METHODS FOR THE MEASUREMENT OF INFILTRATION

H. G. Wilm
(Presented in abstract by C. H. Diebold)

The measurement of infiltration has, in recent years, assumed increasing importance as a means of estimating the relative absorptive capacities of soils under different vegetal types or kinds of land-use. The utility of infiltration-criteria rests partly on the assumption that surface-runoff in any appreciable volume is deleterious and that it results in movement of soil and in excessive peak-rates of stream-flow. Based on this assumption, a land-use providing maximum infiltration-capacities may be considered optimum for retention and storage of precipitation. In hydrologic investigations, too, a knowledge of relative infiltration-indices may assist greatly in the synthesis of hydrographs, or in the estimation of expected rates of flood-flow in streams. In watershed-management studies, infiltration-indices obtained for soils under several types of plant-cover and land-use are helpful in providing a basis for judgment as to optimum watershed-conditions for water-yield and erosion-control.

Problems in the measurement of infiltration

In general, two distinct methods of attack have been applied to the appraisal of watershed infiltration-capacities. In the first, extensively used by hydrologists with varying success [see 3, 4, 5, 7, 12, 13 of "References" at end of paper], watershed infiltration-indices are obtained by analysis of stream-hydrographs. This method obviously provides indices only for complete drainage-units and often fails to lend itself to appraisal of the relative importance of various types of land-use in regulating infiltration.

The second general approach involves the use of artificially sprinkled plots with portable equipment [1, 2, 6, 8, 9, 10, 11]. Because of its inherent flexibility, this method may be easily disposed to fit any desired design for experiments or watershed-surveys. As frequently found in new investigations, a number of instruments have been devised for infiltration-studies, employing a wide variety of plot-sizes and methods of sprinkling. Two types of equipment (the Soil Conservation Service type-F and type-FA plots) are being widely used in flood-control surveys, although as yet no conclusive proof has been offered as to the advantage of these apparatus over other types.

Apparently, the dominant characteristic of plot-measurement of infiltration is its great variability. Even acknowledging the fact that plot-data must be relative rather than quantitative in nature, studies made in different regions, or with different instruments, show excessive variation and some discrepancies in results. Often, the variability of measurements even within a relatively homogeneous soil or plant-cover type is so great as to impose serious doubt upon the validity of average infiltration-indices.

Objectives of the investigation

In order to provide at least a partial solution to problems in the measurement of infiltration by sprinkled plots, this series of experiments was designed to accomplish three specific objectives: (1) To determine the relative reliability of various instruments in common use; (2) to evaluate the comparative importance of various factors such as "rainfall"-intensity, soil-temperature, and characteristics of the soil and plant-cover which might logically be expected to influence infiltration; (3) to suggest efficient methods of attack for future experiments or surveys, which should successfully isolate and control at least the more important sources of variation, and should provide maximum accuracy and efficiency in the appraisal of infiltration as measured by sprinkled plots.

It is recognized that, under the first two of these objectives, any single investigation may yield results of only local application. Since, however, this study is rather new in conception as applied to its particular field, even the general trends which have been discovered, together with the universally applicable principles of experimental design, may prove to be of justifiable value to future workers in the field of infiltration.

Scope of experiments

Location--All experimental work was done during the summer of 1940 in a valley of the Rocky Mountain Front Range, about 27 miles northwest of Colorado Springs, Colorado. The area studied is part of the Manitou Experimental Forest, a research center for investigations in watershed- and range-management maintained by the Forest Service. The valley, about 7,600 feet in elevation, is relatively gentle in topography, with slopes varying from two to 35 per cent or occasionally more. Although naturally range-land, covered with a native growth of bunchgrass (Muhlenbergia montana and Festuca arizonica) and associated species, much of the area has been cultivated.

In general the soils, derived from Pikes Peak granite, Sawatch sandstone, and Manitou limestone, are very coarse and gravelly. Partly because of their high feldspar-content, however, the content of coarse gravel is much reduced by continuous cultivation and exposure to weathering. Where vegetation is thin or absent and soil-losses have occurred, a distinct "erosion-

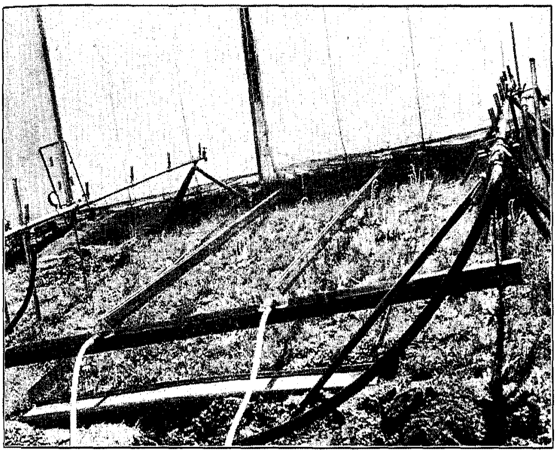

Fig. 1--Modified type "F" plot, with trough rain-gage in place [Runoff is collected in the covered trough (foreground) and conveyed to a collector tank]

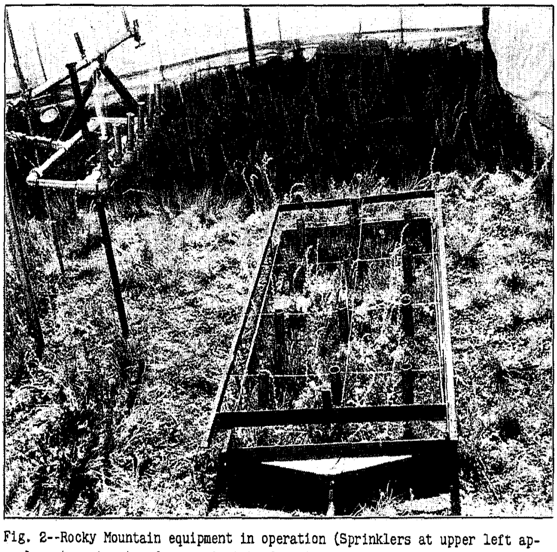

Fig. 2--Rocky Mountain equipment in operation (Sprinklers at upper left apply water at rate of approximately four inches per hour, measured in battery of 12 small rain-gages; runoff is collected at nearest end of plot)

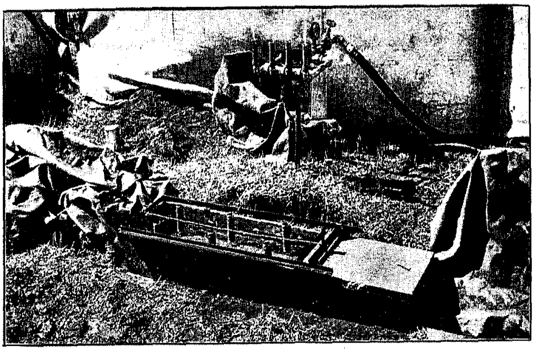

Fig. 3--Modified North Fork plot in an abandoned field [Sparseness of vegetation is in marked contrast to conditions in valley bunch-grass (Fig. 2)]

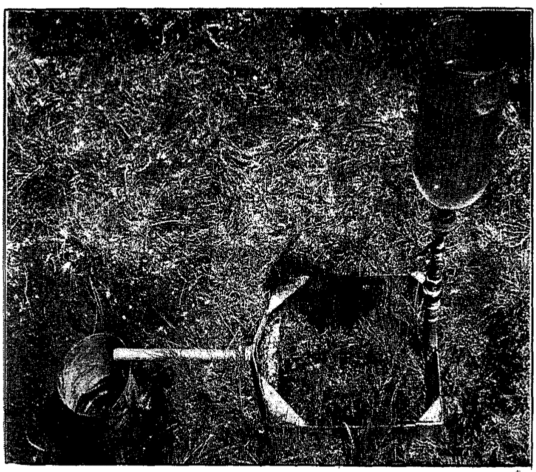

Fig. 4--Square-foot plot, with water applied through perforated pipe along right edge of frame; runoff is collected at the left

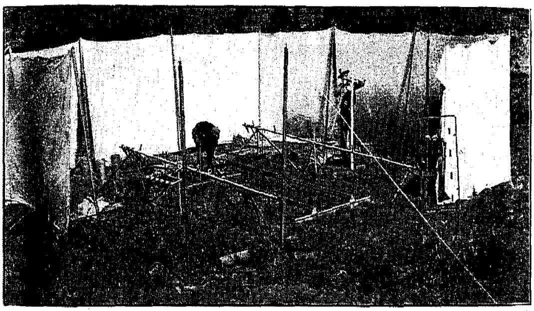

Fig. 5--General view of single group of infiltration-plots, set up in valley bunch-grass type (Arranged from left are a Rocky Mountain plot, a type "F" plot, and modified North Fork equipment; the square-foot plot is not visible; when closed, the canvas shelter gave adequate protection from ordinary winds)

pavement" of coarse gravel often occurs on the soil-surface.

The climate is typical of the mountainous Front Range of Colorado. About 80 per cent of the yearly total precipitation falls between April and September 30--most of this amount in the form of rain and often in storms of high intensity.

Instruments studied

Five types of instruments were employed, each of which has been more or less commonly used for the measurement of infiltration:

(1) Type-F infiltrometer (modified)--Specifications were obtained from the Soil Conservation Service for this type of equipment, and modified slightly in construction. The plot-frame is 6.6 by 12 feet in dimensions (Fig. 1). Rainfall was measured in two trough gages, each 12 feet long and one inch wide, placed parallel to the long axis of the plot and along lines bisecting the right and left halves of the plot. This method was considered to provide improvement over the use of pans or tarpaulins for measuring precipitation before and after each infiltration-test, which fail to give a record of water actually applied during the test. Water was applied by a motor-driven pump through 13 type-F sprinklers, placed according to Soil Conservation Service specifications. Runoff-water, passing through a screened collector trough, was measured by an electric point gage in a calibrated container.

(2) Rocky Mountain infiltrometer--This plot is bounded by a rigid, non-adjustable frame, 2 by 4 feet in dimensions (Fig. 2). Water was applied by three type-F sprinklers, from the same pump which furnished precipitation for the type-F and modified North Fork equipment. After some experiments with methods for measuring precipitation-rates, a group of 12 circular rain-gages was adopted, providing a rainfall-sample of one per cent of the plot-area. These cans, each one inch in diameter (inside) and four inches tall, were strung on wires tightly drawn over an angle-iron frame. The frame and gages were available in duplicate, to facilitate rainfall-measurements by alternate use during a test-run. The catch in all gages was read in a single graduate, to provide an average rainfall-figure for the plot. Runoff passed through a collector trough into an eight-inch collector can; volumes were measured in a 1,000-cc glass graduate.

(3) Modified North Fork equipment--This plot resembles the Soil Conservation Service type-FA infiltrometer, with an area of 2.5 square feet (Fig. 3). Water applied through two type-F sprinklers was measured by means of six rain-cans, each one inch in diameter; runoff was measured in 1,000-cc graduates.

(4) Pearse square-foot apparatus--As indicated in Figure 4, this equipment consists of a light frame one foot square, with a runoff-plate along the lower edge. Water was applied from a graduated container to the upper edge of the plot through a perforated pipe. Water applied and runoff were measured in cubic centimeters.

Organization and field-procedure

The whole series of field-experiments was divided into two main steps, preceded by a careful calibration of all plot-equipment, including a study of the accuracy of rain-gages used to measure "rainfall", or the volumes of applied water. The first actual study of infiltration (hereafter called "initial study") included measurements by all four instruments discussed above, taken on 30 different sites in the bunchgrass cover-type. While the four types of equipment were grouped together at each site in order to minimize environmental variation within the site, local variation was subjected also to statistical control by measurement of a number of concomitant factors: "Rainfall"-intensity; soil-temperature during the test; ground-slope; plant-cover density; and gravel-content of the soil. All tests were made on "wet" soil; four hours before the experimental run on each site, the whole area was sprinkled for 15 minutes at a rate of four inches of rainfall per hour. All equipment was protected from wind by a canvas shelter (Fig. 5). In each run, water was applied for 50 minutes at a rate of approximately four inches per hour, with measurements of rainfall and runoff at ten-minute intervals.

Finally, a second complete infiltration-experiment was conducted to check the results of the initial study. In this case, for the sake of compactness, only the three smaller infiltrometers were used, and variability within each site was controlled by replication of each method in a 3 by 3 "Latin square" [14] on each study-site. By the use of Latin squares, even the natural variations within a single site could be partly isolated; since each infiltration-instrument occurred once in each row and column of each square, any differences in infiltration between rows or columns were free of instrumental variation and represented only variability of site. In this final study, measurements were taken on six sites in each of two plant cover-types, including abandoned agricultural fields as well as the bunchgrass-type. All sites were chosen on a ground-slope of 15 per cent. Again, a group of concomitant factors was measured to provide statistical control of otherwise unregulated variants. In the field-work, one whole row was tested simultaneously, with water applied for 50-minute intervals; all three rows in a single site were run in one day. After each day's tests, a new site was laid out and wetted by sprinkling, as in the first infiltration-study. All other field-procedure resembled that for the initial study, except that soil-samples were taken for volume-weight determination as well as for gravel-content. The volume-weight samples were obtained by driving a four-inch steel cylinder into the soil, removing its soil-contents, and measuring the excavated volume by refilling the cavity with a measured quantity of sifted, dry sand. Four samples were taken in each Rocky Mountain plot, two in the North Fork plot, and one in each square-foot plot.

Characteristics of data

Rainfall--The figures used in analysis were those secured during the last 20 minutes of each 50-minute infiltration-test. Based on results of the preliminary rain-gage calibration, rainfall-data for the Rocky Mountain and North Fork plots were corrected for consistent deviation of rain-gage measurements from the total volumes of water applied. All values were expressed in inches per hour.

Infiltration--Data for this variable were obtained by subtracting runoff during the last 20 minutes from the volume of water applied during the same period, after correcting for "lag". The resulting figures were expressed in inches per hour.

Soil-temperature--These values were average temperatures in degrees Fahrenheit, taken one-half inch below the soil-surface on each plot during the last 20 minutes of each test.

Gravel-content of soil--For each combined sample on each plot, a sieve-analysis was used to determine the percentage of the total oven-dry sample composed of particles larger than 0.149 mm.

Volume-weight of soil--Used only in the Latin-square study, these data were the oven-dry weights of samples taken for each instrument, expressed in grams per cubic centimeter of original volume.

Plant cover-density--On each plot, the total density of living and dead organic material was estimated ocularly, and expressed as a percentage of the total plot-area.

Ground-slope--In the initial study, the slope of each plot was expressed in per cent; all plots were established on a slope of 15 per cent in the Latin-square study.

Results and discussion

The data for both studies were analyzed by the methods of variance and covariance [14], accompanied by examination of simple and adjusted averages and statistics of variation.

When average infiltration-rates obtained by the various infiltrometers are compared (unadjusted averages in Table 1), the immediate impression is one of striking variability between methods, and even between results obtained in the two separate studies for any single method. Since no absolute value of infiltration can be known for the soil on which these tests were made, the amount of variation observed among the methods can only result in a feeling of uncertainty as to the validity of any of the results. When, however, consideration is given to the natural heterogeneity of any soil, it is apparent that this factor alone may induce variability in results, since even a single type of instrument used on different sites is exposed to variations in soil-permeability. A comparison of different instruments is exposed to similar discrepancies; any indicated difference between infiltrometers must include some variation of site as well as actual differences between methods. The variability of infiltration from site to site is clearly shown by the "mean squares" for each of the instruments in the initial study (Table 2). From these data--the squared standard deviations for each method--can be computed their standard deviations, the standard errors of averages obtained with any number of observations, or the number of plots needed to provide any desired standard of accuracy. For the purpose of this study it is unnecessary to go beyond the mean squares themselves, however, as these statistics express directly the relative variability of the several infiltrometers. The Rocky Mountain and modified North Fork instruments are approximately equal in variability, for example, while the square-foot plot is about 3-1/2 to 4 times as variable as the other two methods. In other words, four times as many square-foot plots are needed to provide averages as "reliable" as those ob-

Table 1--Average infiltration-rates by four infiltrometers

Method	Initial study		Latin-square study[a]	
	Unadjusted, inch/hour	Adjusted, inch/hour	Unadjusted, inch/hour	Adjusted, inch/hour
Type "F"	2.793	3.513	.....	.....
Rocky Mountain	2.110	2.110[b]	1.471	1.754
Modified North Fork	1.781	2.463	1.636	1.931
Square-foot	3.115	1.746	2.113	1.534

[a]Average values for both plant-cover types.

[b]Not adjusted for concomitants, as none proved significant for this method in the initial study.

Table 2--Relative errors in measuring infiltration by four methods (Initial study)

Method	Mean squares for error	
	Unadjusted	Errors of estimate
Type "F"	0.4516	0.2570
Rocky Mountain	0.7157	0.7157[a]
Modified North Fork	0.6416	0.3166
Square-foot	2.5760	1.0231

[a]The non-significant regression for this instrument accomplished no reduction in error, so that this figure is the unadjusted mean square.

tained by any given number of North Fork plots.

In examining this variability, both within and between infiltrometer-types, it is of fundamental interest to consider its causes. If all methods showed uniform variation between sites and no great discrepancy between averages, it might--perhaps erroneously--be assumed that all of the variance is due to variability of site, and none to instrumental errors. Then any indicated differences in average infiltration between instruments could be charged to variations in sampling the "universe" of infiltration in the soil involved. If this were the case, the differences between averages should not be significantly greater than the standard errors of the differences. Computation of the variance between instruments demonstrates, however, that the unadjusted average infiltration-rates for the several infiltrometers actually do differ significantly among themselves as shown by Tables 3 and 4. In these Tables, the significance of comparisons is shown by the ratios between the variances of comparisons and the "error" mean squares [14].

A certain, as yet poorly defined, amount of variability, then, must be charged to the individual instruments themselves, since they disagree even in sampling the same sites in the same general soil and cover-type. But what causes this variation; is it attributable to any factors inherent either in the instrument or in the environment, which can be subjected to control? Since several possible factors were measured in the field-work, perhaps this question can be partially answered by further analysis of results.

Table 3--Variance of infiltration as measured by four methods (Initial study)

Source of variation	Degrees of freedom	Mean squares
Total	119	1.3684
Between means of		
Infiltrometers	3	11.2389[a]
Sites	29	2.4312[a]
Interaction (error)	87	0.6738

[a]Highly significant ($p < 0.01$).

Accordingly, the next logical step was to segregate the individual influences of all controlled factors, and to calculate a new set of average infiltration-rates, adjusted to average values of all important associated factors.

In the initial study, this was accomplished by computing the multiple covariance of average infiltration by the four instruments on factors such as rainfall-intensity, soil-temperature, and the other measured concomitants. Of these, only rainfall-intensity was found to exert a significant influence; and soil-temperature, although not statistically significant, showed

Table 4--Variance and covariance of infiltration as measured by three instruments

Source of variation	Average infiltration[a]		Errors of estimate[b]	
	Degrees of freedom	Mean squares	Degrees of freedom	Mean squares
Total	107	0.4370	105	0.3147
Between means of				
Instruments	2	4.0018[c]	2	0.2900
Squares = 11 D/F				
Plant types	1	2.6499	1	0.4805
Sites within types	10	0.9721	10	0.7392
Rows within squares	24	0.4128	24	0.2522
Columns within squares	24	0.2717	24	0.2131
Interaction (instruments x squares; experimental error)	22	0.2446	20	0.2280
Internal error	24	0.1905	22	0.1636

[a]These mean squares express the relative amount of variation isolated by each factor, unadjusted for regression.

[b]Residual errors, after adjusting for the regression of infiltration on rainfall-intensity and soil-temperature. The regression-coefficient for rainfall ($b_{y1.2}$) is +0.3129; for soil-temperature ($b_{y2.1}$), it is +0.0076.

[c]Highly significant ($p < 0.01$).

trends strong enough, and sufficiently consistent, so that it was considered worth while to include this factor in further analyses. Significant differences were again found between adjusted average infiltration-rates measured by the four infiltrometers ($F = 13.01$). Since regressions for individual instruments might also be expected to differ from one based on the average of all instruments, individual regressions were computed for each type of infiltrometer. As these were actually found to differ significantly from the average regression, the formulas obtained for each instrument were used in obtaining adjusted averages and errors of estimate (Tables 1 and 2).

A similar procedure was followed for the Latin-square study, with the additional feature that errors were further reduced by isolating variance due to plant-type, site, and variation within site, expressed by the variance between rows and columns within each Latin square (Table 4).

Considering first a comparison of the unadjusted and adjusted values for each method in both studies (Table 1), an exceedingly interesting fact becomes apparent. Obviously the concomitant factors must have exerted an appreciable influence on measured infiltration, as the new averages are in general rather different from the unadjusted means. This fact is important; it means that unadjusted averages should not be used in comparing different "populations" of infiltration, wherever any concomitant factors may be expected to exert a substantial influence.

As to differences between individual instruments, the adjusted average infiltration measured by the type-F plot is much higher than rates shown by the other three instruments; the square-foot plot shows relatively low rates; and the other two instruments agree very well with each other in both studies.

Another result of consequence is shown in the statistics of variance and covariance. In Table 2, for instance, isolation of the influences of rainfall-intensity and soil-temperatures--especially rainfall--is shown to have materially reduced the errors of the initial study. For the type-F plot, the "error" mean square was reduced by regression from 0.452 to 0.257; in other words, the precision of measurements by this method was almost doubled by placing concomitant factors under statistical control. It would be difficult to overstate the importance of this fact to field-workers in infiltration.

The profits involved in experimental and statistical control of variables are even more strongly presented by statistics of covariance for the Latin-square study (Table 4). In this analysis the data for all three types of apparatus were combined to demonstrate the isolation of a number of components of variation.

As a first step, the Latin-square data were analyzed by variance alone; the results are shown under "Average infiltration" in Table 4. From the total variation in the study (mean square = 0.4370, standard deviation = ±0.661 inch per hour) were extracted the variances due to instruments, plant-types, sites within types, rows and columns, the interaction between instruments and squares, and internal error. The experimental error (interaction) was much reduced by this means (to 0.2446), and the variation between instruments was shown to be significant. When regression alone was applied to the total variance, a material reduction in error was found (from 0.4370 to 0.3147)--even without extracting the discontinuous components of variation. Finally, as might be expected, a minimum figure for "error" was reached (0.2280, standard deviation = ±0.477 inch per hour) by a combination of variance and regression in an analysis of covariance.

Comparing adjusted infiltration-averages and statistics of variance and covariance for the Latin-square study, it will be seen that the use of regression has resulted in a great reduction in differences between instruments. For unadjusted averages, the variance between infiltrometers was significant and quite large (F = 16.36); when the means were adjusted for the influence of rain-intensity and soil-temperature, however, the differences became so much smaller that they were no longer significant (F = 1.27). This considerable reduction of error by the measurement and analysis of concomitant factors which influence measured rates of infiltration is of particular importance to the design of infiltration-surveys. As shown by the data in Table 4, apparently most of the variance of unadjusted averages, for other factors as well as for instruments, was associated with variations in rainfall-intensity and soil-temperature. When measured rates of infiltration were adjusted to average values for these concomitant factors, most of the differences between instruments and plant-types were removed; and even the differences between sites and between rows and columns within squares were reduced. As a result, it is evident that the use of unadjusted averages may not only be accompanied by excessive computed errors, but may also indicate fictitious differences between cover-types or other factors which are the principal object of investigation.

Conclusions

By means of the group of studies which has been described and analyzed above, it is hoped that several useful facts have been demonstrated.

In the first place, infiltration-rates are characteristically variable. Judging from the relative magnitudes of measured variances of adjusted averages, the largest part of this variation occurs between sites in a single plant-type, and a smaller amount of variation may be charged to errors of instruments and technique.

As to the instruments themselves, any of the four infiltrometers can be expected to give only relative estimates of true infiltration. For some reason, perhaps associated with differences in distribution of applied water, the type-F instrument gave results higher than rates obtained with the three smaller instruments, which agreed relatively well among themselves. It is believed, however, that any of these four infiltrometers should give satisfactory estimates of relative infiltration-rates.

Perhaps the result of greatest consequence in this investigation is its demonstration of the reduction of experimental errors by the measurement and analysis of important concomitant factors. In this particular environment and of all the factors measured, rainfall-intensity appeared to exert the greatest influence upon infiltration. In other regions, other factors may be found important; in any case, it is imperative that measurements be taken of all significant variables, in every study of survey of infiltration. By a relatively small amount of additional field-work on each plot, the errors of individual measurements may be so greatly reduced that actually less plots may be needed for the whole survey than would otherwise be required; and the results will actually exhibit a materially greater degree of reliability.

Acknowledgment--Sincere acknowledgment is made for the aid of staff members of the Rocky Mountain Forest and Range Experiment Station, and for invaluable assistance in computations and analysis by Work Projects Administration Project No. 4294.

References

[1] E. L. Beutner and others, Sprinkled-plot runoff and infiltration-experiments on Arizona desert soils, Trans. Amer. Geophys. Union, pp. 550-558, 1940.

[2] Central States Forest Experiment Station, Infiltration studies, St. Francis Watershed, Missouri, mimeo., 1940.

[3] W. W. Horner and C. L. Lloyd, Infiltration-capacity values as determined from a study of an eighteen-month record at Edwardsville, Illinois, Trans. Amer. Geophys. Union, pp. 522-541, 1940.

[4] R. E. Horton, The role of infiltration in the hydrologic cycle, Trans. Amer. Geophys. Union, pp. 446-460, 1933.

[5] R. E. Horton, Surface runoff phenomena: Part I--Analysis of the hydrograph, Horton Hydrologic Laboratory, Pub. 101, 1935.

[6] R. E. Horton, Analysis of runoff-plot experiments with varying infiltration-capacity, Trans. Amer. Geophys. Union, pp. 693-711, 1939.

[7] R. E. Horton and R. Van Vliet, Determination of areal average infiltration from rainfall and runoff data, U. S. Dept. Agric., Office of Land Use Coordination and Flood Control, mimeo., 1940.

[8] G. W. Musgrave, The infiltration capacity of soils in relation to the control of surface runoff and erosion, J. Amer. Soc. Agron., v. 27, No. 9, pp. 336-345, 1935.

[9] G. W. Musgrave and G. R. Free, Some factors which modify the rate and total amount of infiltration of field soils, J. Amer. Soc. Agron., v. 28, No. 9, pp. 727-739, 1936.

[10] P. B. Rowe, The construction, operation, and use of the North Fork infiltrometer, U. S. Dept. Agric., Flood Control Coord. Com., Misc. Pub. 1, 1940.

[11] A. L. Sharp and H. N. Holtan, A graphical method of analysis of sprinkled-plot hydrographs, Trans. Amer. Geophys. Union, pp. 558-570, 1940.

[12] L. K. Sherman, The Horton method of determining infiltration-rates, Trans. Amer. Geophys. Union, pp. 312-316, 1936.

[13] L. K. Sherman, Deviation of infiltration-capacity from average loss-rates, Trans. Amer. Geophys. Union, pp. 541-550, 1940.

[14] G. W. Snedecor, Statistical methods (third edition), Iowa State College Press, 1940.

Rocky Mountain Forest and Range Experiment Station,
Fort Collins, Colorado