Reprinted from
Int. Assoc. Sci. Hydrol. Bull. 67, pp. 131-137
1966

DESIGN CRITERIA FOR INTERCEPTION STUDIES

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ABSTRACT

Rain intercepted by forest vegetation is an important loss of water. Although interception has been widely studied, variation in sampling intensity, sampling methods, and data analysis often prevents cross comparison of study results. This report, gleaned from over fifty studies, defines variability of interception parameters and provides sampling designs for obtaining estimates to selected levels of probability for each parameter mean. A new method for estimating stemflow greatly reduces variability inherent in the traditional single-tree method, coefficients of variation averaging only 20 per cent when measured on randomly selected plots. Regression analysis clearly defines the relation of gross rainfall to interception loss, which, within regions of like vegetation, probably varies within narrow limits. These sampling and analytical methods will insure that results of different studies are comparable.

INTRODUCTION

Man's best water supplies usually originate from rain falling on forest land. Only part of this rainfall is actually available to satisfy man's requirements. The remainder is dissipated by evaporative processes, one of which is water intercepted by forest vegetation and litter. Because it may be possible to decrease interception losses by altering forest vegetation, the volume of water reaching the soil and potentially available to man may be increased. In any event, interception in humid forested regions can reach 254 mm (10 inches) or more annually, a depth of water greater than average annual streamflow from continental United States. The hydrologist needs to obtain a close estimate of this interception loss, for it represents a volume of water which, not reaching the soil, is lost to man.

Both climate and phytomorphological factors control rainfall interception by forests. We deal only with rainfall in this paper, the climatic variable of primary interest in design of hydrometeorological networks. The phytomorphological variables, such as species, size, density, arrangement, and structure of stands, presents totally different sampling problems which must be evaluated in terms of study objectives.

Some definitions of terms commonly used in interception studies will be useful to people unfamiliar with this phase of forest hydrology.

Interception is the process by which rainfall is caught on forest vegetation and redistributed as throughfall, stemflow, and evaporation.

Gross rainfall is the total amount of rainfall measured in the open or above the forest canopy.

Throughfall is rainfall which reaches the litter directly through spaces in the forest canopy and as drip from leaves, twigs, and stems.

Stemflow is rainfall which, having been caught on the canopy, reaches the litter or mineral soil by running down the stems.

Canopy interception loss is rainfall evaporated from standing vegetation.

Litter interception loss is rainfall retained on the litter layer and evaporated without adding to moisture in the underlying soil.

Total interception loss is rainfall evaporated from canopy and litter.

Total interception loss cannot be measured directly but must be estimated from samples of gross rainfall, throughfall, stemflow, and litter interception loss. To decide on a sampling procedure, the hydrologist should know (1) the variability of each parameter of interception loss, and (2) the desired reliability of his estimate for each parameter. Experience data from prior studies of forest interception are the best source of variability information. Our purpose in this paper is to summarize the best design criteria gleaned from our own experience and from reviewing more than fifty studies of interception loss in forests of the United States.

Parameter variability

Most of the variability criteria needed to design a statistically sound sampling program are shown in figure 1. These curves were constructed from data contained in thirteen studies from which coefficients of variation could be determined. Although studies conducted in the eastern United States provide data for this figure, it should be applicable in other parts of the country except for very open stands.

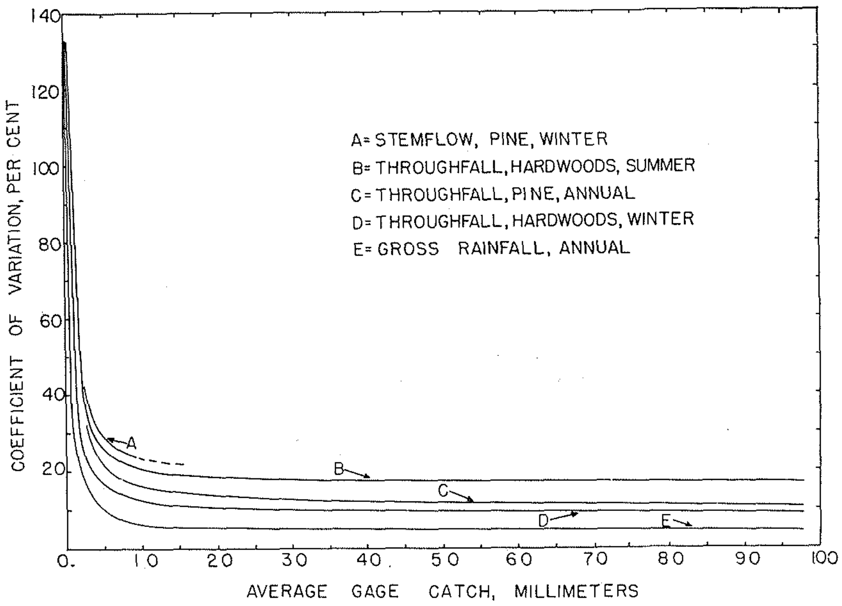

Fig. 1 — The relation of coefficient of variation to selected interception loss parameters·

Figure 1 shows clearly that (*a*) for all parameters, variation decreases sharply with increasing gage catch up to 10 mm (0.4 inch) but is stable for larger gage catch, (*b*) gross rainfall is least variable of all interception parameters, (*c*) throughfall variation in deciduous stands is higher during the growing than dormant season, (*d*) throughfall variation in pine stands is unaffected by seasons, and (*e*) stemflow is somewhat more variable than throughfall, but remains at these low levels of variation only when sampled on plots to be described later in this paper.

Reliability of estimates

Each parameter of forest interception represents a different sampling problem, and studies must be designed to estimate each to appropriate accuracy levels. Selection of required accuracy is one of the most difficult problems facing students of interception. It is an important decision, determining study feasibility as well as cost. Simple, arbitrary selection of specific accuracy rarely is possible, and the scientist must continually strive for the most reliable estimate of each parameter consistent with costs.

At this point a statistical distinction between accuracy and precision is helpful. As used in this paper, accuracy refers to success in estimating true values; precision refers to the clustering of samples about their own averages (Freese, 1962). To illustrate this distinction, several rain gages exposed 30 cm from trees might provide a precise estimate of throughfall at that point but a very inaccurate estimate of throughfall for the forest stand. Randomization of samples within forest stands gains both precision and accuracy in estimating interception factors. In the remainder of this paper, we assume that randomization procedures will be followed to assure both precise and accurate estimates of population means.

A fundamental assumption of interception loss sampling is that gage catch is a true measure of water which would reach the soil in the absence of gages. This assumption is untrue but the error is well within allowable limits when conventional gages are properly exposed. Gross rainfall routinely is sampled to about 5 per cent accuracy in conventional meteorological work. Figure 1 shows that we must be content with less accuracy in throughfall sampling where stems, branches, and foliage are interposed between sky and gages. Still less accuracy is likely in stemflow sampling because branch arrangement and bark roughness vary endlessly between trees.

Gross rainfall

Conventional rainfall sampling is dealt with authoritatively in other symposium papers, so our remarks on this subject will be few and brief.

Success of interception studies hinges on adequately sampled gross rainfall, assumed to be an independent variable measured without error. This assumption is not limiting if gross rainfall is sampled precisely, and relatively few gages do give the necessary precision. Wilm et al. (1939), used the standard error equation to determine numbers of gages needed to sample gross rainfall within stated limits of accuracy. In this equation

$$n = \frac{S^2}{(S_{\bar{x}})^2} \tag{1}$$

n is number of gages needed, S^2 is variance, and $(S_{\bar{x}})^2$ the desired variance of mean rainfall. They found that per cent accuracy of gross rainfall sampling was inversely related to storm size. Realizing this, they based allowable error on the amount of annual rainfall contributed by storm classes. Errors of 10, 5, and 2.5 per cent were allowed for storms of 0 to 0.5, 0.5 to 1.0, and over 1.0 inch, respectively. In most interception studies, experience has shown that gross rainfall will be sampled to sufficient accuracy using two to four properly shielded gages in large openings near study sites. However, figure 1 and equation (1) provide a basis for determining exact numbers of gages needed for a specific accuracy.

The foregoing discussion assumes that rainfall sampling sites will be on the same slope and aspect as canopy and litter interception plots, that gages will be properly shielded and well clear of hills, trees, or buildings which can influence air turbulence. Unfortunately, the necessary large openings do not exist close to many study sites.

Foresters attempt to solve this problem by installing gages in small clearings which provide an unobstructed sky view of 45 degrees around gage orifices. Gage exposure providing less interference with air movement often is impractical, particularly in mountains. Several English investigators are experimenting with carefully shielded treetop gages, feeling that eddying wind actually increases rain falling into small forest clearings. However, until meteorologists agree on a method for accurately sampling rainfall in forests, we recommend the 45 degree opening. If gross rainfall estimates so obtained are later proven biased, a correction factor can easily be applied.

THROUGHFALL

Throughfall is much more variable than gross rainfall (fig. 1), and either more or larger samples are needed to estimate its volume reliably. Some American investigators have used troughs 4 to 100 feet (1.22 to 30.48 m) long in attempts to reduce variation by integrating uneven throughfall patterns. Their reasoning appears sound, but REIGNER (1964) found that trough gages introduce a bias because raindrops splash out unless troughs slope more than 25 per cent from horizontal. WILSON (1950) stated that wind direction significantly affects trough gage catch because the aerodynamic effects of wind differ across and parallel to the long axis. REYNOLDS and LEYTON (1963) found that throughfall variability was only slightly less for troughs than for frequently moved 5-inch (12.70 cm) diameter gages. We, too, have found little difference in throughfall variability between trough and 8-inch (20.32 cm) U.S. Weather Bureau standard gages. In absence of any real difference in catch variability between gage types, we favor cylindrical gages moved periodically to new random locations. They are easily obtained and readily positioned in the field. Also, since gross rainfall usually is sampled with cylindrical gages, their use in throughfall sampling avoids the problem of comparing data from different gage types.

Investigators of interception rarely make clear how they arrived at numbers of gages to be used in their experiments. WOOD (1937) solved equation (1) for numbers of gages needed to estimate throughfall and rainfall to the same precision. He concluded that 18 throughfall gages were needed to equal the precision of 2 gross rainfall gages. However, equation (1) does not permit a statement about the probability of achieving a specified accuracy. STEIN (1945) corrected this deficiency with an equation based on the standard error of the estimate and Student's t distribution. In this equation

$$n = \frac{t^2 S^2}{d^2} \tag{2}$$

n is the number of samples, t is from a t table for the desired confidence level and the degrees of freedom, S^2 is estimated variance of the population, and d is the desired difference between sample and population mean.

Choice of allowable error will depend on study objectives, usually compromising storm size distribution with practicality. Larger per cent errors can be tolerated for small storms because they comprise a minor part of total throughfall error. If we follow the example of WILM et al. (1939), and allow 2.5 per cent error for rains greater than 1 inch (25.4 mm), it is unrealistic to expect greater accuracy in throughfall estimates. Because variation in throughfall is twice that of gross rainfall (fig. 1), a 5 per cent throughfall error seems reasonable for storms of this size.

If study objectives require measurement of throughfall for storms of 25 mm (1 inch) and larger to within 5 per cent, figure 2 shows that 20 gages give this accuracy 90 per cent of the time. The resulting throughfall error for 0.5, 0.25, and 0.05 inch storms would be about 6, 8, and 24 per cent respectively, a negligible depth of water. This gaging density should suffice for most study objectives.

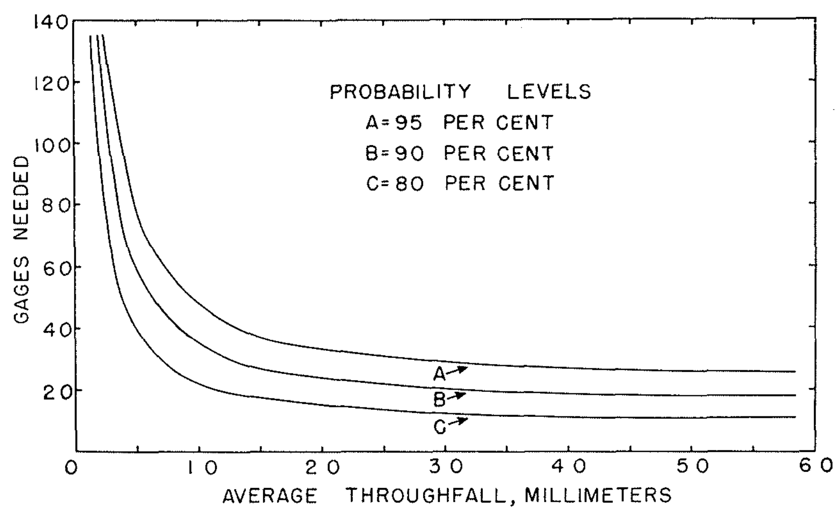

Fig. 2 — Cylindrical gages needed to sample throughfall in pine stands at 5 per cent accuracy and selected levels of probability.

STEMFLOW

Small in volume and expensive to measure, stemflow is often neglected in studies of interception. Nevertheless, accurate estimates of interception loss require that it be sampled. In conventional installations, narrow collars sealed to trunks of sample trees divert downflowing water into storage containers for measurement. Estimates of crown projectional area, i.e., the forest floor overhung by sample trees, permit conversion of stemflow volumes to depths of uniformly distributed water beneath sample trees. This method is undesirable because trees vary greatly in size and species and because selection of sample trees and estimates of crown projectional area may be subject to large personal bias.

Measuring stemflow from all trees on randomly located plots provides a better sampling method. Stemflow from plot trees is led to large central containers, measured, and converted to rainfall depth over the plot area. Variation between plots will be very high if plot diameters are much smaller than crown diameters of plot trees. However, if plot diameter is at least 1.5 times the crown diameter of the largest plot trees, or 20 m^2 (0.005 acre) for very small trees, the coefficient of variation is only slightly greater than that of throughfall (fig. 1). With single-tree samples, coefficient of variation is 10 to 20 times greater.

Some unpublished data from our interception study in white pine provide comparisons of stemflow calculated by each method. Stemflow during a 44 mm (1.72-inch) storm averaged 7.6 mm (0.30 inch) on two plots with a standard deviation of 0.25 mm (0.01 inch). When estimated on the individual tree crown projectional area basis, it averaged 5.8 mm (0.23 inch) with a standard deviation of 3.30 mm (0.13 inch). Since meteorological and stand variables were identical, these calculations clearly demonstrate the statistical superiority of the plot over the single-tree method of measuring stemflow. Plots also have economic advantages, being cheaper to establish and service while allowing easier data analysis.

The number of plots needed to sample stemflow depends on stand characteristics and desired accuracy. Stemflow in all-aged stands is more variable than in even-aged plantations. In our interception study in uniform stands of white pine, we use five plots to sample stemflow within about 12 per cent accuracy. Solving equation (2) for n using variance from our stemflow data, we calculate that seven plots would be required for sampling within 10 per cent and thirty-three plots for 5 per cent accuracy. Since a relatively small part of gross rainfall reaches the forest floor as stemflow, a larger error can be tolerated for stemflow than for throughfall sampling. In most interception studies, five to ten randomly located plots should provide reliable samples of stemflow.

Litter interception loss

After each storm, some rain remains in the litter layer, unavailable to plants, but subject to evaporation. It, too, must be considered in water balance accounting. The variables controlling litter interception loss are (1) amounts of litter on the forest floor, (2) its moisture holding capacity, and (3) local climate which controls wetting and drying.

Accurate estimates of litter weights on the forest floor are essential because weight and interception loss are directly proportional. However, litter weight is highly variable, even in uniform stands. BLOW (1955) reported that 40 one-tenth milacre (0.405 m^2) samples were required to estimate hardwood litter weight within 5 per cent error. FRANKLAND et al. (1963) reported that 48 samples, each 10 cm (4 inches) in diameter showed insignificant litter weight differences at the 95 per cent confidence level between three woodlands in England. Limited information on litter variability prohibits general statements about weight variation or the number of samples required to define it. Therefore, a preliminary investigation of variation is prerequisite to any litter interception study. Having defined litter variation and selected the desired accuracy of estimate, numbers of samples needed can be computed from equation (2).

From the few reports available it appears that forest litter has about the same maximum and minimum water holding capacity, regardless of species. Because local climate controls water loss, wetting and drying curves are needed to describe litter moisture responses to average climatic conditions. Points on these curves are usually expressed as moisture content of litter on an oven-dry weight basis. These curves permit estimates of litter interception loss between storms and can quickly be summed to estimate annual or seasonal totals.

Methods of analysis

Throughfall, stemflow, and total interception loss usually are reported as (1) percentages of gross rainfall, or (2) regression equations. Per cent values describe only the average relation of gross rainfall to throughfall for a specific storm regimen. KITTREDGE'S (1948) review indicated enormous regional percentage variation in interception losses; e.g., interception loss in the beech-maple type varied from 6 to 43 per cent. Because interception losses vary with storm size, percentages derived in one area are inapplicable to areas having different storm size distribution. Furthermore, statements of experimental error are not possible in percentage estimates unless tied to specific storm size class intervals.

Regression, on the other hand, describes the relation between gross rainfall and interception parameters over the entire range of storm size sampled. Because the relation of interception parameters and gross rainfall is independent of storm size, these results can be extended to other areas, provided prediction is restriced to storm sizes from which the relation was derived. The standard error of regression (Sy. x) also is useful, indicating reliability of the prediction equations.

HORTON's (1919) study of interception illustrated the superiority of regression over percentage analysis. This pioneer American effort should have provided ample precedent for use of regression analysis; unfortunately most American investigators failed to follow his lead. To illustrate, we (HELVEY and PATRIC, 1965) recently reviewed thirty-eight interception studies from the hardwood region of eastern United States. Of the twenty-four published studies containing interception data, only six reported the relation between gross rainfall and interception parameters as regression equations. The striking uniformity of these six equations led us to derive regressions from all available studies. Then it became inescapably apparent that interception losses varied within narrow limits for the entire hardwood region of eastern United States. It is quite possible that regression analysis of data from other countries will establish similar rainfall-interception relationships within regions of like vegetation.

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