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THE INFLUENCE OF RAINFALL INTERCEPTION ON STREAMFLOW

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INTRODUCTION

In vegetated regions, plant surfaces are one of the first resistances precipitation encounters in its journey through the hydrologic cycle. The term interception is applied to this phenomenon and includes all processes that affect the catchment, storage, and disposition of precipitation on plant and litter surfaces. Interception has been studied for almost a century (Hoppe, 1896) and has probably received more attention than any other component of the forest water balance. Summaries of forest interception studies in the United States have shown that losses range from 10 to 35 percent of annual precipitation (Zinke, 1967; Kittredge, 1948). Thus, interception is a major hydrologic process which alters the quantity, timing, and areal distribution of water input and output on a catchment.

The subject is appropriate for consideration at this conference since approximately 66 percent of the land surface in South Carolina's Piedmont is in commercial forests (Haines, 1967), and the management of these forests will have a significant bearing on the future water resources of the state. Today, I wish to restrict the subject of interception to one facet--the loss of rainfall intercepted by forest stands, and the relationship of this loss to streamflow and the water balance of forested catchments.

PHYSICAL ASPECTS OF INTERCEPTION LOSS

Horton's (1919) study was one of the first attempts to evaluate rainfall interception as a physical process. He described interception loss for an individual tree (exclusive of litter interception) as

$$I = S_j + K_1 E_r T \qquad (1)$$

where I is interception loss in inches depth over the projected area of the canopy, S_j is interception storage capacity in inches depth over the projected area of the canopy, K_1 is the ratio of the evaporating surface to the projectional area, E_r is evaporation rate in inches depth per hour during the storm, and T is storm duration in hours. Equation (1) can be restated (Kittredge, 1948) for a given storm as

$$I = S_j + (K_1 E_r T/P_s)\ P_s \qquad (2)$$

where P_s is inches of precipitation per storm. This equation separates the interception loss process into two components: (1) rainfall stored on a tree and later evaporated, and (2) rainfall evaporated from a tree during the storm. Leonard (1967) discussed these components theoretically and suggested that the relationship between interception loss and precipitation is best described by an exponential curve. However, in practice most interception studies have considered the percentage of rainfall evaporated during a storm ($K1E_rT/P_s$) as constant, and interception loss has been described for a given forest stand in regression form as a linear function of precipitation per storm (assuming storage capacity is filled). In any case, it is clear from equation (2) that periodic interception loss can be regarded primarily as a function of periodic precipitation and the number of times storage capacity is filled within the specific period. Equally clear is the fact that a wide range of constants must exist for forest communities since the quantity of evaporating surface is highly variable.

This brief examination of the interception loss process implies that manipulation of forest cover can substantially alter amounts of precipitation reaching the forest floor. This has been demonstrated by Niederhof and Wilm (1943) and Rogerson (1967) who observed that throughfall increased with intensity of thinning in stands of lodgepole pine (*Pinus contorta* Dougl.) and loblolly pine (*Pinus taeda* L.).

TERMINOLOGY

Before proceeding further in this discussion, definition of terms to be used is appropriate. A complex array of terminology has emerged from interception studies, but definitions by Helvey and Patric (1965) are most suitable and will be followed throughout this paper (Table 1).

Various relations can be stated using these terms, but the one of most interest is

$$I = P - (T + S) + L \qquad (3)$$

Several interpretation problems may arise from this equation. First, only a few interception studies have measured litter interception and, therefore, total interception loss usually has been reported as

$$I = P - (T + S) \qquad (4)$$

Interpretation of results has been handicapped further in some cases by failure to measure stemflow. Omission of litter interception results in conservative estimates of total interception and exclusion of stemflow gives an overestimate of interception loss.

Table 1. Definitions of interception terms from Helvey and Patric (1965).

Term	Symbol	Definition
Gross rainfall	P	Rainfall per storm measured in the open or above the vegetative canopy.
Throughfall	T	That portion of gross rainfall which directly reaches the litter through spaces in the vegetative canopy and as drip from leaves, twigs, and stems.
Stemflow	S	That portion of gross rainfall which is caught on the canopy and reaches the litter or mineral soil by running down the stems.
Net rainfall	R	Water that enters the mineral soil after penetrating the forest canopy and litter, sometimes called "effective rainfall."
Litter interception loss	L	Rainfall retained in the litter layer and evaporated without adding to moisture in the underlying mineral soil.
Total interception loss	I	Rainfall per storm retained by the canopy and litter and evaporated without adding to moisture in the mineral soil.

Secondly, some investigators have questioned the effect of interception on the water balance of forest catchments and the use of "loss" in interception terminology. Arguments given in the literature are unclear but appear to be centered on whether or not interception losses are completely additive to normal transpiration. This problem is of most concern when interception losses are inserted into an empirical water balance accounting scheme which depends upon a separate estimate of potential evapotranspiration.

INTERCEPTION LOSS AND STREAMFLOW

Evidence thus far suggests that more than 90 percent of intercepted rainfall is an additional loss to normal transpiration for some coniferous species (Thorud, 1967; Leyton et al., 1967). Field studies by Leyton et al. (1967), Patric (1966), Rutter (1963), and Helvey (1967) indicate that during winter months, loss of intercepted water exceeds that estimated by potential evaporation formulas. Therefore, interception losses must have a considerable influence on water yield during this period. Results from watershed experiments have shown that substantial increases in water yield can be obtained upon removal of forest vegetation (Hibbert, 1967; Hewlett and Hibbert, 1961) and one might suspect that part of the increased yield is due to reduced interception; but major changes in other evaporative processes are also reflected in streamflow increases, thereby obscuring interception effects.

Recent watershed experiments at the Coweeta Hydrologic Laboratory in the Southern Appalachians of western North Carolina have provided new and important information on how interception losses can affect water yield through other forms of vegetation manipulation; in this case, conversion of forest types. In 1956 and 1957, two mountain catchments within the Coweeta basin were converted from native hardwoods to eastern white pine (*Pinus strobus* L.) plantations. Results of these two experiments are very similar and for illustrative purposes, data are presented only for a single catchment.

Watershed 1 is a 40-acre, south-facing catchment with deep permeable soils derived from Carolina gneisses. Watershed relief is 900 feet and slopes, which average 48 percent, supported a predominately oak-hickory forest. Prior to cutting, basal area averaged 84 square feet per acre. Of the 68 inches of mean annual precipitation during the 10-year calibration period, 31 inches left the basin as streamflow. In 1954, all vegetation within the cove type (25 percent of the watershed area) was deadened with chemicals. The entire watershed was clearcut during October-December 1956; slash was scattered and partially burned, and white pine seedlings (2-0 stock) were planted at a 6- by 6-foot spacing during the winter of 1957. Thereafter, competing hardwood sprouts were cut or sprayed with chemicals as required to release the pine. By 1967, trees were 20 feet in height (Figure 1), averaged 32 square feet basal area with a stocking of 720 trees per acre, and had attained a mean breast height diameter of 2.9 inches.

The relationship of flow from an adjacent control watershed and Watershed 1 was determined by regression analysis during the 10 years prior to treatment when both watersheds were in an undisturbed hardwood cover. After treatment, actual minus predicted flow represents the change in streamflow due to conversion.

The first water year (May-April) after clearcutting, streamflow increased 5.8 inches. From the second year after pine planting until the sixth year, the change in streamflow remained relatively constant at about +2.3 inches per year. Thereafter, streamflow from the clearcutting treatment steadily declined at a rate of more than 1 inch per year as the pine crowns closed. By 1966, a significant net decrease in streamflow of 1.9[1/] inches was observed. The next year, white pine basal area reached 32 square feet per acre and streamflow dropped 3.7 inches below that predicted for the original mature hardwood stand. Thus by 1967, total annual water yield from the 10-year-old pine plantation was approximately 4 million gallons less than it would have been from the original hardwood stand.

Monthly distribution of water yield reductions in 1966 and 1967 are depicted in Figure 2. Although most months contributed to the annual decrease, streamflow reductions were greatest during the dormant season. During 1967, flow in May and June and November through March was significantly less (0.95 probability level) than expected for the previous hardwood cover. The same pattern of increasing monthly streamflow reductions observed from 1966 to 1967 was also evident in data from preceding years.

These reduced flows are attributed primarily to increased interception loss by the pine. Hewlett (1958) and Kramer (1952) have recounted physical and physiological reasons why evapotranspiration differences may exist on conifer- and hardwood-covered watersheds. Considerable evidence from field studies has also accumulated which shows that interception losses are typically greater in conifer than in hardwood stands. Helvey's (1967) interception experiments at and near Coweeta show larger interception losses from 10-year-old pine than from mature deciduous forests. Using interception equations by Helvey (1967) and Helvey and Patric (1965) and the amount and frequency of rainfall actually received on Watershed 1, interception losses from these two cover types was estimated for 1967. Figure 3 shows substantially larger interception losses from the young pine stand when hardwoods are leafless. These interception differences are highly correlated with the observed reductions in streamflow during November through March.

1/ Annual streamflows are significantly different at the 0.95 probability level if they differ from the predicted flow by more than ±1.2 inches.

Water yield reductions are insignificant from July through October, when both stands are in full leaf and interception differences are small. Streamflow reductions in April,[2/] May, and June are probably due to both interception and transpiration differences since white pine foliage is capable of transpiring before and during leafing out of hardwoods. Thus, agreement between interception loss and observed streamflow changes is excellent.

Helvey's (1967) data also showed that average annual interception loss was 9 inches greater for 60- than 10-year-old pine stands. Therefore, even greater reductions in streamflow due to interception alone must be expected as the pine matures, and it is reasonable to anticipate significant water yield reductions during the summer low flow months.

This watershed study and supporting interception data provide strong evidence that interception loss is a major hydrologic process affecting the quantity and timing of streamflow when cover types are changed from mature mixed hardwoods to white pine. Can similar streamflow responses be expected in the Piedmont and Coastal Plain regions of the Southeast when hardwood sites are converted to pine species? The question is indeed pertinent to South Carolina's Piedmont region since a survey (Haines, 1967) showed an area increase of 20 percent in pine and oak-pine cover types and a concurrent 17 percent decline in hardwood types between 1958 and 1967. Loblolly pine (Pinus taeda L.), the leading forest species, currently occupies about 1.3 million acres in the region.

Studies of rainfall interception for pine species endemic to the Southeast are summarized in Table 2 for Piedmont (Clemson) and Coastal Plain (Charleston) conditions. Equations used in estimating hardwood interception are based on a review by Helvey and Patric (1965) of interception studies throughout the eastern United States. Estimates for pine are calculated from equations of throughfall and stemflow derived by various investigators for stands with specific structural characteristics. Calculated losses for pine and hardwood are based on the 45-year precipitation average at Clemson and Charleston and 1-day rainfall frequencies for storms greater than 0.10 inch at each of these sites (Kronberg et al., 1961). These estimates do not include litter interception loss since equations for this component of total interception were available only for white pine and hardwoods. For either of these cover types, annual litter interception loss is about 2 to 5 percent of gross precipitation.

From these calculations, it is clear that annual interception losses for mature pine are appreciably greater than for mature mixed hardwoods. Furthermore, young pine stands tend to intercept more rainfall than hardwoods and even interception losses from heavily thinned stands of loblolly pine (Rogerson, 1967) equal those of mature hardwoods.

2/ April 1967 represents an unusual event; previous years showed consistent reductions in water yield for this month.

Table 2. Annual interception loss by pine and hardwood stands.

Reference	Study Location	Species	Age	Stems Per Acre	Basal Area	Annual Interception Loss[1] IL = P - (T + S) Clemson	Charleston
			Years	Number	Ft^2/Acre	Inches	Inches
Hoover, 1953	Union, S.C.	Loblolly pine	10	760	103	5.0	4.4
Rogerson, 1967[2]	Oxford, Miss.	Loblolly pine	25	50	40	4.6	4.0
			25	620	190	12.2	10.3
Boggess, 1956	Dixon Springs, Ill.	Shortleaf pine	14	800	110-135	4.9	4.4
Lawson, 1967	Hot Springs, Ark.	Shortleaf pine over-story and	Mature	265	98		
						9.2	8.1
		Hardwood understory		615	28		
Helvey, 1967	Highlands, N.C.	White pine	10	800	76	7.0	6.1
			35	280	120	8.6	7.5
			60	135	153	12.1	10.4
Helvey and Patric, 1965	Eastern U.S.	Mixed hardwoods	Mature			4.3	4.0

1/ Average annual precipitation for Clemson is 53.9 inches delivered in 75 storms and for Charleston 45.7 inches in 67 storms.

2/ Stemflow was not measured in this study.

Differences in annual interception loss of about 3 and 4 inches for Charleston and Clemson are indicated between well stocked loblolly-shortleaf pine and mature deciduous forests. The magnitude of pine and hardwood differences is less at Charleston due to the quantity, frequency, and seasonal distribution of rainfall. At this time we should also recognize that transpiration losses are probably larger for pines before and during leafing out of hardwoods; therefore, evapotranspiration differences between these two cover types may be much greater than those indicated by interception data alone.

Individual interception studies cover just a portion of the broad spectrum of forest conditions in a region and must be used with caution when applied to other sites. It is noteworthy that a complete interception study (including litter loss) has never been reported for southern pines. Nevertheless, our current knowledge suggests that when hardwood stands are converted to pine or vice versa, interception losses undergo a large change and the resulting decrease or increase in precipitation delivered to the forest floor can have a substantial effect on streamflow. Since it is now clear from the Coweeta experiments that this interception loss does lower streamflow, continuation of the trend toward conversion of hardwood sites to pine will eventually reduce water yield. It is, therefore, important for resource managers to be aware of the potential effect of different forest types on the water resources of the Southeast.

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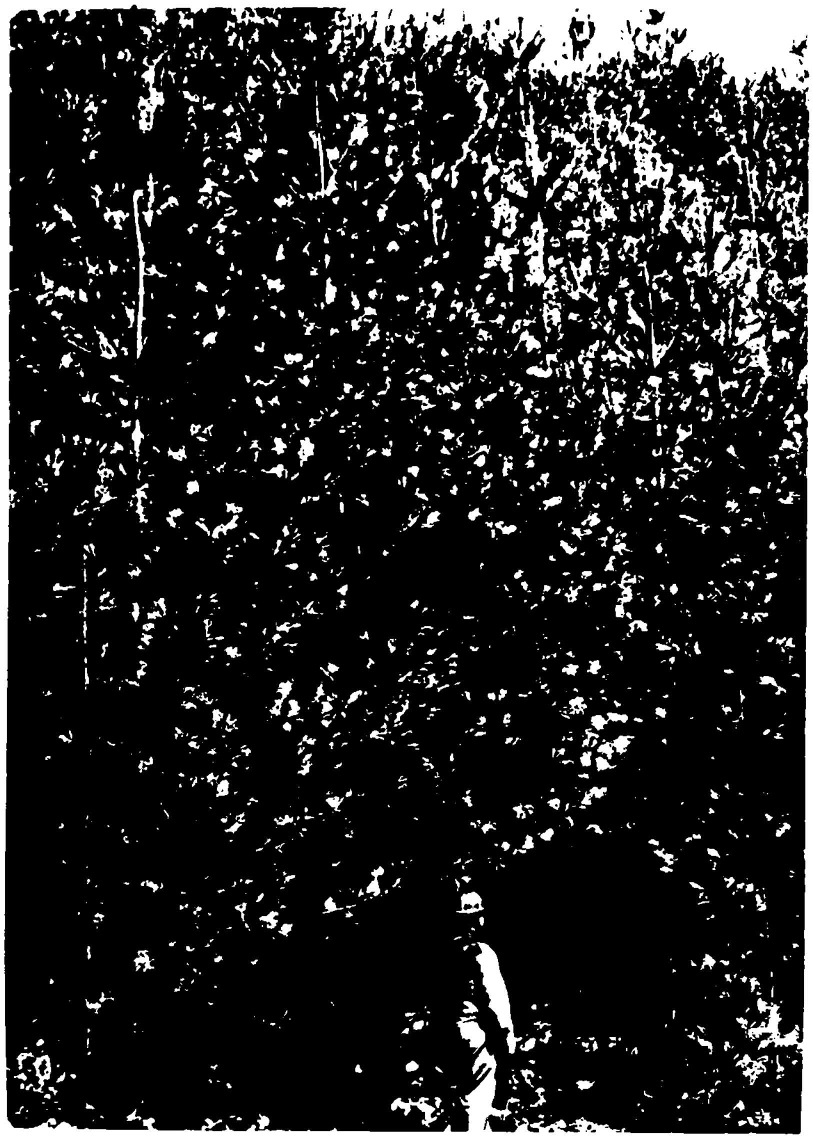

Figure 1. After 10 growing seasons, this white pine plantation on Watershed 1 averages 20 feet in height with a stocking of 720 trees per acre and a basal area of 32 square feet per acre.

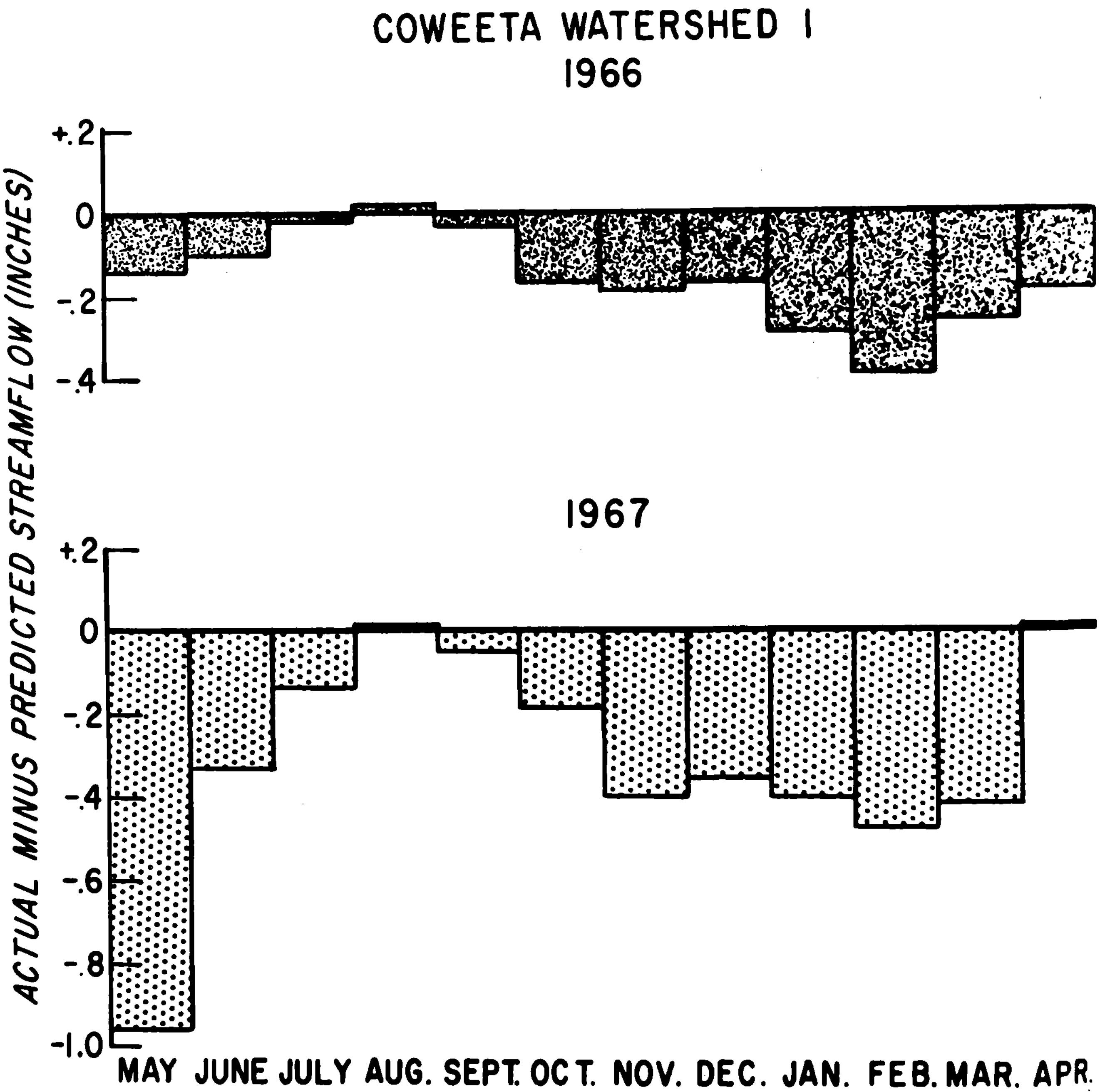

Figure 2. Actual minus predicted monthly streamflow for Coweeta Watershed 1 during 1966-1967 water years (May-April water year).

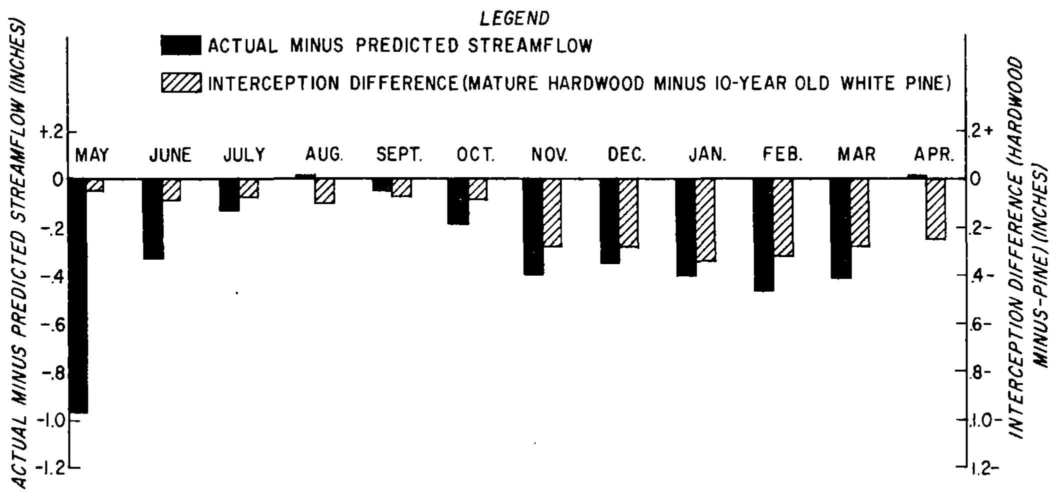

Figure 3. Comparison of actual minus predicted monthly streamflow for Watershed 1 in 1967 and differences in monthly interception for 10-year-old white pine versus mature hardwoods.

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