A Method of
Determining Surface Runoff
by "Routing" Infiltrated Water
through the Soil Profiles

Donald E. Whelan
Lemuel E. Miller
John B. Cavallero

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Donald E. Whelan, the senior author, is hydrologist in the Northeastern Forest Experiment Station. Lemuel E. Miller and John B. Cavallero, formerly with the Experiment Station, are now serving in the U. S. Corps of Engineers, Mr. Miller at Jacksonville, Fla., and Mr. Cavallero at Philadelphia, Pa.

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INTRODUCTION

TO DETERMINE the effects of watershed management on flood runoff, one must make a reliable estimate of how much the surface runoff can be reduced by a land-use program. Since surface runoff is the difference between precipitation and the amount of water that soaks into the soil, such an estimate must be based on the infiltration capacity of the soil.

In the past, infiltration rates have usually been calculated by means of an infiltrometer. This is a mechanical device that sprays water to simulate rainfall, at a fixed rate. The runoff can be measured, and infiltration can be calculated.

But use of the infiltrometer is very expensive in sampling a large number of soil and cover conditions. And the results of infiltrometer studies are difficult to interpret and use, because the infiltration rates obtained are valid only for the particular soil-cover complex on which the infiltrometer run is made.

So when the Northeastern Forest Experiment Station undertook a flood-control survey of the Allegheny River watershed, a better way was sought for obtaining data on runoff and infiltration. The result was a new method of determining infiltration, by "routing" infiltrated water through the soil profile.

With this method, the total infiltration and surface runoff can be determined for any soil profile, and for any rainfall pattern regardless of its variations in intensity and duration.

This method is especially well adapted for evaluating the hydrologic effects of a land-use program. It was used for this purpose in the flood-control survey.

DATA USED

In developing this method, a detailed hydrologic study was made of the storm and flood of July 17-18, 1942, on the headwaters of the Allegheny River in western New York and Pennsylvania. The watershed studied is that portion of the Allegheny River above Red House, N.Y.; its drainage area is 1,690 square miles.

Rainfall

The U. S. Weather Bureau (<u>8</u>)[1] stated in its report on this storm that the point-rainfall values were among the highest measured in the United States for durations of 24 hours or less. The maximum point-rainfall was estimated at 37 inches. Most of it fell within a 12-hour period. This

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[1] UNDERLINED NUMBERS IN PARENTHESES REFER TO LITERATURE CITED, PAGE 15.

storm consisted of a protracted period of recurrent thunderstorm activity.

Since the total storm rainfall over the area studied varied from about 3 to 37 inches, the rainfall was divided into 10 rainfall-depth classes. The average total storm rainfall was determined for each rainfall-depth class. The intensities of each rainfall-depth class were based on the recording rain gage at Smethport, Pa. The periods of uniform intensity varied from 2 minutes to 1 hour. The average total storm rainfall over the watershed above Red House was estimated at 8.5 inches.

Runoff

The U.S. Geological Survey (4) published in its flood report detailed discharge records on this watershed for the period July 18-29, 1942. From an analysis of the flood hydrograph, the flood runoff was found to be 3.1 inches; 2.1 inches of that was surface runoff and 1.0 inch was subsurface runoff.

The average amount of infiltrated water was therefore 6.4 inches, the difference between the total storm rainfall of 8.5 inches and the surface runoff of 2.1 inches.

Land-Use Inventory

The total amount of water that infiltrates into a soil profile during a storm depends upon the percolation rate, transmission velocity, and retention and detention storage values of each horizon in the soil profile (5). These values vary by soil-cover complexes, especially in the upper soil horizons.

Therefore a land-use inventory was made to determine the areal extent of each soil-cover complex (as classified below) and the average depth of its soil horizons. The horizons measured were the topsoil, B, and C in open land; and the humus, lower A, B, and C in woodland.

Open land was classified by land use and by kind of tillage: up-and-downhill or on the contour. Woodland was classified by humus depth and type, and by presence or absence of grazing. All areas were classified by soil texture and soil drainage.

The land-use inventory of the watershed was based on a random-plot-sampling method in which direct and stereoscopic interpretation of aerial photographs was used, supplemented by field examination (2).

Soil-Water Relationships

A study of soil-and-water relationships was made in the field simultaneously with the land-use inventory (6). Undisturbed soil samples--by horizons--were taken of the principal soil-cover complexes.

Samples were tested in a field laboratory to obtain percolation rates, transmission velocities, and retention and detention storage values for each horizon. Average values for each of these variables were determined for the individual horizons of each soil-cover complex. These values were applied to the respective areas of the soil-cover complexes as established by the land-use inventory.

Surface Detention Storage

Surface detention storage occurs whenever the rainfall intensity exceeds the percolation rate of the uppermost soil horizon. When the rainfall intensity is high and sustained enough to saturate the uppermost soil horizon, the percolation rate of the surface soil then becomes equal to that of the next horizon below that is not saturated.

The depth of surface detention depends on the type and density of the vegetal cover. For example, studies by the Soil Conservation Service indicate that soil with a cover of row crops has a surface detention storage of 0.02 inch when the crop rows run up-and-downhill; and 0.25 inch when they run along the contour.

In computations of surface runoff, this surface detention storage was considered instantly available for use whenever rainfall excess occurs. When the rainfall excess exceeds this storage, the difference becomes surface runoff.

However, water in surface detention storage infiltrates into the soil after subsequent drainage of the soil profile. In a severe storm of long duration, surface detention storage may be utilized over and over again because of the variation in rainfall intensities.

Retention And Detention Storage

Retention storage is the amount of water the soil can hold against the pull of gravity. Detention storage is the difference between saturation and retention storage.

The retention storage space that is available at any time depends on previous rainfall and evapo-transpiration. It is estimated that the retention storage was about satisfied at the beginning of this storm on July 17, 1942.

Water in retention storage is held in the smaller pore spaces and as a closely adhering film on the soil particles. One can expect any deficiency in retention storage to be satisfied first as the wet front moves downward.

Detention storage consists of the larger pore spaces through which water moves at the pull of gravity. Percolation rates and transmission velocities depend on the size, character, continuity, and amount of detention pore space (1).

Percolation Rate

Percolation rates of saturated soil samples were measured in the field laboratory. Since it was evident that these rates were higher than those that occur in the natural soil profile, these rates were reduced by trial-and-error methods until it was found that a factor of 2 would give a volume of surface runoff of 2.1 inches for the July 1942 storm on this watershed as estimated from the flood hydrograph.

A possible reason for this difference in percolation rates may be the method of measurement used in the laboratory. In testing the field samples, water was introduced at the top of the sample and free discharge of air and water was permitted at the bottom. In the natural soil profile, air is compressed as water infiltrates, and the air can escape only at the surface of the soil.

Transmission Velocity

Transmission velocity is the speed in inches per hour of the wet front as it moves down through the soil. The maximum velocity can be computed from the fundamental flow equation Q = AV, in which Q is the percolation rate, A is the percentage of pore space in detention storage, and V is the transmission velocity.

When the supply of water equals or exceeds the percolation rate and detention storage and percolation rate remain constant with an increase in depth, the transmission velocity of the wet front is constant. Any change in either detention storage or percolation rate as the wet front moves to a lower soil horizon, however, will be reflected in the transmission velocity.

When the rate of supply is less than the percolation rate, the transmission velocity varies directly as the rate of supply. In our computations the time of transmission through each horizon was used; it is equal to the depth of the horizon divided by the transmission velocity.

Subsurface Runoff

Subsurface runoff was considered on a watershed basis only and not by separate soil-cover complexes. Lateral drainage of the soil profile by subsurface flow makes it possible for additional water to be infiltrated into the soil profile. The effect of subsurface flow can be compensated for by increasing the percolation rates by the rate of contribution to lateral flow. This compensation is included in our factor for modifying percolation rates to agree with the flood hydrograph analysis.

THE 'ROUTING' PROCEDURE

The infiltrated water was "routed" through the soil by carefully accounting for the time stages in the movement of the wet front and the changes in water storage in each soil horizon. The computations were facilitated by considering detention storage, percolation rate, and time of transmission to have uniform values throughout each soil horizon.

As an example, the details of the "rooting" procedure are shown (table 1) for grazed woodland with mull humus and a medium-texture, imperfectly drained soil. The maximum storage capacity, percolation rate, and time of transmission for the different soil horizons were as follows:

	Retention storage (inches)	Detention storage (inches)	Percolation rate (inches/hr.)	Time of transmission (hours)
Surface	--	0.100	--	--
Humus	0.870	.378	15.10	0.023
Lower A	1.404	.740	6.50	.103
Upper B	1.490	.754	2.40	.305
Lower B	1.630	.426	1.40	.298
C	--	--	.30	--

Tabular Computation

The first line of table 1 shows that during the first period of uniform rainfall intensity (0.167 hour), 0.772 inches of rain fell at an intensity of 4.63 inches per hour. Since this intensity was less than the percolation rates of the humus (15.10) and the lower A horizon (6.50), this rain was infiltrated into those upper horizons as fast as it fell. But the upper B horizon had a percolation rate of only 2.40; so the water could infiltrate into this horizon no faster than the percolation rate.

At the end of this time increment, the humus had stored 0.106 inches of water. This was calculated as transmission time of the soil horizon (0.023 hour) times the rainfall intensity. The rest of the rainfall for this period flowed down into the lower A horizon.

Water flowed into the lower A horizon for a period of 0.144 hour. This was calculated as rainfall period (0.167) minus transmission time in the humus (0.023). Water flowed out of the lower A horizon for 0.041 hour--0.144 minus the horizon's transmission time, 0.103.

Since the percolation rate of the upper B horizon was less than the rainfall intensity, this percolation rate controlled the inflow to the upper B horizon. The percolation rate (2.40) times the length of time water flowed into the horizon (0.041) gave the amount of water that infiltrated into this horizon: 0.098 inch. All this was stored in this horizon.

Table I.--Computations used in 'routing' infiltrated water through the soil to determine surface runoff

(FOR GRAZED WOODLAND WITH MULL HUMUS AND MEDIUM-TEXTURE, IMPERFECTLY DRAINED SOIL)

RAINFALL			INFILTRATION						
Time increment	Rainfall intensity	Amount of rainfall	Surface			Humus			Lower A
			Inflow	Storage	Outflow	Accumulated time	Storage	Outflow	Accumulated time
Hours	Inches	Inches	Inches	Inches	Inches	Hours	Inches	Inches	Hours
0.167	4.63	0.772	0.772	--	0.772	0.167	0.106	0.666	0.144
.167	2.32	.387	.387	--	.387	--	.053	.440	--
.500	.91	.450	.450	--	.450	--	.021	.482	--
.167	.31	.052	.052	--	.052	--	.007	.066	--
.167	.23	.039	.039	--	.039	--	.005	.041	--
.083	1.69	.142	.142	--	.142	--	.039	.108	--
.583	.27	.154	.154	--	.154	--	.006	.187	--
.333	0	0	--	--	--	--	--	.006	--
.167	1.01	.167	.167	--	.167	--	.023	.144	--
.417	.06	.026	.026	--	.026	--	.001	.048	--
.250	.52	.129	.129	--	.129	--	.012	.118	--
.083	1.54	.129	.129	--	.129	--	.035	.106	--
.083	3.60	.296	.296	--	.296	--	.092	.239	--
.167	.47	.078	.078	--	.078	--	.120	.050	--
.333	.17	.013	.013	--	.013	--	.033	.100	--
.167	1.54	.257	.257	--	.257	--	.240	.050	--
.167	8.26	1.375	.288	.100	.188	--	.378	.050	--
.167	0	0	--	.050	.050	--	.378	.050	--
.033	12.75	.426	.060	.100	.010	--	.378	.010	--
.216	1.25	.270	.065	.100	.065	--	.378	.065	--
.250	1.75	.438	.075	.100	.075	--	.378	.075	--
.333	.04	.013	.013	.013	.100	--	.378	.100	--
.250	.05	.013	.013	--	.026	--	.329	.075	--
.083	.47	.039	.039	--	.039	--	.343	.025	--
1.667	0	0	--	--	--	--	--	.343	--
1.000	.05	.052	.052	--	.052	--	.001	.051	--
1.000	0	0	--	--	--	--	--	.001	--
1.000	.01	.013	.013	--	.013	--	--	.013	--
1.000	.04	.039	.039	--	.039	--	.001	.038	--
.333	.08	.026	.026	--	.026	--	.002	.025	--
.250	.52	.129	.129	--	.129	--	.012	.119	--
.167	1.54	.257	.257	--	.257	--	.035	.234	--
.083	3.09	.257	.257	--	.257	--	.071	.221	--
.167	.78	.129	.129	--	.129	--	.018	.182	--
.500	.10	.052	.052	--	.052	--	.002	.068	--
.167	2.00	.335	.335	--	.335	--	.046	.291	--
.167	.62	.103	.103	--	.103	--	.014	.135	--
.167	3.87	.643	.643	--	.643	--	.089	.568	--
.250	2.16	.541	.475	.100	.375	--	.378	.086	--
.167	0	0	--	.050	.050	--	.378	.050	--
.083	2.78	.232	.075	.100	.025	--	.378	.025	--
.083	.31	.026	.025	.100	.025	--	.378	.025	--
1.333	0	0	--	--	.100	--	.078	.400	--
.083	.31	.026	.026	--	.026	--	.079	.025	--
16.000	0	0	--	--	--	--	--	.079	--
1.000	.01	.013	.013	--	.013	1.000	--	.013	.977
1.000	.01	.013	.013	--	.013	--	--	.013	--
1.000	.01	.013	.013	--	.013	--	--	.013	--
1.000	.01	.013	.013	--	.013	--	--	.013	--
10.083	0	0	--	--	--	--	--	--	--
.083	.31	.026	.026	--	.026	--	.007	.019	.060
1.583	0	0	--	--	--	--	--	.007	--
.250	.62	.154	.154	--	.154	.250	.014	.140	.227
.417	.05	.026	.026	--	.026	--	.001	.039	--
.083	1.24	.103	.103	--	.103	--	.029	.074	.060
57.167	--	8.886	--	--	--	--	--	--	--

INFILTRATION (continued)										RUNOFF
Lower A		Upper B			Lower B			C	Total rainfall infiltrated	
Storage	Outflow	Accumulated time	Storage	Outflow	Accumulated time	Storage	Outflow	Storage		
Inches	Inches	Hours	Inches	Inches	Hours	Inches	Inches	Inches	Inches	Inches
0.568	0.098	0.041	0.098	—	—	—	—	0.585	0.772	—
.607	.410	.208	.499	—	—	—	—	.585	1.159	—
.377	.712	.708	.754	0.457	0.403	0.426	0.031	.616	1.609	—
.393	.050	—	.754	.050	—	.426	.050	.666	1.661	—
.384	.050	—	.754	.050	—	.426	.050	.716	1.700	—
.467	.025	—	.754	.025	—	.426	.025	.741	1.842	—
.479	.175	—	.754	.175	—	.426	.175	.916	1.996	—
.385	.100	—	.754	.100	—	.426	.100	1.016	1.996	—
.479	.050	—	.754	.050	—	.426	.050	1.066	2.163	—
.402	.125	—	.754	.125	—	.426	.125	1.191	2.189	—
.445	.075	—	.754	.075	—	.426	.075	1.266	2.318	—
.526	.025	—	.754	.025	—	.426	.025	1.291	2.447	—
.740	.025	—	.754	.025	—	.426	.025	1.316	2.743	—
.740	.050	—	.754	.050	—	.426	.050	1.366	2.821	—
.740	.100	—	.754	.100	—	.426	.100	1.466	2.834	—
.740	.050	—	.754	.050	—	.426	.050	1.516	3.091	—
.740	.050	—	.754	.050	—	.426	.050	1.566	3.379	1.087
.740	.050	—	.754	.050	—	.426	.050	1.616	3.379	—
.740	.010	—	.754	.010	—	.426	.010	1.626	3.439	.366
.740	.065	—	.754	.065	—	.426	.065	1.691	3.504	.205
.740	.075	—	.754	.075	—	.426	.075	1.766	3.579	.363
.740	.100	—	.754	.100	—	.426	.100	1.866	3.592	—
.740	.075	—	.754	.075	—	.426	.075	1.941	3.605	—
.740	.025	—	.754	.025	—	.426	.025	1.966	3.644	—
.583	.500	—	.754	.500	—	.426	.500	2.466	3.644	—
.334	.300	—	.754	.300	—	.426	.300	2.766	3.696	—
.035	.300	—	.754	.300	—	.426	.300	3.066	3.696	—
.001	.047	—	.501	.300	—	.426	.300	3.366	3.709	—
.004	.035	—	.236	.300	—	.426	.300	3.666	3.748	—
.008	.021	—	.157	.100	—	.426	.100	3.766	3.774	—
.054	.073	—	.155	.075	—	.426	.075	3.841	3.903	—
.157	.131	—	.236	.050	—	.426	.050	3.891	4.160	—
.249	.129	—	.340	.025	—	.426	.025	3.916	4.417	—
.080	.351	—	.641	.050	—	.426	.050	3.966	4.546	—
.010	.138	—	.629	.150	—	.426	.150	4.116	4.598	—
.206	.095	—	.674	.050	—	.426	.050	4.166	4.933	—
.211	.130	—	.754	.050	—	.426	.050	4.216	5.036	—
.729	.050	—	.754	.050	—	.426	.050	4.266	5.679	—
.740	.075	—	.754	.075	—	.426	.075	4.341	6.154	.066
.740	.050	—	.754	.050	—	.426	.050	4.391	6.154	—
.740	.025	—	.754	.025	—	.426	.025	4.416	6.229	.157
.740	.025	—	.754	.025	—	.426	.025	4.441	6.254	.001
.740	.400	—	.754	.400	—	.426	.400	4.841	6.254	—
.740	.025	—	.754	.025	—	.426	.025	4.866	6.280	—
—	.819	—	—	1.573	—	—	1.999	6.865	6.280	—
.002	.011	.874	.004	.007	5.69	.003	.004	6.869	6.293	—
.002	.013	—	.004	.013	—	.003	.013	6.882	6.306	—
.002	.013	—	.004	.013	—	.003	.013	6.895	6.319	—
.002	.013	—	.004	.013	—	.003	.013	6.908	6.332	—
—	.002	—	—	.006	—	—	.009	6.917	6.332	—
.019	—	—	—	—	—	—	—	6.917	6.358	—
—	.026	—	—	.026	—	—	.026	6.943	6.358	—
.064	.076	.124	.076	—	—	—	—	6.943	6.512	—
.005	.098	.541	.028	.146	.236	.146	—	6.943	6.538	—
.075	.004	—	.022	.010	.319	.150	.006	6.949	6.641	—
—	—	—	—	—	—	—	—	—	6.705	2.245

The storage in the lower A horizon was computed as the difference between inflow (0.666) and outflow (0.098), or 0.568 inch.

This procedure was carried out for each period of uniform rainfall intensity during the storm. As the amount of rainfall increased and the soil horizons became saturated, the percolation rates determined the speed at which the water infiltrated through the various horizons.

The amount of surface runoff was computed simply by subtracting the amount of water infiltrated from the total rainfall. In this example, of 8.886 inches of rain 2.245 inches were surface runoff.

Graphic Story Of The Storm

The routing procedure is shown graphically in figure 1. The uppermost graph in this figure shows amounts of rainfall by successive periods of uniform intensity. The unshaded portions of the bars show infiltrated water, the shaded portions surface runoff. The graphs below show the relationship of storage to storm duration for each soil horizon.

During the first part of the storm the soil was able to absorb 3.4 inches of rainfall in 3 hours and 40 minutes without any surface runoff occurring. However, at the end of this period the lower A and the B horizons were saturated and could transmit water only at the percolation rate of the C horizon.

The next two bursts of rain, lasting 20 minutes, completely utilized the remaining storage space in the humus horizon and surface detention, and more than 1 inch of runoff resulted. Since the humus could then absorb water only at the percolation rate of the C horizon, 1.1 inches of rainfall in the next 40 minutes resulted in about 0.9 inch of surface runoff.

During the next 8 hours a large part of the water temporarily stored in the humus, lower A, and well-drained B horizons drained into the C horizon. This made additional storage space available in these upper horizons. Then several additional bursts of rain caused these horizons to become saturated again and resulted in about 0.2 inch of surface runoff.

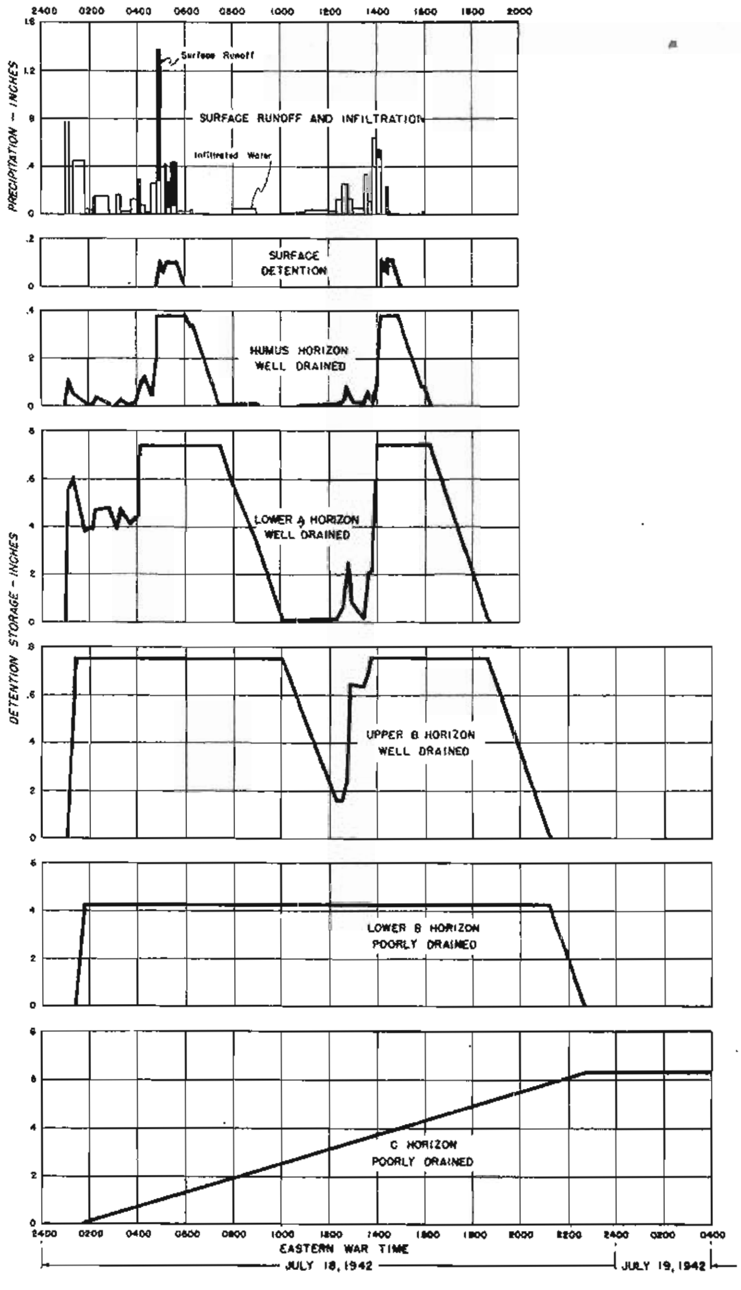

Figure 1.--Sample 'routing' of infiltrated water through the soil horizons of a grazed forest with mull humus and medium-texture imperfectly drained soil.

For any given storm and its antecedent conditions, there is a definite limit to the total amount of water that can infiltrate into a soil. The maximum limit for a given storm occurs when the humus, lower A, and B horizons are saturated for the duration of the storm and supply water to the C horizon at a constant rate. This condition seldom occurs, because intervals of little or no rainfall generally cause a slackening in the supply of water. These slack periods give the humus and lower A horizons time to drain.

The recovery of detention storage space in the upper soil horizons—as in this example—enables the soil to absorb a series of rainfall bursts (3). Thus the aggregate gain in infiltrated water is far more than the detention storage capacities of the humus and lower A horizons.

Summary Of 'Routing' Studies

During the survey of the Allegheny River watershed, a large number of such "routings" were made for several soil-cover complexes. The results of these "routing" studies are shown in figure 2.

The upper graph shows how the amount of infiltrated water increased as the total storm rainfall increased. The lower graph shows the relationship between surface runoff and total rainfall.

These graphs indicate how deep humus and the practice of growing crops on the contour serve to increase infiltration and thus reduce the amount of flood runoff.

DISCUSION

There are several advantages in this method for computing surface runoff. Consideration is given not only to the total storage of water in the soil, but also to all periods of total or partial recovery of storage space. Any retention storage space available because of evapo-transpiration is easily taken into account during the routing procedure.

This method is applicable for evaluating a land-use program. Effects of contour tillage and improvement in veg-

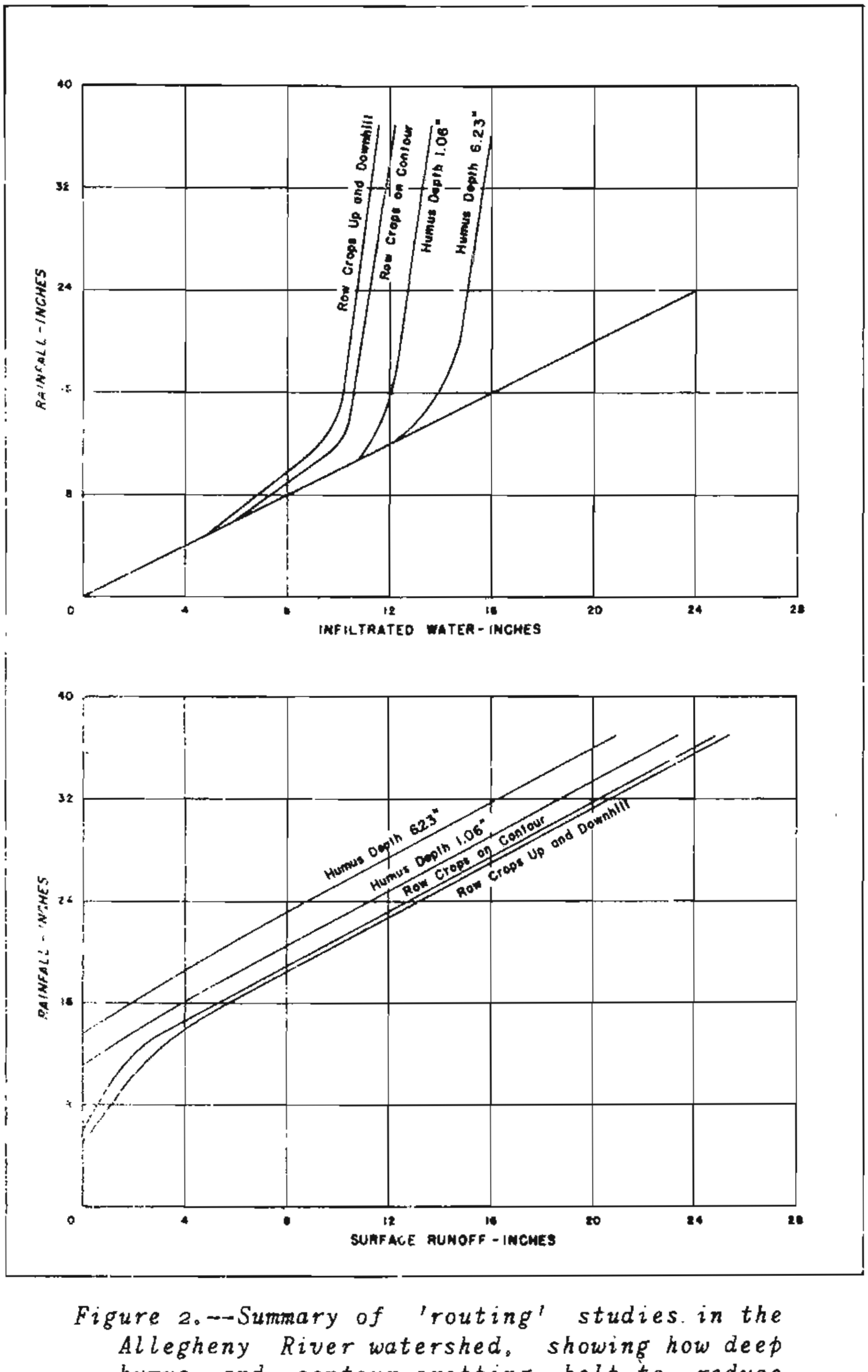

Figure 2.--Summary of 'routing' studies in the Allegheny River watershed, showing how deep humus and contour cropping help to reduce surface runoff.

etal cover can be evaluated in terms of increased surface detention storage. Effects of increase in humus depth can be evaluated in terms of greater storage and infiltration recovery (6).

With this method the amount of water infiltrated into the soil can be computed for any storm and any distribution of its rainfall intensities. The infiltration capacity of any soil can be determined from the retention and detention storage values, percolation rates, and transmission velocities of the different soil horizons. The infiltration capacity of the soil profile can also be determined at any time during the storm.

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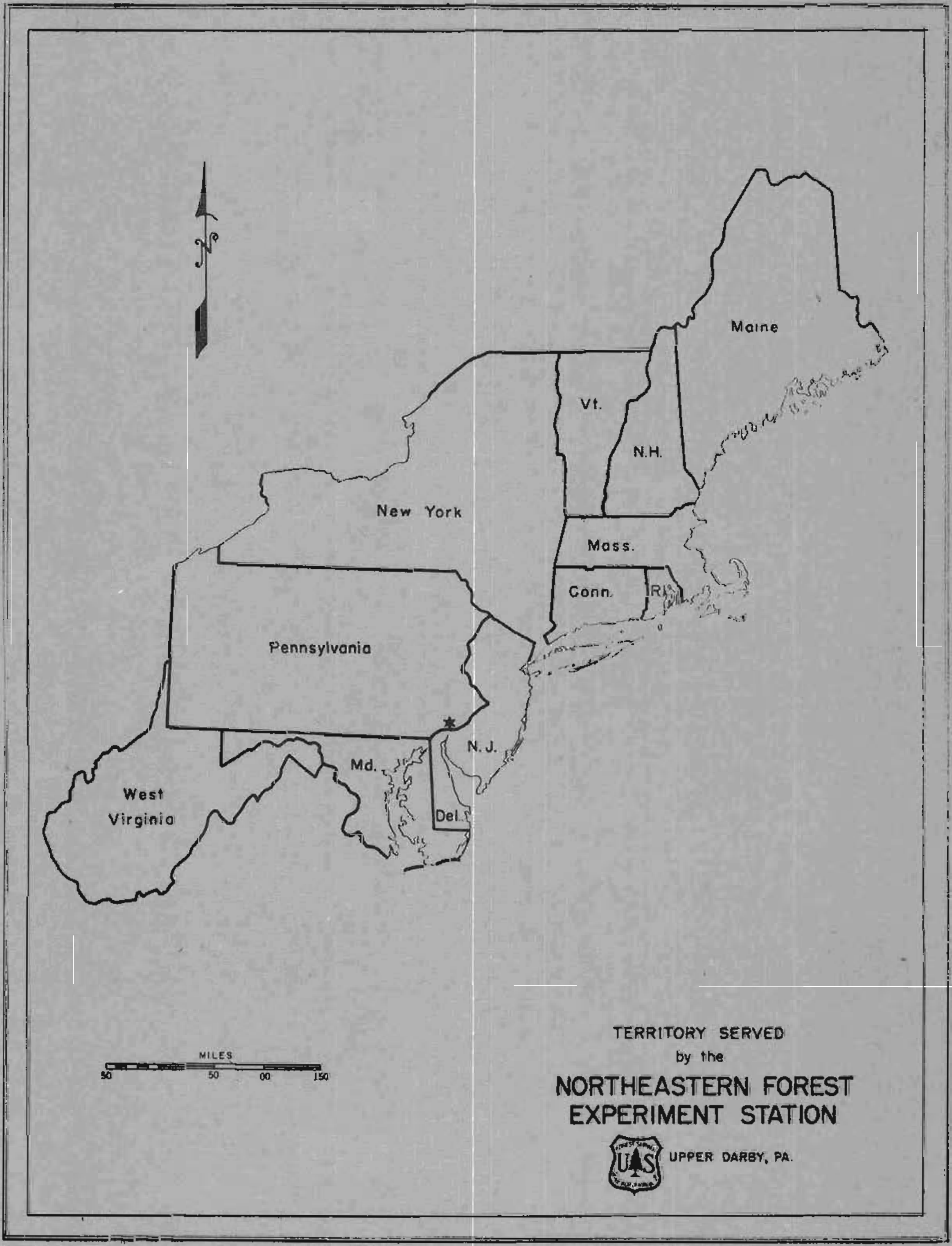

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