carefully compared with flow from the control catchment remaining in forest. Although Bates and Henry did not use regression techniques, they demonstrated conclusively that cutting the scrub aspen and coniferous vegetation on the 81-hectare catchment did increase streamflow. The study proved a technique, and it demonstrated that yield changes could be quantitatively assessed.

Other studies followed, both in this country and abroad. In the United States, the U.S. Forest Service has led research in forest-water relations since the early 1930's. In South Africa, rising concern over the effects of afforestation on water stimulated the Jonkershoek Research Station in 1935 and Cathedral Peak in 1945. During the 1950's studies were begun in East Africa to investigate the influence of forest and land use practices on streamflow. Other countries are developing similar programs of research, but most of these are still in the initial stages.

SUMMARY OF RESULTS

Table 1 contains a brief description of thirty-nine catchment studies, treatments imposed, and effects on water yield for several years following treatment. Except for the last seven studies listed in Table 1 (Pine Tree Branch to end of table), treatment effects were determined by the control watershed method (Kovner, 1956; Kovner and Evans, 1954; Wilm, 1943) and were reported significant at the 5 percent level. Unless otherwise indicated, treatment effects are expressed as depth over the entire catchment area, even if only a portion of the catchment was treated. Additional information pertaining to the experimental areas follows.

Coweeta Hydrologic Laboratory

The Coweeta Hydrologic Laboratory was established by the U.S. Forest Service in 1934 to study forest hydrology in the humid mountain region of the southeastern United States. The Coweeta basin comprises 1740 hectares of steep forest land with tight bedrock and numerous small, distinct catchments. About 100 separate storm events each year dump 2 m of water on the basin, less than 5 percent coming as snow. Precipitation is quite well distributed throughout the year, varying from an average of about 200 mm in March to 100 mm in October. At Coweeta, twelve catchments have been subjected to various cutting and cover conversion treatments since 1940. One of these, Watershed 13 is the site of the only cutting experiment ever replicated in time.

Fernow Experimental Forest

Gaging began in 1951 on several small catchments at the Fernow Experimental Forest in the Allegheny Mountains of West Virginia. Except for lower precipitation and shallower soils, the Fernow catchments are similar to those at Coweeta. Studies were designed to determine effects of logging practices and cutting operations on streamflow. Results of five treatments are reported here.

H. J. Andrews Experimental Forest

Two watersheds have been treated at the H. J. Andrews Experimental Forest on the western slope of the Cascade Range in Oregon. In this area, the climate is characterized by heavy rainfall during winter months and little or no rainfall during midsummer months. The study objective was to determine how logging affects streamflow under this climatic régime. Significant increases occurred after each treatment phase, but they were small in actual volume, amounting to less than 0.1 mm per day during the low flow season.

San Dimas Experimental Forest

At San Dimas, in southern California, two watersheds were selectively treated by cutting and deadening only vegetation thought to use proportionately large quantities of water. In this semiarid climate, winters are moist, and potential evapotranspiration greatly exceeds rainfall during hot, dry summers. When only 1.7 percent of total catchment area was cut along the stream in Monroe Canyon, the first-year increase in streamflow was equivalent to 625 mm of water over the area actually treated. On another catchment, the chaparral on moist, deep soil (40 percent of the area) was sprayed with herbicides in early 1958. Flow increased 42 mm over area treated during the subsequent June to September drying season. In July 1960 a disastrous wildfire swept these watersheds and destroyed all vegetation. Dry-season streamflow from both watersheds increased appreciably the first season after the fires, but flow from other untreated but burned watersheds did not.

Sierra Ancha Experimental Forest

Effects of various cutting practices and wildfires on water yield were studied on two high-elevation catchments in Arizona, where two-thirds of total precipitation comes in the winter (some as snow), and summers are hot and dry. Unlike San Dimas, a riparian cut (less than 1 percent of catchment area) did not produce a detectable increase in streamflow on North Fork of Workman Creek, but converting a moist forested site to grass cover on the same catchment did increase flow. On the South Fork of Workman Creek, changes in flow could not be detected following a 45 percent reduction in basal area resulting from selective logging, stand improvement cutting, and wildfire over a 4-year period.

Fraser Experimental Forest

This area is representative of high-elevation areas of the Colorado Rocky Mountains, where three-fourths of the precipitation comes as snow and summers are mild. The Fool Creek Watershed, containing a stand of mostly mature lodgepole pine, was logged in strips and blocks from 1954 to 1956 (40 percent of the area was clearcut). Increases in streamflow appeared mainly in the May–June snowmelt period, but some came during the summer and early fall.

Wagon Wheel Gap

This area is similar to Fool Creek in climate and topography, except that precipitation is lower and is one-half snow. The scrub aspen and coniferous cover on Watershed B (about 16 percent of the area had no forest cover) was clearcut in 1919, and the slash was piled and burned. Increases in flow occurred, but were restricted almost entirely to the snowmelt period.

White River

An insect outbreak on the large White River Watershed in western Colorado in the early 1940's killed up to 80 percent of the spruce stand on 30 percent of the watershed area. Love (1955) estimated that the yearly increase over the affected area was 196 mm. Again the extra water came mainly as increased spring snowmelt.

Kamabuti, Japan

Precipitation on this small area was heavy, with 40 percent coming as snow. Increases following clearcutting were restricted to the growing season. Peak flows were increased as much as 20 percent.

East Africa

The Sambret catchment at Kericho in Kenya underwent clearing preparatory to tea planting beginning in 1959. Increases in flow were not detected until the cleared area had been clean-weeded for tea planting. Presumably, the rapidly growing weeds which sprang up between clearing and clean-weeding used as much water as the high bamboo forest. At Kimakia, Kenya, Watershed A was cleared and planted to Patula pine, and vegetables were grown among the pines until the third year, when the pines were 3 to 5 m high. A large increase in streamflow followed cutting, but no change in seasonal pattern of streamflow was observed.

South Africa

Located near Stellenbosch, South Africa, the Jonkershoek studies were begun in 1935 to evaluate effects of afforestation of the native sclerophyll scrub on water yields. Several experiments are in progress, but only two are of sufficient duration to report at this time. Other studies are in progress at Cathedral Peak in Natal and at Mokobulaan in the eastern Transvaal. The Bosboukloof catchment was 53 percent afforested with Radiata pine in 1940. Beginning about 4 years after planting, streamflow began to decrease as the plantation matured. Mean annual streamflow decreases (water year begins in April) for 4-year periods beginning 8 years after planting were 66 mm (1948/51), 109 mm (1952/5), and 104 mm (1956/9). The Biesievlei catchment was 98 percent afforested with Radiata pine in 1948, and a similar pattern of flow decrease began about 4 years after planting. Again by 4-year periods, the mean annual decreases were 79 mm (1952/5), and 142 mm (1956/9).

Coshocton

At this agricultural research installation in Ohio, abandoned farmland on Watershed 172 (amounting to 70 percent of area) was planted mostly to pine to restore a complete forest cover. Water yield decreased as the forest regrew, about 70 percent of the reduction occurring during the dormant season.

*Pine Tree Branch**

This badly depleted watershed in western Tennessee was reforested in 1946, mostly with southern pine (about 75 percent of total area was replanted). Streamflow decreased as the area became reforested. However, the decrease in flow was attributed to a reduction in surface runoff; baseflow was little changed.

White Hollow

This eastern Tennessee watershed was 34 percent nonforested in 1934 when a study was begun to evaluate effects of land use changes on runoff and sedimentation. Reforestation was complete in 1942, but no net changes in amount of streamflow have been detected.

Central New York

The influence of reforestation on streamflow from abandoned agricultural lands was studied on four small watersheds in central New York. The Sage Brook catchment was 47 percent reforested with conifers in 1932, leaving 13 percent unforested. The treatment on Cold Spring Brook was similar; conifers were planted in 1934 on 35 percent of the area, leaving 14 percent unforested. On Shakham Brook, 58 percent of the area was reforested by 1939; 16 percent of the area was left unforested. Streamflow reductions on these catchments are shown in Table 1. A fourth catchment in the same general area (75 km is the greatest distance between catchments) was not reforested, and its flow did not change during the same period.

Sacandaga River

Eschner (1965) studied the effects of long-term recovery of forest vegetation on water yield from the Sacandaga River drainage in thc Adirondack Mountains above Hope, New York. He reported an increase in forest basal

*Treatments presented thus far have been evaluated by the control watershed approach. Pine Tree Branch and studies following are individually gaged areas where streamflow changes have been evaluated by correlating streamflow with climatic variables.

area from 17 m^2/ha in 1912 to 30 m^2/ha in 1950, when a severe storm substantially reduced the forest stand once more. By correlating runoff with forest recovery and climatic factors, he concluded that between 1912 and 1950, annual water yield was reduced 196 mm, and that after the 1950 storm, water yield increased 45 mm. Changes in flow both before and after the storm were restricted mostly to the dormant season, and were attributed to increased interception as forest vegetation became denser until 1950, and to decreased interception after the 1950 storm.

Naselle River

Martin and Tinney (1962) correlated runoff with logging in the Naselle River drainage in southwestern Washington between 1930 and 1956. They concluded that no change in runoff had occurred as a result of logging the watershed at a rate of 2 percent of the area each year for 27 years. They further postulated that where rainfall is adequate for rapid regrowth of vegetation, there was little reason to expect a significant change in water yield if annual cutting is restricted to a small percentage of the watershed.

DISCUSSION

After careful study of the thirty-nine forest treatment studies reported in this paper, several generalizations can be made:

1. Reduction of forest cover increases water yield.
2. Establishment of forest cover on sparsely vegetated land decreases water yield.
3. Response to treatment is highly variable and, for the most part, unpredictable.

The preceding statements must be qualified when individual experiments are considered, but in general they are accurate. With few exceptions, each study showed a definite response to cover alteration. On the other hand, the magnitude of treatment response varied considerably; complete cutting and burning of scrub aspen forest high in the Colorado Rockies caused streamflow to increase only 34 mm during the first year after cutting, whereas, in the mountains of East Africa, complete cutting and removal of high bamboo forest increased water yield by 457 mm. These extreme examples reflect the diverse nature of the results and hint at the complexity of the causative factors.

For convenience, the discussion is broken into four topics: (1) water yield increases immediately after treatment, (2) decline of yield increases after treatment, (3) amount of yield decreases following afforestation and reforestation, and (4) seasonal distribution of yield increases and decreases.

First-year Yield Increases

For purposes of comparison, it is convenient to express increases in water yield immediately after treatment as first-year increases (increases over a 12-month period beginning with any month, but generally broken at the beginning or end of the growing season). First-year increases for thirty treatments were plotted against percentage reduction of forest cover (Fig. 1). When these studies are considered collectively, there appears to be little relation between amount of increase and percent reduction of forest, except that most of the points lie below a line extending from the origin to a yield increase of 450 mm at 100 percent reduction in cover. The point above the line at the lower left of Fig. 1 is the riparian cut at San Dimas, California, where the increase in flow was large (625 mm), considering only the area treated. The first-year increases from 100 percent reduction in forest cover at Kimakia in Kenya (457 mm) and Coweeta Watershed 17 (408 mm) plot on either side of this line at the upper right of the graph.

It would be premature to suggest that 450 mm is the upper limit of first-year increases in water yield following complete reduction

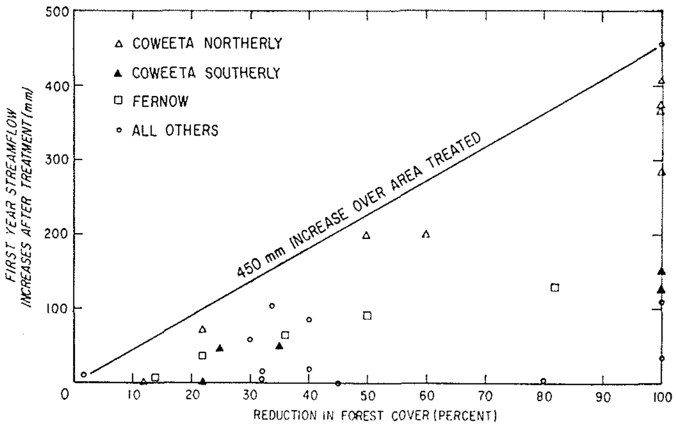

FIG. 1. First-year streamflow increases after treatment versus reduction of forest cover of thirty water-yield experiments, with line drawn to depict 450 mm of increased flow.

of forest cover. However, it is apparent that exceptional climatic conditions must prevail if large increases are to be obtained. Experience to date (Fig. 1) shows that most treatments produce less than 300 mm extra water during the first year after treatment.

At Coweeta and Fernow enough experience exists to allow some conclusions about expected yield increases under humid climates where rainfall is evenly distributed throughout the year. First-year increases at Coweeta fall into two groups (Fig. 2), depending on watershed aspect. Best fit straight lines, extending from the origin through plotted points, indicate the average yield increases experienced at Coweeta on northerly and southerly aspects. Treatments on north and northeast slopes consistently produce first-year increases averaging about 350 mm when equated to the proportion of the watershed area or basal area treated. These results leave little doubt that cutting forest vegetation under Coweeta conditions can give water yield increases up to 400 mm the first year after treatment. The most convincing of these experiments is Watershed 13 (Fig. 3), the only cutting experiment repeated after the forest had regrown. Between September 1939 and

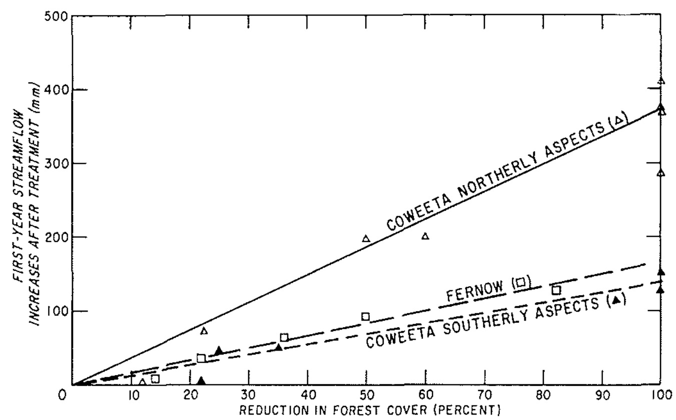

FIG. 2. First-year streamflow increases from Coweeta and Fernow treatments versus reduction in forest cover, showing influence of aspect and the linear relation between area cut and amount of yield increase.

FIG. 3. Coweeta Watershed 13 at end of second growing season after second cut.

January 1940, all woody vegetation on the 16-hectare catchment was cut and left on the ground; regrowth was allowed. The second cut, as nearly like the first as possible, was made in November and December 1962. During the May–April water year following the first cut, streamflow increased 370 mm* (Fig. 4). The increase declined thereafter as the vegetation regrew, but the second cut, 23 years later, produced an increase in streamflow almost identical with the first.

*These streamflow data and others reported from Coweeta are slightly different from those reported in earlier publications because of complete recomputation of all back streamflow records using modern data processing techniques (Hibbert and Cunningham, 1965). However, the data are not materially changed, except in a few instances where errors were uncovered by recomputation.

Treatments imposed on southerly aspects produced much smaller responses than on northerly aspects. Fernow results are included for comparison (Fig. 2). Fernow's watersheds show no differences attributable to aspect, and they plot at a level slightly higher than Coweeta's southerly aspect treatments. These plottings illustrate that at Coweeta and Fernow, a linear relationship exists between percent reduction in forest cover and first-year yield increase. Whether similar relations hold for other locations is unknown, because experience is insufficient to allow comparisons to be made.

Reasons for such large differences in response to treatment between northerly and southerly aspects have been repeatedly sought. Differences in evapotranspiration attributable to variation in solar energy receipt of steep north and south slopes is strongly suspected and is now being intensively investigated.

Small reductions in forest vegetation on two catchments at Coweeta and Fernow failed to produce a detectable increase in streamflow. It has been argued that small vegetative reductions may not increase streamflow as readily as large cuts because stands receiving small vegetative reductions may still use as much water as the original stand. This argument has merit, but is difficult to substantiate because experimental error is often larger than the expected response. This is particularly true when the vegetative reduction is less than 20 percent and the expected yield increase is small.

Attempts to correlate first-year increases in flow with precipitation, or with precipitation minus runoff (an estimate of evapotranspiration when precipitation and total water yield are accurately measured), were only partially successful. Large increases in yield are generally associated with high precipitation, and small increases occur when precipitation is low. Notable exceptions are the Kamabuti clearcut in Japan (mean annual precipitation 2616 mm; increase during first three years averaged 110 mm) and two watersheds at the H. J. Andrews Experimental Forest in Oregon (mean annual precipitation 2388 mm; increase in streamflow less than 10 mm after 30 to 80 percent of the area had been clearcut or logged).

Decline of Water Yield Increases

Yield increases almost invariably begin to decline soon after treatment. Figures 4 and 5 are examples of decline of yield increases at Coweeta. In both figures, the entire period of record is presented as streamflow deviations from regression of the treated watershed on the control. The calibration periods are shown, and deviations from the regression lines during the calibration periods give a visual interpretation of precision of the experiments. Computed experimental error for Watershed 13 is ± 60 mm at the 5 percent level for the year following treatment (Kovner, 1956). The experimental error for Watershed 17 is similar. In Fig. 4 the vegetation was allowed to regrow for 23 years. The curve imposed over the bar graph is Kovner's (1956) log-time trend (the decline of yield increase is a linear function of the logarithm of time in years since treatment). By extrapolating this relationship, Kovner suggested

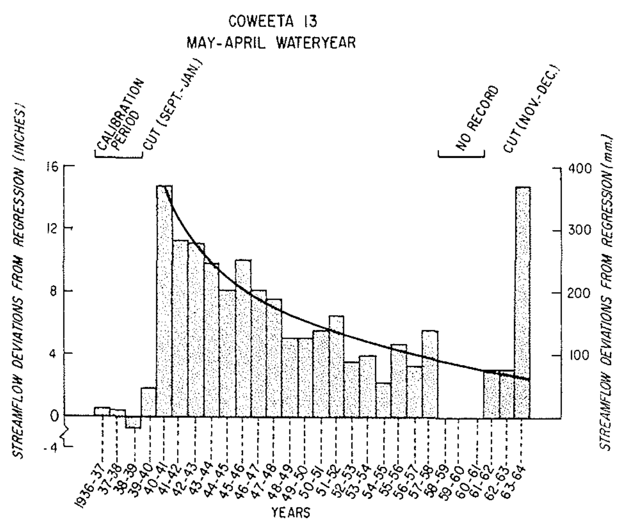

FIG. 4. Deviations from regression of annual streamflow for Coweeta Watershed 13 on annual streamflow for control watershed during calibration (1936-9) and treatment (1939-64) periods.

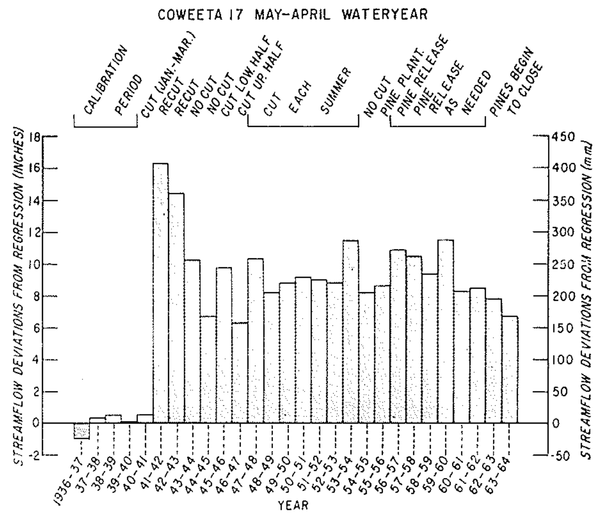

FIG. 5. Deviations from regression of annual streamflow for Coweeta Watershed 17 on annual streamflow for control watershed during calibration (1936-40) and treatment (1940-64) periods.

that increases would be negligible after the thirty-fifth year. By the twenty-third year, when the area was recut, his relationship was still valid.

On Watershed 17* (Fig. 5), the rate of decline of yield increase with time was more rapid, despite cutting of sprout growth the first and second years after treatment. No cutting was done during the third and fourth years, and the decline continued. However, after annual recuts were resumed, streamflow again increased, leveling off at about 235 mm per year above pretreatment level. Similar declines in flow increases after treatment occurred in all of Coweeta's experiments (Hewlett and Hibbert, 1961). The rate of decline was less from the understory vegetation cut (Watershed 19), probably because regrowth of the understory vegetation was slow.

Elsewhere, this general pattern of decline of increased water yield after treatment is apparent, but the rate of decline appears to vary with the rapidity with which revegetation occurs. Fernow's treated watersheds behave similarly to Coweeta's watersheds, and when the high bamboo forest at Kimakia in Kenya was cut, the rate of decline was also very rapid, judging from water yield increases of the first three post-treatment years (457, 229, and 178 mm). Opposed to these rapid declines in treatment effects are the Fool Creek and Wagon Wheel Gap studies in Colorado, and North Fork of Workman Creek in Arizona. In each of these, regrowth of forest vegetation was slow and apparently in line with the decline in treatment response.

Yield Decreases After Establishment of Forest Cover

Streamflow generally decreases after forest cover is established on nonforested areas.

*Earlier analyses of Coweeta 17 treatment effects, including the analysis in the preliminary draft of this paper presented by the author at the International Symposium on Forest Hydrology in September 1965, were based on streamflow data which received only partial correction for a shift in the hook gage reference bar used to set the water level recorder to the water level flowing over the weir blade. This analysis is based on data fully corrected between 1936 and 1946 when most of the shift occurred. The correction resulted in a mean increase of 5 percent or 41 mm in annual streamflow during the 11-year period. The magnitude of treatment effects (Fig. 5) was altered by the correction, but the general pattern of water yield increases following cutting was little changed.

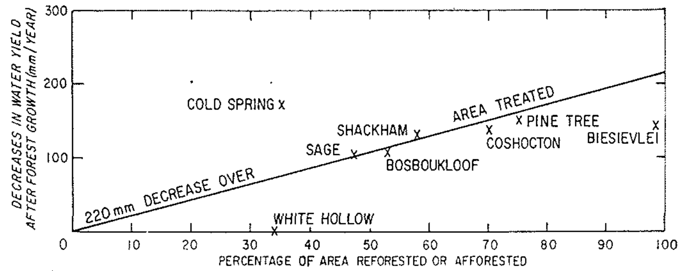

FIG. 6. Decreases in annual water yield versus percentage of area reforested for eight catchments. (Sacandaga results are not included).

Two brush-covered catchments at Jonkershoek (Bosboukloof and Biesievlei) were afforested with Radiata pine in 1940 and 1948. After about 4 years, streamflow began to decrease until 12 to 20 years after planting, when flow was 150 to 200 mm (based on area treated) lower than before afforestation. Results presented by Banks and Kromhout (1963) suggest that during wet years (indicated by high runoff) flow reduction was larger than during dry years.

Other studies, mostly of reforested agricultural lands in the eastern United States, also show that streamflow decreases as new forests develop. Figure 6 contains results of nine studies, showing decrease in annual flow plotted over percentage of area reforested. A straight line extends from the origin to a point on the right of the graph which represents a 220 mm decrease in flow for a completely reforested catchment. Most catchments plot close to the line. However, Biesievlei plots well below the line, possibly because the decrease was evaluated only 8 to 12 years after planting. White Hollow Watershed showed no detectable decrease after 34 percent of the area was reforested. The expected decrease in this case is probably no greater than experimental error associated with the experiment. No control watershed or calibration period was available for analysis of treatment effects.

The decrease in flow from Cold Spring and Sacandaga watersheds is considerably greater than from other treatments in New York. Schneider and Ayer (1961) reported that 35 percent of Cold Spring Brook was reforested with conifers in 1934, and that streamflow had decreased 172 mm by 1959. By equating this decrease to the treated portion of the watershed, the indicated decrease in flow becomes 480 mm, about twice as much as two companion watersheds, Sage Brook and Shackham Brook. Eschner (1965) estimated that basal area of the forest stand on Sacandaga watershed increased from 17 m^2/ha in 1912 to 30 m^2/ha in 1950. This change in forest cover is difficult to evaluate in terms of percentage of catchment area reforested; therefore, the Sacandaga results are not included in Fig. 6.

From experience available to us at this time (Figs. 1 and 6), water yield increases caused by forest reduction appear to be greater than water yield decreases after reforestation. However, this apparent lack of compatibility may not be real; it may simply be a question of insufficient range in observations. If reforestation was carried out at Coweeta, for example, it is assumed that the decrease in water yield after forest regrowth would be about the same as increase from cutting. The decline of the water yield increase as the forest regrew after cutting Watershed 13 supports this assumption (see Fig. 4).

Seasonal Distribution

The seasonal distribution of yield increases varies between studies because of soil depth, physiography, severity of treatment, precipitation, and other factors. The water savings may appear quickly, or be delayed for weeks or months, depending on the factors involved. For example, water yield increases from high-elevation watersheds in Colorado, where one-half to three-fourths of precipitation occurs as snow, appear almost entirely as increases in spring snowmelt. Martinelli (1964) attributes increases as much to reduced interception and increased snow accumulation in openings as to decreased summer evapotranspiration. Increased dormant season interception is considered the major cause of heavy dormant season decreases in flow following reforestation of areas in New York (Eschner, 1965; Schneider and Ayer, 1961). Here again, snow is an important part of annual precipitation.

At Fernow, water yield increases came mostly during the growing season, apparently because savings in evapotranspiration appeared quickly as increased streamflow. At Coweeta, seasonal distribution of water yield increases varied; small increases tended to come mostly during the growing season, whereas large increases were more uniformly distributed throughout the year. On Watersheds 13 and 17, a greater proportion of the water yield increase actually came during the dormant than during the growing season. These patterns of seasonal distribution of increased flow persisted for several years after treatment.

Reasons for such behavior are not clear, but soil depth and other physiographic features of the catchment probably are controlling factors. Kovner (1956) attributed the delay of water increases until the dormant season to lags in transmission of water through the soil reservoir. Apparently, at least part of the reduction in summer evapotranspiration does not appear as streamflow until heavy rains flush it through during the dormant season recharge period. Why these delays are so pronounced on some areas, and apparently lacking on others, needs further investigation.

Monthly analysis of streamflow allows more intensive study of treatment response than annual or seasonal analyses. Figure 7 contains a multiple regression analysis giving monthly streamflow deviations from regression of Coweeta Watershed 37 on its control. This, in effect, is a 19-year history of the relation of streamflow behavior between two

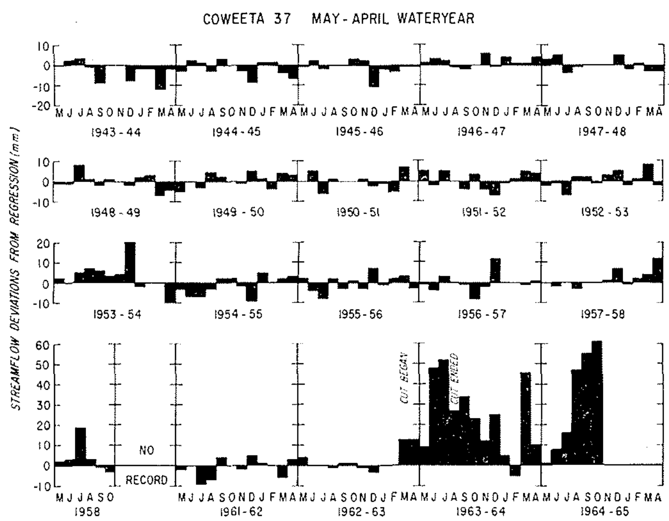

FIG. 7. Deviations from regression of monthly streamflow for Coweeta Watershed 37 on monthly streamflow for control watershed during calibration (1943-62) and treatment (1963-4) periods.

adjacent watersheds. Experimental error at the 5 percent level for each month varies from 5 to 20 mm.

Watershed 37, extending to 1700 m above sea level, is the highest elevation treatment at Coweeta. The area is characterized by steep upper slopes, with shallow soils and extensive rock outcrops in the upper one-third of the catchment. When cutting began in March 1963, streamflow response was immediate, although large increases did not appear until June and July, when cutting was almost complete. Increases began to fall off during late summer and fall months of 1963, and by February 1964, had essentially dropped to zero. In March, a heavy increase appeared presumably because of unseasonally heavy precipitation during that month.

May and June of the 1964 growing season were very dry months; streamflow dropped back to pretreatment level during May, and was only slightly higher during June and July (increases during June and July were just significant at the 5 percent level). In August, streamflow increased after near normal rainfall for July and August. September and October increases were heavy, because of a 500 mm rainfall during a 5-day period at the end of September. This large storm flushed the accumulated evapotranspiration savings from the soil and accounts for the large increases in flow. This phenomenon was also observed on other treated watersheds at Coweeta.

This example of monthly analysis of streamflow serves to illustrate the need for accurate and well-controlled experiments in study of treatment effects. We can rarely afford a 17-year calibration period, but when available, the statistical control afforded by paired watersheds and a long calibration period is most valuable in hydrologic research.

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