ERRATA

Page iv, delete lines 11 and 12 and insert:

Page 7, line 22; before (McCormack, 1960) insert: slopes

Page 13, line 5; for Ganser read Gansner

Page 13, line 18; for Fahrenbacher read Fehrenbacher

Page 14, line 6; for Gross read Grossman

Page 49, after citation of Chow, V. T. (ed.). 1964. insert:

Essex, B. L., and D. A. Gansner. 1965. Illinois' timber resource. Lake States Forest Exp. Sta., U. S. Forest Service, Resource Bul. LS-3. 56 pp.

SUBSURFACE FLOW IN A SOUTHERN ILLINOIS FRAGIPAN SOIL

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INTRODUCTION

In an eight-year study of precipitation and water-yield relationships on the Lake Glendale Watershed, Boggess et al (1965) suggested that the nature of the underlying fragipan soil had a significant effect on the flow characteristics of the drainage. The outflow hydrographs were characterized by sustained recession legs, indicating a substantial amount of detained or delayed flow. The authors stated, "Water yield was composed of both surface (overland) and subsurface flow. ...subsurface flow was a major contributor to total yield, due both to the presence of the slowly permeable fragipan and the relatively low moisture storage capacities of the soil profiles." Subsurface flow was believed to be largely made up of downslope seepage along the top of the fragipan, since a perched water table formed there during prolonged periods of wet weather. No attempt was made in their study to determine the relative amounts of surface and subsurface flow. Research reported in this paper was directed toward determining the contribution of each of these flow components in the total water yield from the Grantsburg soils.

LITERATURE REVIEW

The term "subsurface flow" has been used in varying contexts in the past; therefore, a concise etymology is needed. Apparently the first recorded concept of subsurface flow was outlined by Lowdermilk (1934), who listed "shallow seepage or discharge from wet weather springs" as a component of storm-runoff. Two years later, Hursh (1936), writing of Lowdermilk's observations and his own, defined several terms applicable to the flow in question. First, he listed "storm-seepage or subsurface-stormflow as that portion of the stormflow which infiltrates into the surface soil but moves away from the area through the upper soil horizons at a rate much in excess of normal ground-water seepage." He also defined the term "subsurface runoff as that portion of runoff leaving a drainage area as subsurface flow associated with stream channels." Hursh preferred the term "storm seepage."

Barnes in 1936 (1939) also observed the phenomena of subsurface flow and called it "secondary base flow." However, in 1939 he used the term "storm seepage" and defined it as consisting of "water which has penetrated only the upper soil layers during a rainstorm or thaw and has filtered more or less horizontally through the soil to discharge into the stream-system by seepage." Hursh and Brater (1941) again referred to the phenomenon as storm-seepage. In a later paper, Hursh and Hoover (1941) used the term "subsurface lateral flow" as representing "a basic component of storm runoff from natural forest profiles when they are functioning at or near a point when free draining gravity water is present in the upper soil horizons." Barnes (1944) used still another term, "interflow," to describe the flow intermediate between surface and groundwater flow. Interflow is also used by Linsley, Kohler, and Pauhlus (1958) to describe water which infiltrates the soil surface and moves laterally through the upper soil layers until it reaches a stream channel.

Chow (1964), in the "Handbook of Applied Hydrology," defined the synonyms: subsurface runoff, subsurface flow, interflow, subsurface stormflow, and storm seepage as: "the runoff due to that part of the precipitation which infiltrates the surface soil and moves laterally through the upper soil horizons toward the streams as ephemeral, shallow, perched groundwater above the main groundwater level. A part of the subsurface runoff may enter the stream promptly, while the remaining part may take a long time before joining the streamflow." Subsurface flow is the term used in this paper and is encompassed by Chow's definition.

There is considerable literature concerning subsurface flow; however, it is approached from a watershed basis and the analysis of storm hydrographs. These methods are arbitrary and differ according to region and the individual investigator. Recently, Hewlett and Hibbert (1965) proposed a response factor for classifying the hydrologic response of small watersheds in humid areas. In their concept the traditional hydrograph separations are discarded and replaced by two components: simply, quick flow and delayed flow. Hydrographs of experimental watersheds represent an integration of many factors. Although unit watershed studies are important and useful, they do not allow direct examination of the contribution of specific parts of the watershed ecosystem (Cole and Gessel, 1965).

An alternative to the basin approach is the use of a sample plot technique. Four representative studies have used plot techniques to define subsurface flow in the soil profile. In general, these have been done in humid areas on well-developed soils conducive to a large subsurface flow component. Hursh and Hoover (1941) conducted source of flow experiments on deep forest soils in the Southern Applachian Region. They used 8 x 8 foot plots isolated on three sides by a concrete wall 3 feet deep and 5 inches thick. On the downslope face a collection trough for surface flow was placed on top of the mineral soil and another about 12 inches deep and approximately at the bottom of the A horizon. The plots on 20-percent slopes were wetted to near field capacity before runoff measurements were made. Under artificial rainfall of 1.60 inches per hour for 15 minutes (a total of 0.40 inch), surface runoff accounted for $2\frac{1}{2}$ percent; subsurface runoff (between the surface and the top of the B horizon) accounted for $12\frac{1}{2}$ percent; and the remaining 85 percent (minus evapotranspiration) percolated below the one-foot level. Hursh and Hoover stressed the importance of biological activity in the upper soil horizons, saying: "Roots have penetrated deeply...The annual decay of some roots...and their subsequent channeling by microorganisms and small insects created relatively large continuous openings that serve as hydraulic pathways for the rapid movement of water." On comparable plots where litter was removed for three years, thereby reducing the biologic activity and causing puddling of the surface, surface flow was 20 times higher than on undisturbed plots.

Hewlett (1961) conducted preliminary experiments on deep forest soils at the Coweeta Hydrologic Laboratory in western North Carolina in an attempt to explain long periods of baseflow in an area apparently lacking in groundwater aquifers. He theorized that water in the field capacity range must serve as the main storage aquifer and source of baseflow on steep slopes. Soil moisture movement was measured in an artificial soil profile 18 inches deep, 24 inches wide, and 32 feet long on a 40-percent slope. Results from the drainage of this model, when multiplied by appropriate factors, were equivalent to about 0.3 cubic foot per second per square mile. This was within the range of minimum low flows from the Coweeta Watershed. Again a plot technique was required to determine the specific nature of the flow.

Whipkey (1965) developed a "no-boundary" plot for the measurement of flow from various layers in a soil profile during and after controlled "artificial rain." Timed volumetric samples were taken from a series of troughs installed in a pit so that flow seeping out of various soil layers could be defined. Although four years of data have been collected, these results have not been published. The system is considered reliable and will be used to study the effect of soil types and textural differences within soil types in converting rainfall into stormflow. The plot technique was developed in order to better understand the stormflow processes in the Allegheny-Cumberland Plateau region.

Gessel and Cole (1965) studied the water and nutrient element movement through a forest ecosystem near Seattle, Washington. The study area was in a 35-year-old Douglas-fir (Psuedotsuga menziesii (Mirb.) Franco) stand growing on Barneston gravelly loam, a soil originating from glacial outwash. Tenth-acre plots were equipped with six tension microlysimeters. Four of the lysimeter plates were set at a depth of 36 inches, and two were just beneath the forest litter. Previous studies had shown that 40 to 70 percent of the incoming precipitation might appear as subsurface flow. In the 1965 study, flow rates reached 0.1 inch per hour at the 36-inch depth under natural conditions, and 0.2 inch per hour after clear-cutting.

In each of these cases, plots were necessary to determine precisely the flow contribution of a specific layer in the soil profile. The densely compacted fragipan characteristic of the Grantsburg series obviously restricts the downward percolation of water and forces a substantial lateral movement to the stream channels or intersecting sloping surfaces. The magnitude of subsurface flow over the top of the fragipan can perhaps best be determined with a plot technique.

AREA DESCRIPTION

The University of Illinois Dixon Springs Agricultural Center is located in northern Pope County in southern Illinois. A general description of southern Illinois will be delineated with emphasis on the Grantsburg soil. Figure 1 shows the areal extent of the Grantsburg and associated soils.

Physiography

The majority of the Grantsburg soils are located in the Shawnee Hills section of the Interior Low Plateaus Province (Fig. 1) as described by Leighton et al (1948). Popularly known as the "Illinois Ozarks," the Shawnee Hills are characterized by a mature dendritic drainage pattern deeply incised into essentially level bedded sedimentary bedrock predominately of sandstone (McCormack, 1960). Smaller areas of Grantsburg to the north lie in the Mt. Vernon Hill Country of the Central Lowland Province (Leighton, 1948). The Hill Country composes the southern portion of the Illinois drift sheet and is characterized by mature topography of low relief with restricted upland prairies and broad alluvial valleys along the larger streams.

Grantsburg soils occur at elevations ranging from 400 to 1,100 feet above sea level. Slopes are usually well rounded, although abrupt slope changes with rock outcrops are not uncommon. The entire series drains into the Ohio River. The Grantsburg soils occur primarily on convex slopes and some concave lower valley slopes. It is estimated that 18 percent of these soils occur on 1½- to 4-percent slopes, 30 percent on 4- to 7-percent slopes, 48 percent on 7- to 12-percent slopes, and 4 percent on 12- to 18-percent (McCormack, 1960).

SOUTHERN ILLINOIS

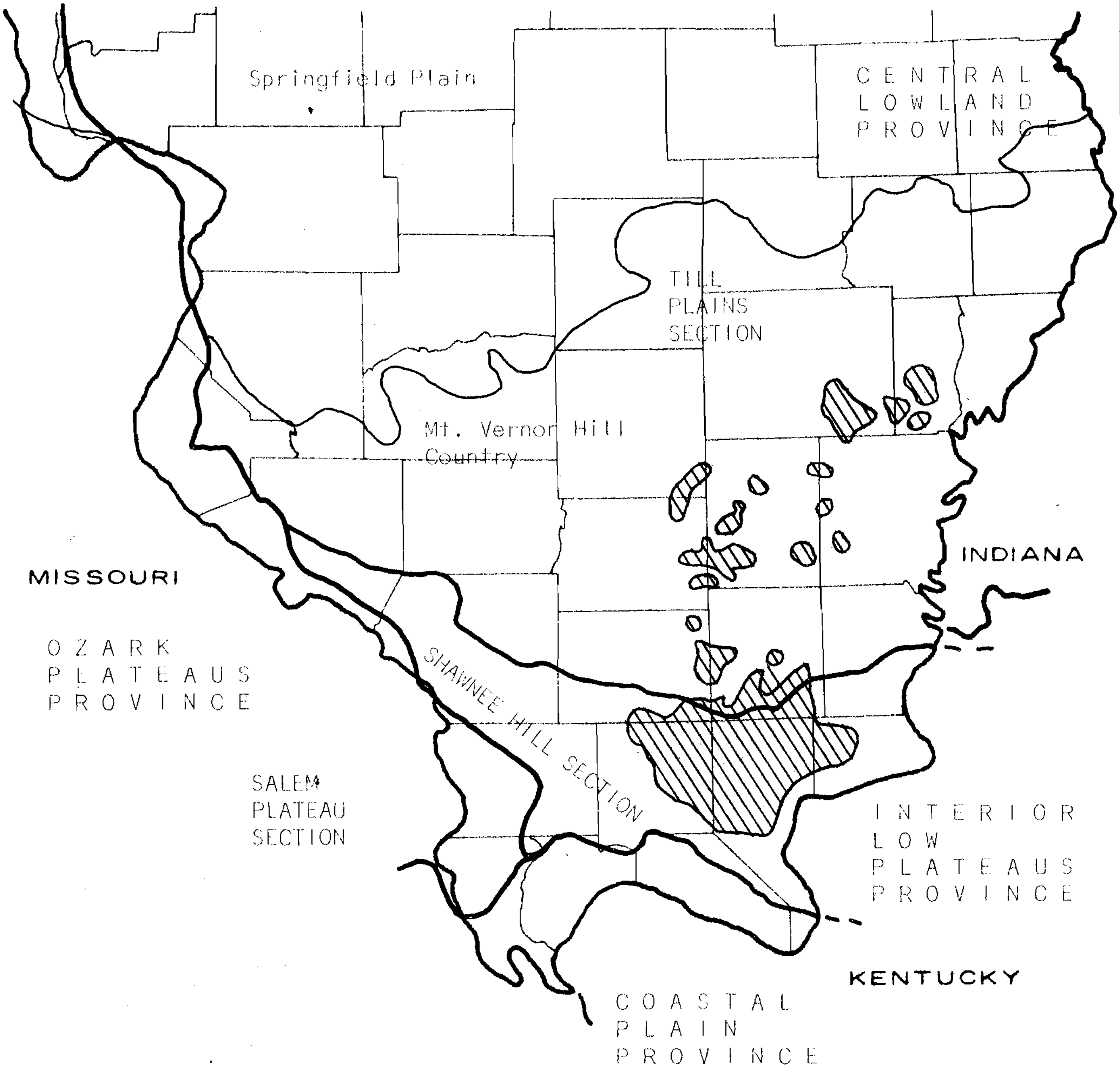
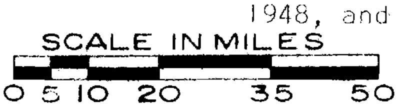


Fig. 1. Physiographic divisions and location of Grantsburg and associated soils in Illinois. (After Leighton et al, 1948, and McCormack, 1960)



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Geology

The bedrock underlying the northern two-thirds of the Grantsburg soils is classified as the Tradewater and Caseyville groups of the lower Pennsylvanian series. The southern one-third is underlain by the upper and middle Chester groups of the upper Mississippian series. A 1- to 3-foot zone of weathered sandstone usually occurs on top of the bedrock. Faulting is prevalent in southern and eastern Pope and Hardin counties (Pryor, 1956). Groundwater supply is considered poor, with most domestic wells penetrating the sandstone strata in the Pennsylvanian system in northern Pope County, and the faulted Chester rocks in southern Pope and Hardin counties. Deeper wells, sufficient for municipal and industrial supplies, penetrate the creviced Valmeyer limestone beneath the Chester rocks. The better sandstone wells near the Dixon Springs Agricultural Center safely yield 6 to 8 gallons per minute.

The soil parent material is loess $3\frac{1}{2}$ to 10 feet deep that overlies the sandstone bedrock.

Climate

The climate of Illinois has been discussed in detail by Page (1949). From this work, Bazzaz (1963) extracted the following pertinent information for southern Illinois:

> Southern Illinois has a continental climate, with hot summers and cool to cold winters due to its mid-continent location away from major water bodies. Much of the precipitation in Illinois is associated with the coalition of warm, moist Gulf air masses with cold continental air masses moving across the state. During the coldest half of the year, temperatures in southern Illinois are sufficiently warm to produce thunderstorms and summer type precipitation. Highest monthly precipitation occurs during March, April, and May (4.35 to 4.99 in.), while September and October are the driest months (2.68 to 2.86 in.). The higher winter precipitation in this area results from the increased winter cyclonic activity. In addition to these variations from month to month, there is quite a variation in monthly and annual precipitation from year to

> year (Table 1). Of the total precipitation, less than 10 percent falls as snow (10 to 14 in. of snow) with the highest amount falling during the month of February. Although the Ozark region receives more moisture than any other part of the state, it is subjected to droughts during the summer. They are frequently of such a duration and intensity that they seriously affect plant development (Bazzaz, 1963).

Twenty-six years of precipitation records for the Dixon Springs Agricultural Center are shown in Table 1. Mean annual, maximum, and minimum precipitation on record (1938-1965) were 46.83 inches, 71.4 inches (1949), and 29.5 inches (1944), respectively. Record maximum, minimum, and mean monthly precipitation is also given.

> Extreme variations in temperature are expected in such a climate. These variations are considerably less during the warmer half of the year. In Southern Illinois winters are milder when compared with the rest of the state. July is the warmest month of the year with a mean of 80° F., while January is the coldest with a mean of 37° F.
>
> The length of the growing season, defined as the number of days between the date of last killing frost in spring and the first one in the fall, is between 190 and 200 days in the eastern part of the Ozarks and up to 210 days in the western part. This period extends, on the average, from April 13 to October 23...(Bazzaz), 1963).

Hydrology

Of the annual average precipitation of 44 inches in southern Illinois, 14 to 17 inches occur as streamflow. Minimum runoff for 6-, 12-, 18-, and 24-month periods average 0.10, 1.00, 2.00, and 6.00 inches, respectively. The lowest annual precipitation expected once in five years is 36 inches, with 20 inches occurring once in 50 years. The highest annual precipitation, expected to occur once in five years, is 54 inches, and 70 inches once in 50 years. Thunderstorms occur an average of 54 times per year, with a maximum of 10 storms in June. Evapotranspiration ranges from 28 to 30 inches, of which 90 percent occurs in the six-month period from April through September. The potential evapotranspiration ranges from 34 to 36 inches, indicating an

Table 1. Twenty-six-year rainfall, Glendale Experiment Station (Dixon Springs Agricultural Center).

	Month												
	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
Average	4.13	3.86	5.24	4.16	4.67	3.78	3.92	4.10	3.08	2.45	3.52	3.52	46.31
Minimum[1]	0.28	0.24	0.73	1.43	1.99	0.42	0.87	1.20	0.80	0.00	0.40	0.47	--
Maximum	17.29	8.81	12.10	8.13	11.05	10.57	14.25	9.36	11.24	6.56	9.97	8.89	--

[1]The lowest annual precipitation was 29.54 inches in 1944, and the highest was 71.39 in 1949.

average annual soil moisture deficit of 4 to 8 inches (Illinois State Water Survey, 1957).

On the Lake Glendale Watershed, the mean annual precipitation (1954-62) was 48.7 inches, and runoff accounted for 16.7 inches per year, or 34 percent of the average annual precipitation. Evapotranspiration and other losses accounted for the difference, approximately two-thirds of the average annual precipitation. The regression of water-year runoff on water-year precipitation follows the relationship $\hat{Y} = 0.51X - 8.40$ (Boggess et al, 1965).

Streamflow in southern Illinois is highly seasonal. Continuous flow usually occurs during the "winter" (November through May), when the soil profiles are fully recharged and evapotranspiration demands are at a minimum. During the growing season, soil moisture reserves are rapidly depleted, streams dry up, and active flow occurs only after long periods of rainfall, or as the result of intensive storms.

The periodicity of flow has been determined for an intermittent stream which drains half of the 2.11-square-mile Lake Glendale Watershed (Boggess and Russell, 1964). For an eight-year period, the average annual number of days without flow varied from 76 to 153, or an average of 121 days. During the drier summer months (June through October), flow may not occur at all for any one month. The eight-year average flow for the month of September was less than three days. There was no flow for four years in both September and October, while there was continuous flow every year for the months of February, March, and April.

Vegetation

Deciduous forests are native to southern Illinois. Three regional types are delineated by Braun (1964). The largest, centrally located area is the Prairie Peninsula Section of the Northern Oak-Hickory Region. The Interior Highlands Section of the Southern Oak-Hickory Region occupies a small section along the Mississippi River, and the Hill Section of the Western Mesophytic Region occupies a small section along the Ohio River.

Essex and Ganser (1965) include in the 16 southernmost counties a large area of oak-hickory forest, oak-gum-cypress forest along the present and ancient river valleys, and elm-ash-cottonwood forest toward the northern interior of the southern unit. Thirty percent of the land is forested, with 70 percent in cropland, pasture, range, and other land. Of the commercial forest area (1,086,000 acres), 96 percent is in hardwoods, 3 percent in pines (planted), and 1 percent in the oak-pine type.

Soils

The Grantsburg and related soils series are of paramount concern in this study of the subsurface flow. The Grantsburg series comprises moderately well-drained Grey-Brown Podzolic intergrading to Red-Yellow Podzolic soils (by the 7th Approximation, the classification is: Order, Alfisol; Suborder, Udalf; Great Group, Fragiudalf; Subgroup, Typic Fragiudalf; Family, Fine silty, Mixed, Mesic; Series, Grantsburg) developed in loess 80 inches or less in thickness (Fahrenbacher, 1965). These soils are characterized by a moderately well to strongly developed fragipan occurring 24 to 36 inches below the surface and 24 to 36 inches thick, although the lower boundary is often indefinite (Fehrenbacher, 1956). The fragipan, which limits both root penetration and the downward movement of water (Boggess, 1963), is defined as: "a horizon in the profile that is very slowly permeable, compact or dense, hard (and brittle) when dry, and moderately friable to friable when moist (Winters and Simonson, 1951)." Fragipans in Illinois differ from claypans in that they are usually relatively low in clay but have a high silt and/or sand content (Fehrenbacher, 1956). In addition, fragipans in Illinois involve two other morphological features: (1) The fragipan is found within the lower sequum of a bisequal solum; and (2) the occurrence in the lower sequum of a polygonal network of gray, silt loam that extends downward from the A_2 horizon (commonly known as the gray layer) and delineates prismatic structural units (Gross et al, 1959).

The Grantsburg soils are related to the Hosmer and Ava soils of southern Illinois and the Grenada series extending southward from Kentucky into northern Mississippi. Figure 2 illustrates the areal distribution of various soils associations in southern Illinois. The terrace and bottom-land soils (Area A) are the presumed major loess source (Grossman et al, 1959). However, Beavers (1957) suggested that much of the fine clays have come from scattered areas throughout the central United States. In the thicker loess areas bordering the Mississippi and Wabash river valleys, weathering or soil development has not progressed far enough for fragipans to have formed; however, there is little doubt that soil development in these thick loess areas is in the direction of fragipan formation (Fehrenbacher, 1956).

> The Grantsburg soils differ from the Ava soils in having more pronounced, more highly cemented fragipans and in having developed from thick or moderately thick loess over bedrock rather than from thin loess over leached Illinoian till. They are intermediate in distinctness of fragipan between the Hosmer and Grenada soils. They differ from Hosmer soils in their shallower depth to the fragipan, their more distinct fragipan that has larger more pronounced polygonal structure blocks, their somewhat greater clay content in the B horizon, and their lesser degree of base saturation. The fragipan in the Grantsburg profile is more advanced than that in the Hosmer soils but not as advanced as that in Grenada soils. In the Grantsburg profile the gray horizon (A_2) is not so thick and the destruction and movement of clay is of a lesser degree than in Grenada soils. Grantsburg soils have greater base exchange capacity and a less prominent fragipan than the Grenada series (McCormack, 1960).

An official description of a cultivated Grantsburg is given below (McCormack, 1960).

Soil Profile: Grantsburg silt loam cultivated.

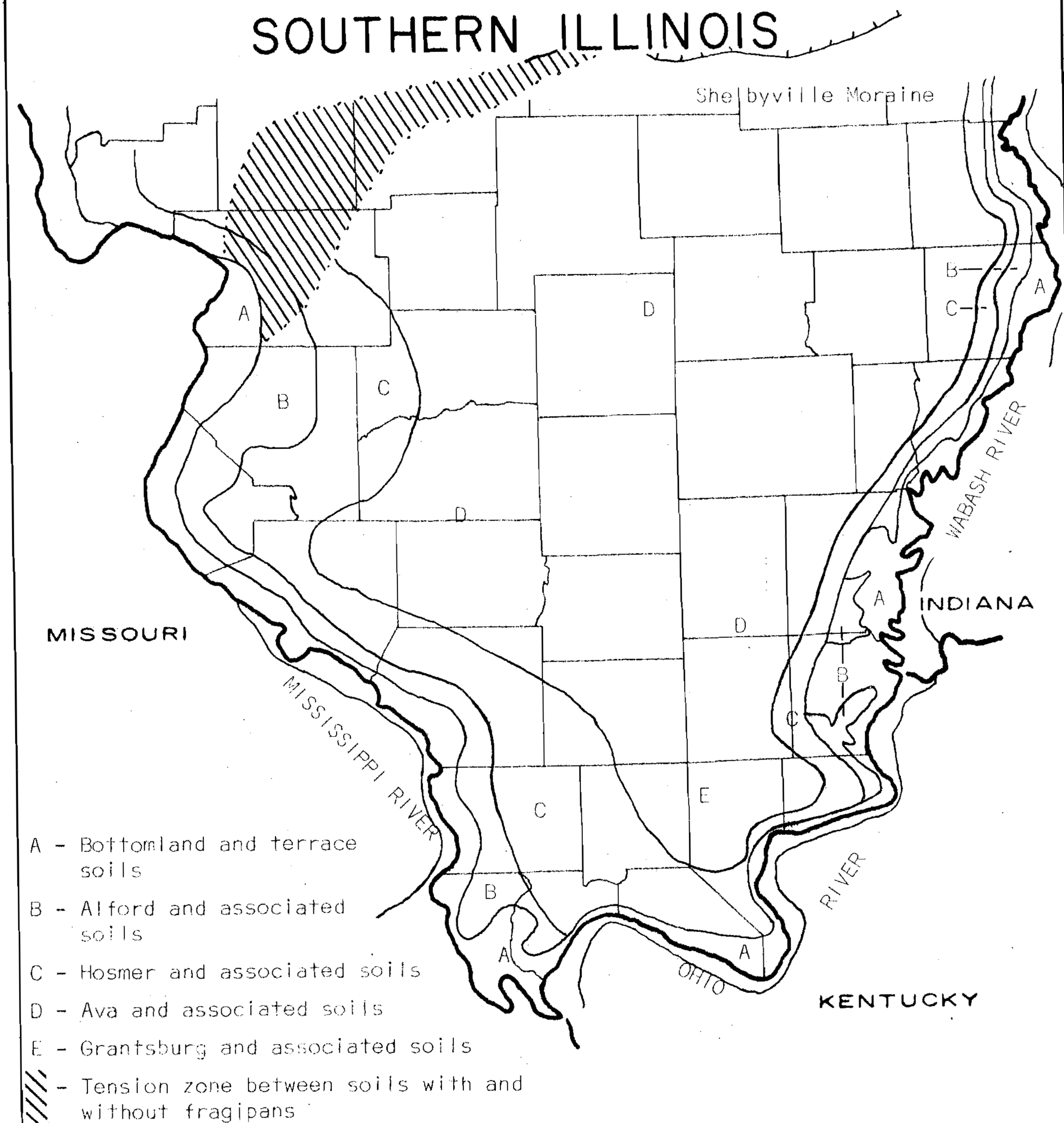

Fig. 2. Areal distribution of various soil associations in southern Illinois in relation to the major rivers and main loess sources (A areas). (After Grossman et al, 1959.)

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A_p	0- 6"	Brown (10YR 4/3) silt loam; weak fine crumb structure; friable; strongly acid.
A_2	6-10"	Brown (10YR 5/3) silt loam; medium platy structure; strongly acid. 4 to 8 inches thick.
B_1	10-20"	Strong brown (7.5YR 5/6) light silty clay loam; moderate to strong medium subangular blocky structure; strongly acid. 6 to 10 inches thick.
B_2	20-25"	Yellowish brown (10YR 5/6) light silty clay loam; moderate medium subangular blocky structure; few iron-manganese concretions; strongly acid. 5 to 8 inches thick.
A'_2	25-29"	Brown (10YR 5/3) light silty clay loam to silt loam mixed with light gray (10YR 7/2); the light gray is the color of both coatings and seams and sometimes fragments of irregular shape; brown is the color of nodules on moderate medium subangular blocky peds; some very dark grayish brown (10YR 3/2) iron-manganese concretions; strongly acid. 3 to 5 inches thick.
B'_2	29-35"	Dark brown (7.5YR 4/4-4/6) to dark yellowish brown (10YR 4/4) silty clay loam highly mottled with light gray (10YR 4/2); weak coarse prismatic structure breaking into moderate medium subangular to angular blocks; polygonal cracks 1 to 2 inches wide filled with light gray (10YR 7/1) material usually extend from below through the B'_2 into the A'_2; dark brown (7.5YR 4/4) clay films on peds, some iron manganese concretions; strongly acid. 8 to 12 inches thick.
B'_3	35-45"	Yellowish brown (10YR 5/4-5/6) heavy silt loam mottled with light gray (10YR 7/2); weak coarse blocky to subangular blocky structure with polygonal cracks similar to horizon above; some clay films; strong acid. 8 to 12 inches thick.
C'	45-55"+	Brown (10YR 5/3) to yellowish brown (10YR 5/4) silt loam mottled with light gray (10YR 7/1; nearly massive, breaking into large, irregular shaped, compact and dense clods which when dry are strongly cemented and very hard; polygonal cracks or gray channels present and extend below this horizon but become narrower and less regular at greater depths; strongly acid.

The prime notation is used to identify horizons which are part of the fragipan sequence.

A summary of soil characteristics determined from samples taken 18 feet from Plot No. 2 are given in Table 2. Bulk density samples were determined from four replications using a king tube. Soil fractions were

Table 2. Mechanical analysis, bulk density, available water-holding capacity, and percent moisture retained at tensions of 1/10, 1/3, 1.12, 2, 3, 6, 9, 12, and 15 atmospheres.

Depth	Bulk density	Sand	Silt	Clay	Avail- above water	Atmospheres of tension 1/10	1/3	1.12	2	3	6	9	12	15
Inches		- - -	Percent-	- -	Inches									
0- 6	1.16	4.4	65.7	29.9	1.10	38.1	27.4	19.2	17.0	15.9	14.2	13.0	12.1	11.6
6-18	1.31	3.5	65.7	30.8	2.77	36.9	30.9	21.5	18.2	17.5	15.8	14.3	13.8	13.3
18-30	1.50	5.2	65.0	29.8	3.53	38.2	32.4	21.8	18.5	17.8	16.5	15.2	15.7	12.8
30-42	1.56	--	--	--	--	--	--	--	--	--	--	--	--	--
42-54	1.57	--	--	--	--	--	--	--	--	--	--	--	--	--
54-66	1.66	--	--	--	--	--	--	--	--	--	--	--	--	--

determined using the hydrometer method (Buoyoucos, 1951) for clay, a No. 325 seive for sands, and the residual for silt. Moisture contents at 1/10, 1/3, 1.12, 2, 3, 6, 9, 12, and 15 atmospheres were determined on pressure-membrane and pressure-plate equipment after Richards (1954). A fragipan transect parallel to and 3 feet from Plot No. 2 is shown in Fig. 3. The fragipan was located by a soil tube using resistance and visual soil criteria.

The permeability of the Grantsburg soils is reported to be very slow (McCormack, 1960). The least permeable fragipan layer had a hydraulic conductivity of 0.03 inch per hour, with soil above the fragipan ranging from 0.10 to 0.20 inch per hour. Boggess (1963) has shown significant differences (Table 3) among the soils with hardwood, pine, and abandoned field vegetation in the surface layers.

Table 3. Hydraulic conductivity under three vegetative covers.

Depth from surface, inches	Hydraulic conductivity, inches per hour		
	Hardwood	Pine	Abandoned field
0.3	3.26	1.92	0.45
3-6	1.75	1.55	0.30

The pore space relationships have also been investigated by Boggess and are shown below under three vegetative covers (Fig. 4). "The uneroded hardwood site is used as a standard, and the data from the pine and abandoned field sites are referenced to corresponding depths of the former. Retention and detention storage capacities for each site are shown in Figure 5."

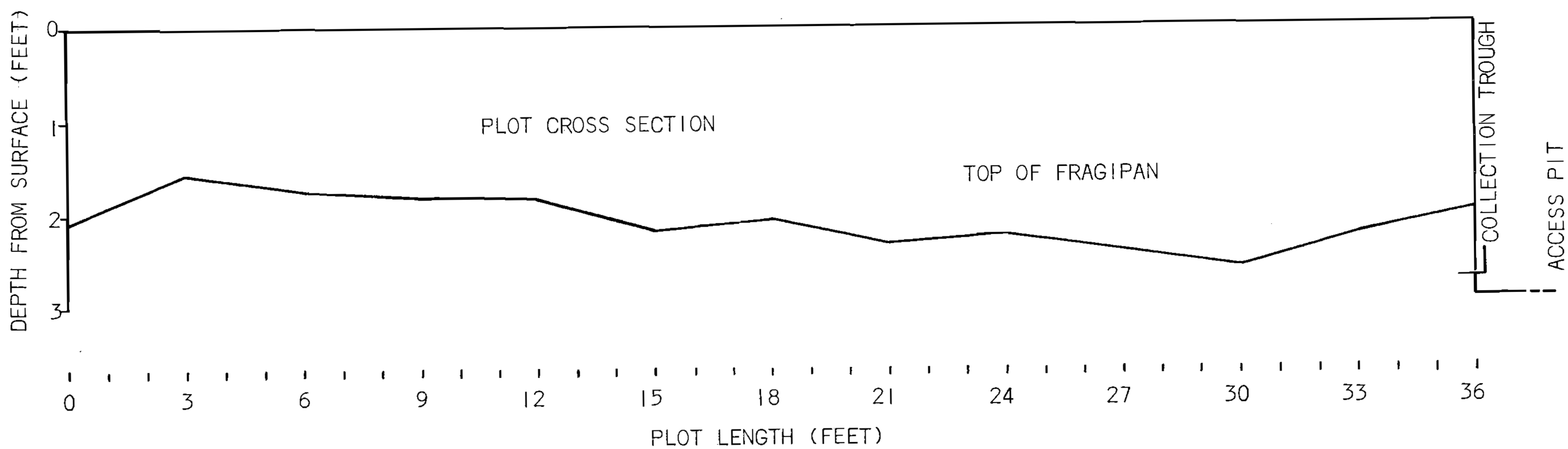


Fig. 3. Fragipan location in Plot No. 2.

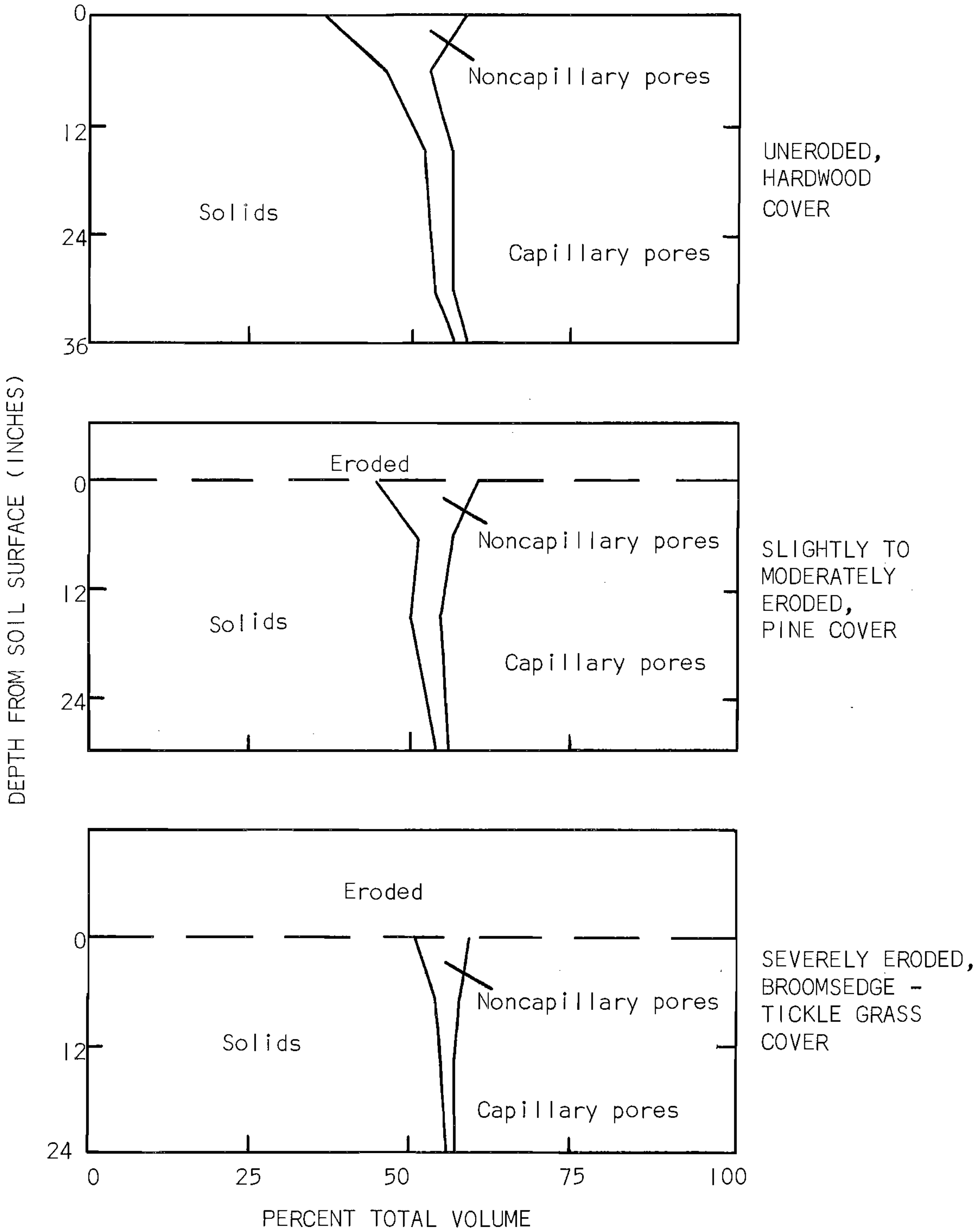
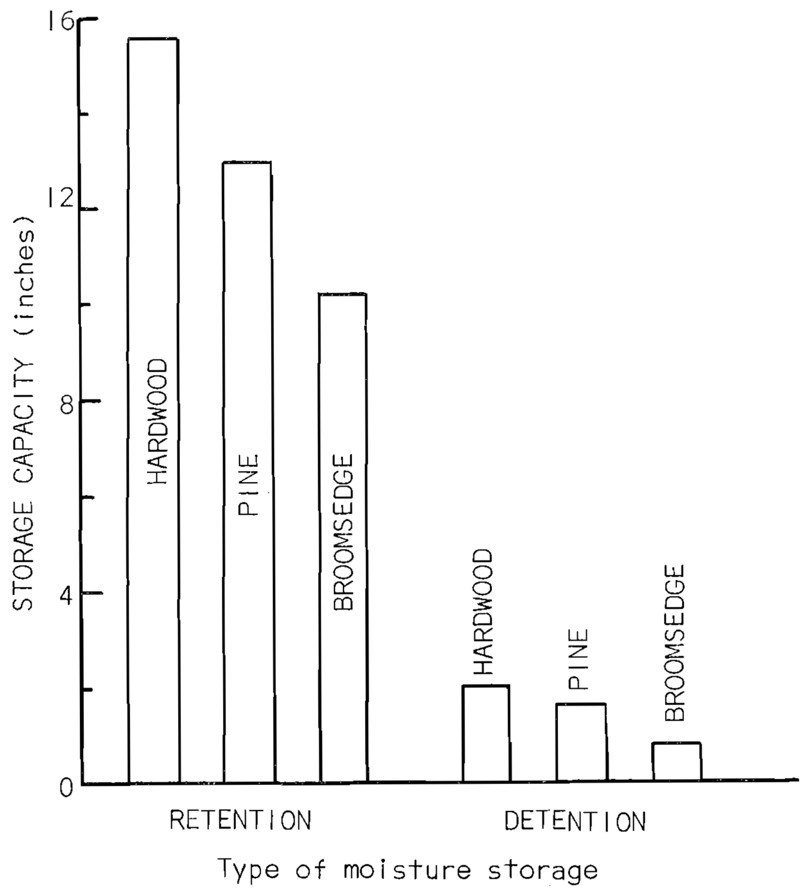


Fig. 4. Pore space relationships of a Grantsburg silt loam under three vegetative covers.



EROSION RATING

Hardwood site . . . . None

Pine site . . . . Slight to moderate

Broomsedge site . . . . . . Moderate to severe

Fig. 5. Moisture storage (dry weight basis) and erosion rating of a Grantsburg silt loam under three vegetative covers.

PLOT TECHNIQUE

The experimental plots were located in a 20-year-old plantation (6 x 6 foot spacing) of loblolly pine (Pinus taeda L.). The area known locally as the "Cate Pines" is located near the warehouse complex of the Dixon Springs Agricultural Center and is approximately 2 miles northwest of the Lake Glendale Watershed (37^{O} 25' N. Latitude; 88^{O} 40' W. Longitude).

Each plot measured 18' x 36' with the long axis parallel to the slope. Plots were isolated from the surrounding area by a machine-cut trench, 3 inches wide and approximately 36 inches deep (or well into the fragipan). An 8-mil vinyl sheet was then placed against the plot wall, and the trench was back-filled with the original soil. A pit 4' wide, 18' long, and 4' deep was excavated at the downslope end of each plot to allow installation of metal collecting troughs at the soil surface and the top of the silt pan. The downslope plot face was also sealed with plastic and held in place by a plywood wall supported just above the lower trough lip by wedge bracing. This prevented slumping of the plot face and directed subsurface flow into the lower collection trough.

Water was applied through perforated plastic hose installed around the perimeter of each plot and oriented for even distribution of the "artificial rainfall." The amount of water applied was controlled by a pressure gauge and a Rockwell water meter. Three access tubes for the Nuclear-Chicago neutron probe were installed in an attempt to monitor the downward movement of water. Surface runoff was diverted to a stilling and recording "well" apparatus located sufficiently downslope. Subsurface flow was collected in a recording rain gauge installed in a pit, 15 feet downslope in one case, and in the plot access pit in the other. The measurement techniques are discussed further in the Appendix. A pictorial record of a plot installation is shown in Figs. 15 through 22 in the Appendix.

The first plot (Plot No. 1) was located on a lower, 6 percent slope, and the second plot (Plot No. 2) on an upper, 7.5 percent slope. Two test "runs" in the fall of 1965, when only subsurface flow was measured, yielded these results in percent of total rainfall: Plot No. 1, 19.90 percent and 21.29 percent subsurface flow; Plot No. 2, 21.37 percent and 7.66 percent subsurface flow. Rainfall infiltrated the soil and percolated downward until capillary pore space was satisfied and subsurface flow began. The low figure for the second run of Plot No. 2 was due to a leak which was corrected in the summer of 1966. Later runs on Plot No. 2 were all in the 20 percent range. Subfreezing temperatures prevented any further runs in 1965. During the winter, internal cracks from freezing and thawing developed in Plot No. 1. Runs during the summer of 1966 resulted in the quick appearance of subsurface flow and greater rates of transmissibility than those of the stable Plot No. 2 when corrected for profile depth and hydraulic gradient. Upon dismanteling the plots, the disturbed area in Plot No. 1 appeared to be concentrated near the outflow corner of the subsurface collection trough. This could explain the quick appearance of subsurface flow and channeling of surface water to the subsurface trough. Because of the faulting in Plot No. 1, hydrograph analysis was only done for Plot No. 2. As a matter of record, a tabular summary of flow components is given for both plots.

RESULTS AND DISCUSSION

Total Subsurface Flow

A summary of the field data for Plot Nos. 1 and 2 is shown in Table 4. The significant contribution of subsurface flow over the fragipan is shown in Column 6. For the shallower Plot No. 2, the total subsurface flow accounts for 19.7 percent of the applied rainfall; and on the deeper, disturbed Plot No. 1, subsurface flow accounts for 24.4 percent of the rainfall.

Transmissibility

Because of the plot technique used, the subsurface flow can best be described by the transmissibility of the soil mass above the fragipan. The coefficient of transmissibility, a hydraulic groundwater term, is defined as: "the rate of flow of water, in gallons per day, through a vertical strip of the aquifer 1 foot wide and extending the full saturated thickness under a hydraulic gradient of 1 foot per foot at the prevailing temperature of the water" (Walton, 1962). The coefficient of transmissibility is shown in Column 11. The average coefficient is 238 gallons per day through a 1-foot wide vertical section of soil 2' 1" deep. The actual amount of water transmitted through the saturated soil mass averaged 35.58 gallons per day (hydraulic gradient of 0.1495 foot per foot). Over the ranges of soil depth to fragipan and slope, the Grantsburg soils under pine forest and saturated conditions, can be expected to yield from 7 to 120 gallons per day, with an average range of 39 to 67 gallons per day. This flow appears either in the stream channels or is forced to the surface where eroded slopes intersect the fragipan.

Table 4. A summary of field data for Plot Nos. 1 and 2.

Column 1	2	3	4	5	6	7	8	9	10	11	12	13
Date	Rate, gal./min.	Rainfall duration, min.	Total gallons applied	Surface flow (Percent)	Subsurface flow (Percent)	Evapotranspiration (Percent)	Unaccounted (Percent)	Average air temp., °F.	Average soil temp., °C.	Coefficient of transmissibility, gal./day	Actual transmissibility, gal./day	Soil depth to fragipan, feet
Plot No. 1												
July 19	3.65	345	1,259.3	64.9	21.4	16.7	- 3.0	80.5	27	419	50.48	3.000
July 26	3.08	293	902.5	39.6	28.4	26.5	5.5	79.0	26	419	50.48	3.000
Aug. 3	3.09	543	1,680.0	49.6	24.6	9.2	16.6	68.0	25	586	70.64	3.000
Aug. 23	3.24	734	2,376.0	56.9	23.2	5.2	14.7	65.0	25	528	63.68	3.000
Plot No. 2												
July 19	2.39	700	1,674.5	60.9	20.4	12.9	5.8	80.5	27	245	36.64	2.083
July 26	2.08	745	1,549.0	42.7	20.6	15.9	20.8	79.0	26	245	36.64	2.083
Aug. 3	2.32	739	1,715.6	45.0	17.3	9.3	28.4	68.0	25	249	37.20	2.083
Aug. 23	2.09	779	1,624.8	44.0	20.5	7.8	27.7	65.0	25	213	31.84	2.083

Hydraulic Conductivity

The amount of water applied and measured as either surface or subsurface flow, as well as evapotranspiration, was measured in gallons; however, the runoff hydrographs were converted to an area basis and are presented in inches per hour.

The four hydrographs of Plot No. 2 are shown by semi-logarthmic plots in Figs. 6 through 9. Pertinent time information is summarized in Table 5. The rather quick occurrence times for July 19 are due to soil moisture conditions near field capacity as reflected in the four-day antecedent precipitation of 1.5 inches, with 0.40 inch falling on the morning of the 19th.

Peak flow rates are given in Table 6. Peak flow rates culminated around 10 p.m. or later, and hence evapotranspiration is considered negligible. These inch-per-hour rates may be considered as hydraulic conductivity values, although they were not determined by the standard, small-sample, field or laboratory methods. The average infiltration rate for the total soil mass was 0.092 inch per hour, which agrees with VanDoren and Kingbell's (1949) range of 0.09 and 0.17 inch per hour for the 2- to 5-inch and 9- to 12-inch soil depths, respectively. The hydraulic conductivity of the fragipan averaged 0.028 inch per hour. This is in excellent agreement with Van Doren and Klingbell's figure of 0.03. Smith and Browning (1946) reported fragipan hydraulic conductivity values ranging from 0.01 to 0.10 inch per hour for lump samples of massive and laminated structure in West Virginia soils. Winters and Simonson (1951) reported a 0.02 inch per hour for samples of the more strongly developed fragipan in the Grenada soil series of western Kentucky and Tennessee.

The amount and character of the pore space will, along with fluid properties and hydraulic gradients, determine the hydraulic conductivity of

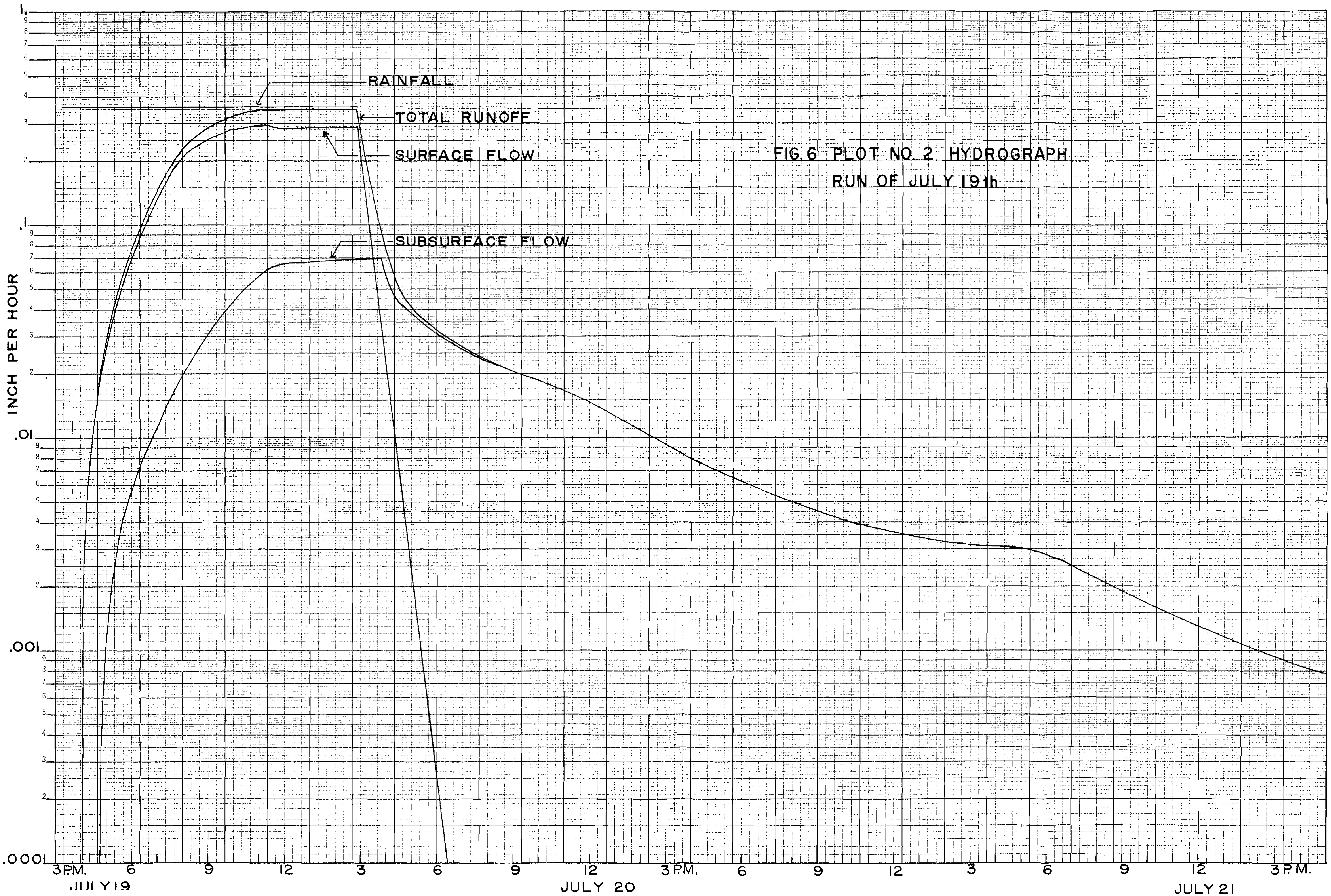
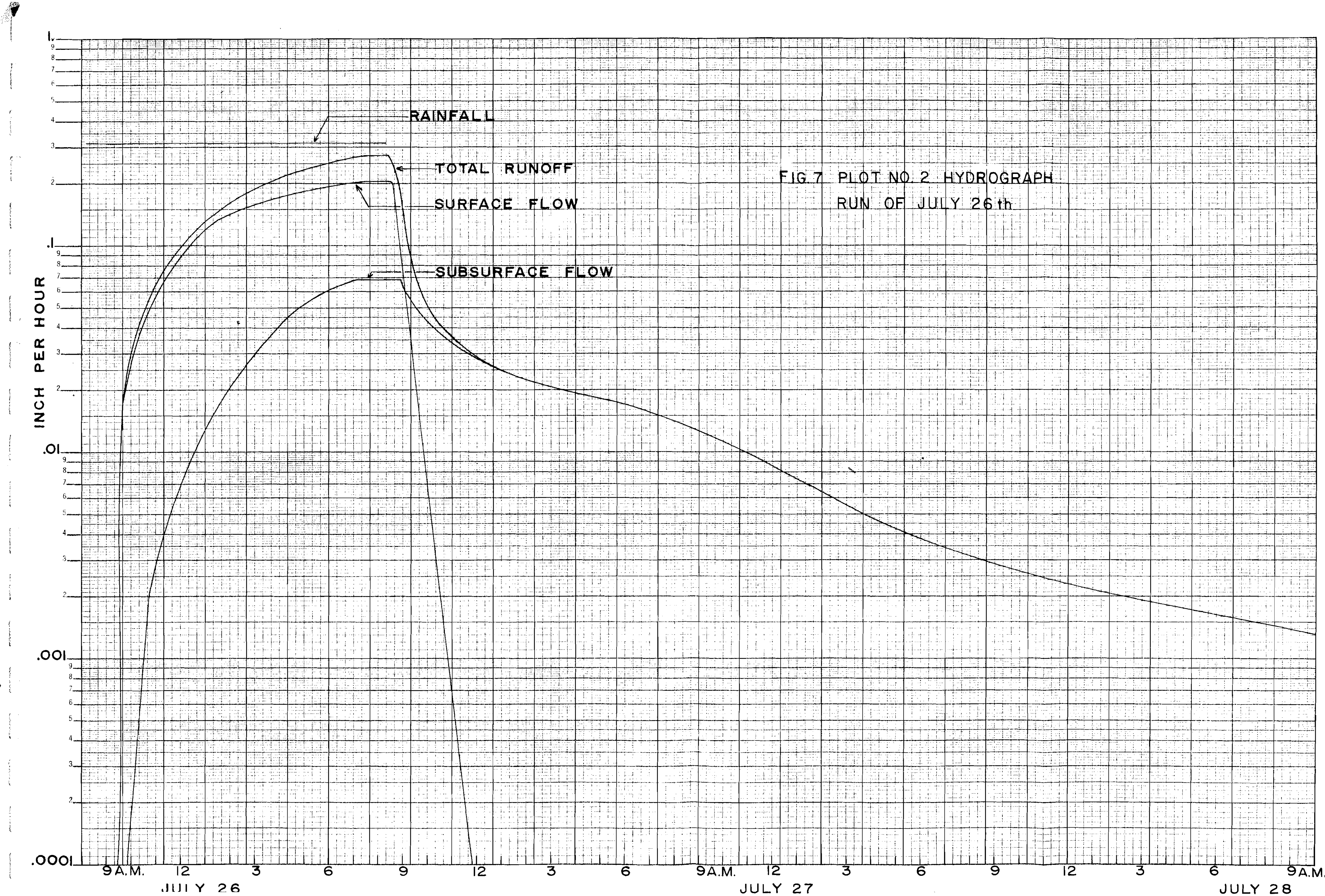


FIG. 6 PLOT NO. 2 HYDROGRAPH
RUN OF JULY 19th



RAINFALL
TOTAL RUNOFF
SURFACE FLOW
SUBSURFACE FLOW
FIG. 7 PLOT NO. 2 HYDROGRAPH
RUN OF JULY 26th
INCH PER HOUR
1.
.1
.01
.001
.0001
9 A.M.
12
3
6
9
JULY 26
JULY 27
JULY 28

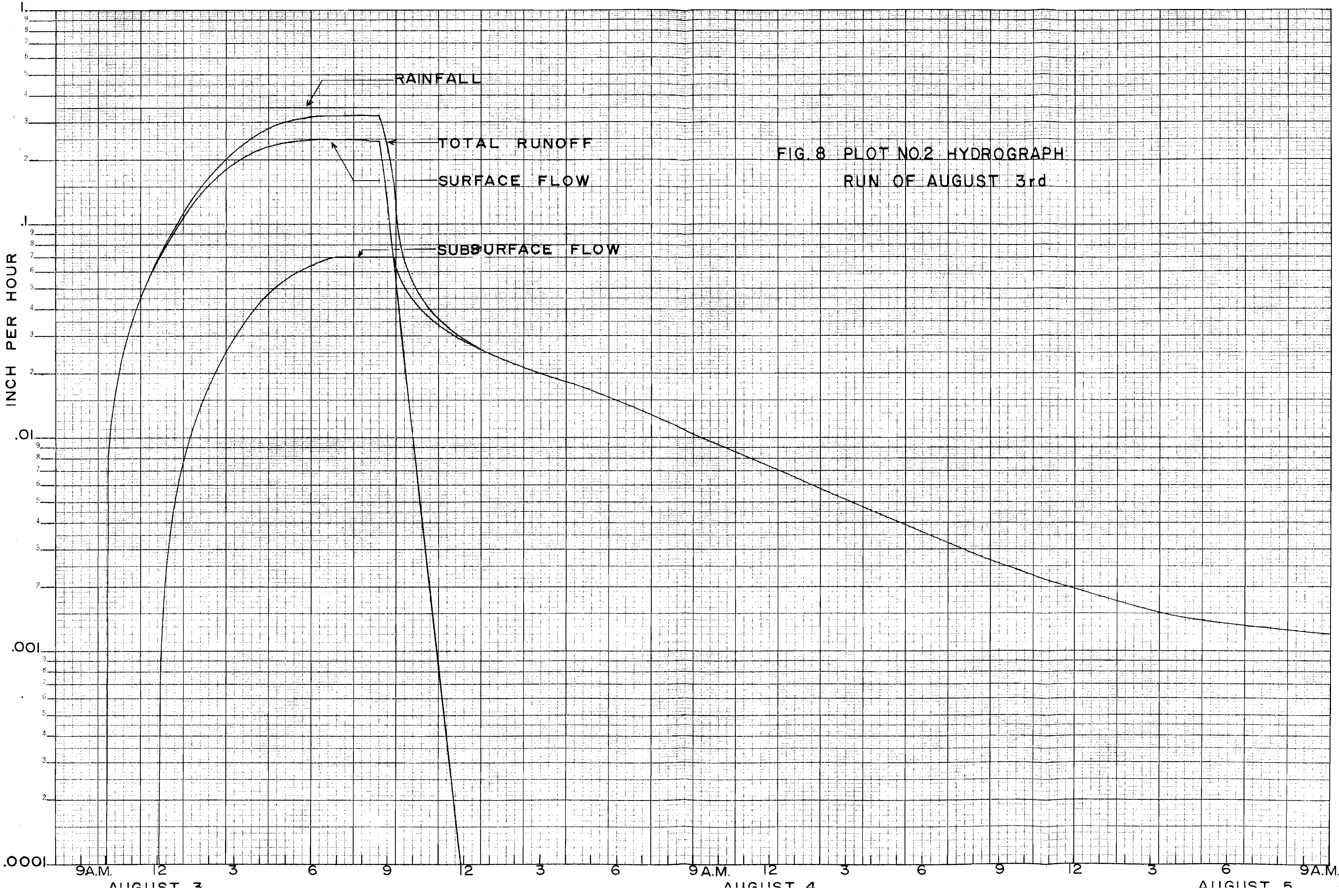


FIG. 8 PLOT NO.2 HYDROGRAPH
RUN OF AUGUST 3rd
RAINFALL
TOTAL RUNOFF
SURFACE FLOW
SUBSURFACE FLOW
INCH PER HOUR
1.
.1
.01
.001
.0001
9A.M.
12
3
6
9
12
3
6
9A.M.
12
3
6
9
12
3
6
9A.M.
AUGUST 3
AUGUST 4
AUGUST 5

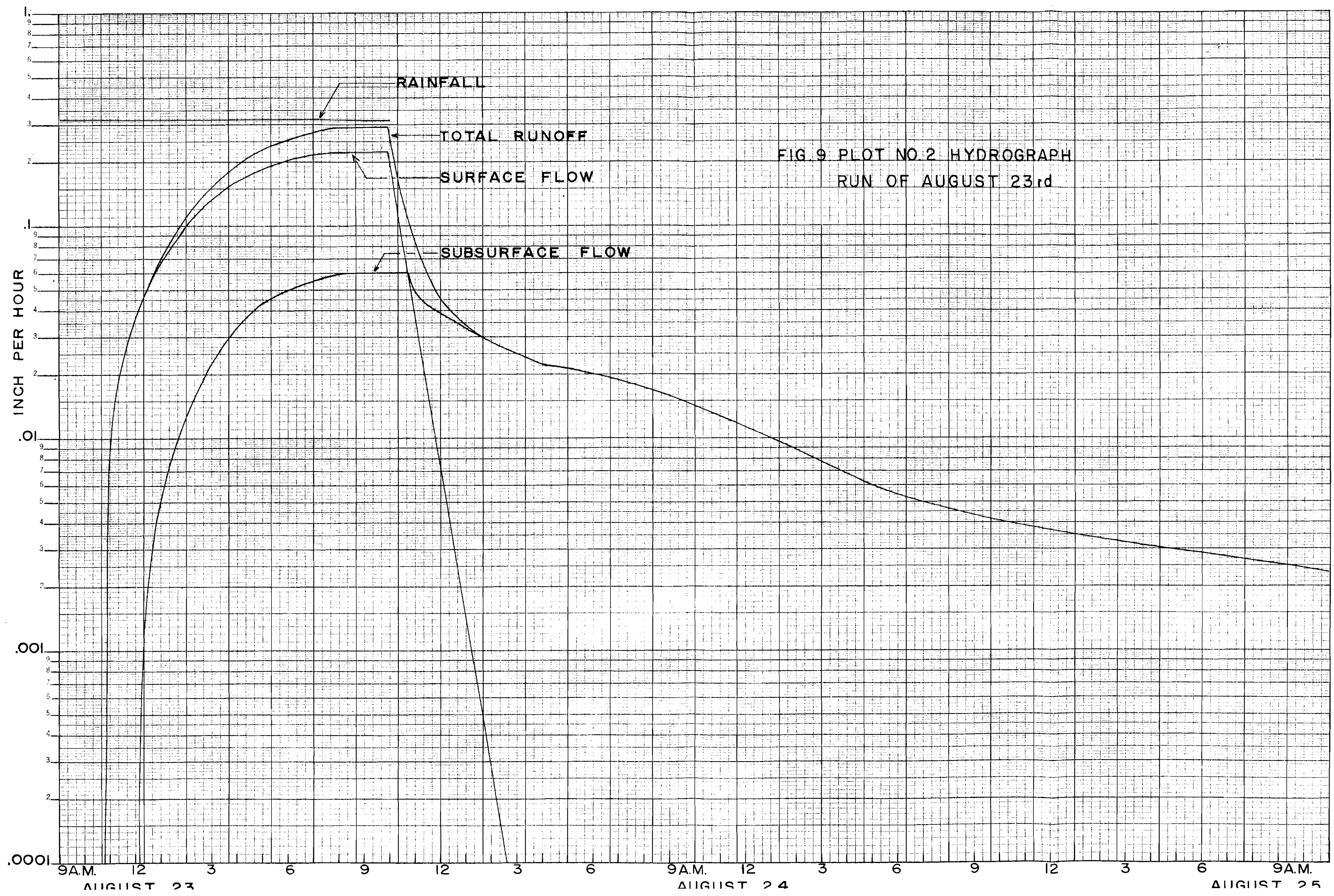


FIG. 9 PLOT NO.2 HYDROGRAPH
RUN OF AUGUST 23rd
RAINFALL
TOTAL RUNOFF
SURFACE FLOW
SUBSURFACE FLOW
INCH PER HOUR
1.
.1
.01
.001
.0001
9A.M.
12
3
6
9
AUGUST 23
AUGUST 24
AUGUST 25

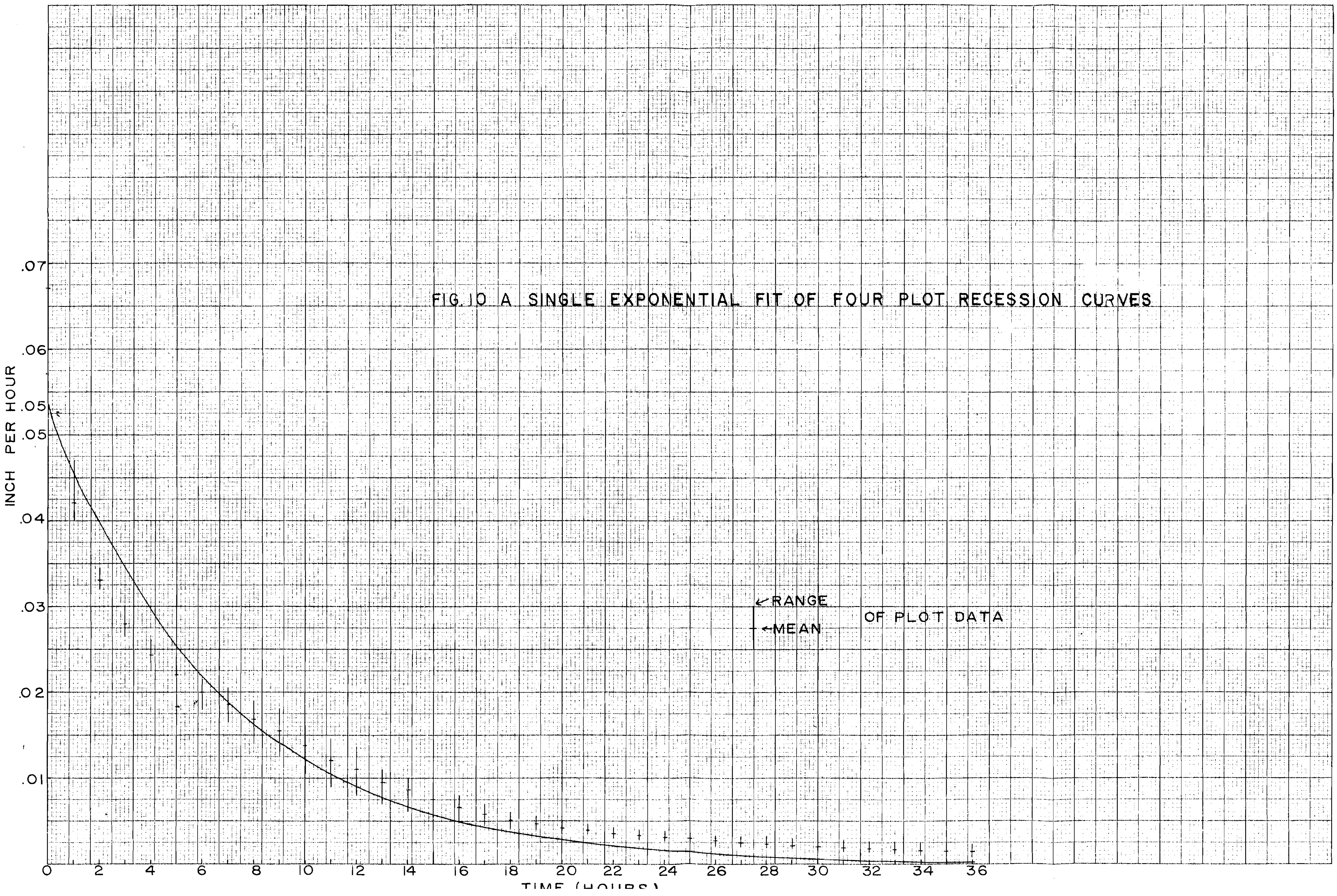


FIG. 10 A SINGLE EXPONENTIAL FIT OF FOUR PLOT RECESSION CURVES
RANGE
MEAN
OF PLOT DATA
INCH PER HOUR
.07
.06
.05
.04
.03
.02
.01
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36

Table 5. Time characteristics of Plot No. 2 hydrographs.

Date	Time from rainfall initiation to surface flow	Time from rainfall initiation to sub-surface flow	Time from rain-fall to near hydrograph peak	Time from surface peak to sub-surface peak	Four-day antecedant rainfall, inches
July 19	45 min.	1 hr., 10 min.	7 hrs., 50 min.	55 min.	1.50
July 26	1 hr., 15 min.	1 hr., 40 min.	10 hrs., 50 min.	35 min.	0.65
August 3	1 hr., 30 min.	3 hrs., 30 min.	10 hrs., 30 min.	40 min.	0.50
August 23	1 hr., 40 min.	3 hrs., 30 min.	10 hrs., 50 min.	40 min.	0.55

Table 6. Saturated, peak rates of flow.

Source of flow	Date			
	July 19	July 26	August 3	August 23
	Rate in inches per hour			
Rainfall applied	0.360	0.315	0.350	0.315
Surface flow	0.285	0.205	0.250	0.220
Total subsurface flow	0.075	0.110	0.100	0.095
Subsurface flow above the fragipan	0.069	0.069	0.070	0.060
Subsurface flow through the fragipan	0.006	0.041	0.030	0.035

a soil. As noted previously, Boggess has shown long-term differences in pore space associated with three vegetational cover types. Hydraulic conductivity of the relatively permeable upper soil layers strongly reflected these different pore space relationships. Abandoned and cultivated fields with moderate erosion can be expected to produce greater surface runoff than uneroded hardwood forests. Small runoff plots under hardwood cover would probably not reflect a decrease in surface flow due to the shingle action of hardwood litter; however, this seldom becomes a factor on large drainages because topographic changes provide an opportunity for storm water moving over the litter to pass into the soil at some point before the stream is reached (Hursh and Hoover, 1941).

Recession of Subsurface Flow

The discharge of subsurface moisture above the fragipan follows the decay equation $A_t = Q_o K^t$ (Barnes, 1939), where Q_t and Q_o are values of the discharge at any two instants separated by the time interval t, and K is a constant known as the depletion factor. The mean recession leg of subsurface flow, plotted on rectangular coordinates, is shown in Fig. 10. A fit (r^2 = 0.933) of the single exponential decay equation[1] is a reasonable expression of the recession curve from the plots except that it underestimates the initial discharge(maximum conductivity). On first examination, this would suggest that the plot design may be such that water channeled through crevices or along the plot sides may yield peak rates above the natural rates expected to occur; however, the agreement of "hydraulic conductivity" values

[1] Data analyzed by IBM 7094 digital computer using Dr. S. G. Carmer's program, "Estimation of parameters in linear and non-linear regression-model number 3," Department of Agronomy, University of Illinois.

with those reported by other authors does not support this argument. The plots "seasoned" for nearly a year before the final runs were made, and there was no visual evidence of channeling either during the runs or upon examination of the plots after they were dismantled.

The single exponential equation was used by Barnes (1939) to describe the recession of storm-seepage from a 1,500-square-mile drainage. Fully saturated, equilibrium conditions of the plot study could hardly be expected on such a large drainage. On the other hand, small drainages on shallow Grantsburg soils, such as the Lake Glendale Watershed, could easily reach complete saturation during large storms, particularly during the winter and early spring when soil moisture storage is completely satisfied. A probable explanation of the deviation of peak flow values from the estimated values is the fact that the plots reached equilibrium under a constant hydraulic head which would yield a higher rate of conductivity than predicted by the equation. The decay equation describes drainage from a porous medium and would not account for any additional hydrostatic forces caused by the constant surface runoff.

The beginning of the recession curve can be better estimated by adding a second exponential term[2] to the first, giving the general equation $Q_t = A_1K_1^t + A_2K_2^t$, where there are two A and two K constants. The fitted equation, $Q_t = (.03759)(.90089)^t + (.02941)(.28870)^t$, gave an excellent fit ($r^2 = 0.989$) of all the data, bringing the estimated peak discharge up to 0.06700 inch per hour (Fig. 11). The addition of the second exponential term significantly ($P > 0.01$) reduced the residual sum of squares, and the

[2] Data analyzed by IBM 7094 digital computer, using Dr. S. G. Carmer's program, "Estimation of parameters in linear and non-linear regression--model number F9," Department of Agronomy, University of Illinois.

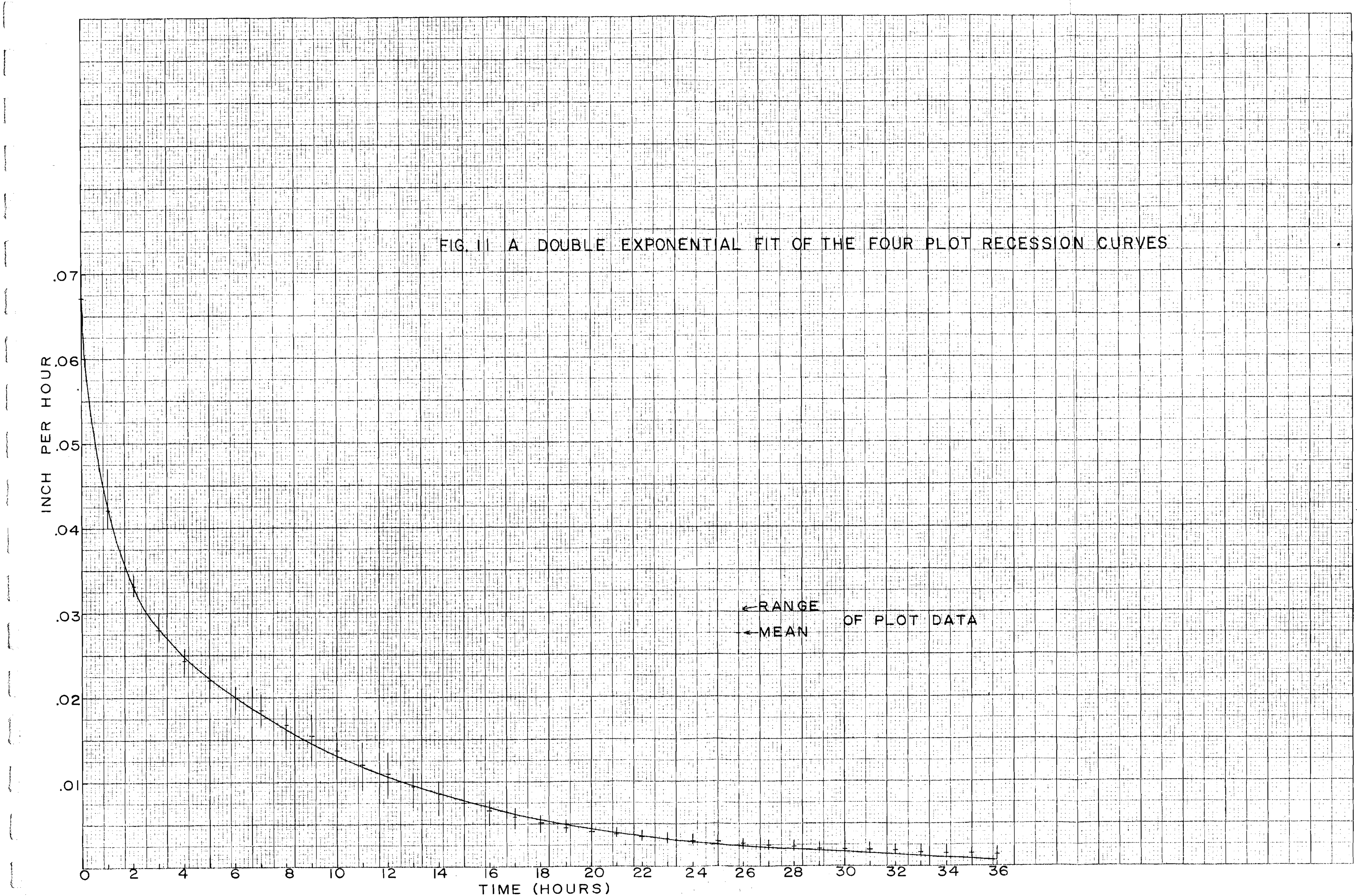


FIG. 11 A DOUBLE EXPONENTIAL FIT OF THE FOUR PLOT RECESSION CURVES
INCH PER HOUR
.07
.06
.05
.04
.03
.02
.01
←RANGE
←MEAN
OF PLOT DATA
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36
TIME (HOURS)

pooled variance of the four replications at each time period was 0.00000259. Discharge values varied from a peak of 0.07 to a low of 0.0008 inch per hour after 36 hours of drainage.

A Comparison with the Lake Glendale Watershed

Direct comparisons from a plot to a watershed are very difficult. The problems involved can be grouped into three broad areas: (1) the variability of storms in comparison with the uniform intensity and areal distributions of the plot rainfall; (2) the blow-up factor from plot to watershed assumes homogeneous conditions on the watershed; and (3) the watershed hydrograph includes channel characteristics and base flow, while the plot hydrograph does not.

In spite of these problems, an attempt was made to trace a subsurface recession leg for inlet hydrographs from 1.04 square miles of the entire Lake Glendale Watershed. To minimize the errors involved, the average of four storms, meeting rigid criteria, was used for the hydrograph separation. The storms were 9 hours or longer in duration, exceeded 2 inches of total rainfall, occurred on wet soil conditions as defined by Boggess et al (1965), and contained only one peak. The four storms: January 20, 1958; July 22, 1958; January 21, 1959; and January 15, 1962, were the only ones meeting these criteria out of 480 storms from October 1956 to October 1962 (Boggess et al, 1965).

The hydrograph separation (Fig. 12) shows only the recession leg of the combined storm average. Baseflow was separated by the method described by Chow (1964) and was subtracted from the total hydrograph to yield direct runoff. Next the recession leg of subsurface flow from the plot, expanded by an area factor and converted to cfs (cubic feet per second) was plotted by tying the lower end into the time associated with the appearance of only

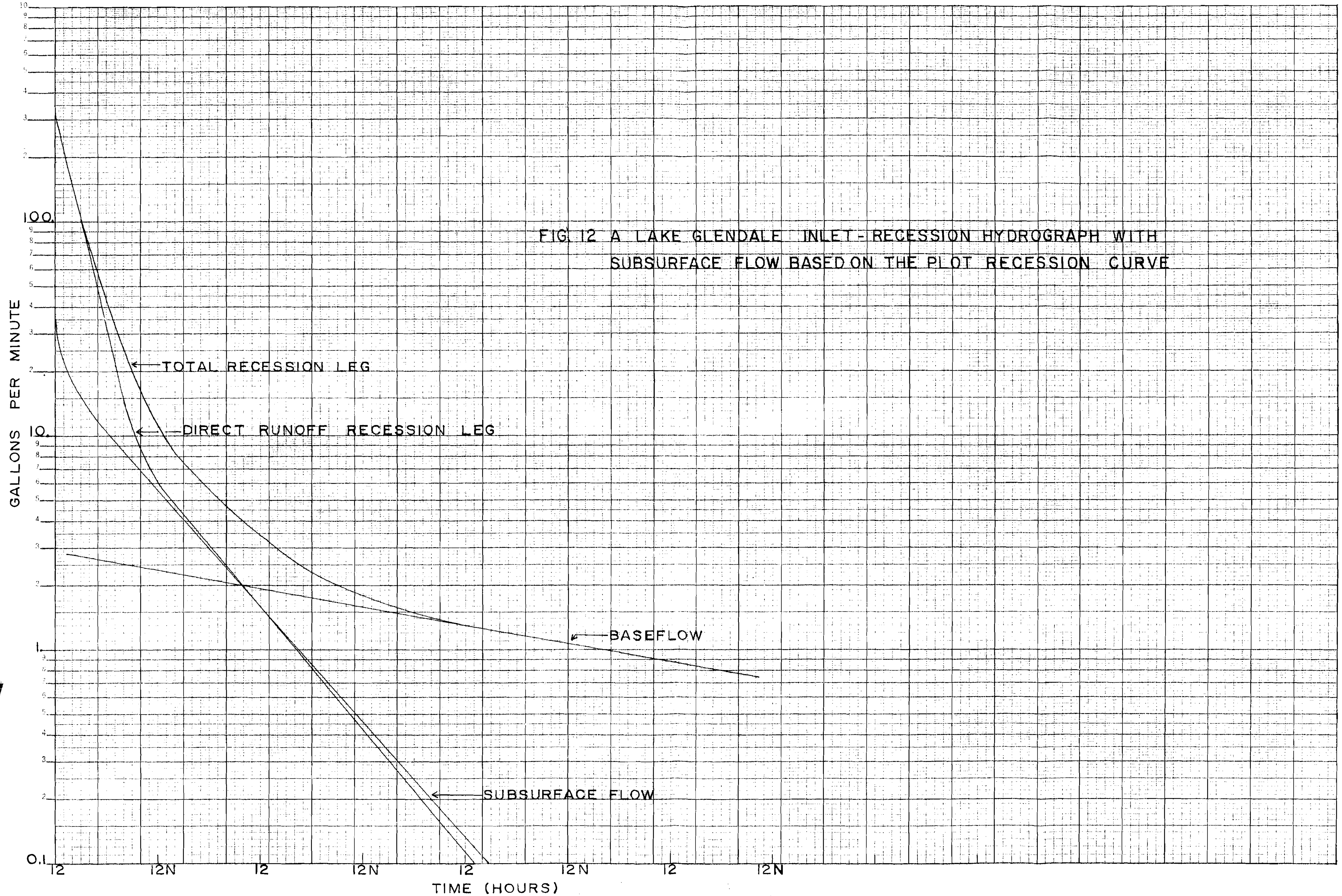


FIG. 12 A LAKE GLENDALE INLET - RECESSION HYDROGRAPH WITH SUBSURFACE FLOW BASED ON THE PLOT RECESSION CURVE

baseflow on the watershed hydrograph. Considering all of the problems in this comparison, there is a remarkable fit of the subsurface and direct runoff separations in their lower straight-line portions with only a slight difference in slope. From the hydrograph separation, it appears that surface runoff lasted for approximately 15 hours and that subsurface flow persisted for an additional 36 to 40 hours before the stream returned to baseflow conditions. Stage hydrographs for the entire Lake Glendale Watershed (2.11 square miles) follow this general time pattern for storms falling during periods when soil moisture storage is satisfied--"wet soil" storms as described by Boggess et al (1965).

CONCLUSIONS

Based on plot determinations, subsurface flow provides a significant component of the total water yield, comprising 29 percent of the direct runoff and about one-fifth of the total water, applied as artificial rainfall to plots whose soil moisture storage capacity was satisfied. Measurable subsurface flow lasted for 36 hours, followed by some "dripping" for an additional 12 hours. These flow periods, based on a comparison of hydrographs, appear comparable to those on the 2.11 square mile Lake Glendale Watershed during periods when the soil moisture is above field capacity. Such conditions occur during the winter and early spring when evapotranspiration is at a minimum.

Subsurface flow in the Grantsburg and similar soil series is caused by a well-developed fragipan which impedes the downward movement of water in the profiles. Following recharge during the fall and winter, these soils may develop a perched water table, which may cause tillage difficulties if it persists into the spring months.

The fragipan acts as a barrier to groundwater recharge by routing subsurface flow to stream channels, or to the soil surface on severely eroded slopes. As a result, groundwater resources of the southern Illinois uplands are notoriously poor and streamflow is very low or nonexistent during the summer and fall. Towns and cities away from main watercourses often depend on impoundments to provide water for their needs. Data from our study indicate that from one-third to one-fourth of the direct runoff into such impoundments results from subsurface movement of water.

APPENDIX

INSTRUMENTATION

Collection System

Collection troughs were installed at the soil surface, and well into the fragipan at a depth of 36 inches on Plot No. 1 and 26 inches on Plot No. 2. The surface troughs were constructed of sheet metal as shown in Fig. 13. The forward edge of the surface trough was inserted by first cutting an entrance slit 2 inches deep and driven an additional 2 inches to effect a seal. The trough-soil interface was sealed with black plastic cement. Troughs were supported by shelf brackets on the plywood facing.

The subsurface troughs were inserted in a 5-inch slit cut in the plot face using a chain saw with a used chain and bar. Several sharpenings of the chain were necessary in order to maintain a clean cut. The trough was then inserted and driven in, leaving clearance for the plywood wall.

Both troughs were built in 10-foot sections and transported to the plot area, where they were overlapped and soldered to meet the exact dimension of the plot. Copper screen wire covered each outlet and on the subsurface trough extended the full length, bridging the interior right angle to prevent clogging from sloughing soil. Inch and one-half drains were provided in each trough and were reduced to receive a one-inch i.d. (inside diameter) light-weight plastic hose. The flexible hose was secured on 2 x 2 boards to provide rigidity where needed. There was enough gradient for the pipe to take 5 gallons per minute; however, a $1\frac{1}{2}$-inch or larger pipe would have given a much larger leeway. Even when supported, the plastic pipe undulated enough to require twice the gradient recommended for straight pipe.

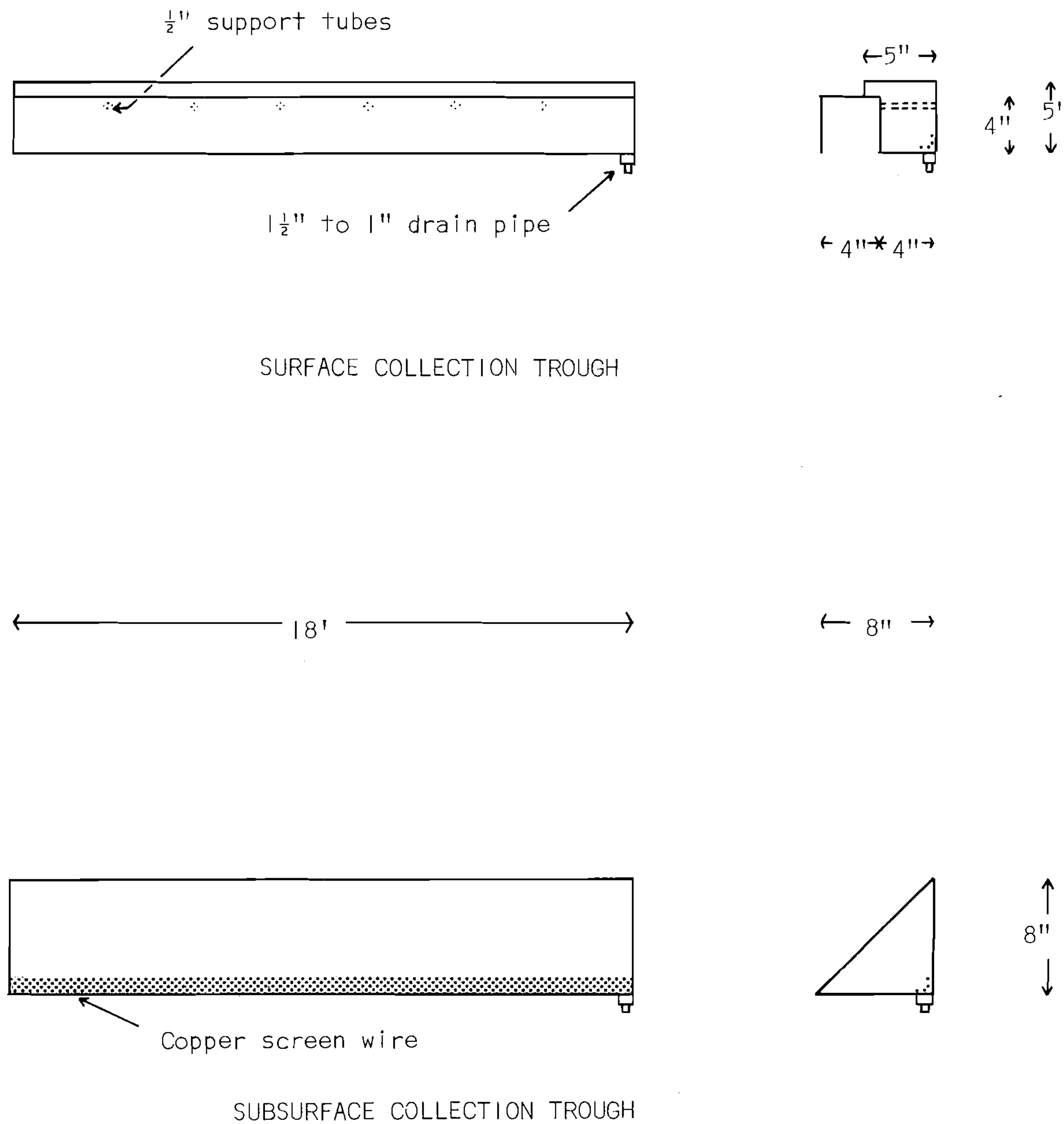


Fig. 13. Collection trough design.

Measurement of Artificial Rainfall

The metering device for rainfall is shown in Fig. 19. The incoming pressure was maintained at 40 psi or better for more accurate metering on the Rockwell Model SR Water Meters. The meter measures to the nearest one-tenth gallon and surpasses the American Water Work Association's specifications for accuracy. Water was applied to the plot through plastic lawn-soaking hose (Fig. 22) turned on its side and fastened to the plot boundary boards, 6 inches above the ground. This arrangement provided good distribution of moisture on the plots. Initial "rainfall" rates were estimated for 4- or 5-minute intervals on the water meter. The average rate used was for the entire period of moisture application.

Measurement of Surface Runoff

The measurement of surface runoff was accomplished by a weir and water stage recorder apparatus. The inexpensive device, shown in Fig. 20, consisted of two 55-gallon barrels inverted and connected by their 3/4-inch outlets. One barrel served as a stilling well, while the other provided the catchment and 30° weir. The top (the original bottom) of the "weir" barrel was cut out to receive surface runoff. The top of the "stilling" barrel was left intact to provide a base for the Stevens Type F recorder, and a hole was cut for the weight and float. The Stevens Type F Model 61 recorder was equipped with a 1:1 gauge scale, provided by pulley shaft gear 84 and drum shaft gear 56. The spring-driven clock was provided with clock shaft gear "A" 80 and drum shaft gear "B" 20 for a total chart time of 24 hours. This is the most sensitive combination available unless the faster (12-, 8-, or 4-hour) A. C. current, synchronous motor clock can be used. The 2-inch outlet on one of the barrels was fitted with a valve for drainage. The entire apparatus was installed on a concrete base formed to receive the 3/4-inch linkage and

2-inch drain, and a convenient intermittent stream provided the necessary gradient for collecting the flow.

The barrels were calibrated in two steps. The first was a volume calibration with recorder stage heights for a storage capacity of about 78 gallons between an arbitrary starting point and the bottom of the weir notch. This calibration was done in 5-gallon increments to allow for irregularities in the barrels. The volume method provided a more precise determination of initial low flows than was possible by using the weir. The initial starting point was chiseled into the barrel, and care had to be taken in filling the barrels to this mark. A simpler and more precise method would be to install a vertical elbow to the drainage valve and allow the barrels to initially drain to the top of an attached standpipe.

The second step was a rate calibration for flows passing through the weir. Known rates from 0.5 to 6.5 gallons per minute were run into the weir barrel, and resulting heights of flow were marked on the stage recorder. For maximum precision, all heights were measured on the recording chart with a 60 engineers scale. The rating curves (Fig. 14) for each plot were nearly identical. The barrels were calibrated before and after the series of four runs, and in each case the latter curves were identical to the initial ones. All measurements taken from the resulting hydrograph of surface runoff were in 15-minute intervals unless the change in slope was sharp enough to warrant $7\frac{1}{2}$-minute intervals. Bertoni et al (1958) used similar 30° weirs with constructed plate-metal tanks instead of barrels.

Measurement of Subsurface Flow

Subsurface flow was measured in recording rain gages (Stevens Recorders Type OEV) located in sealed pits sufficiently deep to provide the necessary gradient from the subsurface collection troughs. The weighing buckets were emptied each time the limit of the recording chart was reached. A manual time record was also kept for each emptying. Discharge hydrographs were constructed by recording the time and volume for each vertical trace on the drum chart, or in the case of very low flows, each hour. The data were then grouped into approximately hourly intervals with necessary finer divisions at slope changes. The original data were in gallons per minute to find total yield and were then converted to inches per hour for hydrograph analysis.

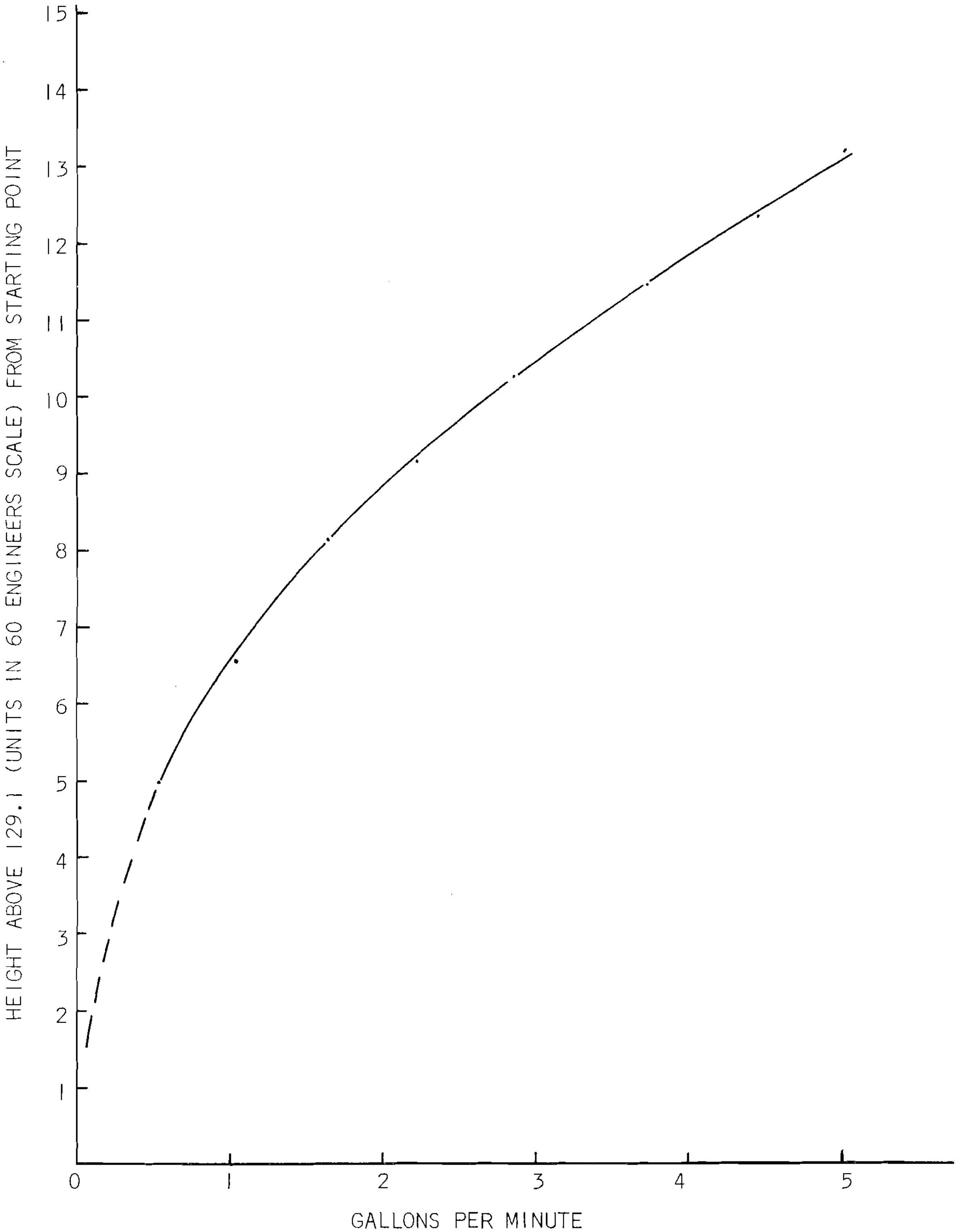


Fig. 14. Rating curve for Plot No. 1.

Fig. 15. Access pit at the lower end of Plot No. 1. Note the black vinyl already laid in the side trench.

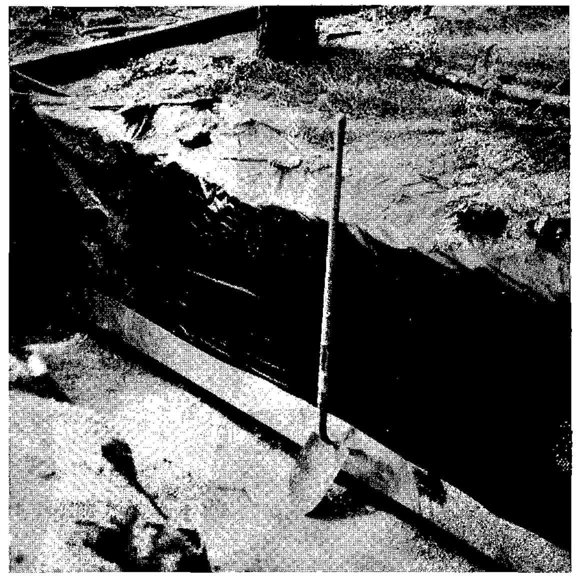


Fig. 16. The entire plot was sealed against this vinyl sheet. Note the installed subsurface flow collection trough.

Fig. 17. The plywood wall supports the surface runoff trough as well as protecting the plot face. The plywood extends into the bottom trough, but does not rest on it.

Fig. 18. Careful replacement of needle litter and partially decomposed organic matter repairs the perimeter of the plot disturbed by the trenching operation.

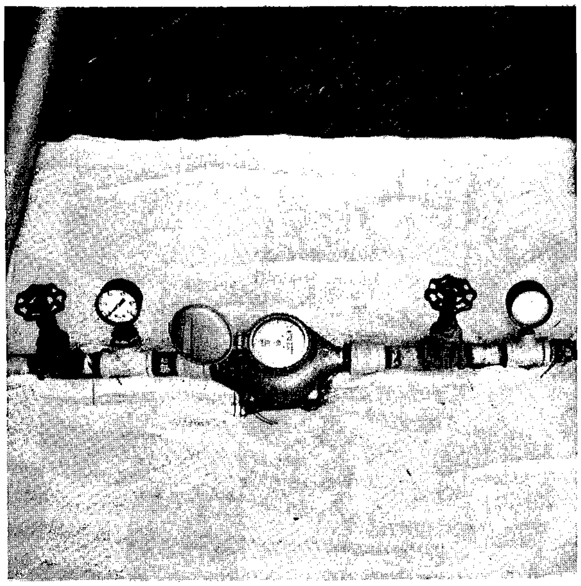


Fig. 19. Rainfall was measured with a water meter and pressure gauges.

Fig. 20. Stilling and weir barrels were used for surface run-off measurement.

Fig. 21. A recording rain gauge measured the subsurface flow.

Fig. 22. Plot No. I ready for operation.

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