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WATERSHED SCALE RAINFALL INTERCEPTION ON TWO FORESTED WATERSHEDS IN THE LUQUILLO MOUNTAINS OF PUERTO RICO

F.N. SCATENA

USDA Forest Service, Institute of Tropical Forestry, Rio Piedras, Puerto Rico (U.S.A.)

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ABSTRACT

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Interception losses were monitored for one year and related to vegetation characteristics in two forested watersheds in the Luquillo Experimental Forest of Puerto Rico. Total watershed interception was then modeled by weighting values of throughfall measured in representative areas of different vegetation types by the total watershed area of that vegetation group.

Annual canopy throughfall equaled 59% of annual rainfall whereas stemflow represented 2.3%. Canopy throughfall was greatest in gaps and along stream channels with 91% of the total falling over 75% of the watershed area. However, 50% of the total stemflow came from less than 12% of the total stems.

Reported values of throughfall in the Tabonuco type forest of the Luquillo Mountains are typically 20 to 30% less than values reported for many montane and lowland tropical forests. These differences result from a high frequency, low intensity rainfall regime rather than the physiognomic character of the forest.

INTRODUCTION

Changes in the quantity and quality of precipitation as it passes through vegetative cover are important components of both hydrologic and nutrient budgets. This paper documents and models interception losses on two, humid subtropical (sensu Holdridge, 1967) watersheds in the Luquillo Mountains of Puerto Rico.

Throughfall over any period depends on the balance between precipitation, evaporation and canopy storage (Horton, 1919; Leonard, 1967; Rutter et al., 1972). If the watershed is divided into different vegetation types based on similarity in throughfall and stemflow, the total throughfall over the watershed can be expressed as:

$$P_g = \Sigma T_n A_n + \Sigma S_m D_m \quad (1)$$

where P_g = total throughfall reaching the ground, T_n = canopy throughfall

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from vegetation type n, A_n = area of vegetation type n, S_m = stemflow from stem type m and D_m = number of stems in type m.

Using eqn. (1) to estimate total watershed throughfall becomes a problem of determining the minimum number of vegetation types necessary to describe the system at the required level of accuracy. In this study, measured throughfall was compared with actual canopy and stem conditions to estimate the percentages of throughfall for different vegetation types. The total area of each vegetation type was then determined by a systematic survey of the watersheds. Watershed throughfall for different time periods was calculated by weighting the average throughfall and stemflow measured in representative areas of each vegetation type by the total area of that vegetation group.

Measurements reported here were made in two of the Bisley Research Watersheds of the U.S. Forest Service. These adjacent watersheds drain 13.0 ha of highly dissected mountainous terrain that range in elevation from 265 to 455 m. Both watersheds are covered by Tabonuco type forests and were selectively logged at various times between 1860 and 1940 (Scatena, 1988).

The dominant tree in the watersheds is the Tabonuco (*Dacryodes excelsa*) which often comprises as much as 35% of the canopy (Wadsworth, 1970). Structurally the forest has three dominant layers, a discontinuous emergent strata, a continuous upper stratum at 20 m, and an understory layer. Leaves are mesophyllous and often covered with epiphytic growth.

METHODOLOGY

Nomenclature is adapted from Hamilton and Rowe (1949) and is based on the last vegetative surface encountered before precipitation reaches the ground surface. Stemflow is that portion of the gross rainfall which reaches the litter layer by running down the stems of vegetation. Canopy throughfall is defined as the portion that passes through the canopy without running down the stems of vegetation. Therefore, total throughfall is the sum of canopy throughfall and stemflow.

Rainfall, canopy throughfall, stemflow and canopy structure were monitored from October 1, 1987 to October 1, 1988. Total rainfall was measured by three different devices: a plastic funnel collector projected above the canopy and connected to a ground level storage bottle by 25 m of plastic tubing; a recording gage in a clearing adjacent to the watersheds; and for the last 8 months of the study, recording gages located on a 25 m canopy observation tower and on the adjacent forest floor. Both the funnel collector and the tower gages are located on the divide near the center of the combined drainages. For consistency, the total rainfall values reported here are those recorded by the funnel collector which had a similar design to the throughfall collectors. Nevertheless, all three rain gages recorded similar values.

After testing several methods, gallon plastic jugs fitted with sealed 18 cm diameter screened funnels were used to measure throughfall. These bottles were found to be superior to trough and open can collectors since they are not subject to excessive losses by evaporation or raindrop splash.

Collectors were placed in randomly selected lines that were located throughout the watershed and transected ridges, hillslopes, gaps and stream channels. Within individual transects, bottles were evenly spaced at distances of either 5 or 10 m. Additional bottles were placed to cover special cases: herb layers in a clearing adjacent to the watersheds, species not represented in the random transects and in gaps that developed during the measurement period.

A total of 22 collectors were monitored for one year and were used to calculate monthly and yearly totals. However, as many as 35 collectors were operational at any given time and were used to determine the throughfall of different vegetation types. Each collector was sampled weekly and before and after numerous individual rainfall events. Since the collectors were sealed except for the 1 cm diameter funnel entrance, losses due to evaporation from the collectors were considered negligible.

Stemflow was collected from 30 cm tall plastic collars that were a modified version of those developed by Likens and Eaton (1970). Each collector was fitted with a plastic drainage outlet and sealed with silicon cement. The canopy area corresponding to each stem was measured in the field and considered the catchment area of each collector.

In the Bisley watersheds stemflow was measured on individual stems of *Dacryodes excelsa* and *Sloanea berteriana*. Average stemflow for other common species was taken from previous studies in the Luquillo Mountains (Clements and Colon, 1970; Sollins and Drewry, 1970; Frangi and Lugo, 1985).

The botanical and structural character of the canopy was determined for a square-meter column above each collector after 6 months and 1 year of measure ments. Canopy attributes included the percent open area, number and type of vegetative strata, the number of branches that intersect an imaginary square-meter column above the bottle, stem density and landscape position.

The percent open cover above each collector was determined using a spherical densiometer. The number of vegetative strata was calculated as the presence or absence of emergents, canopy, suppressed, understory and herb level vegetation.

Measured throughfall volumes were compared with canopy characteristics using multiple regression, cluster analysis and common sense. These comparisons were then developed into a canopy-throughfall classification system which is discussed below (Table 1).

In order to determine aerial extent of different canopy types, the throughfall-canopy classification system was applied to the nodes of a 40 by 40 m grid that criss-crosses the research watersheds. At each node, the canopy was classified into one of the throughfall groups. A total of 98 grid points were evaluated. Areas of stream channel openings and recent gaps were measured directly with a tape and compass.

The potential amount of water stored on leaf surfaces were determined for nine major wood and herb species. Ten fresh leaves from each species were weighed dry and reweighed after being submerged in water to determine water storage per unit area of leaf. Leaf area was measured with an Licor Area meter

(Model LI–3100). Total canopy storage was then estimated from the product of storage per unit area and the leaf-area index.

RESULTS

Between October 1987 and October 1988 the total precipitation at the watersheds was 5745 mm. Over the same period, a gage 7.7 km away at the

TABLE 1

Canopy-throughfall classification for the Bisley Research Watersheds, Luquillo Experimental Forest, October 1987 to October 1988

Class	Form	Number of strata	Branch number index	Canopy area index	Throughfall (%)	Area (%)	Location and species
Large recent gaps	Closing canopy, emerging herb layer	0–2	0–30	30–100	88	2	large recent gaps without herbs
Open	No or poorly defined strata	0–1	0–40	90–100	85	10	small gaps, palms, *Cecropia peltata*
Riparian	Open upper canopy, herb strata	0–1	0–50	80–100	80	5	Active stream channel, adjacent areas
Monostrata	Upper canopy with open understory	1–2	40–60	60–90	66	36	Floodplains, old gaps tabonuco, mahogany
Multistrata	Closed upper canopy, with layered understory	3–4	60–80	30–60	48	35	Ridges, tabonuco, *Sloanea, berterian Manilkara bidendata*
Closed	Closed upper canopy, layered understory, herbs	> 5	> 80	< 30	27	12	Sheltered slopes

University of Puerto Rico's El Verde Field Station recorded 1.3 times its long-term average (Alejo Estrada-Pinto, pers. commun., 1988).

The total canopy throughfall collected in different bottles ranged between 0 and 107% of total rainfall for individual showers and between 24 to 95% of the annual rainfall. Annual canopy throughfall, as estimated by the average of the 22 permanent collectors was 58% of total rainfall.

Linear regression of weekly and storm throughfall vs. rainfall were significant ($P = 0.1$) for sample sites. Stemflow also demonstrated a significant linear relationship with total rainfall. However, like observations in other forests, stemflow was more variable than throughfall. No significant increase in prediction of either throughfall or stemflow was achieved by more complicated regression models—logarithmic, quadratic, or exponential.

Average monthly total throughfall, as estimated by the mean of all collectors, ranged from 48 to 68% of total precipitation. Average weekly throughfall ranged from 0 to 81%. Variability between individual events and weeks was greater than the spatial variability between events. Furthermore, the spatial variation in throughfall over a given time period decreased with increasing rainfall.

Approximately 28% of the total rainfall occurred in less than 10% of the calendar days. Furthermore, 30% of the annual throughfall occurred over the same period. Throughfall was measured in the below canopy recording gage; 73% of the hours rainfall was measured in the above canopy collector.

Canopy storage capacities were estimated from the recording gages placed on the canopy tower and in the forest, and the measurements of water retained on individual leaves. No throughfall was measured in the recording gage when rainfall was equal to or less than 0.51 mm h^{-1}. For comparison, projecting the intercept of the event rainfall–throughfall regression developed for relatively dense canopied *Manilkara bidendata* by Sollins and Drewy (1970) gives an estimate of 0.85 mm h^{-1}. Event-based measurements of throughfall by Clements and Colon (1970) indicated that between 0.76 and 1.27 mm of rain were needed to saturate the canopy and produce throughfall.

The leaf area index for the Tabonuco forest has a mean of 6.4 and ranges from 1.95 in ravines to 12.6 on slopes and ridges (Odum et al., 1963; Odum et al., 1970a). Water stored on leaves ranged from 40 g m^{-2} for palms to 170 g m^{-2} for *Cecropia peltata*. The species *Dacrodes excelsa, Swietenia macrophylla, Manilkara bidendata, Sloanea berteriana,* and various herbs had storages between 80 to 100 g m^{-2}.

Based on these values, canopy storage could range from 0.08 mm for palm-filled ravines to 1.3 mm for Tabonuco-covered ridges. The average value for the watersheds, based on the relative stem density of each species is 0.82 mm.

Direct field observations indicate that saturated leaves shed water in drops that range between 2 and 3 mm in diameter. The largest drops typically occur at the elongated ends of leaves which are commonly called drip-tips (Richards, 1966).

DISCUSSION

Canopy characteristics and throughfall

Measurements of throughfall in collectors dominated by single species, and the research of other workers (Odum et al., 1970a, 1970b; Sollins and Drewry,

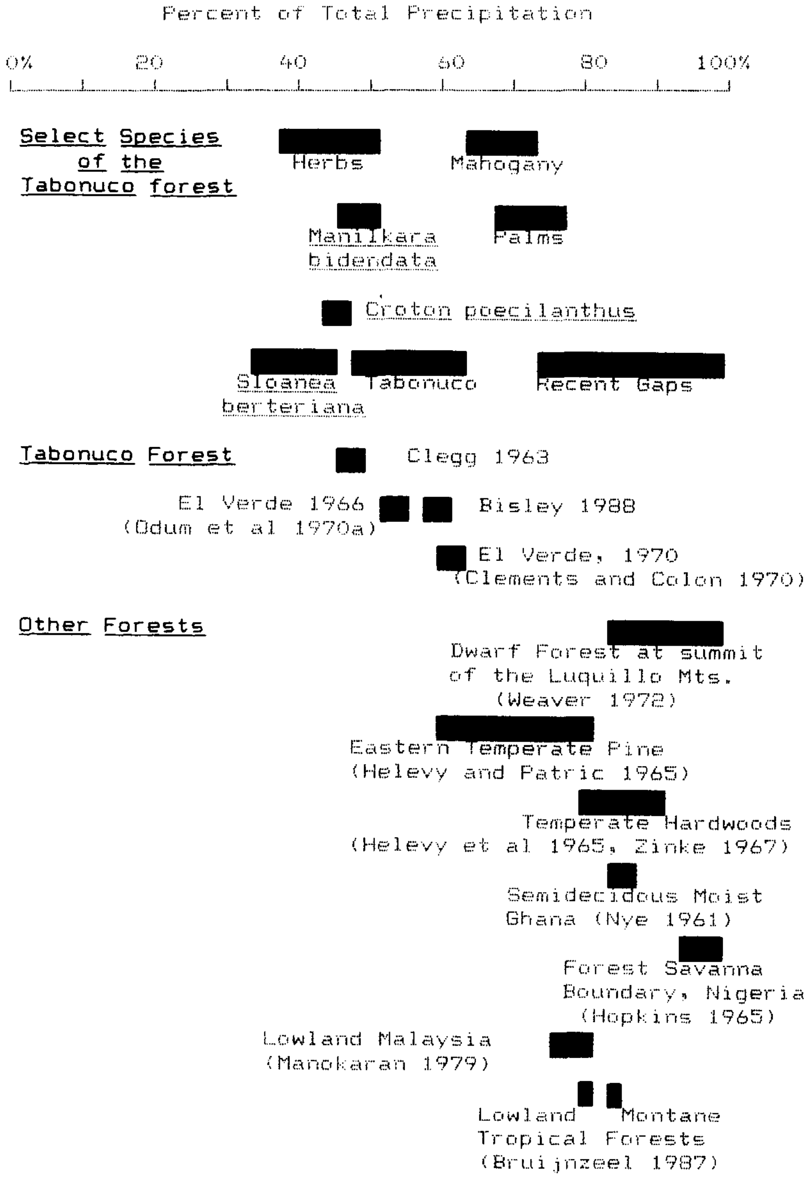

Fig. 1. Average canopy throughfall for various species and locations. Bar length represents range or standard deviation of reported values.

1970; Frangi and Lugo, 1985) indicate that canopy throughfall varies between 35 to 85% for some of the common species in the Tabonuco forest (Fig. 1). This variation apparently results from differences in vegetation morphology which in turn influence the balance between surface tension, gravitational and mechanical forces (Leonard, 1967) and ultimately water storage capacity. However, since the vast majority of the forest canopy is formed by the intertwining of different species, variations between species is less important than spatial variations in canopy structure.

Generally, mountain palms (*Prestoa montana*), mahogany (*Swietenia macrophylla*) and *Cercopia peltata* have relatively high volumes of annual throughfall. Species with dense canopies and less throughfall include tabonuco, *Manilkara bidendata,* and *Sloanea berteriana.* Interestingly, many species with relatively high throughfall occur in gaps and openings.

The magnitude of interception by dense herb layers in openings is comparable to interception by the forest canopy (Fig. 1). However, the effects of mechanical energy on the exposed herbs result in greater temporal and spatial variability. Relatively large variations in interception losses appear to be common with herb and grass (Zinke, 1967).

The range in average canopy throughfall between dominant species of the Tabonuco forest is greater than that reported for temperate hardwoods (Fig. 1). However, greater variations are expected in a forest with higher species diversity. Furthermore, the similarity between various deciduous hardwoods is partly explained by the presence of long leafless periods when variations due to inherent differences in leaf morphology or canopy area are obscured. Although some species in the Tabonuco community are deciduous, the period of leaflessness is relatively short and generally occurs over the dry season when less than 15% of the annual rainfall occurs.

Like throughfall, the relative amounts of stemflow also depend on the nature of the vegetative surface and the balance of forces acting on the fluid. However, because of their ridigity and limited exposure, relatively large mechanical forces are needed to shake droplets from stems. Therefore, stemflow should primarily depend on the supply of water from the canopy and the balance between evaporation, surface tension and gravitational forces.

In general, stemflow appears to be greatest on smooth barked trees with wide funnel-shaped canopies. The presence of epiphytes, vines, rough or articulated trunks decrease stemflow since they increase the total area available for retention. The rate of tree growth may also affect stemflow since fast growing trees tend to have smooth bark and fewer epiphytes (Frangi and Lugo, 1985).

Analysis of canopy characteristics above 22 individual collectors indicates that the percent of canopy cover, the stratification of the canopy, the number of individual branches above the collector, and stand density are the most important variables explaining differences in annual throughfall volumes. Multiple linear regression of these variables explained 65% of the variation in annual throughfall between collectors.

When collectors from areas that experienced major changes in canopy structure during the measurement year (discussed below) were not included in the analysis, 81% of the variation in annual canopy throughfall between collectors could be explained. Additional variation is apparently due to species-specific differences in vegetative cover, and local differences of exposure that influence mechanical energy.

Following the comparison of throughfall amounts and canopy characteristics a canopy-throughfall classification system was developed (Table 1). This classification not only includes the most important variables in the multiple regression analysis, but also includes descriptive qualifiers. Although the classification is only applicable to the Tabonuco forest of the Luquillo Mountains, relative amounts of throughfall between different classes should be similar in other forests.

Watershed throughfall budget

The amount of throughfall falling over both watersheds was modeled using eqn. (1) and the canopy-throughfall classification (Table 1). Total watershed throughfall for different periods was estimated by weighting measured volumes of throughfall in the different vegetation types by the proportionate area of each vegetation type (Table 2). Since total watershed throughfall for any period is based on actual measurements, temporal variations in interception losses due to differences in storm intensity were implicitly accounted for.

Total watershed stemflow was estimated from species specific measurements and the total number of stems per species in the watersheds (Table 3). In the Bisley watersheds stem flow was measured for *Dacryodes excelsa* and *Sloanea berteriana*. Average stemflow values for *Dacryodes excelsa* and an understory sampling were taken from Sollins and Drewry (1970). Values for palms were from Frangi and Lugo (1985). Stem density values are based on measurements

TABLE 2

Estimated annual canopy throughfall at the Bisley Research Watersheds Luquillo Experimental Forest, October 1987 to October 1988

Canopy type (1)	Total area % (2)	Annual throughfall % (3)	Weighted throughfall column 2 × 3 (%) (4)	Total throughfall (%) (5)
Monostrata	36	66	24	41
Multistrata	35	48	17	29
Closed	12	27	3	5
Open	10	85	9	15
Riparian	5	80	4	7
Recent gaps	2	88	2	3
Total canopy throughfall (sum of column 4)			59	

TABLE 3

Estimated annual watershed stemflow at the Bisley Research Watersheds, Luquillo Experimental Watersheds, October 1987 to October 1988

Species (1)	Total stems (%) (2)	Annual stemflow (%) (3)	Weighted stemflow column 2 × 3 (%) (4)	Total stemflow (%) (5)
Sloanea berteriana	21	0.96	0.20	8.8
Dacryodes excelsa	17	1.5	0.26	11.4
Palms, *Cercopia peltata*	12	9.8	1.18	51.8
Understory	15	0.7	0.11	4.8
Others	35	1.5	0.53	23.2
Total annual watershed stemflow (sum of column 4)			2.28	

from the 40 × 40 m grid that crosses these watersheds (Scatena, unpublished data).

Model estimates indicate that the percentage of annual precipitation hitting the litter layer is 61% of the total rainfall. Total throughfall estimated from the sample mean of all the throughfall and stemflow collectors is similar, 58%. The similarity between the two estimates indicates that 22 stationary collectors were sufficient to encompass the variability of the system.

Across the watershed, canopy throughfall can vary from less than 30 to almost 90%. However 91% of the canopy throughfall comes from 75% of the area. Nevertheless, 25% of the total throughfall passes through relatively open canopies before reaching the ground surface. In these areas, the opportunity for leaching and recycling nutrients is considerably less than in areas of dense-type canopies.

In contrast to the relatively homogeneous distribution of throughfall, over 50% of the total stemflow comes from less than 12% of the stems. Furthermore, stemflow in any stand can vary from less than 1% to almost 10%. This indicates the localized importance of stemflow and suggests that stemflow is relatively more important in gaps and ravines where palms and *Cercropia peltata* are relatively more abundant.

Temporal variations in throughfall

Monthly variations in precipitation and throughfall during the study period reflect the inherent seasonality of precipitation in the Luquillo Mountains (Fig. 2). Although relative differences in monthly rainfall are considerably less than in most continental areas, there is a vast seasonal trend to total rainfall. Furthermore, total throughfall in one month can exceed the total rainfall in an adjacent month.

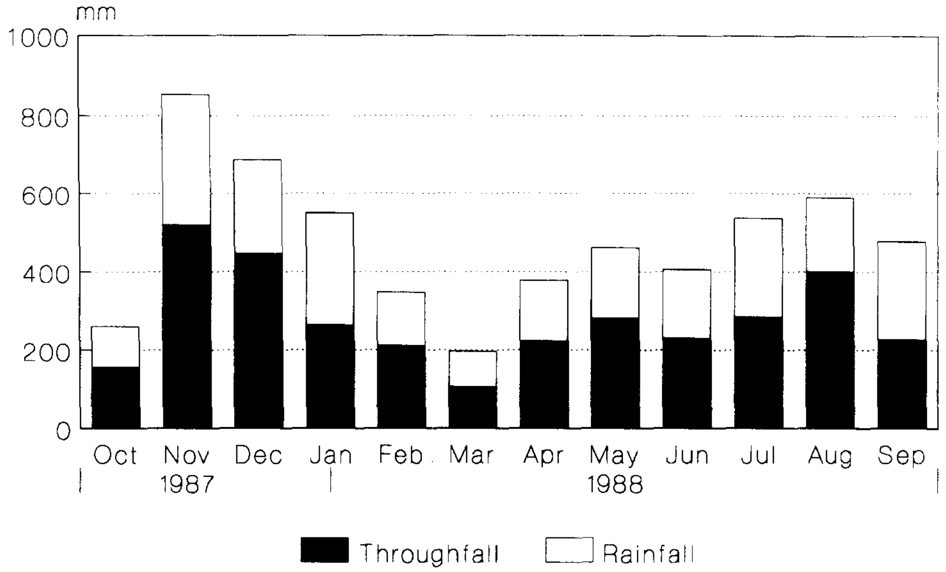

Fig. 2. Monthly rainfall and throughfall.

Over the year of measurement, nearly 20% of the bottles experienced changes in the overlying canopy that greatly affected net throughfall. However, only one bottle received less throughfall due to canopy changes. In this case a branch fall sheltered the underlying bottle from incoming throughfall. All other canopy changes were losses of vegetative cover due to canopy breakage that resulted in increases in throughfall.

The greatest variations in throughfall between storms of similar magnitude were noted in collectors adjacent to understory palms and beneath the herb layer of gaps. In these situations, variations in mechanical energy between events resulted in significant differences in canopy storage and throughfall.

Variation in throughfall as a gap regenerated were also noted. Two perpen dicular transects were placed in a large, 1332 m^2, elongate, gap that was approximately 5 months old at the beginning of the study. As the year progressed, the growth of herbs within the gap and the closing of the canopy from the sides resulted in significant decreases in local throughfall.

For example, during the first three months of measurements, a collector situated near the center of the gap and on top of the fallen tree was above the emerging herb layer. By the last three months of collection, the herb layer had engulfed the collector and caused a 45% decrease in total measured throughfall. Throughfall for the entire gap was 21% less over the last three months of measurements compared to the first three months even though the total rainfall was similar. In general, regeneration resulted in greater decreases in throughfall near the center of the gap than along the shaded edges.

These observations indicate that management schemes aimed at increasing runoff by reducing interception through canopy thinning will produce short lived, if any, positive results in fast growing forest environments.

Comparison with other forests

The magnitudes of throughfall measured in the Bisley watersheds are comparable with other measurements from the Tabonuco forest of the Luquillo Mountains (Fig. 1). Nevertheless, throughfall in the Tabonuco forest is typically 20 to 30% less than the 80 to 85% value found in many montane and lowland tropical forests (Bruijnzeel, 1987). These differences apparently result from regional meteorological influences rather than the physiognomic character of the forest.

Canopy throughfall measurements for the Tabonuco forest typically range between 50 and 60% of the total annual rainfall (Fig 1). Variations between the percentage of throughfall measured by single recording gages (Odum et al., 1970a; Sollins and Drewry, 1970; this study) multiple open collectors (Clegg, 1963), troughs (Clements and Colon, 1970) and the bottles used in this study are less than 10%. This consistency is surprising considering the lengthy discussions on throughfall sample design that have appeared in the literature.

Estimates of maximum canopy water storage for most grasses, shrubs and trees average about 1.3 mm (Zinke, 1967) compared to the 0.82 mm estimate for the Bisley watersheds. Storage for an East African forest was estimated at 0.89 mm (Jackson, 1975) while storage estimates for Eastern hardwoods range between 0.3 and 1.6 mm (Helevy and Patric, 1965) and from 0.25 to 9.14 mm in temperate climates (Zinke, 1967).

The relatively low saturation values in the Bisley watersheds are apparently due to the abundance of palms which have a low saturation value and the presence of drip-tips on the leaves of other vegetation. Nevertheless, while Tabonuco forest vegetation may have low canopy saturation values and morphological adaptations designed to shed water, the annual interception losses are relatively high.

The low annual throughfall of the Tabonuco forest is apparently due to regional meteorological conditions and the resulting rainfall regime. The Luquillo mountains are located within the trade wind belt and are constantly under the influence of moisture laden air flowing in from the sea. The intertropical convergence zone, which is responsible for much of the heavy rainfall in the tropics, is seldom felt (Riehl, 1979) and most precipitation is orographic in origin.

The result of the trade-wind influence on the Luquillo Mountains is a long, flat-peak rainy season characterized by brief low-intensity showers originating from orographic cooling. Normally 25 to 145 cumulus clouds pass any given spot per day (Odum et al., 1970a) and there are over 1600 rain showers per year (Brown et al., 1983). Approximately 78% of these showers last 1 h or less

(Clements and Colon, 1970). Sustained heavy cloudiness of larger rain systems only occurs one third of the time.

Nearly 80% of the hourly rainfall in the Tabonuco type forest has intensities less than or equal to 2.5 mm h^{-1} (Odum et al., 1970a) and approximately 50% of the total annual rainfall falls in showers with intensities less than 5 mm h^{-1} (calculated from Odum et al., 1970a). Furthermore, the frequency of hourly throughfall was 73% during an unusually wet period at Bisley and 61% during a relatively dry period at the El Verde field station (Odum et al., 1970b).

The predominance of high frequency, low intensity rain showers does not preclude the possibility of high intensity rainfall. Moreover, rainfall resulting from easterly waves and hurricanes in the Caribbean has been greater than 500 mm in a single day and over 2700 mm in several days (Gupta, 1988). Furthermore, throughfall and cloud drip in the cloud forest at the summit of the Luquillo Mountains approached 100% during an unusually wet period (Weaver, 1972). Likewise, when over 200 mm of rain fell in 24 hours, the event throughfall at Bisley was 81%.

Although high throughfall can occur, the net result of the steady trade winds and the orographic cooling is a relatively low annual throughfall. This is in sharp contrast to tropical forests influenced by the intertropical convergence zone, continental or monsoonal climates. In these areas, a greater percentage of the annual precipitation occurs in high intensity events that saturate the canopy and have relatively high throughfalls.

For example, in the lowland rain forests of Malaysia, an annual rainfall of 2381 mm fell in a total of 166 rainy days. The resulting canopy throughfall was 78% (Manokaran, 1979). In the Luquillo Mountains, 269 d yr^{-1} have at least 3 mm of rain (Brown et al., 1983) and the average canopy throughfall is typically less than 60%.

The relative consistency of temporal variations in throughfall across the Tabonuco forest (Fig. 1) appears to be typical of other areas of uniform climate. Interception rates in Eastern Hardwoods communities of the US are remarkably similar (Helevy and Patric, 1965) as are values for temperate grasses, shrubs, and trees (Zinke, 1967). Throughfall in eight neighboring forest communities in Australia have no significant difference between communities and only minor differences between native forests and plantations (Duncan et al., 1978). Nevertheless, the structural differences between the communities were considerable. Differences in annual throughfall between adjacent secondary forests and pine plantations in Jamaica were also only 2% (Richardson, 1982).

These observations on the consistency of throughfall in neighboring forest communities suggest that at regional scales, large differences in throughfall result from variations in the magnitude and frequency of precipitation rather than from inherent differences in the structure of the vegetative cover.

CONCLUSIONS

The effective processes influencing throughfall vary with the scale of observation. On the scale of individual leaves, interception storage is influenced by the morphology of the vegetation and the balance of evaporation, surface tension, gravitational and mechanical forces. Within forest variations result from changes in canopy structure and temporal variations in mechanical energy. At the regional scale, differences in throughfall can result from variations in the magnitude and frequency of rainfall rather than inherent differences between forest communities.

Since annual throughfall is strongly dependent on the magnitude and frequency of rainfall rather than forest physiognomy, management schemes designed to increase throughfall and runoff with canopy thinning will produce limited results in most areas. Furthermore, in fast growing forests where understory vegetation increases when canopies are opened, any increases in throughfall due to thinning will be short lived.

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