THROUGHFALL VARIATION IN A MIXED DECIDUOUS FOREST

by

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INTRODUCTION

Importance of rainfall interception in the water economy of a forest stand has been debated since the last century. As early as 1893, Fernow *et al.* stated that the amount of precipitation withheld from the forest floor varies considerably according to type of precipitation (rain or snow) and the species of trees forming the forest, as well as the density and age of the stand. Subsequent studies have concentrated on estimation of this water loss as well as redistribution of precipitation that reaches the forest floor by flowing down stems and falling from the canopy.

Hamilton and Rowe (1949) developed terminology of interception loss which has guided the formulation of current definitions by Helvey and Patric (1966). In a given storm, the total amount of rainfall measured in the open or above the forest canopy is called gross rainfall. Interception refers to the process by which rainfall is retained on forest vegetation and litter (recently fallen leaves, twigs, and fruits). Rainfall retained on the standing vegetation and evaporated represents canopy interception loss, whereas rainfall retained in the litter layer and evaporated represents litter interception. Total interception loss then, is the sum of canopy and litter interception loss. The portion of rainfall which reaches the litter through openings in the canopy and by dripping from aerial parts of the canopy is called throughfall. Additional intercepted rainfall reaches the litter and mineral soil by flowing down stems (the process of stemflow). The combination of stemflow and throughfall represents net rainfall, or water that reaches the forest floor after penetrating the forest canopy. This terminology will be used throughout this study.

Variations in the proportions of throughfall, stemflow, and interception have been recorded in numerous studies. Most of the studies have been done with single trees or in plantations. The results of these studies show that throughfall varies systematically with position under the canopy (Eschner, 1967). A few investigators (Kittredge *et al.*, 1941; Rutter, 1963; Reynolds and Leyton, 1963) have determined patterns of throughfall under single trees in natural stands. However, patterns are complicated in natural stands by the overlapping of tree crowns (Eschner, 1967).

Variations in soil moisture from place to place within a forest have seldom been studied. Some investigations have dealt with the influence of stemflow on soil moisture. Hoover (1953), in his study of plantation grown loblolly pine, noted the importance of the volume of stemflow entering soil at the base of individual trees. Stemflow added to the base of a tree resulted in an unequal distribution of water. Soil was recharged with moisture to a considerable depth near the tree, but only the surface soil horizons in the spaces between trees received moisture. This same pattern of moisture distribution was also observed in a scrub-oak stand (Eschner, 1960). Surface soil moisture between sprout clumps was considerably less than moisture at the base of each sprout clump.

Voigt (1960) reported this same pattern in soil around the base of a beech tree after water had been poured down the stem. Using electrical resistance units, he detected movement of water down the roots into the soil, wetting a zone 25.4 cm from the tree. With pine, stemflow had no measurable effect, but throughfall increased with distance from the tree, and soil moisture accumulated to a depth of approximately 60 cm. The results of a study on Norway spruce also indicated the presence of a soil moisture pattern similar to the pattern of throughfall (Reynolds and Leyton, 1963). These authors stated that additional measurements are needed to confirm this pattern.

Most of these studies point out the significance of stemflow as a concentrated application of water to a small soil surface area surrounding individual trees. It is expected that the soil moisture distribution beneath individual trees would be similar to the pattern of throughfall. Consequently, concentric zones of increasing soil moisture would be found at increasing distance from the tree base (Eschner, 1967). This pattern of soil moisture distribution, as with the pattern of throughfall, becomes complicated in a forest stand where overlapping tree crowns create an uneven distribution of throughfall over the forest floor. However, I have not found published studies that relate throughfall patterns to soil moisture distribution in mixed hardwood stands.

This study is concerned with estimating gross rainfall and the variability of throughfall in a mixed hardwood stand. It is also an attempt to develop a throughfall sampling design for obtaining results which can be used in interpreting patterns of surface soil moisture distribution. Composition of the forest stand, as well as topography of the area, are included as they relate to the patterns of throughfall and soil moisture distribution.

MATERIALS AND METHODS

Location of Study Area

The study area is on the lower, western end of Price Mountain, approximately four miles southwest of Blacksburg, Montgomery County, Virginia. The forest is a portion of the 1200-acre Fishburn Forest which belongs to Virginia Polytechnic Institute and State University. The study site is at approximately 2200 feet elevation in the northwestern corner of the forest.

Sampling of throughfall and soil moisture was done in a shallow gulley, with a basin approximately 24 m wide, and on its bordering slopes. The relatively level basin of the gulley is bounded by a north slope, ranging from 22 to 34 percent inclination, and a south slope, ranging from 13 to 29 percent inclination. Total width of the gulley, measured from ridge top to ridge top, is approximately 115 m. Periodically, the bottom is dissected by an intermittent stream which results from runoff from both slopes as well as runoff from the junction point of the two slopes, approximately 200 m above and east of the study site. The site is small enough that gross precipitation should not vary greatly over the area. Forest cover is also relatively uniform.

Climate of Study Area

The climate of Montgomery County has been summarized from meteorological records of a Blacksburg weather station for the period, 1941-1970 (Crockett, 1972). Montgomery County has a humid, continental type of climate modified by elevation. Elevations range from 400 m to 1130 m above sea level, with most of the county around 610 m. The Blacksburg area has moderately cold winters and relatively cool summers. Average annual temperature during the 30 year period was 11.4°C with an average January temperature of 0.61°C and an average July temperature of 22°C. Temperatures range from 10°C to 32.2°C during the leafy (growing) season. Leafless (dormant) season temperatures range from 3.9°C to 7.2°C (Crockett, 1972).

Rainfall is well distributed throughout the year, with maximum amounts in July and minimum amounts in November. During the 1941-1970 period, monthly rainfall amounts varied from 0.64 cm to 26.14 cm. Average annual rainfall is 97 cm. Orographic storms, as well as convectional type storms which yield small amounts of precipitation, predominate in the summer. Winter storms are generally more frontal and yield greater amounts of precipitation per storm. Some winter precipitation occurs as snow, with an average of 50.80 cm per year. However, yearly snowfall amounts are extremely variable (Crockett, 1972).

Prevailing winds are from the west. The gently rolling to steep topography of the area alters wind direction, causing air currents to flow parallel to the mountain ridges which are oriented northwest to southwest (Crockett, 1972).

Soils of Study Area

Soils of the study area are classified as Calvin shaly silt loam. These excessively drained, shallow soils occur on 7 to 60 percent slopes on the foothills of Price Mountain. They are formed from the weathered products of acid shale, shaly sandstone, and silt stone. Surface layers are very friable, brown silt loam 13-20 cm deep (Agricultural Extension Service, V.P.I., 1964). The top portion of this surface soil is a mor humus averaging 2.5 cm in depth with a range from 3 to 7 cm.

The surface layers are underlain by bedrock of hard, acid shale, silt stone, and shaly sandstone. This bedrock is a portion of the Price Formation, dating from the Mississippian Age. The entire formation contains sedimentary rocks, including non-marine shales and sandstones, which occur along with coal beds in Montgomery County (Agricultural Extension Service, V.P.I., 1964).

Vegetation of Study Area

The forest of the study area is a portion of the oak-chestnut association of the eastern deciduous forest of North America (Braun, 1950). The study site is in a multi-storied stand of uneven-aged, mixed hardwoods which have not been distrubed for approximately 50 years. Red maple (Acer rubrum), scarlet oak (Quercus coccinea), chestnut oak (Quercus prinus), and white oak (Quercus alba) are dominant trees of the overstory. Dominant trees of the understory include sourwood (Oxydendrum arboreum), dogwood (Cornus florida), and mockernut hickory (Carya tomentosa).

Stems greater than 2.5 cm DBH (diameter breast height, 1.37 m) were tallied within plots established for throughfall analysis and within an area 5 m from the plot boundaries. The total area sampled for each plot was 300 m^2. In addition, cover of shrubs and seedlings, under 2 m height, was estimated.

Sampling Gross Rainfall

Gross rainfall was measured for forty storms from August 6, 1972 to June 19, 1973. Measurements were recorded from nine gauges located in two clearings near the study site. A standard 20.32 cm (8 inch) Weather Bureau rain gauge was mounted on stakes and leveled in one clearing. Four polyethylene gauges, each with an orifice diameter of 14.7 cm and a depth of 18 cm, were randomly placed around the standard gauge. Three of these were placed in 17.5 cm deep produce cans and sunk approximately 12.5 cm into the ground. The fourth polyethylene gauge was placed in the top of three fused produce cans, elevating the gauge orifice to approximately 60 cm above the ground surface. Surrounding vegetation was cleared to provide an unobstructed sky view of 45 degrees around the gauge orifices (Helvey and Patric, 1966).

The second clearing contained four randomly placed gauges as described for the first clearing. Two of these were sunk in the ground to a depth of 12.5 cm. The other two gauges were mounted in fused produce cans, with orifices elevated 60 cm above ground surface. A modified Alter wind shield was placed around one of the elevated gauges for detection of wind effects on rain catch. As in the first clearing, surrounding vegetation was removed.

Measures of gross rainfall in the open were recorded for the standard gauge and the 8 polyethylene gauges within 24 hours following each storm. Regression analysis of rainfall catch in 8 auxillary gauges on catch in the standard gauge was performed to determine the best estimate of gross rainfall in the open for each storm.

Sampling Throughfall

Five plots, each 5 X 10 m were laid out in the study site. The first and second plots were located on the south slope, approximately 39 and 12 meters from the bottom of the gulley. A third plot was laid out adjacent to the base of the south slope. The fourth and fifth plots were laid out on the north slope, approximately 5 and 15 meters from the bottom.

Plots were subdivided into 10 subplots, 2 X 2 m each. These were arranged in two parallel rows separated by a 1 m strip, which was used as a pathway to eliminate trampling of soil within subplots. A produce can, containing a 14.7 cm diameter polyethylene gauge, was sunk and leveled at each subplot corner. Accumulated throughfall in each of the 120 gauges was measured with a graduated cylinder after each storm.

Subplots in this network occupied a wide range of positions irrespective of distance from tree trunks. Consequently, there were some subplots which could possibly receive stemflow. However, a great majority of the subplots were in positions far enough removed from any tree trunks to be free from the influence of stemflow.

Sampling Soil Moisture

A single soil core sample was taken from each subplot on June 1 and June 22, 1973, for analysis of moisture content. Both of these days were considered to be "wet season, field capacity days", occurring three days after a period of heavy rain preceded by a wet period. Such days represent significant occasions for examination of soil drainage patterns (Stewart and Adams, 1968).

Individual samples for both dates were taken a minimum of 60 cm apart within subplots. The core samples were extracted with steel, carbonated-drink cans. The cans were 6.5 cm in diameter and 11.8 cm deep, with a total volume of approximately 390 cm^3. Sampling was accomplished by scraping away the litter layer and driving a can into the soil surface layer as far as possible without obstruction by rocks or roots. Extracted cores were covered on both ends with aluminum foil to prevent evaporation during transport from field to laboratory.

In the laboratory, the soil wet weight and soil volume for each sample was determined. Next, the aluminum foil was removed from the bottom of each can and replaced with a piece of filter paper secured with a rubber band. The samples were placed on wire mesh screens in a sink and allowed to absorb water from below for at least 24 hours or until saturated. Each sample was then placed on a 250 ml beaker to drain. When drainage stopped, it was assumed that the sample water content approximated saturation.

Samples were oven-dried to a constant weight at 105°C. Dry bulk density, volume of water as a percent of soil volume, and water content as a percent of dry weight were calculated for each sample. In addition, soil moisture as a percent of saturation was calculated for each sample.

RESULTS

Vegetation Analysis

Data on basal area and number of stems per plot are listed in Table I. There were five plots in all, plots I and II on the south slope, plot III in the basin of the gulley, and plots IV and V on the north slope. These values were then grouped according to overstory tree stratum (25.4^{+}cm DBH), understory tree stratum (10.2-25.3 cm DBH), and understory sapling stratum (2.5-10.1 cm DBH). The number of stems and total basal area for each species was computed for each of the plots (Table II). In addition, an estimate of area covered by seedlings and shrubs, under 2 m high, was recorded (Table III).

The overall summer canopy of the study site was estimated to be 80-95 percent closed. Lowest canopy closure (approximately 80 percent) occurs in plot IV where there is a large opening in the overstory canopy. Canopy closure is greatest (approximately 95 percent) in plot I where there is a dense overstory formed by the crowns of chestnut oak (*Quercus prinus*) and white oak (*Quercus alba*). Overstory canopy closure is approximately 85 percent in plot II and 90 percent in plots III and V.

Understory trees are relatively numerous in plots III and V (Table I). However, understory trees, as well as saplings, are more widely distributed in plot III, and the estimated shrub and seedling cover is very low (Table III). Consequently, plot III is relatively open in appearance beneath the overstory canopy. A somewhat more closed appearance is characteristic of plots II and V. A relatively dense understory canopy in both of these plots is attributed to the abundance

Table I. Basal area and number of stems per plot (300 m^2), by canopy classes: saplings (2.5-10.1 cm DBH), understory trees (10.2-25.3 cm DBH), and overstory trees (25.4^+ cm DBH).

ITEM	PLOTS* I	II	III	IV	V	TOTAL
Saplings						
Number of stems	5	10	8	7	8	38
Basal area (dm^2)	1.92	3.67	3.03	2.27	3.61	14.50
Understory trees						
Number of stems	5	7	8	7	12	39
Basal area (dm^2)	8.68	15.40	21.68	15.07	28.02	88.85
Overstory trees						
Number of stems	4	4	6	4	4	22
Basal area (dm^2)	48.78	25.80	38.10	26.05	44.33	183.06

*plots I and II on the south slope; plot III in the basin of the gulley; plots IV and V on the north slope.

Table II. Estimated cover by shrubs and herbs ($<$ 2m high).

PLOT	EST. COVER (%)
I	50
II	40
III	20
IV	30
V	40

Table III. Number of stems and basal area (dm^2) of each species per plot ($300m^2$).

	PLOT									
	I		II		III		IV		V	
SPECIES*	# stems	Basal area	# stems	Basal area	# stems	Basal area	# stems	Basal area	# stems	Basal area
Acer rubrum	2	8.77	8	24.33	10	30.09	4	6.15	2	0.95
Amelanchier sp.	--	---	1	0.10	--	---	1	0.85	4	3.93
Carya tomentosa	--	---	1	0.25	1	6.45	5	1.64	9	8.82
Cornus florida	2	0.50	--	---	--	---	2	0.59	--	---
Lirodendron tulipitera	--	---	3	7.17	4	13.59	--	---	--	---
Nyssa sylvatica	1	2.01	--	---	2	3.13	--	---	--	---
Oxydendrum arboreum	1	2.01	3	1.75	1	0.32	--	---	--	---
Pinus strobus	1	1.48	--	---	--	---	--	---	--	---
Quercus alba	4	11.36	--	---	2	7.54	3	9.91	2	11.80
Quercus coceinea	1	9.23	--	---	2	1.69	5	24.36	5	43.86
Quercus prinus	2	24.02	5	11.27	--	---	2	10.44	2	6.60
Total	14	59.38	21	44.87	22	62.81	22	53.94	24	75.96

*nomenclature follows Gleason and Cronquist (1963).

of understory trees and saplings (Table I).

Dominant trees for each plot are evident from the data presented in Table II. Chestnut oak (*Quercus prinus*), scarlet oak (*Quercus coccinea*), and white oak (*Quercus alba*) are dominant overstory and understory trees in plots I, IV, and V; whereas red maple (*Acer rubrum*) is dominant in the overstory and understory canopies of plots II and III. Understory trees and saplings of each species listed in Table II are scattered throughout the study site. However, tulip poplar (*Liriodendron tulipifera*) appears to be somewhat restricted to the south slope (in plots II and III) and mockernut hickory (*Carya tomentosa*) appears to be more abundant on the north slope (in plots IV and V).

Gross Rainfall Analysis

Gross rainfall in the open was recorded for 40 storms, from August 6, 1972 to June 19, 1973. For each storm, measurements of gross precipitation in the nine gauges, located in two clearings, were subjected to a nested analysis of variance test for significant variance among gauges, between sites and among storms. The results showed no significant variance component among gauges or between sites. Over 99 percent of the variance component was among storms. Therefore, it seemed appropriate to use all gauges from both sites in the regression used to estimate gross rainfall for each storm. During this time period, rainfall ranged from 0.38 cm to 13.28 cm, averaging 2.85 cm per storm.

Storms were grouped according to leafy (growing) season and leafless (dormant) season rainfall for analysis of gross rainfall and throughfall variation. Leafy season included 15 storms, occurring from August 6, 1972 to October 29, 1972 and from May 1, 1973 to June 19, 1973. A total of 25 storms occurred in the leafless season from November 2, 1972 to April 28, 1973.

Gross rainfall during the leafy season ranged from 0.38 cm to 13.28 cm, with an average of 3.23 cm. Storms of this season were predominantly moderate to heavy in intensity. A consistent pattern of storm intensity and duration in relation to total rainfall per storm was not observed. However, storms yielding more than 2.5 cm gross rainfall were generally long in duration (continuing more than 24 hours) and moderate to heavy in intensity.

Leafless season rainfall ranged from 0.71 cm to 7.83 cm, with an average of 2.62 cm. Five of the storms were a mixture of rain with sleet or wet snow. As in the leafy season, rainfall was extremely variable, showing an inconsistent pattern of storm intensity and duration in relation to total precipitation. However, storms were predominantly longer in duration than in the leafy season.

Throughfall Analysis

Throughfall measurements were recorded during the same time periods as gross precipitation. Most of the statistical tests on variations in throughfall were done on an IBM computer (V.P.I. Computer Center), using programs in SAS (Statistical Analysis System; Barr and Goodnight, 1972).

Mean throughfall was computed from the 120 gauges for all 40 storms. An analysis of variance on mean throughfall among storms showed highly significant differences (Table IV). To determine which means were significantly different, a Student-Newman-Keuls test was performed. This test is similar to Duncan's New Multiple Range Test, but uses a different set of critical values for computation of least significant ranges (Sokal and Rohlf, 1969). The results revealed several, non-significant ranges, primarily for storms yielding less than 1.6 cm gross rainfall (Table V).

Throughfall expressed as a percentage of gross rainfall was computed for each of the 40 storms and plotted in a scatter graph (Figure 1). The arrangement of the points suggests an ascending convex curve. This indicates that throughfall tends to be more constant for storms yielding greater than 2.5 cm gross rainfall. Average throughfall for this period (August 6, 1972 to June 19, 1973) amounted to 80.66 percent of gross rainfall. When average throughfall percentages were computed for each plot (Table VI), the two highest throughfall percentages were in the plot in the basin of the gulley (III) and the lower plot of the north slope (IV). The two lowest percentages were in the upper plot of the south slope (I) and the upper plot of the north slope (V).

Values of throughfall as a percentage of gross rainfall are somewhat meaningless unless they are related to storm size distribution. For example, during short, low intensity storms, percentage values may underestimate rainfall interception loss because most of the rain remains on the canopy foliage and branches, especially in still air. Conversely, percentage values overestimate interception loss during high intensity storms because additional water losses are small once the canopy foliage or branches become saturated (Helvey and Patric, 1965). For this reason,

TABLE IV. Analysis of Variance: throughfall means (cm) for 40 storms.

Source	DF	Sum of Squares	Mean Square	F
Storm	39	21604.682	553.9662	2369***
Error	4760	1113.181	.233861	
Total	4799	22717.863		

*** Prob > F = .0001

TABLE V. Multiple comparisons of means by Student-Newman-Keuls Test. Nonsignificant ranges are indicated by vertical lines (P≥.95).

Gross Precipitation (cm)	Mean Throughfall (cm)			
0.38	0.16			
0.41	0.29			
0.97	0.46	+		
0.71	0.55	|		
0.79	0.63	+	+	
0.82	0.72		|	+
0.95	0.73	+	|	|
0.86	0.77	|	|	|
0.91	0.80	|	+	|
1.17	0.85	|		|
1.06	0.90	|		|
1.19	0.91	+		|
1.18	1.00			|
1.42	1.11	+		|
1.29	1.12	|		|
1.42	1.13	|		+
1.72	1.23	+		
1.61	1.37	+		
1.66	1.40	+		
1.87	1.55	+		
1.92	1.57	+		
2.11	1.73	+		
2.08	1.74	+		

TABLE V. Multiple comparisons of means by Student-Newman-Keuls Test. Nonsignificant ranges are indicated by vertical lines ($P \geq .95$). (continued)

Gross Precipitation (cm)	Mean Throughfall (cm)
2.51	2.04
2.73	2.20
2.77	2.34 +
2.94	2.45 +
3.01	2.61
3.52	2.84
3.72	2.98
3.64	3.10
4.25	3.46
4.49	3.82
4.70	4.28
5.52	4.70 +
5.86	4.76 +
6.26	4.95
7.83	6.54
8.32	7.09
13.28	10.50

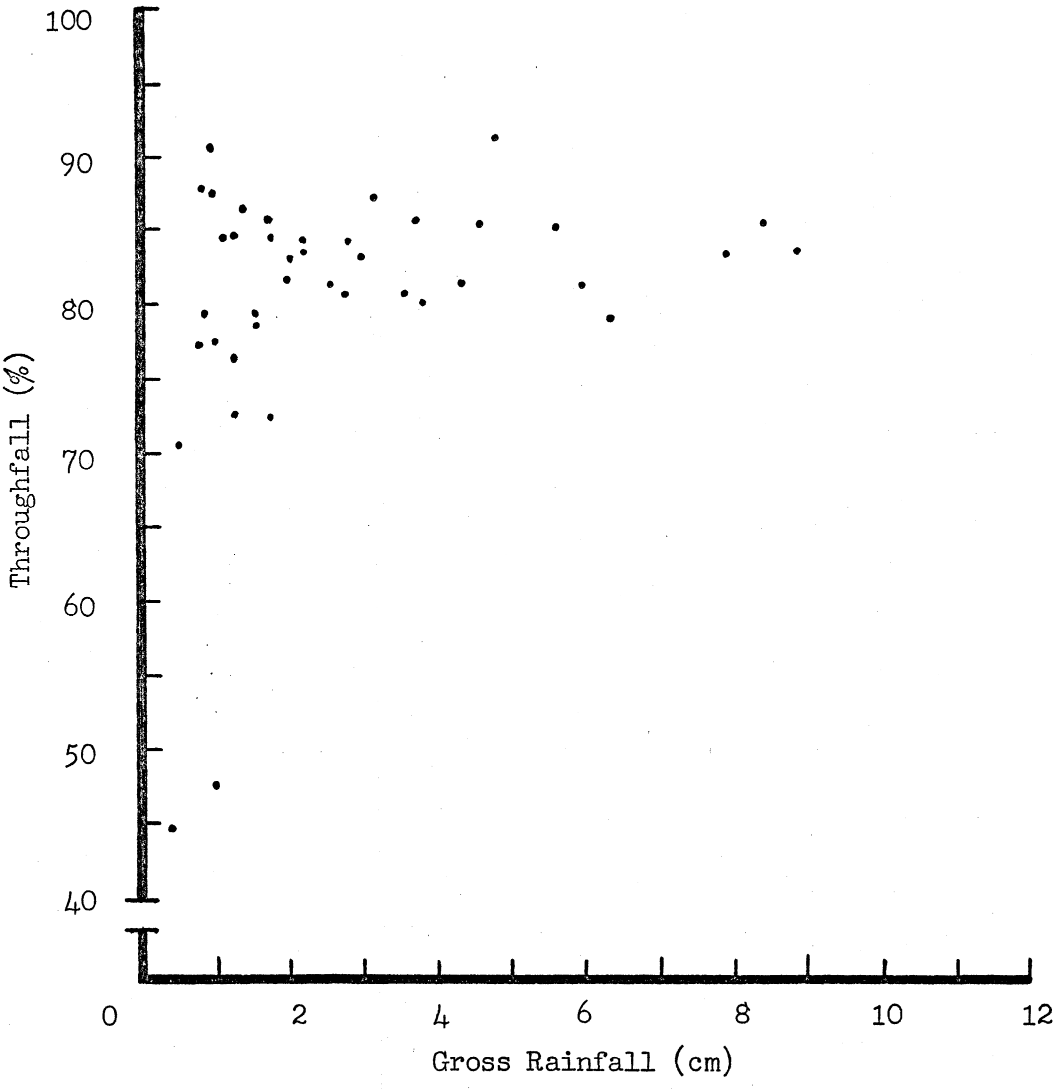

Figure 1. Throughfall expressed as a percentage of gross rainfall for 40 storms.

Helvey and Patric suggest that linear regression analysis gives a better description of the relation between gross rainfall and throughfall. The linear regression equation for throughfall (T) on gross rainfall (P), based on the 40 storms of this study, was:

$$T = .0024 + .820(P)$$

with a squared correlation coefficient, $R^2 = 0.9957$. This coefficient indicates that about 99 percent of the variation in throughfall is accounted for by storm size. The graph of this regression is depicted in Figure 2.

Considerable variation was observed in throughfall catch among the 120 gauges. For instance, throughfall catch ranging from 0.82 cm to 3.6 cm was recorded from a storm of 2.51 cm gross rainfall. Throughfall in excess of gross rainfall was observed in at least one throughfall gauge for 34 of the 40 storms. Occurrences of such point throughfall variability were also observed in differing numbers for the leafy and leafless seasons (Table VII).

Leafy Season Throughfall

Average leafy season throughfall, based on 15 storms, amounted to 78.2 percent of gross rainfall. During this period, average throughfall percentages were highest in plots III and IV (Table VI).

Regression of leafy season throughfall on gross rainfall was conputed and compared with regression equations of other studies in mixed hardwood stands. Helvey and Patric (1965), in their summary of interception studies in the eastern United States, selected all available leafy season throughfall equations derived from mature, mixed hardwood

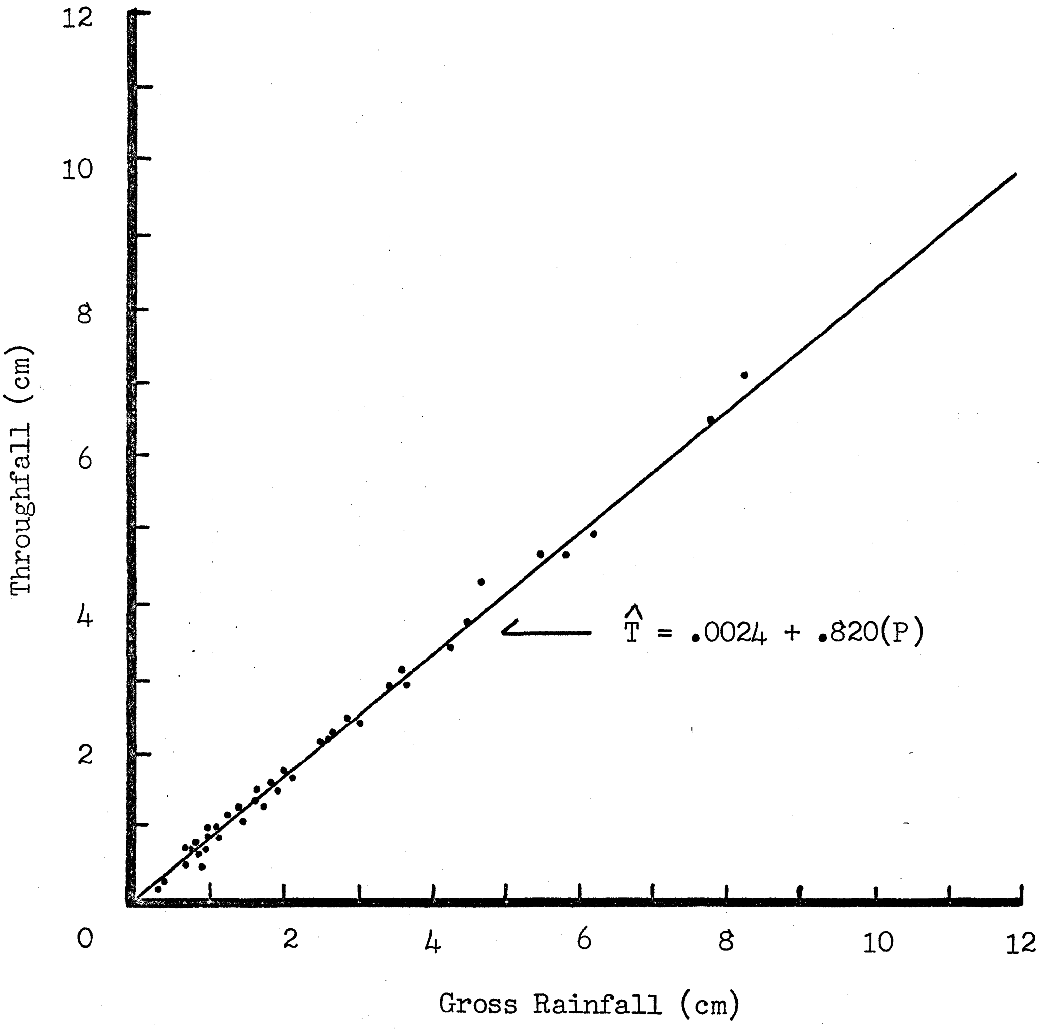

Figure 2. Linear regression of throughfall (T) on gross rainfall (P) for 40 storms.

TABLE VI. Average throughfall as a percent of gross rainfall and average coefficients of variation of throughfall for plots.

ITEM	PLOT				
	I	II	III	IV	V
	Total - 40 Storms				
Avg. % of gross rainfall	79.09	79.92	82.83	83.42	72.20
Avg. coefficient of var. (%)	13.24	11.68	12.17	23.12	12.73
	Leafy Season - 15 Storms				
Avg. % of gross rainfall	75.98	78.45	81.69	79.05	75.84
Avg. coefficient of var. (%)	19.49	16.70	12.17	23.12	12.73
	Leafless Season - 25 Storms				
Avg. % of gross rainfall	80.95	80.80	83.52	86.04	78.01
Avg. coefficient of var. (%)	9.49	8.67	9.16	22.17	9.00

stands and tested them for uniformity. From their results, they developed the equation:

$$\hat{T} = .901(P) - .031$$

which they consider to be applicable for most estimates of leafy season throughfall in mature, mixed hardwood stands anywhere in the eastern United States. The regression equation for this study, based on 15 leafy season storms, was:

$$\hat{T} = .0042 + .818(P)$$

with a squared correlation coefficient, $R^2 = 0.9956$. A comparison of regression lines is depicted in Figure 3. It is evident from the graph that the regression for the present study shows less throughfall for a selected value of gross precipitation than Helvey and Patric's regression. This difference becomes increasingly more pronounced for gross rainfall exceeding 5 cm.

Throughfall catch was quite variable among gauges for differing sizes of the 15 storms. It has been suggested that the relation between coefficients of variation and gross precipitation indicates the extent of this variation, as well as precision of the throughfall estimate (Leonard, 1961; Helvey and Patric, 1965). In the present study, coefficients of variation of mean throughfall were plotted against gross rainfall of the 15 storms (Figure 4). In this graph, the equation for fitting the curve was:

$$\hat{Y} = h + \frac{a}{x} \qquad (1)$$

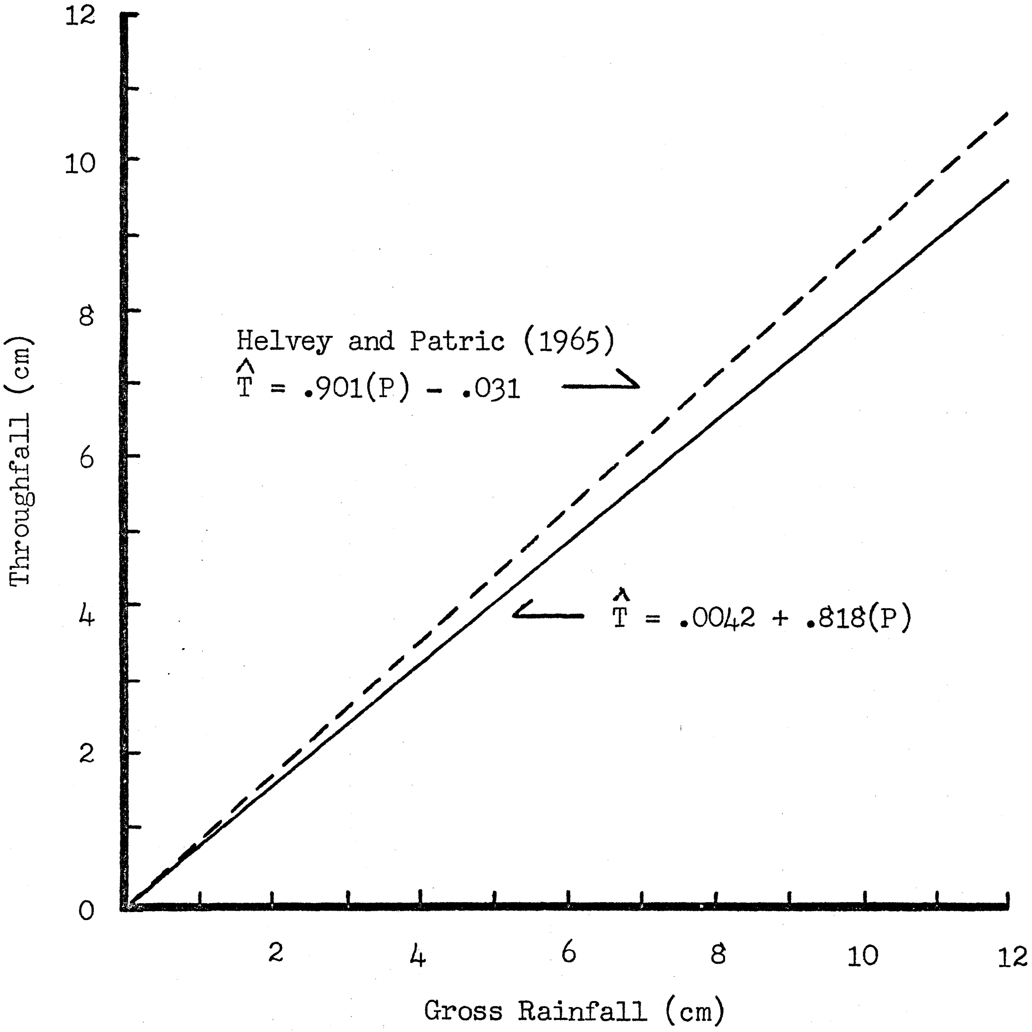

Figure 3. Linear regression of leafy season throughfall compared with leafy season regression by Helvey and Patric (1965).

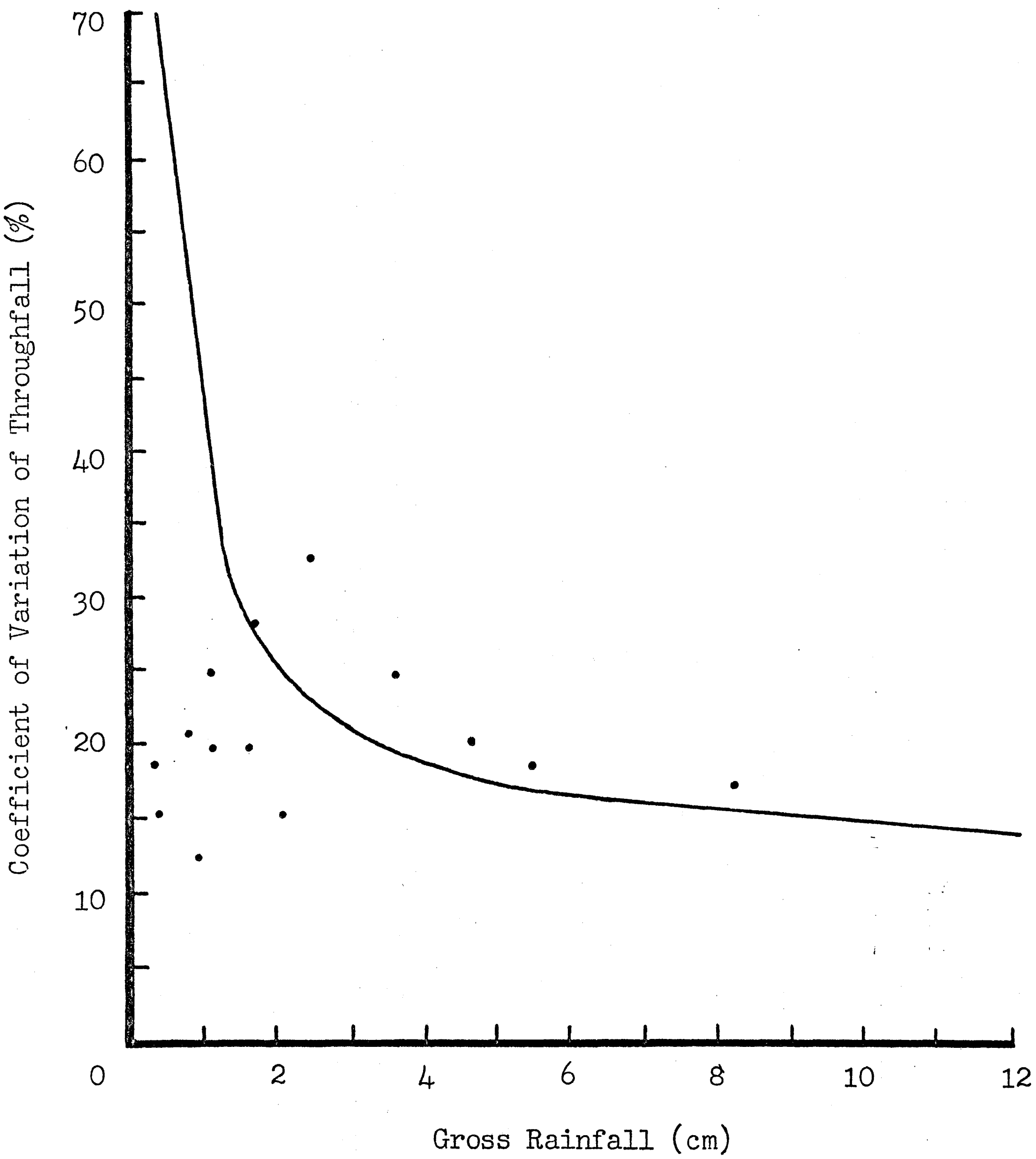

Figure 4. Leafy season coefficients of variation for throughfall.

where:

$\hat{Y}$ = mean coefficient of variation of throughfall

h = height on Y-axis below which none of the points occur

X = gross rainfall

a = constant (coefficient expressing the relation between observed values of Y and X).

The constant coefficient for this graph was computed by solving equation (1) for "a", using $\bar{X}$ (average of 15 gross rainfall values) and $\bar{Y}$ (average of 15 observed coefficients of variation) as estimates for X and Y. Equation (1) then becomes:

$$\hat{Y} = 12 + \frac{26.68}{X}$$

for the leafy season. The curve in the graph was plotted from this equation, using selected gross rainfall values for "X". It should be noted that this equation represents only one of several methods for estimating the relation between the scattered points (I. J. Goode, Department of Statistics, V.P.I., personal communication, 1973). The curve suggests that variability of throughfall among gauges decreases with increasing storm size.

Coefficients of variation for leafy season throughfall were also computed for each of the plots (Table VI). It is evident from these values that the greatest amount of variation among gauges occurred in plot IV. This variation is associated with the presence of a large opening in the overstory canopy of plot IV. In addition, with increasing storm size above 2.5 cm gross rainfall, throughfall as a percent of gross rainfall for each storm increased above the average for the season, while the coefficient of variation tended to decrease. As mentioned earlier, these same storms were predominantly moderate to heavy in intensity.

The extent of between gauge throughfall variation was also noted from the occurrence of throughfall catch exceeding gross rainfall in several of the gauges. The mean number of occurrences of such excessive point throughfall per storm was determined from the frequency distribution of gauge catch and compared with the mean number of occurrences during the leafless season. In addition, the ratio of occurrences was computed for each of the plots. These values are listed by seasons in Table VII. It is obvious from the table that throughfall catch in excess of gross rainfall occurred more frequently during the leafy season.

Leafless Season Throughfall

Leafless season throughfall, based on 25 storms, averaged 81.86 percent of gross rainfall. Highest average percentages of throughfall occurred in plots III and IV, while lowest percentages occurred in plots II and V (Table VI).

The linear regression equation for leafless season throughfall was:

$$\hat{T} = .826(P) - .0089$$

with a squared correlation coefficient, $R^2 = 0.9958$. From their summary of interception studies in mature, mixed hardwood stands, Helvey and Patric (1965) developed the following equation:

$$\hat{T} = .914(P) - .015$$

for estimates of leafless season throughfall. The regression lines of these two equation are depicted in Figure 5. As in the leafy season, the regression line of leafless season throughfall for this study falls below Helvey and Patric's regression line.

Regression equations of leafy and leafless season throughfall were quite similar in the present study. When plotted on a graph, the regression lines were practically superimposed. This similarity between seasons is also indicated by the small difference in throughfall as a percent of gross rainfall between leafy and leafless seasons, 78.2 and 81.86 percent, respectively. The same relation applied when Helvey and Patric's (1965) regression lines were plotted together.

Average coefficients of variation for leafless season throughfall were computed for each of the plots (Table VI). It is evident from the table that average coefficients of variation for the leafless season were less (a difference of approximately 9 to 10 percent) in four of the plots than for the same plots during the leafy season; however, the difference between seasons in plot IV was relatively small.

Leafless season coefficients of variation, computed from mean throughfall in 120 gauges per storm, were plotted against gross rainfall (Figure 6). The equation of the curve is:

$$Y = 6 + \frac{23.12}{X} .$$

It is evident from the graph that variability of throughfall decreases with increasing strom size above 3 cm gross rainfall. Most of the

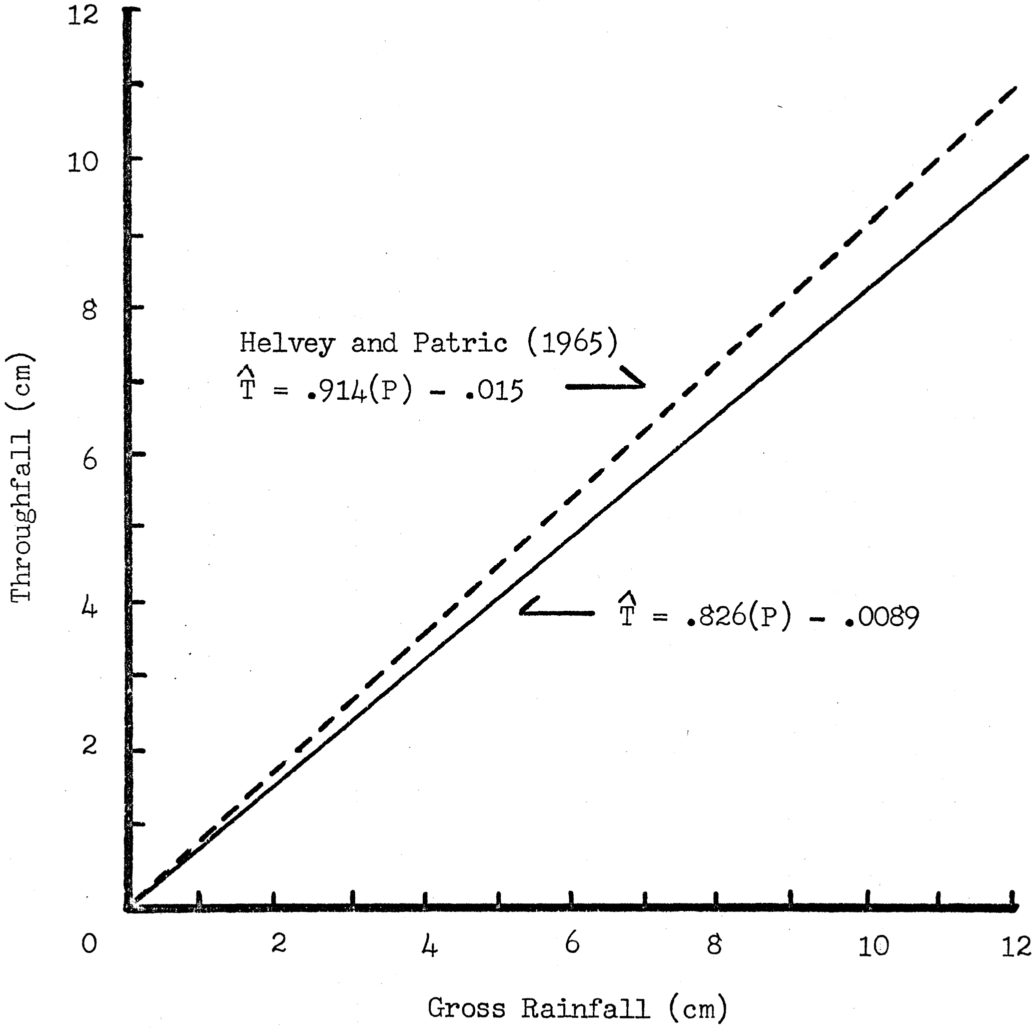

Figure 5. Linear regression of leafless season throughfall compared with leafless season regression by Helvey and Patric (1965).

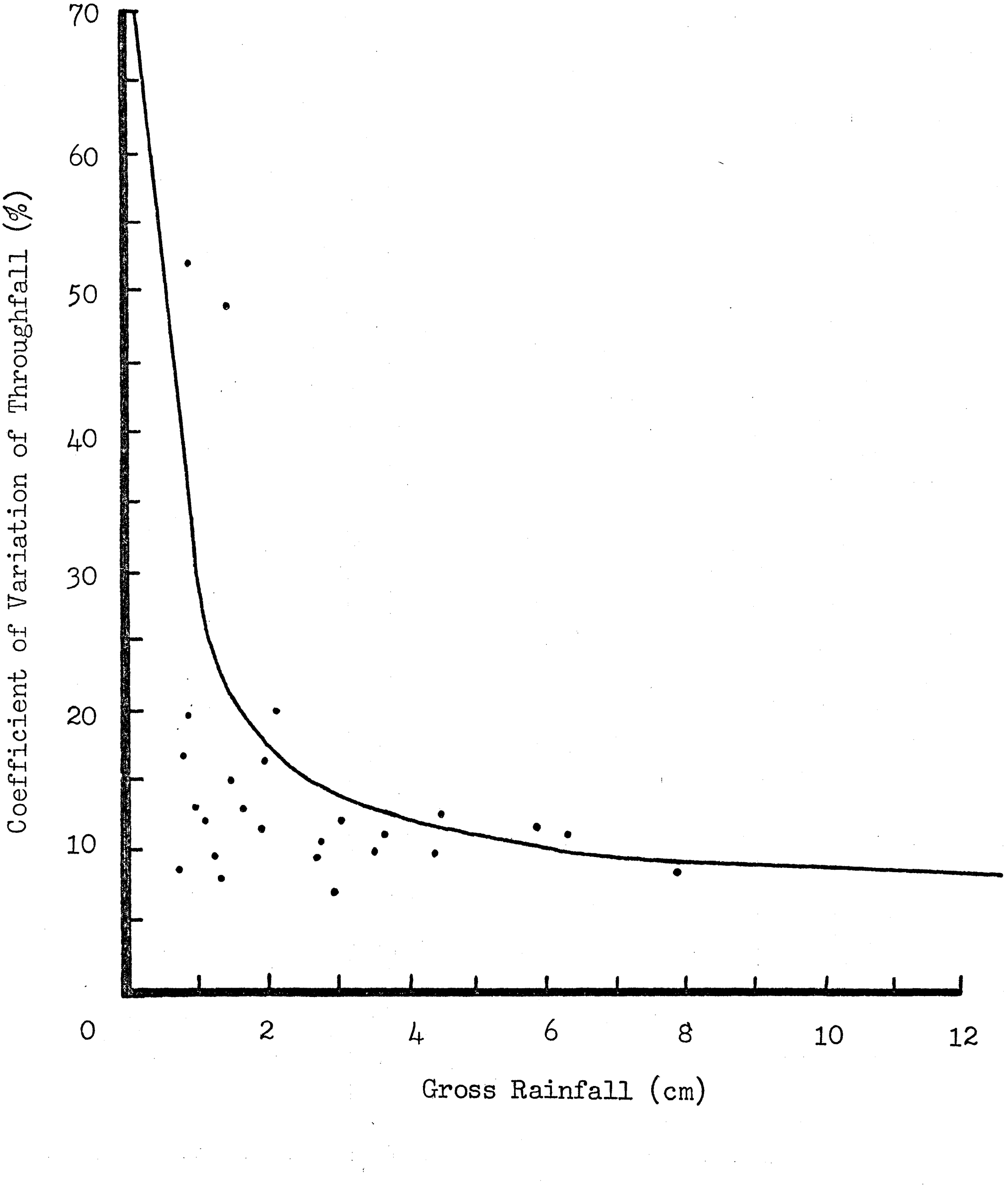

Figure 6. Leafless season coefficients of variation for throughfall.

coefficients of variation are smaller than those of the leafy season. This low variability among gauges corresponds with the low frequency of gauge catches exceeding gross rainfall (Table VII).

Sampling Design Analysis

One of the major problems of measuring throughfall is the development of a sampling design that provides a reliable statistic for comparison of data collected from the same area during a specified time interval. In the past, considerable difficulty has been experienced in obtaining estimates of throughfall which provide a sufficiently low standard error as a percent of mean throughfall. Part of this problem is attributed to the number and position of gauges used to collect throughfall (Rieley et al., 1969). An analysis of the present sampling design was made to determine whether 120 gauges were sufficient to yield an estimate of throughfall within 5 percent of the true mean. This analysis was accomplished with Stein's (1945) equation for determining the number of gauges needed to give an estimate of mean throughfall within a specified level of accuracy. His equation was based on variance of the sample and student's t distribution. In his equation

$$n = \frac{t^2 S^2}{d^2} \qquad (2)$$

"n" is the number of samples, "t" is from a t table for a selected confidence level and associated degrees of freedom, "S^2" is the estimated population (throughfall) variance, and "d" is the desired difference between sample and population (or true) means. It has been suggested that a difference (d) of 5 percent throughfall error is tolerable for

TABLE VII. Mean occurrences of point throughfall in excess of gross rainfall in leafy and leafless seasons.

PLOT	MEAN OCCURRENCES		RATIO
	LEAFY	LEAFLESS	LEAFY:LEAFLESS
I	2.40	0.60	4.0 : 1
II	1.40	0.28	5.0 : 1
III	2.87	0.60	4.8 : 1
IV	3.30	2.20	1.5 : 1
V	1.73	0.28	6.2 : 1

a wide range of storm sizes (Helvey and Patric, 1966). If the "d" value is expressed as a percent of the estimated mean throughfall, then the following equation:

$$n = t^2\left(\frac{c.v.}{d}\right)^2 \qquad (3)$$

is algebraically equivalent to Stein's equation (2). The "c.v." in the equation is the coefficient of variation of the estimated mean throughfall.

In the present study, coefficients of variation expressed as a percent of the estimated mean throughfall were used in equation (3) to determine the number of gauges needed to provide a throughfall estimate within 5 percent of the true mean. A "t" value of 1.98 (95 percent confidence level for over 100 degrees of freedom) was used in these computations. The results showed the 120 gauges were sufficient to give an accurate estimate of throughfall at 5 percent of the true mean for 36 storms, and within 10 percent of the true mean for the remaining 4 storms.

Large percentage standard errors, up to 11 percent of the true mean, have resulted in previous studies with small number of stationary gauges (Reynolds and Leyton, 1963; Rieley <u>et al</u>., 1969). In the present study, estimates of throughfall with a large number of stationary gauges resulted in low standard errors. During the leafy season, standard errors averaged 1.85 percent of the mean, whereas in the leafless season, standard errors averaged 1.34 percent of the mean. It should be noted that, in many of the storms, fewer than 120 gauges were needed to accurately estimate throughfall over the study site. However, the large number of gauges was still necessary for determination of throughfall in each subplot where soil samples were collected.

Soil Moisture Analysis

Water content as percent of soil volume and as percent of soil weight were computed for each of the 50 core samples for the two dates, June 1, 1973 and June 22, 1973. The averages of these quantities by plots are listed in Table VIII. Percentages of throughfall for the storms immediately preceding each soil sample are also listed by average values per plot (Table VIII).

Both sets of samples were obtained on "wet season, field capacity days" (Stewart and Adams, 1968). Both sampling dates were three days after a heavy rain. Samples for June 1, were preceded by a storm yielding 8.32 cm gross rainfall. Throughfall for this storm amounted to 85.28 cm gross rainfall. A storm with 4.7 cm gross rainfall and 91.21 percent throughfall preceded soil samples for June 22.

Means of soil moisture by plots were tested for significant differences between sampling dates by a Student's t-test. The results showed no significant differences in soil moisture, either as a percent by volume or as a percent by dry weight, between sampling dates.

If the plots are ranked by soil moisture and throughfall, it is evident that there is little correspondence between soil moisture and throughfall within plots. In soil samples for June 1, equal ranks were observed for soil water as a percent by volume and throughfall percent in plots III and V. Equal ranks, in soil samples for June 22, were observed for soil water as a percent by dry weight and throughfall

TABLE VIII. Soil moisture as percent by volume and percent by dry weight compared with percent throughfall of storms preceding sampling dates.

	Soil Sample: June 1			Soil Sample: June 22		
	Soil Water		Throughfall	Soil Water		Throughfall
PLOT	% by Vol.	% by Dry Wt.	% of Gross Precip.	% by Vol.	% by Dry Wt.	% of Gross Precip.
I	26.20	29.34	84.61	23.36	27.27	91.59
II	30.43	31.15	81.39	27.72	29.99*	92.21*
III	30.63*	32.84	88.36*	27.61	32.69*	94.42*
IV	30.25	35.48	87.38	27.05	30.46	89.24
V	26.88*	31.21	84.64*	25.48	26.22*	88.59

* indicates that soil moisture variable corresponds with rank of throughfall percent.

percent in plots II, III, and V. However, calculated product-moment correlation coefficients showed no significant correlation of throughfall with either soil moisture as a percent by volume or percent dry weight. Additional soil samples for more storms, as well as consideration of other soil properties, are necessary for detecting any correlation between soil moisture distribution and throughfall.

DISCUSSION

Throughfall Analysis

Interception studies on open grown trees or individual trees in plantations have shown that penetration of rainfall through tree crowns increases with distance from the stem and with gross rainfall. This pattern has been observed beneath individual crowns of hardwoods (Stout and McMahon, 1961), as well as beneath conifers (Kittredge et al., 1941; Reynolds and Leyton, 1963). In these studies, local areas of throughfall concentration were attributed to density of foliage over gauges, as well as greater density of the canopy near the stem (Eschner, 1967).

Throughfall data on open grown trees or individual trees in stands are inapplicable to natural forest conditions. Patterns of throughfall become complicated by intensive overlapping of tree crowns and variation in the degree of overlap. Throughfall also tends to be greater (80-85 percent of gross rainfall) in natural forested areas than beneath heavy-crowned, isolated trees, for which throughfall is only 70-75 percent (Black, 1959; Helvey and Patric, 1965).

As a portion of rainfall reaching the forest floor beneath individual crowns, stem flow is usually inappreciable compared to throughfall. In most studies, stemflow ranged from approximately 1 to 15 percent of gross rainfall, depending on storm characteristics, species, and canopy densities (Voigt, 1960). In a recent stemflow study adjacent to the site of this study, the average stemflow from 50 trees was less than 5 percent gross rainfall for 38 out of 39 storms (E. W. Fisher, Jr., unpublished data). Although stemflow is generally small in quantity, it has been cited as an effective means of recharging subsoil moisture at the base of a tree (Voigt, 1960; Leonard, 1961; Rothacher, 1963; Eschner, 1967).

Several interception studies have focused on throughfall variation in natural hardwood stands. These studies have sought explanations for the causes, magnitude, and implications of spatial variability of throughfall beneath deciduous species of trees. The present study indicates some of the sources of variation beneath the canopy of a mixed, deciduous forest. Variations in throughfall are related to storm characteristics, irregularities of vegetative cover, and different amounts of throughfall occurring at single sampling positions.

Variations of throughfall amounts beneath deciduous canopies have been related to characteristics of gross rainfall (Trimble and Weitzman, 1954; Reynolds and Henderson, 1967). Ideally, size, intensity, and duration of storms should be good predictors of throughfall for a given area. Few studies, however, have been successful in showing a statistically significant correlation between storm intensity, or duration, and mean throughfall. Amount of gross rainfall has generally been found to be the major characteristic of a storm affecting mean throughfall (Reynolds and Henderson, 1967). In the present study, qualitative observations on rain intensity and duration showed an inconsistent pattern of correspondence with observed mean throughfall. Exceptions, however, were observed during the leafy season for storms yielding more than 2.5 cm gross precipitation. These storms were predominantly moderate to heavy in intensity and long in duration. Resultant throughfall percentages were larger than the average for the season, by a difference of 10 to 20 percent.

Individual throughfall means for storms below 2.5 cm showed very little correspondence with storm size, intensity, and duration. This observation is partially substantiated by the analysis of throughfall means for significant differences among storms (Table IV). Several non-significant ranges of means occur for storm sizes less than 1.6 cm. Consequently, amount of mean throughfall can not be predicted entirely by the size of individual storms.

Linear regression of throughfall on gross rainfall has been suggested as the best method of estimating mean throughfall for all possible storm sizes within a given area (Black, 1959; Leonard, 1961; Helvey and Patric, 1965; Rogerson and Byrnes, 1968). Generally, the largest percent of throughfall variation has been accounted for by storm size. Regression of observed mean throughfall for the 40 storms of this study (Figure 2) has shown that storm size accounts for 99 percent of the variation of mean throughfall over the area investigated. It would appear, then, that storm size should be considered when analyzing other causes of variation at different sampling positions beneath the forest canopy.

Throughfall variation in natural forest stands has also been related to differences of canopy cover or density. Seasonal changes of the canopy, referring to leaf extension and leaf fall, also tend to complicate the effect of the canopy on rainfall reaching the forest floor (Trimble and Weitzman, 1954; Leonard, 1961; Helvey and Patric, 1965). As already mentioned (Vegetation Analysis), canopy closure differs among plots in the study area. For this reason, certain plots tend to receive more throughfall.

Greatest amounts were observed in plots III and IV (Table VI). Both plots show low values of canopy closure in comparison with the other plots. Plot III is very open in appearances beneath the overstory canopy. This openness, evidenced by sparseness of understory trees and saplings, as well as slight shrub cover (Table II), permits throughfall to reach the forest floor with less impedance than in plots I, II, and V. Plot IV, however, shows the greatest amount of throughfall, primarily because of the large opening in its overstory. Plots I, II, and V receive less throughfall primarily because of their closed overstory and understory canopies. In addition, the shrub and herb cover is much higher in these plots (Table II). The greater density of foliage in these canopy strata provides more surface area for interception of rain falling to the forest floor in these plots.

The effects of canopy density alone, give only a superficial explanation of throughfall variation. Amount of gross rainfall and its intensity markedly affect amount of rain penetrating the canopy and falling to the forest floor. Trimble and Weitzman (1954), in their study of a mixed hardwood stand in West Virginia, observed that canopy density had very little effect on interception of rain with increasing storm size and intensity. They attributed this relation to the fact that, during high intensity summer storms, previously stored water is physically channeled off downward sloping leaves. Consequently, distribution of throughfall over the forest floor tends to become more even, especially with increasing storm duration. This also implies that throughfall among gauges varies less around its mean with increasing storm size and intensity. The same realtion was also shown by Leonard

(1961) in his study of a mixed hardwood forest in New Hampshire. His results showed a curvilinear, inverse relationship between coefficients of variation of throughfall and storm size for both leafy and leafless seasons. In the present study, this same relation was also evident (Figures 4 and 6).

During moderate to heavy storms in the leafy season, throughfall percentages tended to be more constant from one plot to another, especially for storms exceeding 3 cm gross precipitation. This decrease in variation is also evident in the graph of coefficients of variation for leafy season throughfall (Figure 4). It is evident from the graph that throughfall variability among gauges decreases with increasing storm size. Comparison of coefficients of variation among plots also indicates that variation among gauges is greatest in plot IV, which could probably be associated with its large overstory opening. However, an analysis of variance showed no significant difference in mean throughfall among plots in either season. Additional variation in plot IV, as well as other plots, appears to be related to occurrences of concentrated throughfall at different points beneath the canopy.

The mean number of occurrences of throughfall exceeding gross rainfall was considerably greater in plots III and IV, and greater for all plots during the leafy season in comparison with the leafless season (Table VII). Obviously, these occurrences of excessive throughfall are related to intensity of rain and storm size, as well as irregularities of the vegetative cover. During high intensity storms, or storms of low intensity and long duration, certain areas of the foliage receive water falling from higher level foliage, especially where there is overlap of individual crowns. Consequently, different parts of the canopy concentrate throughfall drip on the forest floor. Certain parts of the forest floor, then, as well as underlying soil layers, may receive considerably larger concentrations of water. The converse of this relation is also true. During light intensity storms, throughfall may reach only those areas of the forest floor located beneath openings extending through all canopy strata. For this reason, the percentage of throughfall in some of the gauges would be considerably less than the average.

Many of the sources of throughfall variation which are related to canopy density are less extensive during the winter when foliage is absent. For example, throughfall percentages are somewhat higher for each of the plots, and, as in the leafy season, plots III and IV received the greatest amount of throughfall (Table VI). Coefficients of variation of mean throughfall are also lower, by a difference of approximately 10 percent, in all plots except plot IV. The graph of these coefficients (Figure 6) is similar to Leonard's (1961) curvilinear relation between coefficients of variation and storm size. In both studies, variation of leafless season throughfall around its mean has been shown to decrease with increasing storm size.

Despite this reduction in throughfall variation with absence of foliage, branch skeletons in each stratum tend to inhibit the free fall of rain to the forest floor. Trimble and Weitzman (1954) cite variation in storm intensity as a partial explanation of variation due to branches. During light intensity storms, a certain amount of rain is trapped on branches and falls to the forest floor as stemflow rather than throughfall. Throughfall may also be less during these light winter storms due to evaporation from branch surfaces during a storm. This explanation appears to apply in the present study, where considerably lower throughfall percentages were observed for light intensity storms. It has also been suggested that branch arrangement may serve the same function as summer foliage in concentrating throughfall drip on portions of the forest floor. Some throughfall gauges may be sheltered by branches, while others receive concentrated drip from branches (Helvey and Patric, 1965). This relation is apparent in the present study from observed occurrences of throughfall exceeding gross rainfall in several of the gauges (Table VII). However, the mean number of such occurrences is considerably lower than in the leafy season. Consequently, branch arrangement may influence throughfall variation in much the same way as foliage, but to a much smaller degree.

All of these sources of variation are evident to a certain extent within seasons. However, variation of throughfall between seasons does not appear to be extremely great. Average throughfall as a percent of gross rainfall is 78.2 percent in the leafy season and 81.86 percent in the leafless season. It is also evident from Figures 4 and 6 that coefficients of variation of mean throughfall do not differ greatly between seasons. These results are similar to observations made in other deciduous stands (Trimble and Weitzman, 1954; Black, 1959; Leonard, 1961).

In the present study, linear regression equations of throughfall on gross rainfall are also quite similar for the two seasons. This similarity is even more pronounced when the regression lines of these two equations are graphed together. The same relation was also observed when Helvey and Patric's (1965) equations were graphed together. Their equations were computed by averaging equations reported in several interception studies on mixed hardwood stands in the eastern United States. However, many of these equations are based on observations from stands which are characteristically different from the stand in this study. Some represent communities other than mature, mixed hardwoods, some represent very young, open stands and others are based on very dense stands. Consequently, the difference of the present throughfall equations from those of Helvey and Patric is possibly attributed to differences of stand structure, as well as differences of climatological factors among all the areas considered in these comparisons.

Sampling Design

Difficulties in accurately measuring throughfall in a forest stand have often been attributed to the number and position of gauges used for sampling (Helvey and Patric, 1966; Rieley _et_ _al_., 1969). Small numbers of stationary gauges yield large standard errors of estimated mean throughfall (Reynolds and Leyton, 1963). For this reason, several studies have proposed the use of small numbers of roving gauges (relocated at selected time intervals) for keeping standard errors below 5 percent of the mean, and for giving accurate estimates of mean throughfall over the entire area of a forest stand (Wilm, 1946; Helvey and Patric, 1965; Rieley _et_ _al_., 1969).

One of the objectives of this study was to develop a throughfall sampling design that could be used in interpreting patterns of surface soil moisture distribution at selected sites. A roving gauge network was considered to be insufficient for repeated estimates of throughfall near soil sample collection sites. Therefore, a stationary gauge network was employed.

Analysis of throughfall measurements from this network showed that this sampling design gave an accurate estimate of mean throughfall with standard errors well below 5 percent of the mean for 90 percent of the storms. The design was also considered to be efficient for detecting differences of throughfall amounts at various positions in the study site (with reference to the use of resulting data on patterns of throughfall for interpreting soil moisture distribution).

Soil Moisture Analysis

Results of the analysis of soil moisture for two sampling dates showed no significant correlation of throughfall with either soil moisture as a percent by volume or percent by dry weight. However, these results cannot be interpreted as evidence for lack of correlation between surface soil moisture distribution and patterns of throughfall beneath a deciduous forest canopy.

Several sampling errors contribute to the inconclusive nature of these data. Determination of maximum saturation for the core samples gave very different values for the two sampling dates. Normally, since the samples were taken from such small areas, there should not have been enough variation in soil properties to alter the range of saturation values for the two dates. However, the June 1 soil cores showed consistently lower saturation values (water by percent dry weight) than cores for June 22. These values differed by an average of about 15 to 20 percent. Consequently, field soil moisture could not be expressed as a percent of saturation for the two separate dates. This error is suspected to be the result of sampling rather than computation of soil moisture quantities from the samples. However, the sampling error is irreconcilable since no further sample replicates were taken for comparison.

It is obvious that additional sampling of soil moisture is necessary for any comparisons of throughfall patterns with soil moisture distribution. Additional samples should also be taken immediately after storms. The samples obtained in this study represented soil moisture on field capacity days, occurring 3 days after a large storm. During this period, considerable drainage occurs (Stewart and Adams, 1968), to the extent that moisture may percolate deeper into the soil. Consequently, the sampling depth in this study may not have been enough to determine moisture resulting from throughfall, since a lapse of time may have allowed this quantity of water to percolate into deeper soil horizons.

The uneven distribution of throughfall over the study site would logically appear to influence the distribution of soil moisture. However, additional sample replicates are necessary for confirmation of any distribution pattern. In addition, consideration should be given to the amount of moisture retained and evaporated from litter, since this represents a portion of throughfall which does not reach the soil (Reynolds and Leyton, 1963; Helvey and Patric, 1965). However, no reports have been found which relate soil moisture distribution to patterns of throughfall in deciduous stands. A complete interception study, measuring throughfall, stemflow, and litter interception loss in relation to soil moisture distribution would definitely be of value.

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THROUGHFALL VARIATION
IN A MIXED DECIDUOUS FOREST

Terry Bond Carden

(Abstract)

Gross rainfall and throughfall were measured in an uneven-aged, mixed deciduous forest in western Virginia from August 6, 1972 to June 19, 1973. Storms were grouped according to leafy (growing) season and leafless (dormant) deason for analysis of gross rainfall and throughfall. Average leafy season throughfall was 78.2 percent of gross rainfall, and leafless season throughfall was 81.86 percent.

Regression of throughfall on gross rainfall explained approximately 99 percent of variation in throughfall. Variations in throughfall were also related to storm characteristics, irregularities of vegetative cover, and different concentrations of throughfall at single sampling positions. Coefficients of variation decreased with increasing amounts of gross rainfall. Throughfall amounts increased with decreasing canopy density over plots. However, an analysis of variance showed no significant differences of mean throughfall among plots.

Throughfall caught in several gauges exceeded gross rainfall in 36 of 40 storms. This phenomenon was more pronounced in the leafy season. There was relatively little difference in throughfall between seasons.

Soil moisture was determined on two dates. No correlation could be demonstrated between soil moisture distribution and throughfall under the forest canopy. The results, however, were inconclusive, owing to the small number of samples taken.