Purchased By
U. S. Department of Agriculture
For Official Use

Some Limitations on Estimates of Infiltration as a Basis for Predicting Watershed Runoff

R. B. Hickok and H. B. Osborn
Life Member ASAE Member ASAE

NUMEROUS hydrology research workers have been engaged for over thirty years in collecting field and laboratory data and, more recently, in developing physical and mathematical models for estimating the infiltration characteristics of soils. Much of this effort has been expended with the hope of being able to predict watershed rainfall-runoff relations.

This phase in the development of watershed hydrology may be regarded as having been inspired by Robert E. Horton in his classic paper in 1933, entitled "The Role of Infiltration in the Hydrologic Cycle" (1)*. Horton referred to infiltration as the physical processes by which rain enters the soil and he introduced the concept of "infiltration capacity" which he defined as: ". . . the maximum rate at which rain can be absorbed by a given soil when in a given condition."

What probably made this concept so attractive to the ensuing generation of hydrologists was that it introduced the notion of a hydrologic *system*, which could be considered in its parts. Horton described the role of infiltration in the system as follows:

> "Infiltration divides rainfall in two parts, which thereafter pursue different courses through the hydrologic cycle. One part goes via overland flow and stream channels to the sea as surface runoff; the other part goes initially into the soil and hence, through groundwater flow into the stream, or else is returned to the air by evaporative processes. The soil therefore acts as a separating surface, and the author believes that various hydrologic problems are simplified by starting at this surface and pursuing the subsequent course of each part of the rainfall so divided, separately. This has not hereto generally been undertaken."

Hydrologists since Horton have labored to enumerate watershed operational functions on the basis of the concept that infiltration divides rainfall into two parts, which thereafter pursue distinct and readily discernible courses through the hydrologic cycle. And a major part of the hydrology research effort for more than 30 years has gone into attempts to evaluate infiltration capacities of differing soils, sometimes termed "rain site" classes, and to translate these capacities into predictions about the runoff behavior of watersheds.

Most of us are now aware of some difficulties in attempting to arrive at meaningful infiltration values for a watershed, and many are familiar with difficulties encountered in predicting such values even for a single soil having a simple profile. Horton's concepts were unrealistically simple and perhaps now, after more than 30 years and with a continuing need to improve our basis for hydrologic designs, it is time to take a new look at these concepts and to see if, in the present or future, more sophisticated studies of infiltration processes can in fact result in "refinement" of runoff prediction.

Soil-Infiltration Relations

First, let us look at some of the relatively simple problems of understanding how infiltration works even on a small area of uniform soil. Horton stated:

> "The surface of a permeable soil acts like a diverting headgate in a stream where the headgate can be opened to a certain width only or closed so as to still leave a fixed opening. With varying rates of flow in the stream all the flow is diverted up to and within capacity of this opening. Similarly, with varying rain intensity all the rain is obsorbed for intensities not exceeding the infiltration capacity, while for excess rainfall there is a constant rate of absorption as long as the infiltration capacity is unchanged."

Thus it seems that the problem is to determine what the size of the opening of the headgate will be at various places and under varying conditions; but this is only part of the problem. We have long known that certain flaws exist in such an analogy, and these have imposed serious limitations on the results of the numerous efforts made to quantify related hydrologic phenomena based on this concept.

Possibly a better (but still very rough) analogy for rain entering a soil surface would be that of water falling on and flowing over the open ends of a closely packed mass of very small diameter vertical tubes or pipes with relatively wide undulating variation in elevation of the surface described by their upper ends. Considering this analogy, it is apparent that the rate at which water may flow into the pipes depends not only on their size, but also on whether the rate of supply is such as to cause ponding over all or only some of their open ends, as these openings are at various elevations. Also, the condition of the entrances to the pipes may vary considerably with rainfall intensity, antecedent moisture, and season. And, at the same time water is entering these pipes, there is a reverse flow of gas that is being displaced by the entering water. This escape of gas in the opposite direction has some effect on the capacity of the system to accept the inflow of water. This gas flow too is affected by rate of rain supply, as related to microrelief and corresponding portion of the soil surface covered with water.

In a series of three papers in 1963 and 1964 by Rubin and Steinhardt, and Rubin, Steinhardt and Reiniger, the dependence of infiltration on rainfall is demonstrated by laboratory experimental results and a mathematical model (2, 3). In their final paper, these authors state that the amount of rainfall entering the soil prior to the onset of ponding on the surface (a requisite for runoff) was a function of the rainfall intensity, and that in general these soil intakes increased with decreasing rain intensity (4). They state further that water intakes at the commencement of incipient ponding were considerably lower than those under complete flooding of the soil surface.

Numerous writers have pointed to the influences also of vegetative soil cover on infiltration. Woodward observed a general increase in both the initial and the final infiltration capacity

Paper was prepared expressly for publication by the American Society of Agricultural Engineers in the TRANSACTIONS of the ASAE. Approved as a contribution of the Southwest Watershed Research Center, Soil and Water Conservation Research Division (ARS), U. S. Department of Agriculture, in cooperation with the Arizona Agricultural Experiment Station, Tucson.

The authors—R. B. HICKOK and H. B. OSBORN—are, respectively, private consultant, land and water resources development and management planning specialist formerly director, Southwest Watershed Research Center (SWCRD, ARS), U. S. Department of Agriculture, and research hydraulic engineer, southwest watershed research center (SWCRD, ARS), U.S. Department of Agriculture.

* Numbers in parentheses refer to the appended references.

Reprinted from: TRANSACTIONS OF THE ASAE, Vol. 12, No. 6, 1969
Published by American Society of Agricultural Engineers, St. Joseph, Michigan

with increased plant cover (5). Harrold reported that, in areas where much of the ground was covered by plants, organic litter on the soil surface was the main site variable affecting rain infiltration (6). Kincaid, Gardner, and Schreiber showed that the time required to infiltrate ½ in. of water in infiltrometer experiments on dry soil plots was closely associated with the total soil cover, including a canopy of shrubs, half-shrubs, grass, litter, and "erosion pavement" (7). Their data indicated that the initial infiltration capacity is largely controlled by conditions at or above the soil surface. This characterizes the influences on infiltration associated with short-duration, intense rainfall, which constitutes practically the total source of surface runoff in the arid southwestern United States.

At this point let us recall the definition for infiltration capacity under consideration here: that is, the maximum rate at which soil in a given condition can accept rain. This should not be confused, as it often is, with the capability of the soil column to transmit water to lower depths. It is only in those limited cases where infiltration capacity and transmission capacity of the soil column are equal that the laws of diffusivity can properly be applied to the estimation of infiltration capacity. Few would argue, we think, that the diffusivity laws controlling the potential movement of the moisture through a soil underlying a concrete pavement would have much to do with infiltration into that soil. While this is an extreme example, some degree of sealing of the soil surface is commonly involved. This sealing is due to the impact of rainfall causing dispersion of the fines, which enter and clog the surface pores, as well as to the swelling of clays near the surface on wetting. Wetability is also a factor affecting the entrance of water into the surface of some coarse-textured soils.

On the other hand, the transmission of water downward through the soil profile may be limited by some relatively impermeable stratum below the surface. In such cases the intake rate of the soil column becomes practically limited to the permeability of this impeding stratum once the storage above that level is filled. This case is unusual for the short-duration thunderstorm rainfalls in arid regions, but is more common in humid regions.

Watershed Performance in Relation To Onsite Infiltration

Up to this point we have considered only the problems involved in estimating the infiltration capacity of a relatively uniform rain site. Now let us consider also the problems of estimating the net infiltration for a conglomeration of surface and subsurface conditions, which is characteristic of most any watershed with an area of more than a few square feet.

Musgrave and Holtan, in their chapter on infiltration in the "Handbook of Applied Hydrology," present comparisons of actual values of runoff from small watersheds with synthesized values based on representative infiltrometer data (8). For a small watershed near Edwardsville, Ill., with no *return flow*, the comparison was good; however, for another watershed having quick return flow of soil water to the surface, the runoff synthesized from infiltrometer data was substantially low. The authors suggest that return flow is not reflected by small-plot data. This is perhaps the greatest hazard in applying such data to watersheds in the more humid areas.

They also report on a companion study near Colorado Springs, Colo., where substantial *runoff transmission losses* occured under semiarid conditions. In this case the losses in swales and channels reduced the sidehill runoff by two-thirds before it reached the watershed gaging station. They state that these losses were essentially accounted for by applying the infiltration capacity as measured by the type F infiltrometer to the area of the swales, for the duration of runoff.

Studies by Kincaid et al on the Walnut Gulch watershed in Arizona indicate that a substantial portion of the infiltration on semiarid watersheds at only a short distance from the drainage divide may be the runoff from above (7). In such cases the summation of the weighted-infiltration values determined on small sample plots, deducted from the total precipitation input to the watershed, would not yield even the approximate runoff. If there is further substantial losses from the runoff after the flow has concentrated in swales and channels, as in the case of the Colorado watershed reported by Musgrave and Holtan, the problem of estimating the net watershed runoff by means of infiltrometer or any small-plot data becomes complex indeed.

Thus, there are very definite limitations to the direct application of small runoff plot or infiltrometer data in estimating watershed runoff. Such use of this type of data may be meaningful in situations where rains are of low intensity and water once infiltrated into the soil remains underground and none reappears as quick return runoff on the surface at lower elevations; and where no part of the water that leaves the rainfall site as runoff subsequently enters the soil at some lower elevation. In humid climates, the interchange or "interflow" that may occur between surface runoff and water moving through the soil, between the headwaters and a second or third-order stream, so confounds the relationship between precipitation, infiltration, and surface runoff at the outlet of a watershed as to far remove it from the realm of simple arithmetic. In arid regions, the variations in high-intensity rainfall and the varying conditions of the soil surface limit the use of infiltration values for predicting runoff without adequate sampling to characterize the spectrum of conditions.

The Unit-Source Watershed

Where do we go for data which will reflect the effects of distinct conditions of soils and cover and management practices on the hydrologic behavior of a watershed to improve our watershed runoff prediction capability? The answer may lie in the unit-source watershed. Unit-source watersheds represent hydrologically unique and identifiable subsystems of surface and subsurface conditions occurring in some definite size, number, and location within the complex watershed system to be analyzed. Their combined runoff outputs, properly routed through the stream channels, do add up to the runoff of the total system.

Unit-source watersheds are the operators on both the on-site runoff and that portion of the rainfall initially infiltrated into the soil. Their functions of mixing, holding, and discharging these two fractions of the rainfall control the storm flow input into the major stream channels. In other words, the unit-source watershed is a mechanism which "bridges the gap" between the rain site (experimental runoff plot and infiltrometer data) and the hydrology of the complete surface watershed system with its multiple runoff sources and significant channel influences on the hydrograph.

These hydrologically distinct units of the total watershed may be characterized according to their soils, geology, cover, treatment, etc. Their rainfall-runoff relations may be estimated by comparison with similar unit-source watersheds or others whose behaviors have been measured and whose physical characteristics have been correlated with their hydrologic behavior.

The concept of unit-source watersheds is being used in studies on the 58-sq-mile Walnut Gulch experimental watershed in southeastern Arizona. In this region the size of unit-score watersheds is limited by the small areal extent of the runoff-producing thunderstorm (9). If the watersheds are too large, the problem of rainfall variability tends to overwhelm the problems of infiltration and antecedent moisture. Therefore,

unit-source watersheds on Walnut Gulch are restricted to no more than one mile in length and no more than ¼ sq mile in area.

Recently, we attempted to use antecedent moisture as a parameter in predicting runoff from LH-6, a small (one-acre) unit-source watershed within the Walnut Gulch watershed. There were nine runoff events on LH-6 in 1967. Rainfall and runoff were measured accurately with a 6-hr weighing-type recording rain gage and a metal 3-ft H-flume, respectively.

When rainfall volumes, intensities, and durations were compared with runoff peaks and volumes, certain patterns were observed (Table 1). First, we compared the maximum rainfall intensities with the peak discharges for each event. The highest rainfall intensity occurred on September 24 and produced the maximum peak discharge. The second highest peak (September 11) occurred from a much lower intensity, but this seemed logical since there was a significant runoff-producing event on the preceding day, which would have "charged" the watershed.

The third highest peak measured (July 31) resulted from a higher intensity than that on September 11. However, this storm followed a relatively dry period of 15 days, so less runoff would be expected. Just two days later, on August 2, a storm which produced the second highest rainfall intensity of the season, plus a greater volume of rainfall than July 31, produced a peak of only one-fourth that of July 31. Furthermore, on August 9, following seven dry days, a very low-intensity rainfall with only 65 percent of the volume of rainfall as on August 2 produced an identical peak discharge to that of August 2. All three storms, July 31, August 2, and August 9, were of short duration. Similar evaluations using volumes and durations of rainfall lead to the same contradictory results.

A researcher, after comparing these values, would probably go back to the original records to find the "error." When he found no error, which was the case here, he would then begin to search for the "answer."

Several limitations in using infiltration as a basis for predicting runoff led to the apparently contradictory results shown in Table 1. For one thing, the potential surface infiltration capacity, after some relatively short period, decreases with increasing dryness, rather than the reverse. This could account for the relatively high peak discharges after long dry periods. On the other hand, the channels and swales can hold more water, up to some point, as they dry out. Channel conditions seem to be more important than soil surface conditions for about one day after a runoff event; and surface conditions become more important after 2 or 3 days. Also, late in the season, infiltration and surface retention seem to remain higher after long dry periods than is the case earlier in the season. This may be due to plant growth. There is no interflow on this watershed.

Probably most important, as indicated in a recent paper by Schreiber and Kincaid, is that the highly variable thunderstorm rainfall tends to mask the effects of infiltration differences (10). They found that most of the variation in runoff from rangeland plots (6 ft x 12 ft) could be statistically explained by variations in rainfall intensity and that antecedent soil moisture conditions had no significant effect on runoff. It may be, therefore, that the variations in rainfall intensities for periods of less than 5 minutes, even on a small one-acre watershed, account for most of the variations in peaks and volume of runoff.

Due to incompletely understood complex processes involved in interflow and infiltration and difficulties in describing the highly variable rainfall input, we may not be able to mathematically model the physical functions of the unit-source watershed's subsystem precisely for some years to come. In the meantime, however, we can effectively employ the "black box" approach to whatever degree is necessary to represent their effect on overall behavior of the total watershed systems to be analyzed.

TABLE 1. PRECIPITATION-RUNOFF FROM A ONE-ACRE RANGELAND WATERSHED

Date of event	Volume of rainfall, in.	Duration of rainfall, min.	Maximum 5-minute intensity, in. per hr	Volume of runoff, in.	Peak discharge, in. per hr	Date of last previous appreciable rainfall	Volume of last previous appreciable rainfall, in.
7/9/67	0.32	22	2.04	0.001	0.01	7/5/67	0.14
7/16/67	0.48	68	1.20	0.009	0.05	7/15/67	0.40
7/31/67	0.38	22	1.86	0.020	0.23	7/27/67	0.20
8/2/67	0.43	26	2.16	0.011	0.06	7/31/67	0.38
8/9/67	0.28	18	1.38	0.006	0.06	8/2/67	0.43
9/10/67	0.59	70	2.10	0.019	0.19	9/1/67	0.41
9/11/67	0.62	44	1.56	0.064	0.30	9/10/67	0.59
9/24/67	0.43	18	2.76	0.076	0.91	9/11/67	0.62
9/25/67	0.20	18	1.62	0.005	0.03	9/24/67	0.43

Conclusions

The infiltration concept, when applied to a watershed, does not generally provide an adequate model of its rainfall-runoff relationship and, for important hydrologic design problems, may lead to unsatisfactory precision in prediction of runoff.

This is true partially because the relations and interrelations of the influences on infiltration of soil characteristics, microrelief, ground cover, and rainfall characteristics are extremely complex and have not been generally represented in mathematical models so far proposed. A second limitation on the usefulness of the infiltration concept is that it is built on the generally invalid assumption that the soil surface divides the rainfall into two parts, which thereafter pursue different courses throughout the hydrologic cycle. This assumption requires a homogeneity of watershed soils and geology which seldom exists in nature. It is because of this limitation that small-plot experimental data may not generally be directly "transplanted" by means of simple area conversion and summation to arrive at a value of the difference between the rainfall input and the surface storage and runoff output of a watershed.

We must develop, in our watershed hydrology research, the means for evaluating the interflows which commonly occur between surface and subsurface waters. Rainfall-runoff patterns which relate various combinations of geology, soils, vegetation, and management may be determined for characteristic unit-source watersheds as the smallest definitely bounded hydrologic subsystem from which the runoff can be simply related (by flow-routing procedures) to the runoff of the complex watershed system.

Apparent net *infiltration* of unit-source watersheds, as derived from analysis of their hydrographs, while not based on a truly valid physical concept, may provide a most useful index to quantify their *overall* operational characteristics and derive relationships of their hydrologic behavior to their measurable physical parameters. It should be clear, however, that such an index will not bear any simple, general relationship to their actual initial absorption of rainfall and thus cannot be synthesized simply from small runoff-plot, field infiltrometer, or laboratory infiltration measurements.

References

1 Horton, Robert E. The role of infiltration in the hydrologic cycle. Trans. A.G.U., 1933.

2 Rubin, J., and Steinhardt, R. Soil-water relations during rain infiltration: I. Theory. Soil Sci. Soc. Am. Proc. 27:1963.

3 Rubin, J., Steinhardt, R., and Reiniger, P. Soil-water relations during rain infiltration: I. Moisture content profiles during rains of low-intensity. Soil Sci. Soc. Am. Proc. 28: 1964.

4 Rubin, J., and Steinhardt, R. Soil-water relations during rain infiltration: III. Water uptakes at incipient ponding. Soil Sci. Soc. Am. Proc. 28: 1964.

5 Woodward, Lowell. Infiltration capacities of some plant-soil complexes on Utah range watershed lands. Trans. A.G.U. Part II, 1913.

6 Harrold, L. L., and others. Report of the Committee on Infiltration—1950-1951. Trans. A.G.U. 32: (6) 1951.

7 Kincaid, D. R., Gardner, J. L., and Schreiber, H. A. Soil and vegetation parameters affecting infiltration under semiarid conditions. Bul. of Internatl. Assoc. Sci. Hydrol. 65:440-453. 1964.

8 Chow, Ven Te. Handbook of applied hydrology. chapter 12—Infiltration by Musgrave and Holtan. McGraw-Hill Book Co., New York, N.Y., 1964.

9 Kincaid, D. R., Osborn, H. B., and Gardner, J. L. Use of unit-source watersheds for hydrologic investigations in the semiarid Southwest. Water Resources Research 2: (3) 381-392. 1966.

10 Schreiber, H. A., and Kincaid, D. R. Regression models for predicting on-site runoff from short-duration convective storms. Water Resources Research 3: (2) 389-395. 1967.