UNITED STATES DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
WASHINGTON D. C.
H. H. BENNETT, CHIEF

THE ANALYSIS OF HYDROLOGIC DATA
FOR
SMALL WATERSHEDS

By

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October 5, 1939

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(4165)

FOREWORD

The methods of analysis presented in this paper were developed by W. W. Horner, Consulting Engineer, in cooperation with L. K. Sherman and Robert E. Horton, Consulting Engineers. They are submitted to the technical workers of the Divisions of Research for such aid as can be derived from them in their studies and analyses.

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INTRODUCTION

The tremendous increase in investigations and in projects dealing with the development of water resources and the removal of water hazards has focused attention on the necessity for a better understanding of the relation between rainfall and surface runoff or stream flow.

Hydrologists and engineers have long understood the irrationality involved in estimating runoff rate as a percentage of mass rainfall. They have recognized that runoff is essentially a residual and can only be rationally evaluated as rainfall minus loss, of which loss by infiltration is a major item.

Without an adequate understanding of the mechanics of infiltration, those factors which control infiltration during and subsequent to a storm period could not be separately isolated, and infiltration has largely been thought of in terms of monthly, seasonal, and annual values.

The conception of "infiltration capacity" introduced by Horton and the improved knowledge of the mechanics of infiltration which has appeared out of the research programs of the Department of Agriculture have completely altered this situation. It is now possible to estimate surface runoff as the approximate equivalent of excess rainfall, which in turn is the summation for a storm period, or a portion of such period, of the

difference between precipitation rate and infiltration capacity rate.

In the light of our present knowledge, there can be no justification for a continuation of the older and cruder engineering practice by which runoff during storm periods was estimated by applying to precipitation a "coefficient of runoff". This type of practice may be expected to be abandoned as rapidly as specific values of infiltration capacity can be made available to the engineer.

The date from which infiltration capacity may be determined are now available from probably several thousand well controlled observations. These observations cover most of the combinations of soils, soil moisture, and vegetal cover likely to be encountered in practical application. These observations have been made on controlled runoff plots under natural rainfall, on controlled plots under artificial precipitation, on small watersheds for a single soil type and vegetal cover throughout full seasonal changes, and on some larger watersheds exemplifying the more common combinations of cultivated land, pasture, and woods. They have been made extensively also on forested areas or in connection with forestry problems.

Infiltration capacity, however, is not in the class of directly observable basic data. It is secondary or derived

data for the production of which hydrologic analysis is required. In order that the secondary data may be fully reliable from place to place and from one condition to another, they should be derived under uniform standard procedure.

One of the most prolific and satisfactory sources of data from which infiltration capacity can be derived has resulted from the small watershed research program of the Soil Conservation Service, including as it does more than a hundred watersheds with records of each precipitation period throughout the life of the project (one to six years). The purpose of the method of analysis herein presented is to facilitate the production of infiltration capacity values from this particular mass of data.

The procedure is in tentative or first draft form, and consists of two parts, an introduction and discussion of the hydrologic principles and factors involved in the analytical work, and in Part II the development of specific procedure for the production of infiltration capacity values.

The objective of the preliminary analysis described herein is to produce values of infiltration capacity and of the march of infiltration capacity for each precipitation period, and to develop curves of infiltration capacity value throughout precipitation periods for each of the soil and cover types in-

volved. Such analysis for separate precipitation periods may then be correlated and the changes with season, cover condition, and soil moisture recognized.

The values produced by the method outlined in Part II should be generally accurate to the nearest 0.2 inch per hour for the first hour of each precipitation period, to the nearest 0.1 inch in the second hour, and to the nearest .05 inch thereafter for the longer storms. For many of the records the accuracy will be greater. That these values are satisfactory for engineering application will be recognized when it is noted that the infiltration capacity rates are to be applied to precipitation rates either of actual storms or of synthetically developed type storms.

Separately, and at a later date, it is expected that there will be issued a Part III which will set up procedure for a second refinement of the infiltration capacity analysis, and which will also provide for the production of data as to surface detention and its relation to runoff rates. Part III will also include discussion of the methods for correlating infiltration capacity with soil moisture, or with antecedent precipitation and temperature. To facilitate this later use of the records, it is suggested that at the time of the preliminary analysis the basic information be carefully annotated as to the occur-

rence of antecedent precipitation and as to temperature throughout possibly a 30-day period preceding the record, and that soil moisture information insofar as it may have been collected be tabulated and attached to the preliminary information.

ANALYSIS OF HYDROLOGIC DATA FOR SMALL WATERSHEDS

Part I

Discussion of Controlling Factors

The term Small Watershed as here used refers to a natural drainage basin within which precipitation intensity is accurately measured at one or more recording gage stations, and runoff from the watershed as a whole is accurately measured through a flume, over a weir or other artificial control, equipped with an automatic recording device, generally a water stage recorder.[1]

The small watershed may have a drainage basin area of from one acre to possibly six thousand acres. Within this range of size, the analytical methods applied will have to be materially varied to secure the best results, and these results will also vary somewhat with respect to the accuracy of the secondary data developed.

The basic data collected consist of a continuous record of precipitation intensity and of runoff rates throughout the specific storm periods, and makes available also mass values of precipitation and runoff for successive increments of time, and for precipitation periods as a whole.

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[1] The definitions of hydrologic terms given herein explain their use in this article. Many of these definitions have not attained general acceptance.

The secondary data, for the production of which the analysis is undertaken, are:

(1) Infiltration Capacity - A conception of infiltration capacity has made possible the development of a new hydrologic technique, and has made possible the use of completely rational relationships in practice between rainfall and surface runoff.

As originally defined by Horton, infiltration capacity is "the maximum rate at which the soil, when in a given condition, can absorb falling rain." It is a significant physical property of the soil. It is a rate value of the same character as precipitation intensity. When subtracted from precipitation intensity for a specific time period the resulting difference is the rate of production of excess rainfall. The summation of such differences evaluates total excess rainfall for any period chosen. Excess rainfall after deducting depression storage may in turn be taken for most drainage basins as sensibly equivalent to volume of surface runoff.

These relationships permit the determination of infiltration capacity from rainfall and runoff data, and the application may be reversed in order to estimate the volume of runoff or stream flow from any storm by which the pattern of precipitation intensity is known when such a storm occurs on an area for which infiltration capacity values may be available.

Under some conditions this factor can be determined only as a mean value for the complete storm period. For many storm periods, however, infiltration capacity may be determined as mean value for a portion of the storm period. Frequently it may be determined from several portions of the storm period where there are definite breaks in the precipitation pattern and in the hydrograph which will permit the isolation of values for a number of time intervals. Where this is possible, the variation in infiltration capacity with respect to time from the beginning of precipitation may be determined, and the resulting characteristic curves developed similar to those which have been determined from artificial sprinkling plots.

Where only one type of soil, land use, and management exists within a small watershed, the values of infiltration capacity will be those related to a particular soil and vegetal cover. Larger watersheds may involve two or more such combinations, in which case a further study of a number of them will be necessary if the infiltration capacity values are to be satisfactorily segregated.

Infiltration capacity values determined for a sufficient number of storm periods throughout the seasons of the year may be analyzed to determine the variation in this factor with seasonal changes in soil conditions, vegetal cover, and other

controlling variables. When the information has been accumulated from a sufficient number of storms, these seasonal changes may be determined with respect to the initial infiltration capacity (beginning of runoff period), the final infiltration capacity (latter part of storm period), and mean infiltration capacity for storm periods of varying length.

(2) Retention and Interception - As used here, retention is that part of the precipitation not disposed of as runoff or by infiltration during the period in which runoff is occurring. It includes depression storage and interception.

The mass value of retention must in general be accumulated out of precipitation before runoff begins, and an equivalent amount remains in depression storage or on the vegetal cover when excess precipitation ends. This is of course strictly true only for a completely homogeneous type of surface, as it is recognized that runoff may begin from some parts of the area while depression storage is being filled as to other parts.

This important factor cannot be isolated readily in the analysis of small watershed data in the same way that it may be determined from small sprinkled plot or runoff plot data. In the type of analysis suggested herein, the total losses during the first phase of the storm period will be made up of retention and of infiltration, the latter often at high capacity rates.

Because of the realtively long time of concentration of the small watershed as compared with the sprinkled plot, retention commonly cannot be determined on a basis of the time interval between the beginning of excess precipitation and of runoff, although for the smaller watersheds this may occasionally be done. The characteristic values of retention for the average size watershed must be worked out from such indications as appear in the more very favorable hydrographs, must be tested against other cases, and final confirmation after preliminary values of infiltration capacity have been determined, attained through the reproduction of the hydrograph itself. Retention will have a limiting mass value equal to the volume of small enclosed drainage areas up to their overflow outlets. This volume may change with changes in cultivation of the area, and to some extent with changes in condition of vegetal cover. This storage volume may be filled when the precipitation is sufficient in amount to satisfy retention. For less volumes of precipitation during a storm period, available retention space may not be filled and actual retention will be less than the maximum possible retention for the watershed under a given condition.

(3) In the course of development of the infiltration capacity and retention factors, other secondary hydrologic data

may also be produced, and to some extent must necessarily be produced for the confirmation of infiltration capacity and retention values. Among these are the characteristics of overland flow, including the relationship between runoff and depth of surface detention and, for the larger watersheds particularly, the relationship between the outflow rate from runoff and channel storage. For the smaller watersheds up to possibly fifteen or twenty-five acres, it may be satisfactorily accurate to include channel storage with surface detentions and evaluate the sum in terms of mean surface detention.

The analytical methods applicable to the analysis of data from small runoff plots under natural precipitation, and from artificial sprinkled plots have been intensively studied and reduced to a rather definite procedure. This procedure is, in some degree, applicable to the analysis for the smaller watersheds, but cannot be directly applied to many of them having an area in excess of fifteen to twenty-five acres. The essential differences between the analytical method for the small plot and that best suited to the small watershed are discussed in connection with various factors entering into the analysis of the latter.

Rain Intensity Diagram - This form of diagram, similar in character to the hydrograph of runoff, in which precipita-

tion intensity is plotted against time of occurrence, has been found to be one of the most useful tools in the small watershed analysis. The extent to which salient features of the hydrology of the watershed may be found to be indicated from such a diagram apparently has not been well appreciated. This graph is, of course, made up from the record of a recording rain gage which is satisfactorily located within the watershed, and upon the general assumption that this diagram will represent reasonably well, precipitation intensity occurrence over the whole drainage basin under analysis.

For the larger watersheds more than one recording rain gage station is available, and the diagram will have to be prepared through the adjustment of the records of two or more gages. Where the rainfall patterns from the several gages controlling the watersheds are essentially similar and the intensity rates for the same time periods not too different, such an amalgamated histogram is a satisfactory basis for the analytical work. It should be noted, however, that such combinations of records cannot be carried out blindly without a full understanding of the effect on the resulting analysis. For example; if, during a particular 10-minute interval, the intensity at one gage is, say, .4" per hour and at another 2" per hour, the direct average value would be 1.2" per hour. If it so happens

that the infiltration capacity during this period was .3" per hour, the analysis of the histogram would indicate excess rainfall over the watershed at the rate of .4" per hour when, as a matter of fact, over the part of the area covered by the first gage there would be no excess rainfall whatever, and over that part reasonably represented by the second gage, there would be a 1.2 rate of excess rainfall. The actual flood flow that would result and which might be expected to be reflected in the hydrograph would be from partial-area runoff and the hydrograph would, in all probability, upon inspection, be seen to be out of harmony with the combined rainfall record.

Where the analysis is undertaken through zoning of the area, precipitation patterns are set up which apply to each zone, a first approximated infiltration capacity curve is applied separately to each of the rainfall diagrams, and the excess rainfall is thus determined for the separate parts of the area. The total excess rainfall is then compared to the mass runoff. Thereafter, the infiltration capacity values are revised until an approximate equality between excess rainfall and mass runoff is produced.

No satisfactory method of directly combining dissimilar rain intensity diagrams has been developed. Where a precipitation record of this kind is encountered, its analysis should

probably not be attempted in the first instance, but may be undertaken later after the approximate values of infiltration capacity have been determined from some small watershed having similar soil and vegetal cover, and through a zoning of the area and the carrying out of the analysis in two separate parts; it might also be done after relatively good information as to the infiltration capacities probably existing at this time had been developed out of the analysis of the same watershed for other storm periods, during which the precipitation pattern was similar on all parts of the area.

It is expected, of course, that the time of the recording rain gages and of the runoff recorder are carefully controlled, but inevitably there will be some records reviewed in which the accuracy of time setting will come under suspicion; for example, one of the first records examined indicated a sharp rise in the hydrograph well in advance of the beginning of the second period of excess precipitation. This might be due to improper time setting of the rain gage or of the runoff recorder, but on the other hand, it might occur if the movement of the storm was slow and up the watershed. Situations of this kind require careful examination, preferably by the personnel in charge of data collection, and also preferably at the time the records are taken off the charts.

The situations outlined above should be compared with that for the small runoff plot where the recording rain gage is situated at the side of the small area, and if perfectly timed should give a very exact representation of the precipitation occurrence on the plot. It may be compared with even greater contrast, with the operation of artificial sprinklers where the rate of precipitation is arbitrarily controlled to produce excess rainfall throughout the whole run.

Hydrograph of Runoff - For the purpose of this type of analysis, the hydrograph of runoff should be invariably plotted in terms of inches per hour in order that the relative rates of precipitation and runoff may be quickly compared by simple inspection, but a more open rate scale can often be used for the hydrograph. Where the hydrographs available are already plotted in second feet, they can be used without re-plotting, but somewhat less satisfactorily, and at the expense of more labor. The hydrograph of runoff should, in all cases, have been corrected for pondage behind the weir or other artificial control. This may not always affect the larger rates of runoff, but will when the change of stage is rapid, and is essential to get the most accurate picture of the beginning and ending of runoff where the area of the pond behind the weir is an appreciable portion of the area of the watershed, even though less than one

or two percent. It is important to check the causes of very small rises of hydrograph, as records have been noted which on first inspection would indicate the occurrence of runoff from the watershed, but which on closer study were found to be the result almost exclusively of rainfall on the pond. This feature, however, will have no appreciable affect on that part of the hydrograph involving considerable rates of flow.

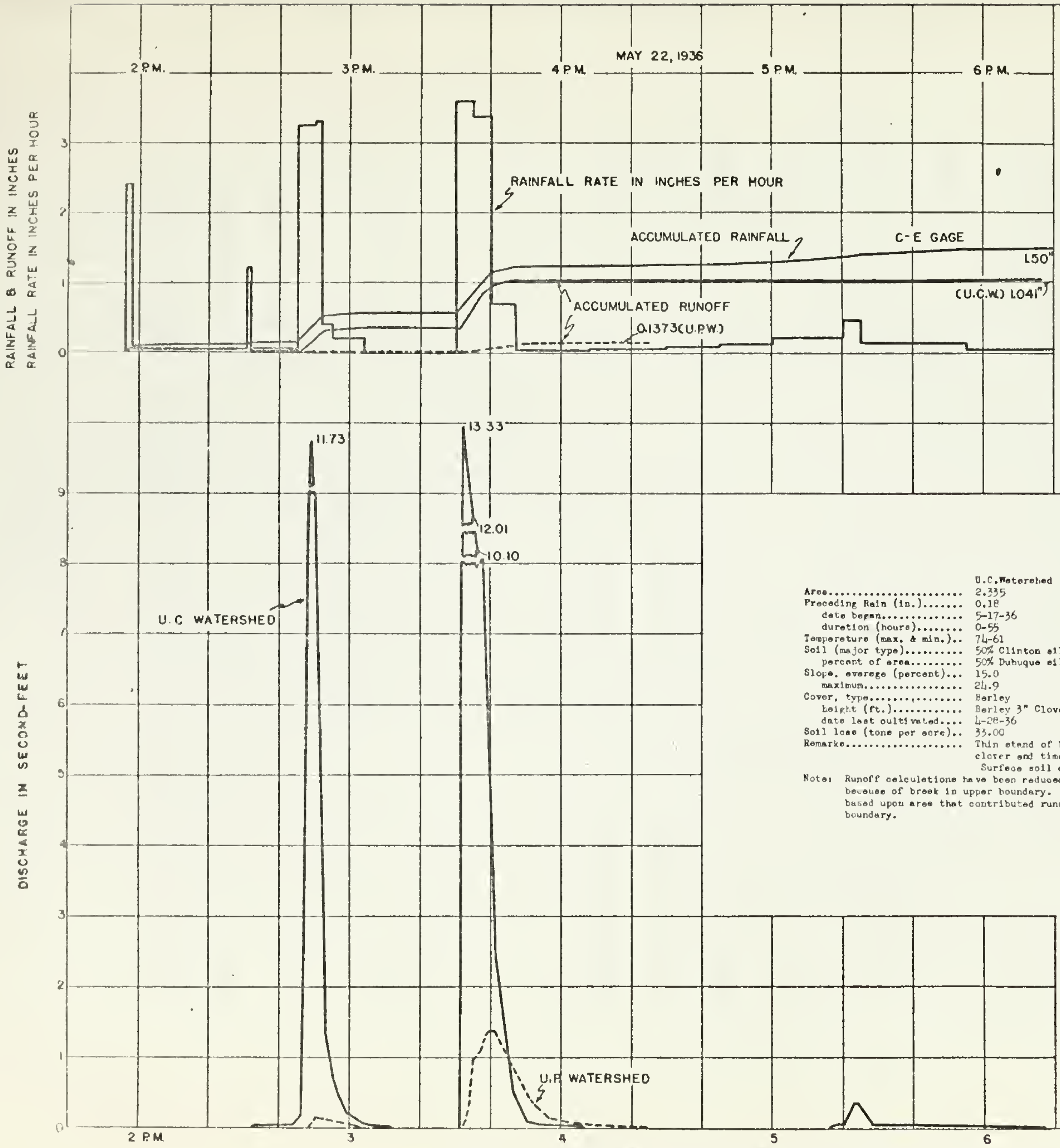
It has been noted that some hydrographs of runoff in their later phases involve rates in excess of those which could be produced by the related precipitation, clearly indicating the presence at that time of the return to the channel by seepage flow of ephemeral ground water already accounted for as infiltration in the earlier phases of the storm period. Where the runoff is clearly in excess of the precipitation which might have produced it (with respect to time relationships) such a situation is obvious and can be discounted in the analysis. A more serious condition is that in which the rate of flow in such later phases of the storm might possibly result from precipitation in the same period, but actually is in part the result of surface runoff and in part made up of returned seepage flow. In border-line cases this situation is difficult to recognize and can only be satisfactorily evaluated after the recession curves throughout a whole year of record have been

studied and standard recession curves have been prepared, obtained from certain simpler records of short storms which do not involve return seepage. In the absence of related precipitation, the difference in volume between an actual recession curve and such a standard curve may be taken as seepage return flow. In the presence of related precipitation, a cut-and-try type of analysis is necessary to develop an approximate idea of the amount of return seepage included in the hydrograph.

For those watersheds and those storms in which erosion occurs at high rates, the hydrograph should always be examined and, to the extent possible, corrected for silt content. The records indicate that for intense precipitation on relatively bare soils of an erodible character the silt may be a very high percentage of the total volume of flow; may produce the occurrence of peak flows as shown by the hydrograph at much higher rates than could be accounted for from excess rainfall, and may often result in a disturbance of the timing of peak flows, which is extremely distressing if not explained. After the study of a number of hydrographs where high silt contents are involved, these characteristics become somewhat obvious, but their correction and reduction to terms of water flow alone can only be done on the basis of rough approximation even when the total silt content for the storm period has been measured.

An occurrence of this type appeared on the hydrographs of the UC Watershed at La Crosse, where the peak flows occurred early in a period of relatively uniform precipitation intensity. The hydrograph for May 22, 1936, (figure 1) for two precipitation periods showed the peak flow well in advance of the middle of the period, and at very high rates (on the order of 6 inches per hour as compared with precipitation rates of less than 4). From the sum of these two rainfall periods, the soil loss is recorded as 33 tons per acre. Considered as silt in the water flow, this would account for a total depth of .12" out of the mass volume of runoff of 1". In all probability, this erosion was concentrated in the first flush of overland flow which may have contained as high as 30% silt by volume, so that in terms of water flow, the silt laden peaks of these hydrographs might be cut down approximately 1/3, and the actual water peak will thus be set back in time.

A similar situation is indicated for the same watershed in the storm of June 1, where the precipitation intensity was only .75" per hour, but the soil loss was 3 tons per acre. It seems probable that a correction for silt would lower the first peak of the first phase of the hydrograph quite materially, and radically change the shape of the hydrograph as a whole.



MAY 22, 1936
Watersheds U.C.W. & U.P.W.

(1) Time (t)	(2) t (min)	(3) d (in)	(4) d (in)	(5) $i = \frac{60\,d}{t}$ in/hr	(6) Std. Gage U.C.W. Depth = 1.51" Col.5 x $\frac{1.51}{1.50}$	Std. Gage St. Pl Depth 1.59" Col.5 x $\frac{1.59}{1.50}$
1:56PM		0				
1:58	2	.08	.08	2.40	2.42	2.54
2:31	33	.10	.02	.04	.04	.04
2:32	1	.12	.02	1.20	1.21	1.27
2:45	13	.13	.01	.05	.05	.05
2:50	5	.40	.27	3.24	3.26	3.43
2:52	2	.51	.11	3.30	3.32	3.50
2:55	3	.53	.02	.40	.40	.42
3:04	9	.56	.03	.20	.20	.21
3:30	26	.56		--	--	--
3:35	5	.86	.30	3.60	3.62	3.82
3:40	5	1.14	.28	3.36	3.38	3.56
3:47	7	1.22	.08	.69	.69	.73
4:08	21	1.23	.01	.03	.03	.03
4:30	22	1.25	.02	.05	.05	.05
4:45	15	1.27	.02	.08	.08	.08
5:00	15	1.30	.03	.12	.12	.13
5:20	20	1.37	.07	.21	.21	.22
5:25	5	1.41	.04	.48	.48	.51
5:55	30	1.48	.07	.14	.14	.15
6:20	25	1.50	.02	.05	.05	.05

	U.C. Watershed	U.P. Watershed
Area	2.335	2.412
Preceding Rain (in.)	0.18	0.18
date began	5-17-36	5-17-36
duration (hours)	0-55	0-55
Temperature (max. & min.)	74-61	74-61
Soil (major type)	50% Clinton silt loam	Dubuque silt loam
percent of area	50% Dubuque silt loam	
Slope, average (percent)	15.0	24.0
maximum	24.9	32.3
Cover, type	Barley	Bluegrass
height (ft.)	Barley 3" Clover-timothy 1/2"	6" to 10"
date last cultivated	4-28-36	
Soil loss (tons per acre)	33.00	.004
Remarks	Thin stand of barley, clover and timothy. Surface soil dry, subsoil moist	Grass not pastured. Very dense cover

Note: Runoff calculations have been reduced 35% on U.P.W. because of break in upper boundary. This correction is based upon area that contributed runoff from above upper boundary.

FIGURE NO. 1 - RAINFALL & RUN-OFF, UPW & UCW WATERSHEDS, LA CROSSE, WIS. MAY 22, 1936

Lag - For the smaller watersheds and the more intense storms, a direct comparison of the diagram of rainfall with the hydrograph will result in an indication of the time lag between related periods of precipitation and runoff. If the instrumental timing is accurate, a further study of the time relationships for salient features in these two diagrams will develop the characteristic stream flow lag of the particular watershed. Where a sufficient number of clean-cut hydrographs are available, the lag can be determined as between beginning of excess precipitation and the corresponding sharp rise of hydrograph; between some salient feature of the precipitation diagram, as a marked high spot intensity or a center of mass, and peak of the hydrograph; and between the end of excess precipitation and the end of surface runoff. While the watershed will appear to produce characteristic values of each of these time relationships, it will be found that each of the values will vary with the intensity of the precipitation.

It is recognized that time lag may result from different situations in basins of different types. For those basins having adequate channels and steep gradients, the effect of channel storage in producing time differences between inflow and outflow will be comparatively small, but where the channels are long the lag may still be considerable and will be largely

a measure of the time of transit of the water. For those basins where the channels have flat gradients, and particularly where the channel itself is subject to over-bank flow, the time lag may be almost entirely representative of the time required to fill the channel storage and might be referred to as storage lag. It is recognized also that the total lag will reflect not only the results of channel flow factors, but also those related to overland flow, and will be primarily representative of time of transit for steep surfaces capable of discharging large volumes of water under small depths of surface detention, and also may be primarily storage lag for flat or rough surfaces where the development of considerable depth of surface detention must occur before inflow and outflow have become stabilized.

Because of this background, the time lag will be small for high values of excess precipitation, and possibly quite long for small values of excess precipitation and also low stages of channel flow. A study of a large number of hydrographs for a particular watershed will permit picking off and tabulating these values as against the controlling conditions, and they will be found extremely useful in the course of a preliminary determination of infiltration capacity and retention.

<u>Infiltration Opportunity</u> - After a study of a few hy-

drographs of a particular watershed and surface condition, the technician will develop an aptitude for detecting the range in which the probable values of infiltration capacity will lie during the different parts of a storm period. For the more sharply defined sudden storms, with the possible infiltration capacities in mind and also with such aid as can be obtained from an examination of the hydrograph, the <u>beginning</u> of excess rainfall and consequently of infiltration opportunity at capacity rates, can often be rather accurately fixed.

A comparison of similar preliminary ideas of infiltration capacity with the salient features of the histogram will often determine rather definitely the end of excess rainfall, but this determination can also be aided by a study of the recession characteristics of the hydrograph. Infiltration opportunity at capacity rate will in all cases continue for an appreciable time, that is, as long as surface detention exclusive of the depression storage which is evaluated as a part of retention, continues to exist on some part of the area. Horton has called attention to the fact that the exhaustion of the surface detention film will begin at the ridge lines and progress down the slope to the stream margin. The end of surface detention and the end of overland flow period must, therefore, coincide. From some hydrographs, the end of the overland flow

period may be approximated from Horton's criterion as occurring at the point of inflection of the recession side. For many hydrographs this point is not clearly apparent and is particularly obscure for those cases where precipitation continues at relatively high rates, but still at less than infiltration capacity rates.

The length of time through which surface detention may persist on some part of the area and consequently the length of time for which infiltration may continue at capacity rate, will be influenced by:

(a) The rate of overland flow down the slope and consequently the rate at which net surface detention is disposed of at the stream margin;

(b) The infiltration capacity rate in the particular time, which will determine how rapidly the net surface detention film will be disposed of, in part, through the ground surface; and

(c) The intensity of precipitation, if any, which is occurring during this period and which will tend to reduce the rate of disposal of surface detention by either of the means set out in (a) and (b). It is imaginable, for example, that if precipitation should continue at exactly infiltration capacity rate, there would be no excess rainfall, but surface detention

would have to be exhausted entirely by flow to the stream margin. If the velocity of overland flow were comparatively low, the period required might be quite long, and the opportunity for infiltration at capacity rates might be so extended as to become a very large part of the total infiltration capacity time.

It is intended in this discussion to indicate that this matter of extended infiltration opportunity at capacity rates may, as to some hydrographs, be a very important item and require the most careful evaluation possible, an evaluation that can be made to best advantage after some idea of the net surface detention-outflow relationship has been developed. Surface detention in turn cannot be approximated until infiltration capacity has been determined.

Obviously, therefore, the analysis for the average small watershed must be carried out through a series of successive approximations and for this reason is quite different from the technique that can be applied to the sprinkling plot or to the small runoff plot where the response between histogram and hydrograph is so immediate that both infiltration capacity and surface detention can be calculated with considerable certainty.

Stages of Analytical Work - The analysis of small watershed data divides itself naturally into two stages, which are referred to here as the Preliminary Analysis and the Detailed

Analysis.

Preliminary analysis is expected to produce approximate values of infiltration capacity for each storm period of record, for many of the storm periods to produce approximate values of infiltration capacity for successive periods during the storm, and from these values to approximate the variation of capacity with time after the beginning of the storm period. It is expected that such preliminary analysis for a large number of storms on a single watershed will permit the production of infiltration capacity curves which in most cases can be accepted as accurate to the nearest tenth of an inch per hour; that a comparison of these curves for a number of storm periods throughout the year will permit the plotting of a tentative curve of seasonal variation infiltration capacity.
The results so obtained will only be confirmed to the extent that the secondary data are found to be consistent throughout; but these results may be tentatively accepted and actually used in application prior to the time that the more tedious detailed analysis can be completed.

The detailed analysis for each storm period would be based on the infiltration capacity curves produced in the preliminary analysis and will involve the preparation of mass curves of infiltration, determination of detention from the

beginning of the storm period to the end of the hydrograph, a separation between surface detention and channel storage for the large watersheds, determination of relation between net surface detention and overland flow, and a final readjustment of infiltration capacity values to secure the best fit of all of the secondary data.

In the course of the Preliminary Analysis a small amount of detailed analysis is desirable in order to give approximate ideas of characteristic surface detention depths as a guide in selecting the period of extended infiltration opportunity at capacity rate after the end of excess rainfall, and also for a somewhat better visualization of retention characteristics of the watershed.

PART II

Preliminary Analysis

It is suggested that where a group of watersheds exists at any research station, analysis be first undertaken of the smallest watershed, as this will give the best response between rainfall and runoff, will permit most clearly a visualization of infiltration opportunity, and of the separation of both the rainfall diagram and the hydrograph into clearly related periods.

Analysis of the larger watersheds can be undertaken to better advantage after characteristic values of infiltration opportunity and infiltration capacity have been determined for the smaller basins.

It is assumed that at the beginning of the analytical undertaking no good idea of infiltration capacity rates is available from any other type of data. If, however, there is located within the watershed a small runoff plot equipped with a recorder, the analysis of such a plot should be carried out first for each storm period before that of the watershed is undertaken. Analysis of such plots is a much simpler and more specific process than that set out here, and a knowledge of infiltration capacity and overland flow characteristics which a study of such runoff data will permit even though at the plot

the soil and surface may be characteristic of only one part of the watershed, may make unnecessary certain of the successive approximations with which the analysis of the watershed data are necessarily involved.

In the absence of any such information from runoff plots, analysis of the watershed data should be undertaken in the following manner:

1. Choose for the first effort a storm period in which precipitation is broken up in separate distinguishable sections and for which the hydrograph also contains several peaks or rises which by inspection are seen to be related to the separate sections of the precipitation diagram.

2. For some rise in the hydrograph, preferably in the middle portion of the storm period, determine from the mass curve the total precipitation for the period responsible for the rise in the hydrograph.

3. Determine from the hydrograph and mass runoff diagram, the total runoff resulting from this part of the precipitation period.

4. The total loss, which is the difference between the mass values, is considered as made up of retention and infiltration at capacity rates. In the absence of any preliminary knowledge with respect to retention, its value must be assumed

out of general experience. From a number of watersheds studied retention appears to lie between .05 and .25 inches out of the periods of high intensity precipitation, and lower values where lower intensities of precipitation are involved.

5. The assumed value of retention subtracted from the total loss gives the estimated mass infiltration which occurred at capacity rates. If a storm period has been chosen in which the precipitation is relatively intense, well in excess of the probable infiltration capacity value, and if the duration of the high intensity is reasonably long, preferably equal to or exceeding the concentration period (generally a storage concentration period) of the watershed, the total mass infiltration will be relatively large compared to the estimate of retention, and a considerable error in choosing a preliminary retention value will not cause a great error in the calculated infiltration capacity rate.

After a number of the hydrographs most satisfactory for this purpose have been analyzed, the most probable values of retention will begin to be apparent, and reasonable judgment with respect to this factor can be applied to other hydrographs involving lower precipitation intensity or shorter duration.

6. The estimated mass infiltration may then be divided by the duration of infiltration opportunity at capacity rate,

to produce a preliminary value of infiltration capacity. This opportunity period will consist of the duration of excess precipitation, which can generally be closely estimated from the rainfall diagram, plus an additional period in which infiltration can take place at capacity rate out of the net surface detention available. A reasonable evaluation of this extended period is one of the most difficult phases of the analysis. For very small watersheds, and where the instrumental timing is quite accurate and the lag time small, the end of overland flow may be estimated from the point of inflection of the hydrograph, but it must be remembered that the time at which the cessation of the overland flow is clearly apparent from the outflow hydrograph will generally be slightly later than the time in which overland flow ceases for the greater part of the stream margin length. In transferring this time from the hydrograph to the histogram, it should be set forward slightly in an amount slightly less than the apparent characteristic lag values for this watershed and storm.

Even though the time of cessation of overland flow can be indicated satisfactorily by this process, it should be rechecked after preliminary values of infiltration capacity have been determined and after approximate value of depth of surface detention at the end of the period of excess precipitation has

been determined. With some knowledge of the infiltration capacity rate and the depth of detention at this last time, and with due consideration of the rate at which any subsequent precipitation may be occurring, a revised estimate can be made of the time after the end of excess precipitation when overland flow would be expected to cease.

It should be recognized that at the end of excess precipitation infiltration will be occurring at capacity rate over the whole basin area, that the area over which this will be occurring will be reduced to zero at the time overland flow ceases, that the change which takes place between these two times will be through exhaustion of the surface detention film both by overland flow and infiltration, that the variation, therefore, will not be along a straight line but along a curve concave upward, and that the average time which should be chosen as time of extended opportunity should be somewhat less than half of the period under consideration, possibly nearer one-third of the period.

7. With the period of extended opportunity determined by trial and judgment as above, the infiltration loss is divided by the total opportunity time and the result is mean infiltration capacity rate for the infiltration opportunity period and may be plotted at a time central within this period.

Preliminary Analysis for the Complete Storm Period. - Values of mean infiltration capacity for separate parts of the storm period should all be plotted on the diagram of rainfall at their proper time locations. The values for separate sections throughout the middle and latter parts of the storm will generally be fairly definite and acceptable as first approximations. The value for the first period of high intensity precipitation often cannot be as accurately determined, as during this period both retention and infiltration capacity will be high and there is no good indication of the probable values of either a value chosen by extending the infiltration capacity curve back from later and better determined points with due regard to the manner in which this curve would intersect the diagram of precipitation is the best that can be arrived at by judgment alone.

It would probably be well to defer a further attempt to determine the infiltration capacity values during such early storm periods until after a large number of storms have been studied. Thereafter the trend of these infiltration capacity values as indicated by all of the storms should be made the subject of a separate study and apparent trend curves should be analyzed by the method used by Horton in his discussion of Neal's paper, and by this method the most probable values of initial or early infiltration capacity rates determined. A

re-study of the early infiltration capacity rates so arrived at, against the diagram of precipitation for these early sections of each storm can then be made to determine the consistency of the values with respect to the retention amounts that would have to exist to justify them. If the use of these calculated infiltration capacity values in these early periods produces a mass value of infiltration through these periods which, when subtracted from the total losses of these periods, gives reasonably consistent values of retention, further verification will have been secured.

Some portion of this study should be included as a part of the preliminary analysis in order that the results of the preliminary analysis may be considered as reasonably useful throughout and may be actually used in application prior to the completion of the detailed analysis.

The best possible knowledge of these early values of infiltration capacities is essential, as it should be remembered that it is expected in application to use infiltration capacity curves against the histogram patterns for particularly chosen storms, and this cannot be done to advantage unless the variation throughout the whole storm period is considered reasonably satisfactory and fairly well confirmed.

EXAMPLE NO. 1

To show the possibilities of producing approximate values of infiltration capacity quickly by this method, the data for a small watershed, designated No. 12, have been selected. This is a small watershed of 2.97 acres having a uniform cover of native prairie grass.

It immediately appears that the rainfall diagram and the hydrograph on Figure 2 do not satisfactorily conform in time, and it is necessary to decide whether the rainfall diagram is not applicable because of the manner in which the storm approached and passed over the watershed or whether there is a time error in one of the instruments. After study, it was decided to arbitrarily move the hydrograph back ten minutes in time, as shown on Figure 3, and this is done to simplify the study although it does not affect volumetric relationships or rate relationships. It does, however, affect detention calculations, if these are to be carried out.

By inspection it is clear that infiltration capacity between 2:25 and 2:40 is well in excess of .35 inches per hour and that the excess rainfall which produced the major rise in the hydrograph came out of this block of precipitation. Therefore, capacity infiltration opportunity began at 2:25. From the appearance of the hydrograph, (Figure 3 c) overland flow

continued for more than ten minutes after the peak. Considering the rates of precipitation and probable rate of infiltration capacity, and the fact that precipitation continued at a one-tenth inch rate, it is decided to assume that overland flow continued for 15 minutes after the end of excess precipitation, and that on the average, opportunity continued for 5 minutes for the equivalent of the whole area, making total infiltration opportunity 20 minutes. Because of the preceding high intensity precipitation, and also of the immediately preceding moderate precipitation, retention out of this particular block of precipitation should be small. It is tentatively assumed at .05 inches. The total precipitation during this period is .65 inches.

Runoff at 3:06 (Figure 2) is scaled from the diagram as .2 inches and the runoff subsequent to 4:16 (same stream flow rate) is scaled as .07 inches. This is from a recession curve which, from the graphs of other watersheds during this storm, might contain some return seepage flow, and the amount is reduced arbitrarily to .05 inches making the total evaluated runoff out of this block of precipitation .25 inches. The total loss is .40 inches and the loss by infiltration at capacity rate is .35 inches. With the opportunity time at 20 minutes, this places the infiltration capacity rate at 1.05 inches per

hour as a mean value at 2:34.

It is obvious that the infiltration-capacity curve has a steep slope, as the block of precipitation beginning at 3:25 produced runoff and therefore the capacity at that time was probably less than .2. It is assumed that the second rise was produced by the 40 minute precipitation between 3:25 and 4:05, (Figure 2) the mass value of which is scaled at .17 inches. The total runoff after 3:06 minus the total runoff after 4:16 is scaled from the mass curve at .15 inches and is arbitrarily reduced to .13 inches for return seepage flow. This would indicate that the loss by infiltration during the 40 minute period of .04 inches or an infiltration capacity rate of .06 inches per hour.

These calculations of infiltration capacity might be taken as one inch per hour at 2:36 and one-tenth inch per hour at 3:44.

The infiltration capacity during the precipitation period beginning at 1:50 cannot be satisfactorily evaluated, as the retention was probably high and the infiltration capacity high, while the runoff was negligible. However, it is evident that some runoff occurred from excess rainfall toward the end of the high intensity precipitation block, which indicates that infiltration capacity must have been on the order of 3 inches per

hour at 2:00 P.M.

The curve of infiltration capacity is drawn through these three points.

A similar analysis was then made for watersheds "W" and "W-1", with the following results:

Time	Infiltration (Inches per hour) W 306 acres	W-1 176 acres
1:45	2.0+	2.0+
2:16	.80	.40
3:25	.13	.10

For the larger watersheds this storm produced a very flat hydrograph which at best will permit of calculating only one mean value of infiltration capacity. At this stage, these three capacity curves would be studied with respect to soil and cover to determine whether there is a satisfactory explanation for the differences. Without having at this time examined the watersheds or studied soil characteristics, it would appear that for winter conditions the soil in this area would be quite tight at a depth of 2 or 3 inches below the surface, but would become cracked and aggregated at the surface and would take infiltration at a high capacity until the surface pore space was filled, but that infiltration capacity values approximately .1 inch per

hour would exist during the greater part of long storms.

For a further check on the infiltration capacity values, and of the time relationship, the rough detailed analysis is carried out for the principal rise during the storm on watershed No. 12. The infiltration-capacity-curve is sketched in across the precipitation block, mass infiltration is calculated throughout this period, the curve of mass precipitation, mass infiltration, and mass runoff are plotted on Figure 3. From these, roughly approximated only, detention is calculated by subtractions and the graph of total detention is plotted with the mass curves.

As a part of the study of time relationships, the detention curve has been developed with the hydrograph in the position shown on the original chart, and also with the hydrograph and mass runoff curves set over to the right first in the amount of 5 minutes, and second in the amount of 10 minutes. From these three curves it will be noted that the time of maximum surface detention is not appreciably affected by these differences in the position of the runoff hydrograph, but the detention curve is varied in amount. The first or upper of these curves represents an obviously impossible condition, as the maximum runoff occurs in advance of maximum surface detention; on the second curve revised by 5 minutes, the two diagrams are almost exactly

in phase; and in the third or lower diagram where the setback is 10 minutes, surface detention occurs reasonably in advance of the similar features of the hydrograph. From this, it seems probable that the time relationships on the original graph are unsatisfactory either from instrumental difficulties or because of the manner in which the storm progressed on the watershed.

It also seems probable from these graphs that this relationship should be revised by an amount between 5 and 10 minutes.[1] As noted above, this question as to timing has no appreciable effect on the infiltration capacity curve.

It is interesting to note also that the maximum surface detention is probably on the order of .3 inch and that the surface detention occurs at the end of intense rainfall, i.e. at 2:40.

A study of surface detention depths after 2:40 together with the infiltration-capacity rate, which during the next few minutes was on the order of .7 inches per hour, would permit a

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[1] This method of checking instrumental timing, or of deducting critical storm movement may be frequently used to advantage. Such a comparison between surface detention and the rise of the hydrograph actually makes possible the detection of time errors of an instrumental character and may often make usable records that would otherwise be useless because of instrumental difficulties.

slightly better decision as to extended infiltration opportunity, but this operation has not been carried out as to this example.

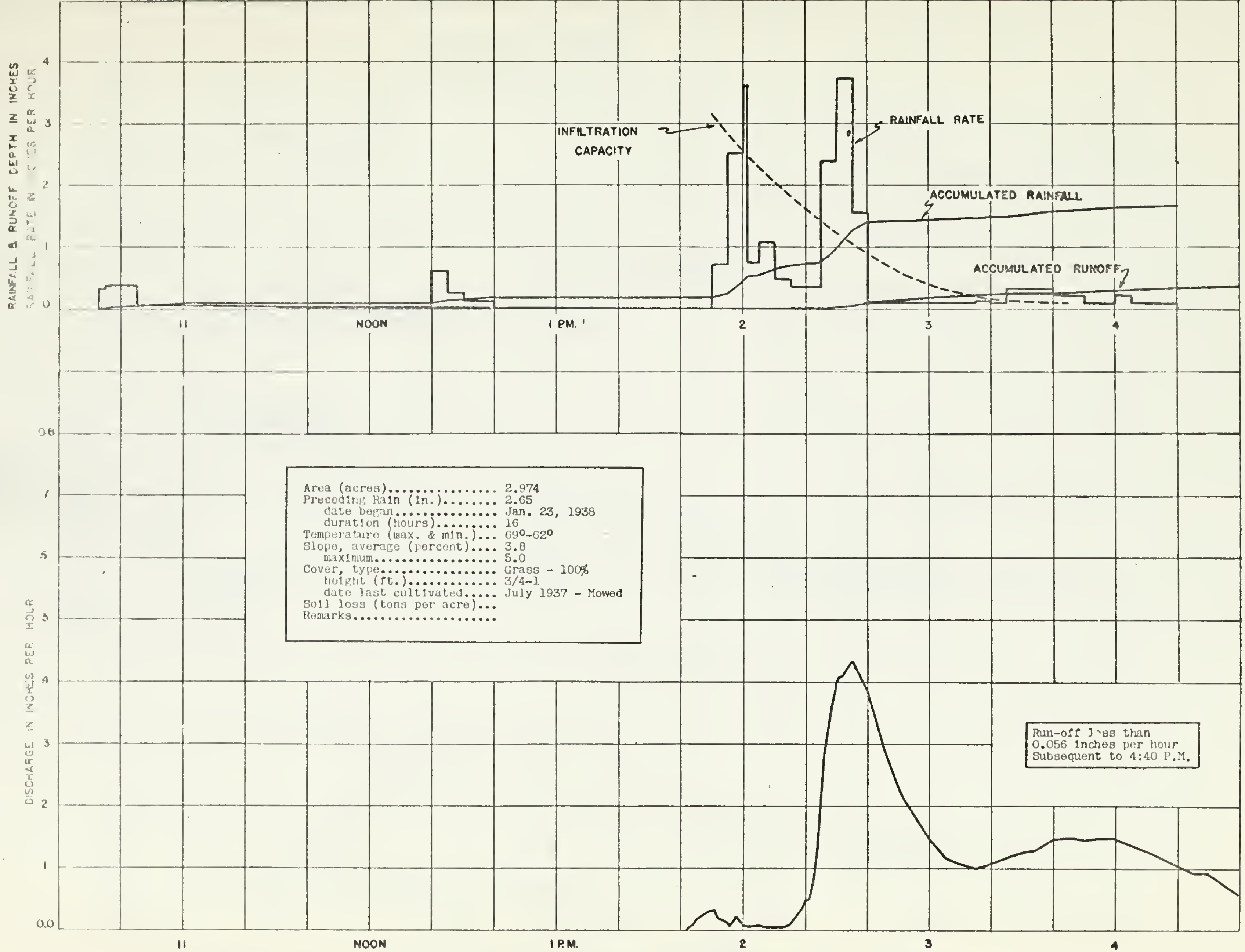

FIGURE 2 - RAINFALL, RUNOFF, AND INFILTRATION ON WATERSHED NO. 12, FEBRUARY, 1938

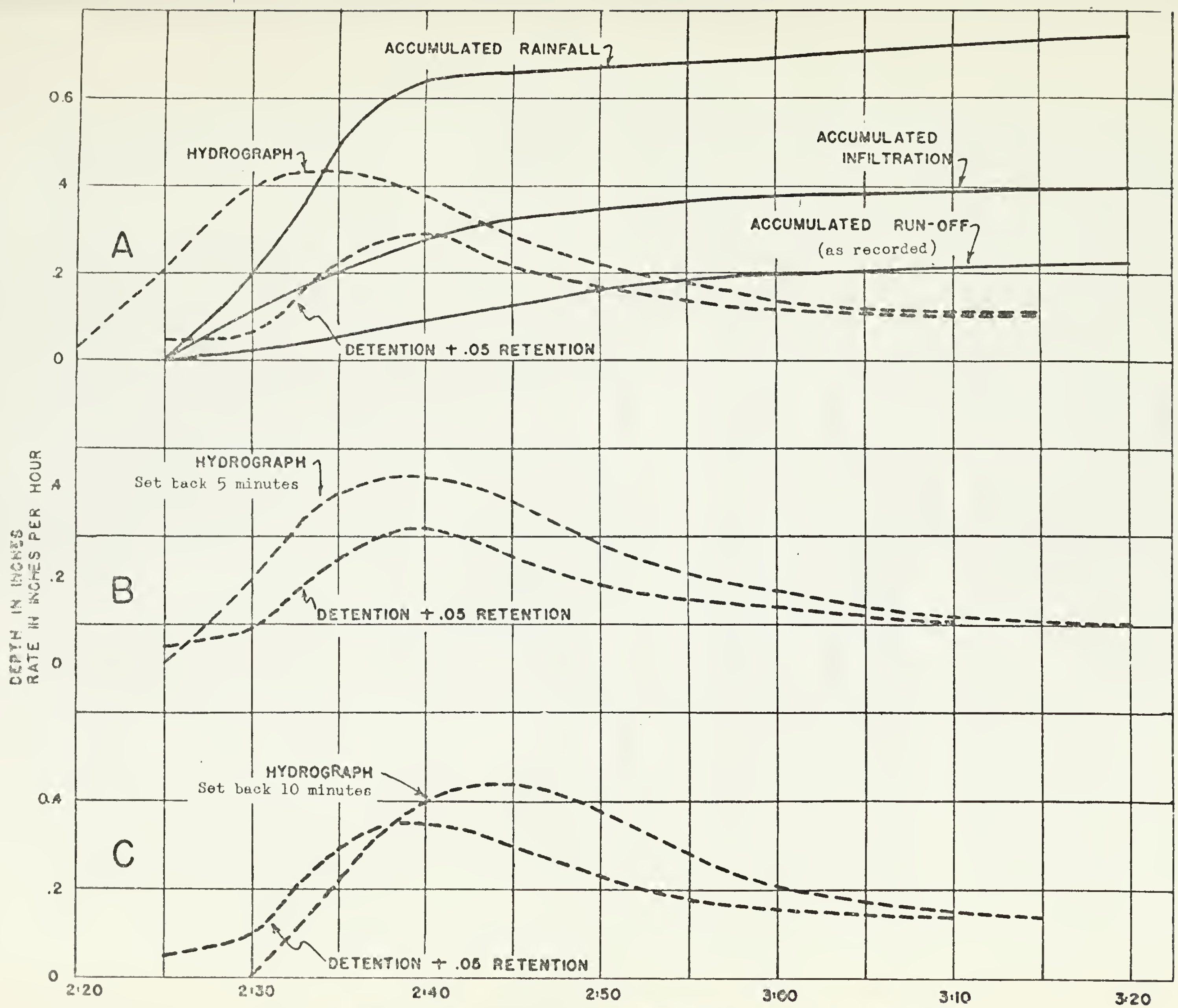

FIGURE NO. 3 - RUN-OFF, DETENTION & TIME CORRECTIONS, WATERSHED NO. 12, FEB. 16, 1938

EXAMPLE NO. 2

Bethany, Missouri

Four small watersheds in Bethany offer an interesting contrast in their runoff characteristics and some good illustrations of conditions that may be met. The storm of July 7 and 8, 1933, is used as an example.

For some of these, good approximations of the infiltration capacity curve could almost be sketched in an inspection of the rainfall diagram, and of the hydrograph, but the four are discussed in more detail in the following paragraphs.

Watershed I-58

In July, 1933, this watershed of 2.11 acres was covered with young alfalfa and some weeds, which apparently gave good surface cover and only moderate possibility for erosion, the soil loss in this storm being .9 tons per acre.

The hydrograph (Figure 4) shows a single peak and a clean-cut recession curve after about 9:16 P.M., indicating that all of the runoff came from the high intensity precipitation block between 8:58 and 9:13. Precipitation in this period is .97 inches and the runoff to 9:32 is .21 inches, making a total loss of .76 inches. After several trials, retention is taken at .07 inches, and infiltration at .69 inches, with infiltration opportunity at 18 minutes, mean infiltration capaci-

ty is 2.30 inches per hour placed at 9:07 P.M. After noting that infiltration capacity must have been above 1.20 inches per hour at 9:38, and above .9 inches per hour at 9:43, and above .38 inches per hour at 10:40, the curve can be sketched so as to roughly parallel that of watershed IJ 1, and then, adjusted across the highly intense precipitation block to a satisfactory balance between excess rainfall, retention, and runoff. This is not done, however, until after watershed IJ 1 has been analyzed as a guide.

The reasons for the slowly receding hydrograph for several hours after 9:30 could only be determined from further observations on the ground, but it seems highly probable that this flow comes from ephemeral groundwater by return seepage.

Watershed IJ 1

This watershed is noted as being strip-cropped, the top half in oat stubble, and young clover, the third strip in corn badly damaged chinch bugs, and the fourth strip in soy beans six inches high.

This graph is particularly interesting because the hydrograph, Figure 4, shows by inspection how the infiltration-capacity curve must cut through the precipitation blocks from 9:13 to 9:28, and from 9:28 to 9:43, as the hydrograph holds up for no other possible reason but decrease in infiltration

capacity. The curve could be laid across these last two blocks to make excess rainfall equal to a related outflow, but the quantities are somewhat too small to justify the effort. The curve can be approximated fully by drawing it through such obvious points.

However, the runoff resulting from the first high intensity precipitation can be evaluated by applying a recession curve to the hydrograph where it flattens out at 9:15. From the resulting runoff .01 inch is deducted for silt content, which seems the most probable explanation of the first of the split peaks and by the same method as was followed above infiltration capacity at 9:07 is fixed at 1.90 inches per hour.

It is obvious also from the hydrograph that the infiltration capacity fell slightly below .35 inches at 10:30 and slightly below .20 inches at 1:30.

These values will fix the curve rather closely throughout.

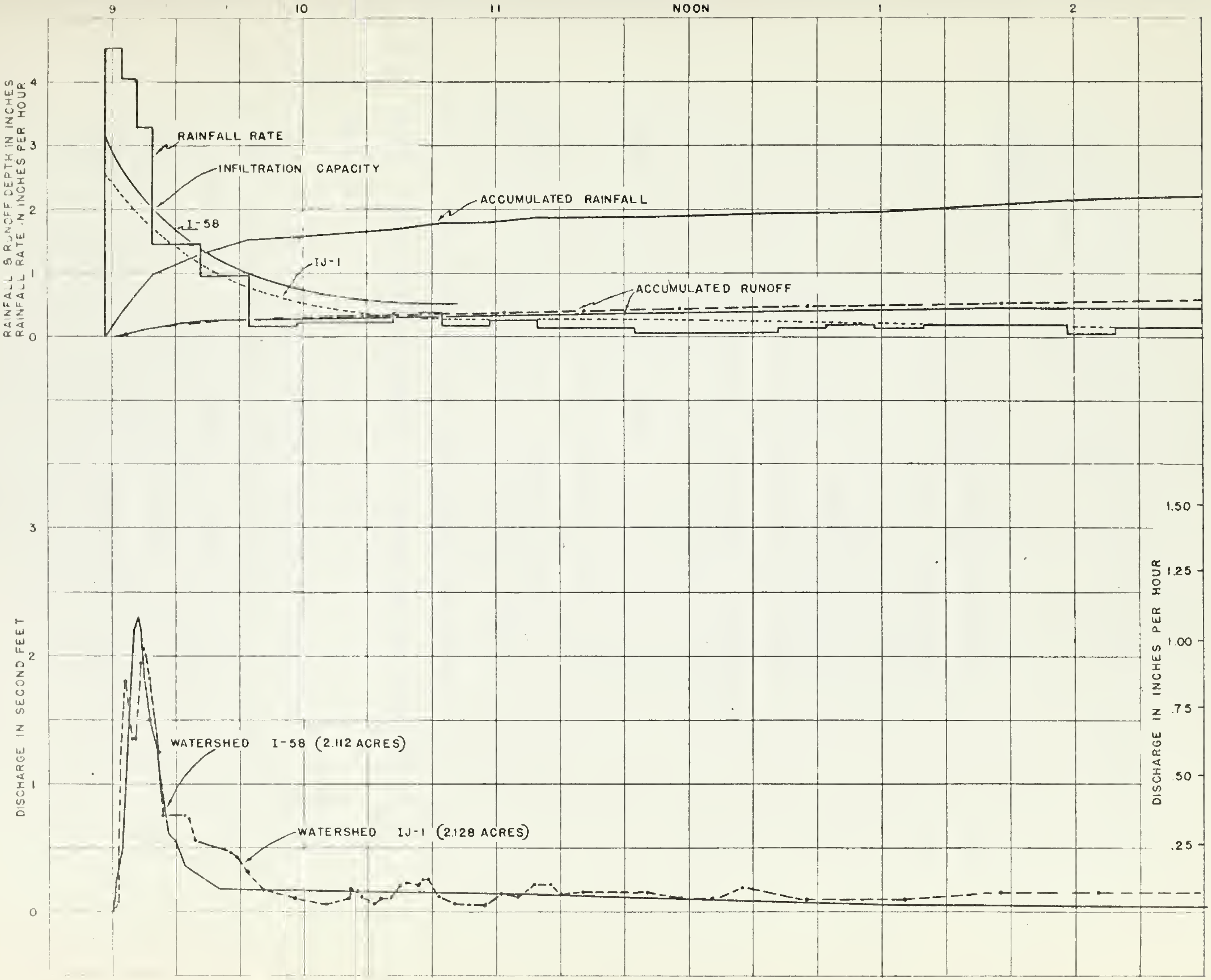

FIGURE 4 - RAINFALL, RUNOFF, AND INFILTRATION, BETHANY MO. WATERSHEDS I-58 AND IJ-1, JULY 7-8, 1933

The shape of this curve for IJ 1 is used as a guide in determining the curve for I-58.

Watershed D 3

This 4.85 acre watershed was in corn four feet high, and cultivated one week before the rain. The soil loss during this rain was 4.5 tons per acre. It may be treated as .02 inches out of the volume of runoff. This capacity curve also obviously is slightly under precipitation rate of about .38 inches per hour at 10:30 (Figure 5) and under the precipitation rate of about 18 inches per hour between 12:40 and 2:00 A.M. It seems to be above .12 inches per hour at 2:15.

For the first high intensity precipitation block the mass precipitation is .98. The mass runoff is .24 inches up to 10:15, from which must be subtracted .07 inches runoff out of the second and third precipitation blocks and .02 inches silt, making the net runoff .15 inches and the total loss .83 inches.

Retention is obviously high as indicated by the delayed rise of the hydrograph, is first assumed at .25 inches, which is later found to be too high, and finally .10 inches which seems to fit best with the hydrograph timing. This leaves infiltration at .73 inches and with infiltration opportunity taken at 20 minutes, makes the infiltration capacity 2.2 inches per hour at 9:08 P.M.

With all of these points as guide, infiltration capacity is drawn in so as to reconcile retention and runoff with the excess rainfall.

Watershed PA-B

This 6.52 acres watershed at this time was in blue grass, dry and short. The total runoff of .02 inches up to 10 o'clock undoubtedly came out of the first high precipitation block. The retention was also obviously high, and was taken at .10 inches. The infiltration loss is .98-02-10 = .86 inches. The opportunity is taken in thirty minutes, and the capacity is 2.6 inches per hour, located at 9.08. The opportunity might possibly be a little longer which would give a lower capacity rate, but this seems improbable inasmuch as no runoff occurred out of the second and third precipitation blocks. The curve is, therefore, drawn in through the 2.6 curve point and just above precipitation diagram elsewhere. The capacity was obviously above .38 inches per hour at 10:40 and there is no indication as to what it may have been later on, beyond the possibility that it may have dropped to .18 inches per hour just before 2:00 A.M. Therefore, this curve is not continued beyond 10:40, and the curve as drawn must be taken as the lowest position which it could have. This curve might be further adjusted after a number of other storms on this watershed have been studied.

This example is an unusually valuable one in extending our conception of the characteristics of stream flow hydrographs. We have almost invariably in the past thought of a rise in the hydrograph as resulting from an increase in precipitation intensity. Here we have a rise of the hydrograph resulting from a rapid decrease in infiltration capacity. It is an unusually convincing example of the fact that the rise of the hydrograph is really due to an increase in the production of excess rainfall, and that excess rainfall being the difference between rainfall rate and infiltration capacity rate will change with the change in either of the two basic rates.

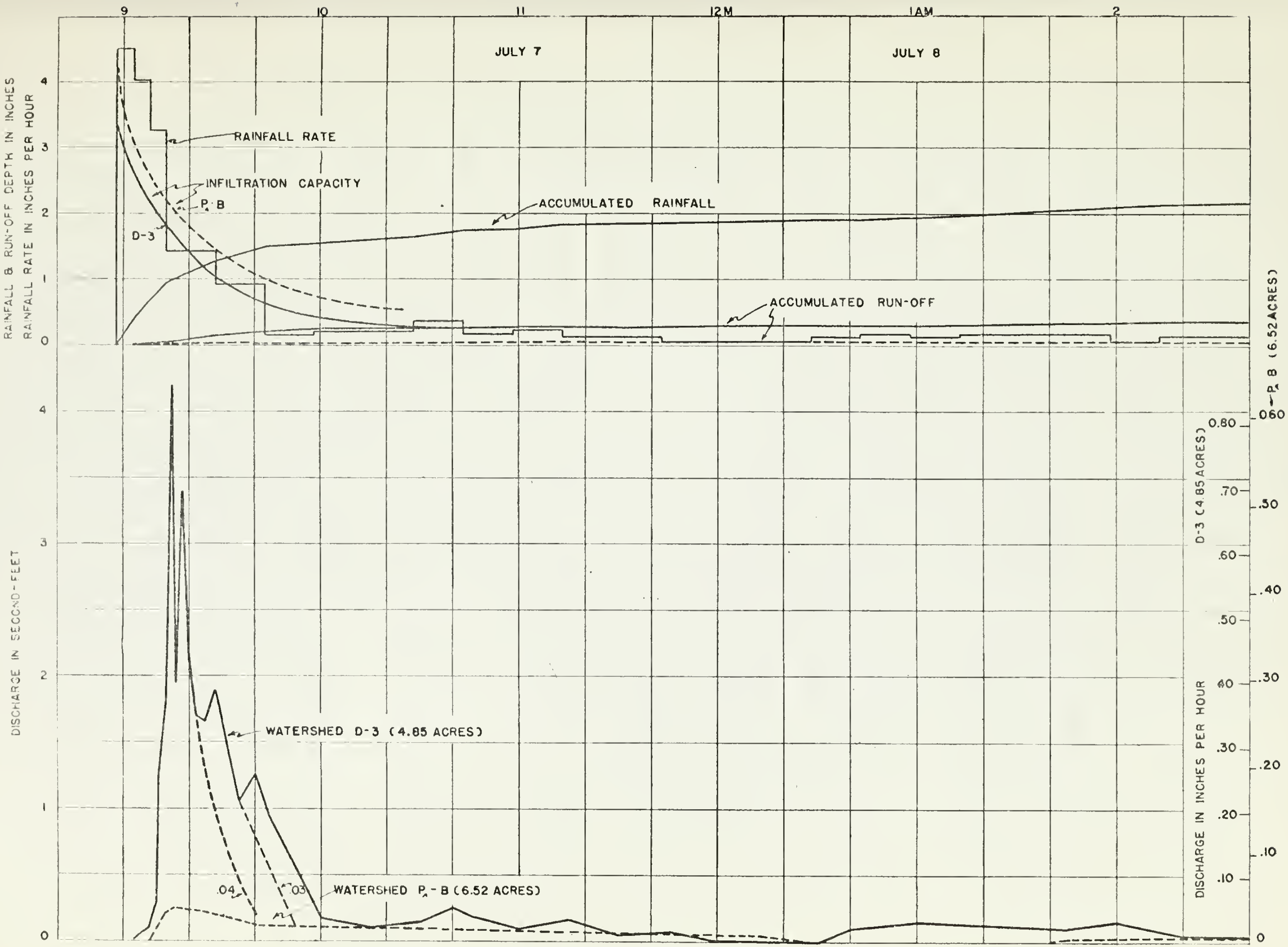

FIGURE NO. 5 - RAINFALL, RUN-OFF & INFILTRATION, WATERSHEDS P_A-B & D-3
BETHANY, MO. JULY 7-8, 1933

EXAMPLE NO. 3

LaCrosse, Wisconsin

The long records now available for the small watersheds at LaCrosse are all susceptible to the determination of infiltration capacity, and this has been approximately determined for a number of storms in 1936.

These hydrographs bring out probably only two unusual features. One is the tendency for a high runoff peak to occur in the early part of a block of precipitation of nearly uniform intensity. The other is the tendency for the hydrographs to take a saw-tooth shape with a number of small peaks, for which there is no justification in the precipitation diagram. These watersheds are unusually steep, having mean slopes of from 15 to 25 per cent, and it may be that the runoff is occurring in a series of bore flows. It seems clear, also, that some of the early peaks must contain a high silt content and not be truly representative of the water flow itself.

In analyzing these hydrographs the silt loss is first transformed into an equivalent water depth in inches over the whole area. This loss is deducted from the peaks occurring at the beginning of high intensity precipitation periods and the diagrams are then analyzed by the method shown in the preceding examples. The resulting curves are particularly interesting in

their apparent relationship to changing seasonal conditions, or to previous cultivation. The two watersheds studied are UCW of 2.34 acres, cultivated throughout and having an average slope of 15 per cent, and UPW of 2.41 acres, in blue grass throughout, but under widely varying conditions of stand and having an average slope of 24 per cent.

To understand the reasons for the variation in values of infiltration capacity shown, it will be necessary to discuss them in light of immediately preceding precipitation changes in condition and cover, and of the dates of cultivating, cutting, etc. The records are well annotated so that such a study could be carried out to advantage, but should be deferred until all of the storms in all of the years of record have been analyzed. As an indication of the trend, a few of the curves have been taken off and replotted on Figure 6.

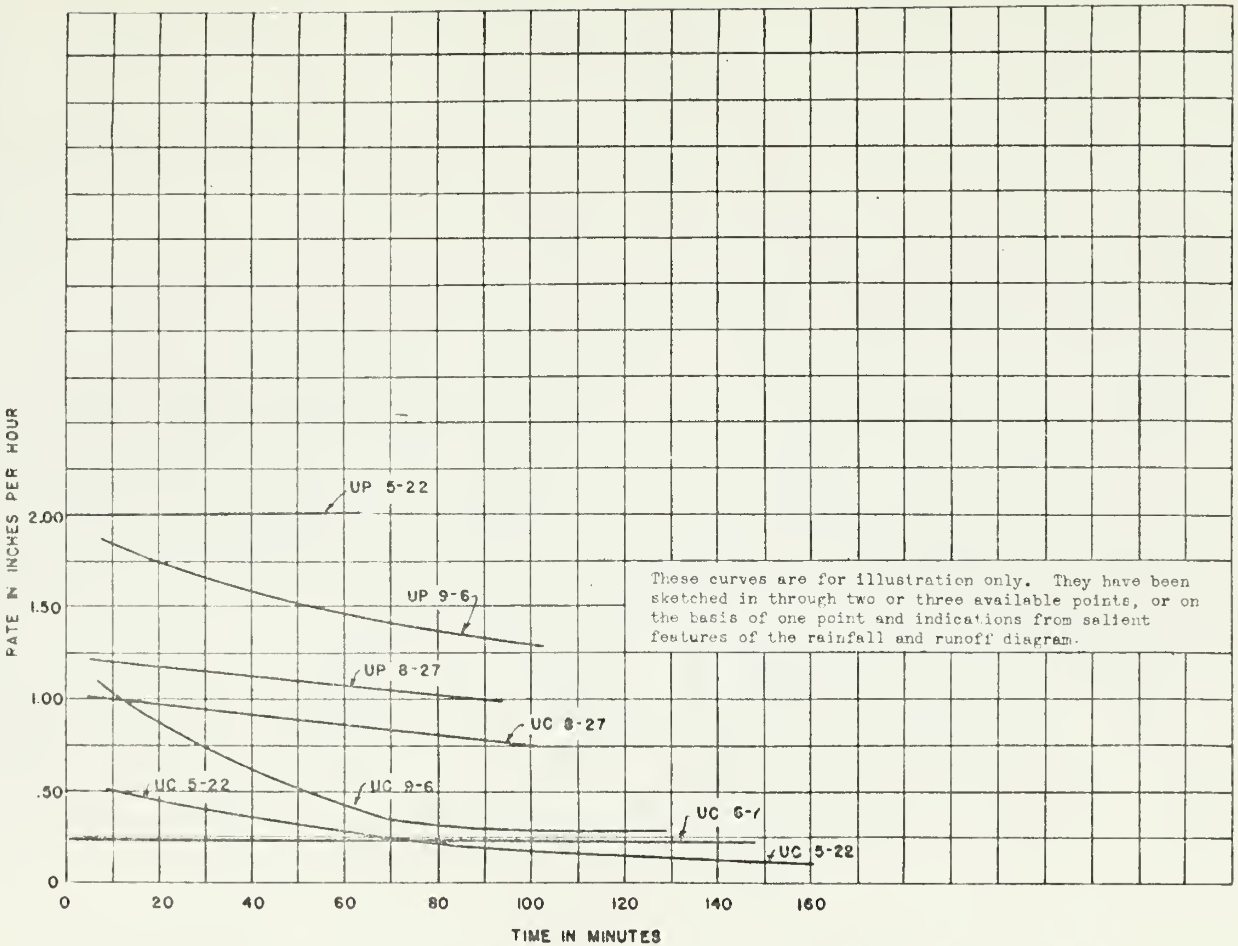

FIGURE 6 - INFILTRATION CURVES FOR 4 STORMS DURING 1936 ON WATERSHEDS UPW & UCW, LA CROSSE, WIS.

EXAMPLE No. 4

Pima, Arizona

The attached diagram for the storm of August 2, 1939 on the Tripp Canyon Watershed at Pima, Arizona is an interesting example of analysis for several reasons. This record represents the largest storm which has been recorded at this site, and it is important to get an approximate idea of the infiltration capacity which existed at this time. The record, however, is faulty in that a stock tank had been built in such a way as to command the upper 100 acres of the 380 acre watershed. The stock tank was empty in the beginning of the storm and had a capacity of 3 acre feet. It over-flowed during the storm so that the hydrograph (Figure 7) at the runoff station represented the runoff from 280 acres during the early part of the storm, and from 380 acres during the latter part of the storm. It has been transformed into runoff rates in inches per hour on the basis of a 280 acre drainage basin up to 6:14 P.M., and a 380 acre basin after 6:16 P.M., recognizing that the resulting hydrograph is probably somewhat incorrect in terms of inches per hour between probably 6:10 and 6:20 P.M.

The capacity of the 3 acre pond is equivalent to approximately .1 inches in depth over the 380 acre watershed. It is found that this amount is not fully sufficient to fill out the

sag between the two peaks, but the most probable hydrograph is drawn in between the two peaks as shown by the dotted line.

There were three rain gages in the watershed -- No. 128 being located above the stock tank, and Nos. 126 and 127 below the stock tank. The last two gages have very closely corresponding rainfall patterns and are accordingly combined and shown on the diagram in a solid line. The record at gage No. 128 in the upper 100 acres is appreciably different and is separately plotted in dash lines.

An inspection of these two diagrams shows that the intense rain occurred later over the upper 100 acres than over the lower watershed. The beginning of the intense precipitation is five minutes later and the block of highest intensity is a full ten minutes later. The center of mass of intense precipitation on the upper 100 acres is 7 or 8 minutes later than that on the lower watershed. Had this upper area been tributary to the lower gage throughout the rain, taking into consideration both the time differences in the rainfall diagrams and the additional time of flow required for the runoff of the upper 100 acres to reach the gage, it would appear that the crest due to the runoff of the upper 100 acres would have appeared at the lower gage at from 6:12 to 6:15, which confirms the conception that if the three acre feet cut by the stock pond had been normally

tributary to outflow, it would have filled in the sag between the two peaks of the hydrograph and would probably not have increased the rate of flow at the crest materially.

The infiltration capacity during this storm is rather definite, and it is quite evident that the bulk of the runoff came out of precipitation falling prior to 6:12.

Taking the precipitation from 5:45 to 6:10 as 2.02 inches, and the total runoff as 1.38 plus .10, equalling 1.48 inches, gives a gross loss of .54 inches, and with retention assumed .04 inches, the infiltration becomes .50 inches, the opportunity at capacity rate is approximately 25 minutes, and the capacity rate 1.20 inches per hour. If, on the other hand, it is assumed that excess rainfall occurred to 6:40, precipitation would be 2.79 inches, runoff 1.48 inches, retention possibly .05 inches, infiltration 1.33 inches, opportunity 57 minutes, capacity rate 1.26 inches per hour.

If it is assumed that excess rainfall ended at 6:25, precipitation is 2.35 inches, runoff 1.48 inches, retention .05 inches, infiltration .82 inches, opportunity 42 minutes, capacity rate 1.17 inches per hour.

These are all in close agreement, and makes it clear that from 6:25 to 6:40 precipitation rate and infiltration capacity were very nearly identical. From 6:10 to 6:25 a small amount of excess rainfall may be in the picture.

From all of this, it is clear that the infiltration capacity was on the order of 1.20 inches per hour practically throughout the storm, although it may have been slightly higher during the first ten minutes. There has been sketched on the diagram a line representing probable infiltration capacity and the values shown are probably accurate within one or two-tenths of an inch, except that the line prior to 6:00 has been given an arbitrary inclination which would be expected of a curve of this type under these circumstances. The flat slope of this line is undoubtedly due to the near satiation of soil moisture deficiency out of antecedent precipitation.

It is also a good guess from the mass curve of runoff, that the 3 acre feet or .35 inches on a hundred acres, when referred to the mass runoff curve set back to fit the later precipitation in the upper watershed, would have reached this value at the stock tank at about 6:18. This would have accounted for the outflow at that point during the whole rising stage of that hydrograph and for a considerable part of the descending limb, so that the runoff actually contributed to the hydrograph from the above stock tank was that related to the recession curve, possibly below the 2 inch per hour rate.

This type of preliminary analysis and the resulting infiltration capacity curve would permit a calculation of surface detention and q-d relationships separately for the early part of

the hydrograph and for the later part of the hydrograph, and out of these relationships it would be possible to make a better reconstruction of the defective middle part of the hydrograph.

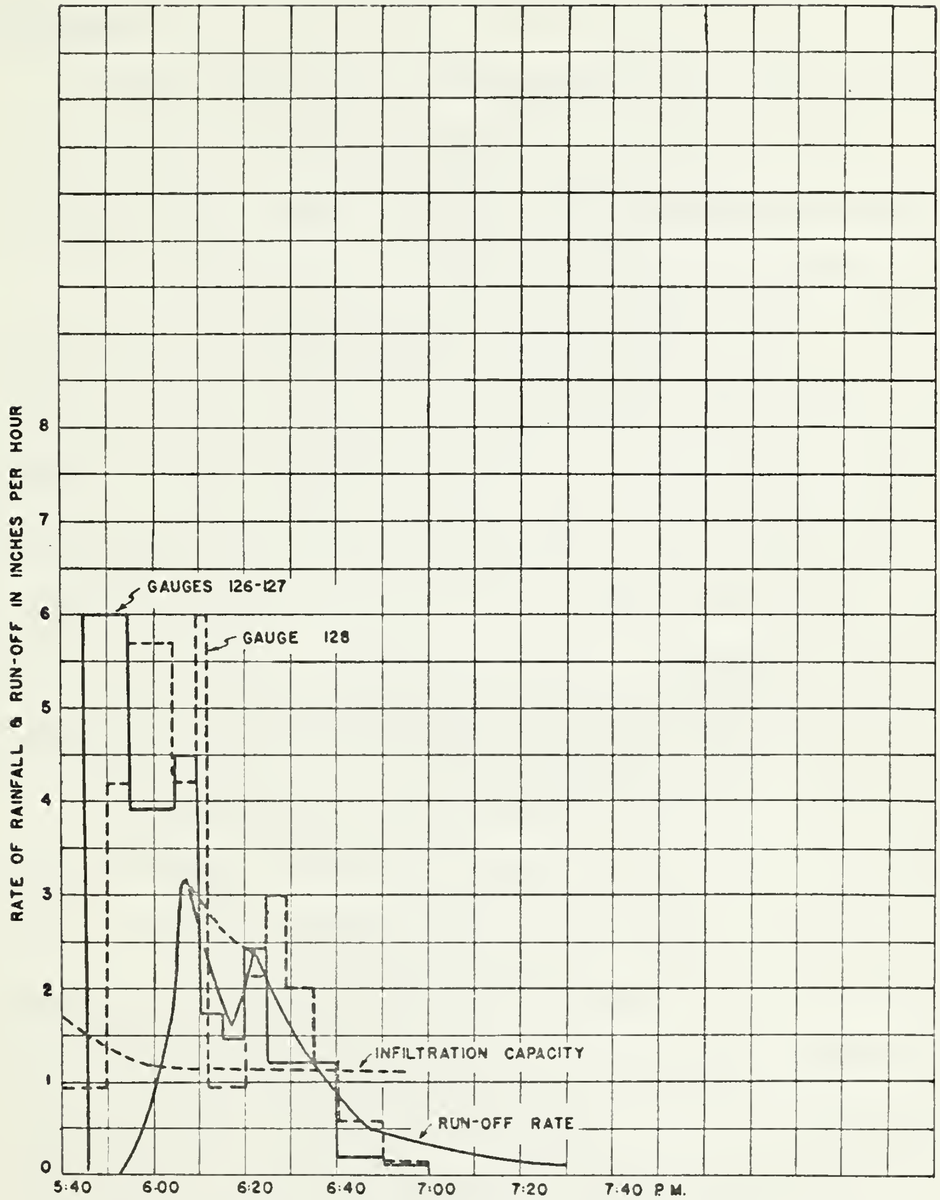

FIGURE NO.7- RAINFALL, RUN-OFF & INFILTRATION, PIMA, ARIZONA. AUGUST 2, 1939

EXAMPLE NO. 5

Globe, Arizona

Conditions

Parker Creek is the field laboratory of the Southwestern Forest and Range Experiment Station, U. S. Forest Service, in the Sierra Ancha about 48 miles northeast of Globe, Arizona.

This rainfall represents the greatest rain in two hours ever recorded in the Southwest on an automatic gage. There are very few records from standard gages which exceed this one of August 5. The areal extent of this storm was very small. The most intense part probably covered the "steep slope plots", yet 1/4 mile away the total rainfall was only half of that recorded by the gage at the experimental plots. Five miles air-line over the mountain, the total rainfall was only about 3/4 inch.

The runoff from these plots is measured in 1/2 cubic-feet tipping buckets, each tip of which appears as a dash on the time chart. In some cases the runoff came so fast that the lines overlapped and the exact number of tips could not be determined. The runoff hydrograph for plot No. 5 (Figure 8) which had the largest runoff is probably not correct in the second intense part of the storm. The station observer believes that the pipe leading to the tipping bucket became clogged, and mud flows accompanying the runoff jumped the watershed boundary in some places.

The plots are bounded by boards about 12" high.

The station observer was watching the plots a little after 5 o'clock and then returned to the station because he thought the rainfall had ceased. Although over 2 inches of rain had fallen up to that time, there had been very little runoff and all the buckets were apparently operating. In the next hour, however, the intensity greatly increased and small bare patches at the head of two of the protected watersheds, Nos. 1 and 3, were sufficient to begin the mud flows mentioned. In one case, water from outside the plots jumped the watershed boundary boards at the head of the plot. Information concerning these details is not complete.

The soil is a "southern brown soil" derived from a quartzite and characterized by a semi-clay-pan in the subsoil and poorly developed lime zone. The cover consists of some grass, about 0.3 density on the protected areas and a chapparal consisting of Beargrass, Yucca, Quercus turbinella and Garrya wrightii.

Analysis

The infiltration-capacity curve can be calculated within relatively small limits of error from this hydrograph. Additional information with respect to silt loss would have been useful in order that the hydrograph might have been modified by allocating the silt to the rises which corresponded to the more intense

precipitation periods and reducing the hydrograph of the water flow accordingly. In the absence of these data, the excess rainfall used may include a considerable volume of silt. If this is true, the infiltration-capacity curve might be appreciably higher than the one worked out. An inspection of the sheet will make the procedure obvious, but essentially it is this:

A recession curve is inserted at "A", (Figure 8), in order to calculate the runoff that would have occurred if there had been no precipitation after 4:30. While this curve is sketched in rather roughly, any error in the results is quite small. In order to get around the defective record after 5:40, the recession curve marked "B" is extended upward by experience and by eye, and has been treated as the recession curve after 5:40 if there had been any further precipitation, and is plotted at "C". This permits of balancing runoff and excess rainfall for the period between 5:20 and 5:40 and locates a point on the infiltration-capacity curve at about 5:31.

The three points fall very consistently on the type of infiltration-capacity curve which might be anticipated.

The values assumed for retention seem reasonable for the type of area described, but the results would be little changed if the retention values were appreciably varied.

Returning to a speculation as to the correct form of the

hydrograph after 5:40, the excess rainfall between 5:20 and 5:35 is .7 of an inch. This value would require a form of hydrograph such as is sketched in free hand at "D", without attempting to check it accurately.

It is quite obvious that the dash of rain at 6:00 o'clock should not have caused any appreciable rise of the hydrograph, although we find often that such dashes do give a small rise. In that we are dealing with average infiltration capacities for the whole area, some parts of the area, such as those which have become silt blanketed or where there are small exposures of tight sub-strata, may produce a small runoff. Occasionally too, a small rise will occur from such a rain falling on little channels or the tail end of the detention film.

The data are sufficient to give a rather accurate infiltration capacity curve covering the two hours between 4 and 6 P. M., and to give a pretty good idea of the character of this curve during the succeeding hour.

Any probable error in any of the assumptions or approximations would affect the position of this curve by not more than .2 inches per hour.

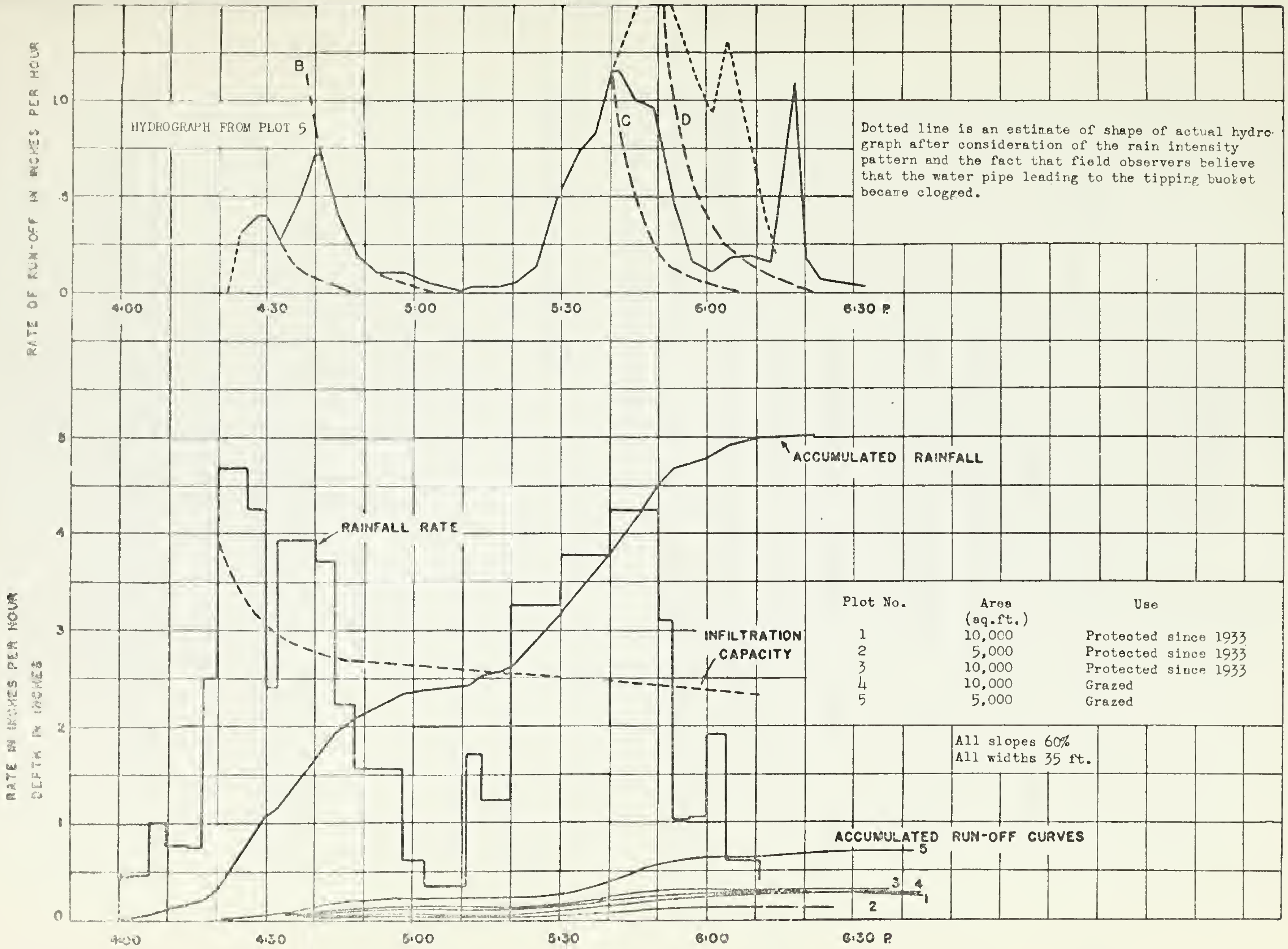

FIGURE NO.8 - RAINFALL, RUN-OFF & INFILTRATION, GLOBE, ARIZONA. AUGUST 5, 1939

EXAMPLE NO. 6

Edwardsville, Illinois

The first five examples cited are the results of a rough form of preliminary analysis and have not been checked in detail, and are intended primarily to indicate the desirable methodology under different conditions. The examples listed here as No. 6 cover the analyses of four storms from a 27-acre watershed at Edwardsville, Illinois, as they have been carried out by Mr. Leonard Lloyd.[1] This work has been more carefully done than that in the preceding illustrations and the infiltration capacity curves are accordingly more accurately placed and better confirmed.

Storm of March 15, 1938

With respect to the first of these storms, that of March 15, 1938, there is an interesting question as to the extent to which ephemeral groundwater seepage is represented in the hydrograph and particularly in the recession curves.

An examination of other hydrographs for summer storms indicates that the recession curve below the .1 inch per hour runoff rate has a base of not more than 1-1/2 hours and ac-

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[1] Graduate student in Hydrology, Washington University, St. Louis, Mo.

counts for mass runoff of not to exceed .06 inches. The first of the two recession curves of March 15th (Figure 9) below this rate has a mass value of .09 and the second of .12 inches. If this excess is treated as groundwater flow, it indicates a seepage rate at 12:00 noon of slightly less than .01 inch per hour, and at 8:00 P.M. of slightly more than .01 inch per hour.

Also, if these values are deducted from the mass runoff for the two storms, the total surface runoff is reduced to .21 inches for the first storm, and .51 inches for the second storm. Such correction seems to be justified to get a closer approach to true infiltration capacity.

A preliminary inspection indicates that infiltration capacity between 8 and 8:20 A.M. is probably slightly above .11 inches per hour. It is possible to determine infiltration capacity by equating the first rise of the hydrograph to the rainfall prior to 8:00 o'clock and also to the rainfall prior to 8:10 A.M. The results are as follows:

Precipitation to 8:00 A.M. .29 inches.

Runoff to 8:05 A.M. .04 inches.

Runoff from normal recession curve below .075 rate is .03 inches

Total runoff .07 inches.

Total loss .22 inches.

Probable value of retention .06 inches.

Infiltration .16 inches.

Opportunity 55 minutes.

Infiltration capacity .17 inches per hour at 7:40 A.M.

Precipitation to 8:10 .32 inches.

Runoff to 8:15 A.M. .05 inches.

Recession curve below .07 inch per hour rate is .02 inches.

Total runoff .07 inches.

Total loss .25 inches.

Probable value of retention .06 inches.

Infiltration .19 inches.

Opportunity 67 minutes.

Infiltration capacity .17 inches per hour at 7:45 A.M. This value of infiltration capacity is taken as the mean and is plotted as .17 inches per hour at 7:42 A.M.

For the second rise of the hydrograph, the rainfall from 8:20 to 9:10 A.M. is .21 inches. The runoff from 8:20 to the corresponding stage on the recessi n curve is .115, or taken at .11 allows the odd half hundredth as groundwater. This is the total value of runoff, as the same recession curve would be taken at each end of this rise. The total loss is therefore .10 with no allowance for retention. Infiltration opportunity is 55 minutes. Infiltration capacity would be taken as .12 at

8:42 A.M.

A similar application is made to the third and fourth rises of the hydrograph. For the third rise rainfall from 2:30 to 3:15 P.M. is .56. Runoff from 2:30 to 4:35 is .38. The actual runoff during recession after 5:40 is .09, making a total of .47 inches, which, with .05 subtracted for groundwater throughout the whole period of the rise, makes the surface runoff .42, the total loss .14 and, with an assumed retention of .04, the infiltration .10 inches, the opportunity 50 minutes, and the infiltration capacity .12 inches per hour at 2:55 P.M.

A similar application to the last rise in the hydrograph makes the infiltration capacity at 4:52, .08 inches per hour.

These values appear to be consistent, and the variation in accordance with that to which we are becoming accustomed. To the extent that the deductions for groundwater are approximately correct, the curves represent true infiltration capacity at the ground surface. If these values are later to be applied in design, then groundwater should be separately evaluated and added to the hydrograph of surface runoff. It would have been quite possible to have determined values of infiltration capacity without deduction for groundwater flow. These values would not have been true infiltration capacity, but might be useful in application in that their use would include an approximation of groundwater

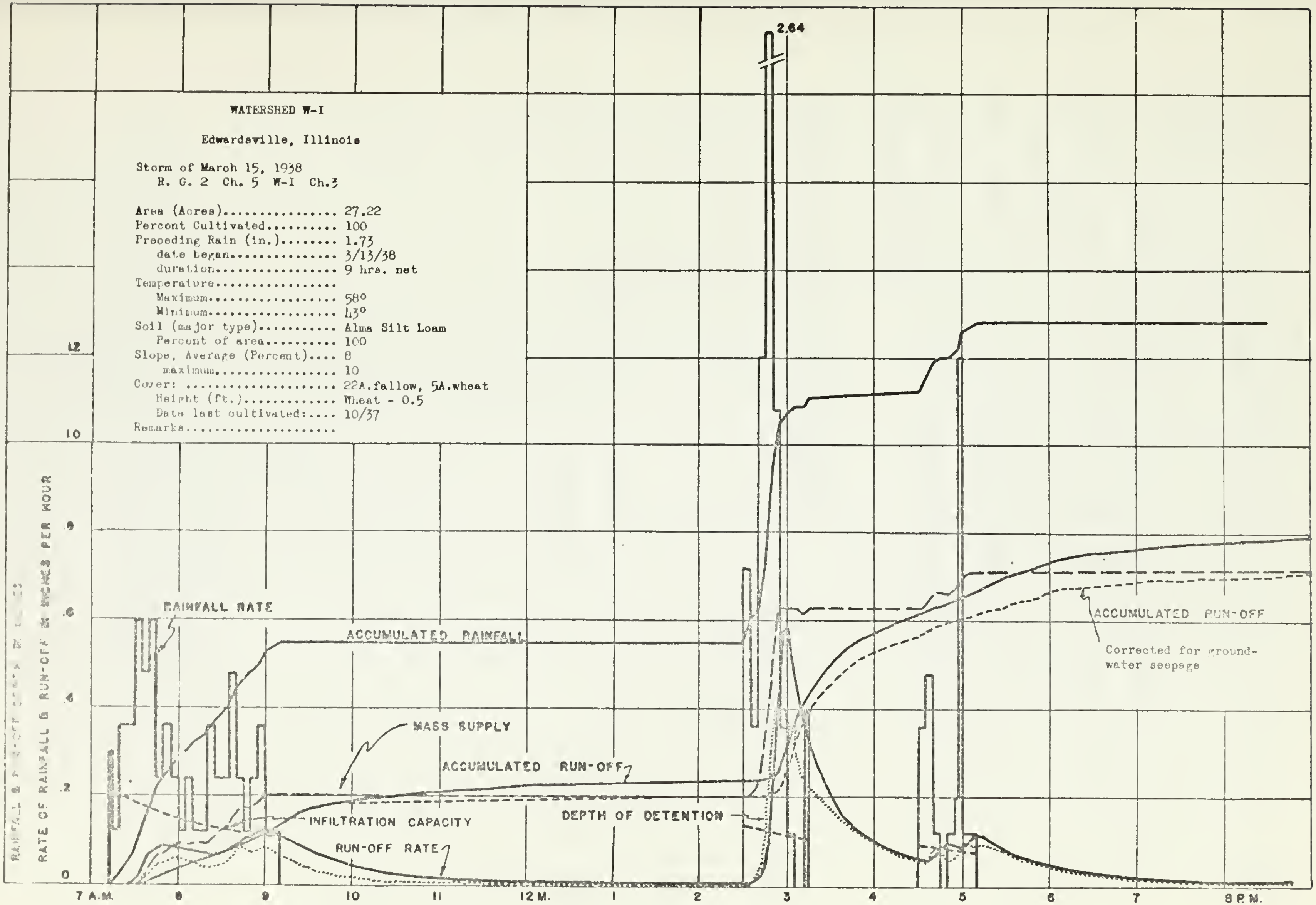

FIGURE NO. 9 - RAINFALL, RUN-OFF, INFILTRATION & DETENTION, EDWARDSVILLE, ILL. W-I MARCH 15, 1938

seepage and would make it possible to avoid a separate evaluation of groundwater flow.

Figure 9 also has plotted on it mass infiltration, mass supply, and surface detention. The latter curve parallels the hydrograph to a sufficient extent to add validity to the analysis. The surface detention curve for a watershed of this size should normally appear slightly in advance of corresponding features of the hydrograph.

STORM OF MARCH 13, 1938 - MORNING

Since a period of more than six hours intervened between the two definite periods of rainfall, the two storms of March 13th are analyzed separately. Rainfall began at 4:35 A.M. (Figure 10) with an intensity of .6 inches per hour and then continued until 6:30 at intensities ranging from .06 to .24 inches per hour. During this time, 29 inches of rain fell without producing appreciable runoff. Runoff actually began at 6:05 A.M., but the quantity of runoff was so small that no conclusive determinations could be made. Rain falling on the pond above the measuring weir and its relatively impervious margins could account for this runoff.

After 23 minutes lapse, rainfall resumed at 6:53 with an intensity of .34 inches per hour. This rain produced runoff at appreciable rates beginning at 7:00 A.M. The question at this

point is whether any of the rain prior to 6:53 was effective in satisfying a part of the retention requirements. Since the average infiltration capacity during the period of rain from 6:53 to 10:13 was later found to vary from approximately .22 to .12 inches per hour, it is evident that the initial period of rain could not contribute toward the actual retention requirements. However, since interception by vegetal cover is included in the retention factor as it enters into this analysis, it is reasonable to assume that the initial rain would satisfy the interception portion of the retention requirement and water held by the grass blades and other forms of cover would be retained over the 23 minute period of no rainfall.

From the above considerations, the additional retention value at the beginning of the rain producing runoff is taken as .04 instead of the .06 value which has been rather definitely established in the analysis of the March 15th storm.

The long period of time covered by the recession curve of this storm indicates that ephemeral groundwater flow undoubtedly existed in the hydrograph of runoff. The quantitative value of this factor was again established by making use of the two July storms which were available.

Due to the fact that each of the July storms occurred at the end of rather long periods of no rainfall, high temperatures

and low relative humidity, it can safely be said that no groundwater flow was present in the hydrograph of these two storms. Comparing the .0224 inches of runoff which occurred in the recession curve of this storm below the .03 inch per hour rate with the .0132 inches of runoff which occurred under each of the recession curves of the July storms below the corresponding rate, indicates that .01 inch of groundwater flow is present in the recession curve of this storm.

With the retention and groundwater flow established as accurately as possible, average infiltration capacities for five definite periods of opportunity can be computed as follows:

I. Precipitation from 6:53 to 8:10, .29 in.

Runoff to 8:20, .014 in.

Runoff after 10:45, .011 in.

Total runoff, .025 - .01 (groundwater) = .015 in.

Total loss, .29 - .015 = .275 in.

Probable value of retention, .04 in.

Infiltration, .275 - .04 = .235 in.

Period of opportunity, 6:53 to 8:15 - 15 minutes (assumed loss of opportunity 7:05 to 7:20) = 1 hr. and 7 min.

Average infiltration capacity, 20 in. per hr. at 7:35

II. Precipitation 7:20 to 8:10, .20 in.

Runoff to 8:20, .0150 in.

Runoff after 10:45, .0123 in.

Total runoff, .0123 + .0150 - .01 (groundwater)
= .017 in.

Total loss, .183 in. = infiltration (no retention allowance)

Opportunity, 7:20 to 8:15, 55 minutes.

Average infiltration capacity, .20 in. per hr. at 7:47

III. Precipitation 8:20 to 10:13, .33 in.

Runoff 8:20 to 10:45, .0563 in.

Total loss, .33 - .056 = .247 in. = infiltration (no retention allowance)

Opportunity, 8:20 to 10:18, 1 hr. 58 min.

Average infiltration capacity, .14 in. per hr. at 9:19

IV. Precipitation 9:00 to 10:13, .23 in.

Runoff 9:00 to 10:45, .045 in.

Total loss, .23 - .045 = .185 in. = infiltration (no retention allowance)

Opportunity 9:00 to 10:18, 1 hr. 18 min.

Average infiltration capacity, .14 in. per hr. at 9:39

V. As a rough check on the above computed values, the over-all average infiltration capacity is computed as follows:

Precipitation, 6:53 to 10:13, .63 in.

Total runoff, .083 - .01 (groundwater) = .073 in.

Total loss, .557 in.

Retention, .04 in.

Infiltration, .517 in.

Opportunity 6:53 to 10:18 minus 15 min. to allow for loss of opportunity during periods of low rainfall = 3 hr. and 10 min.

Average infiltration capacity, 16 in. per hr.

The above values have been plotted on the histogram of rainfall and a smooth curve was drawn through the points. This curve is a curve of varying infiltration capacities throughout the period of rainfall. If the quantity of rainfall represented by the portion of the histogram above this infiltration curve is computed, the quantitative value, which is mass supply, is found to be .13 of an inch. Subtracting the .04 inches retention requirement, which must necessarily come from the supply, gives a value of net supply available for runoff as .03 inches. This checks the total runoff during the storm to within a few thousandths of an inch.

Reference to the graph shows that the rainfall intensity was below the infiltration capacity during the following intervals: 7:00 to 7:20; 7:50 to 8:00; 8:10 to 8:20; 8:30 to 8:40; 8:50 to 9:00 and 10:00 to 10:10.

The question naturally arises as to whether there was any loss of opportunity during these periods. An allowance of 15 minutes was made for loss of opportunity during the first interval, that from 7:00 to 7:20. There is little doubt but that

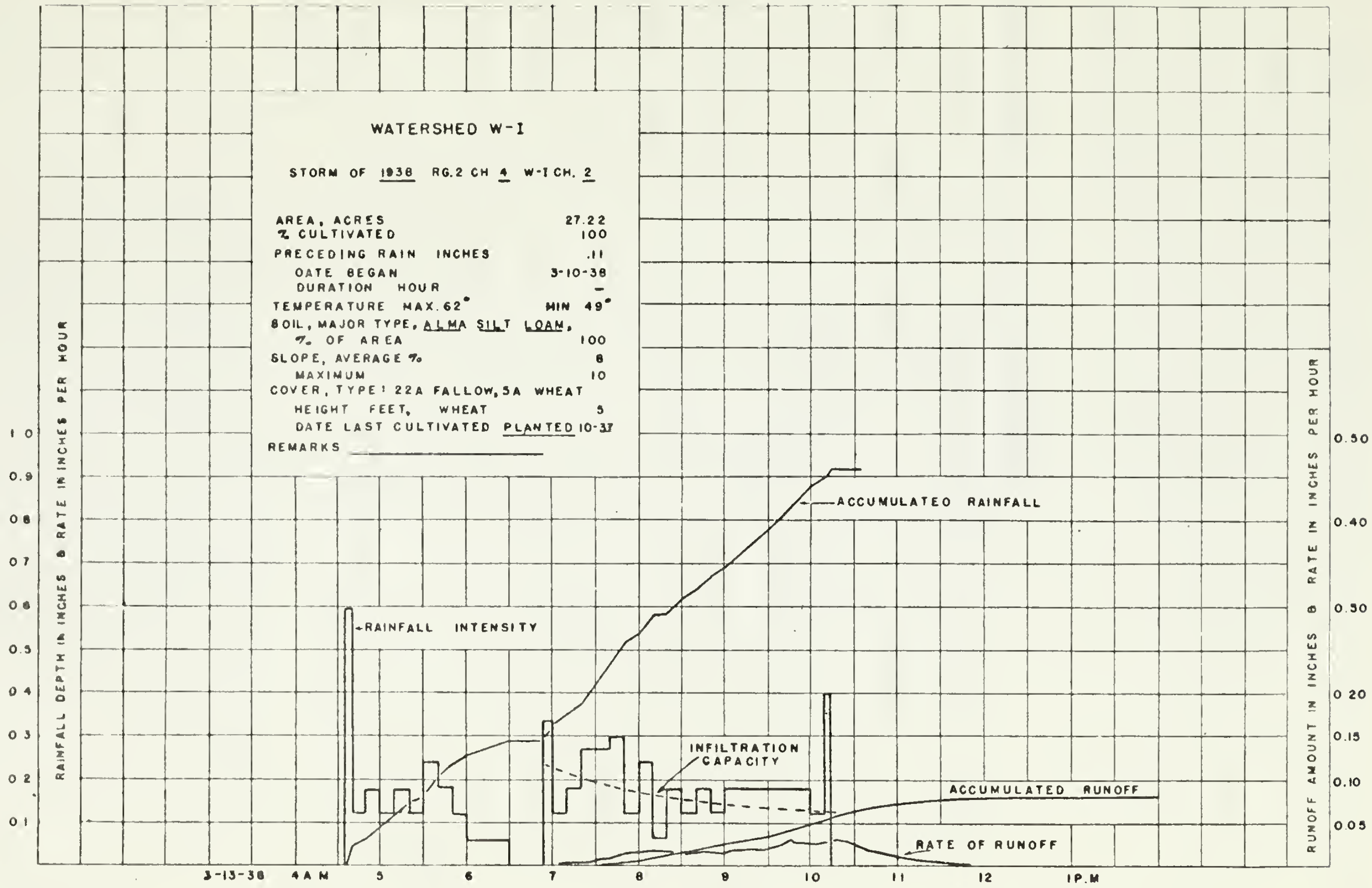

FIGURE 10.—RAINFALL, RUNOFF AND INFILTRATION, EDWARDSVILLE ILL. W-I MARCH 13, 1938 MORNING

the combined effect of surface detention and the rain which did fall during the other intervals was sufficient to extend the opportunity over these gaps. Sufficient detention had not been built up at 7:00 to extend opportunity for more than the 5 minutes allowed.

STORM OF MARCH 13, 1938 - AFTERNOON

After a period of approximately six hours had elapsed, rainfall resumed on March 13th at 5:05 P.M. (Figure 11). Because of the elapsed time between this and the antecedent rainfall, this is considered as a separate and distinct storm from that which occurred on the same day in the forenoon. Rain continued without interruption from 5:05 until 7:50 P.M. with intensities which varied from 3.00 to .06 in./hr. Reference to the graph of this storm reveals two well defined peaks in the hydrograph with general characteristics that should be conducive to a rather exact analysis, but a more careful consideration gives rise to a good deal of question with regard to opportunity.

It is to be expected that the infiltration capacities and their variation would be much the same as that in the preceding storm period. The rain which fell from 5:05 to 5:15 can be neglected since it was obviously at or near intensities corresponding to the infiltration capacity during the same period.

In attempting to evaluate the infiltration capacity by

correlating the first peak in the hydrograph with that rain which produced it, the principal difficulty is encountered in evaluating the time of opportunity. In order to obtain a rational basis for evaluating the extended period, it was necessary to refer to the storm of March 15th, upon which a detailed analysis had been made in regard to the relation between discharge rate and depth of surface detention. Assuming that the infiltration capacity at 5:30 was roughly between .16 and .2 in/hr. there is approximately a .04 deficiency from 5:30 to 5:50. This would mean that approximately .013 inches more rain was needed to satisfy infiltration requirements than was supplied. From the graph of the March 15th storm giving the relation between depth of detention and surface runoff, the depth of detention corresponding to the peak rate of .36 in. per hr. is approximately .25 of an inch. The depth corresponding to the rate of approximately .1 in. per hr. at 5:50 is about .14 of an inch. During the period from 5:30 to 5:50, .04 of an inch of rain fell, approximately .04 of an inch of runoff was recorded, and the depth of detention was reduced in about the same amount as the deficiency in infiltration requirements. Indications, therefore, are that infiltration could occur at capacity rates for some time beyond 5:50.

As in the case of the storm which occurred on the morning of the same day, it was necessary to attempt an evaluation of the

groundwater seepage included in the recession curve of the hydrograph. The two storms for July were used in the same manner as before, and it was found that .026 inch of groundwater flow is included in the hydrograph of this storm.

With the above considerations in mind, and with the use of .06 of an inch as a retention factor, it was possible to compute four values of infiltration capacity in the following manner:

I. Precipitation 5:15 to 6:00, .41 in.

Runoff	5:15 to 6:15	.127	
"	8:10 to 9:20	.035	
"	after 11:00	.029	
		.191 in.	Total runoff
		.025	Groundwater flow
		.166	Net runoff

Total loss, .244 in.

Probable retention, .06 in.

Infiltration, .184 in.

Opportunity 5:15 to 6:00, 45 minutes

Average infiltration capacity, .24 in. per hr. at 5:37

II. Precipitation 6:20 to 7:50, .27 in.

Runoff 6:20 to 8:00, .127 in.

Dropping the .007 to allow for groundwater flow gives a loss of .15 in., all of which is infiltration.

Opportunity 6:20 to 8:05, 1 hr. 45 min.

Average infiltration capacity, .09 in. per hr. at 7:12

III. Precipitation 9:23 to 10:20, .08 in.

Runoff 9:25 to 11:00, .03 in.

Loss, .05 in.

Opportunity 9:23 to 10:20, .92 of an hour

Average infiltration capacity, .06 in. per hr.

IV. An over-all average value for the storm is computed as follows:

Precipitation 5:15 to 7:50, .70 in.

Runoff to 9:20,	.303		
after 11:00,	.029		
		.331 in	Total runoff
		-.026	Groundwater flow
		.305	Net runoff

Loss, .40 in.

Retention, .06 in.

Infiltration, .34 in.

Opportunity 5:15 to 7:55 minus 20 min. to allow for loss of opportunity immediately after 6:00 P.M. = 2 hrs.20 min.

Average infiltration capacity, .14 in. per hr. at 6:35.

Plotting these values at their corresponding times and drawing a smooth curve shows that, while the curve is of much the same shape as that of the preceding storm, the decrease in infiltration capacities is somewhat more rapid. This fact can probably be accounted for by considering that the six hours between this and the preceding rain has permitted a depletion of the field moisture

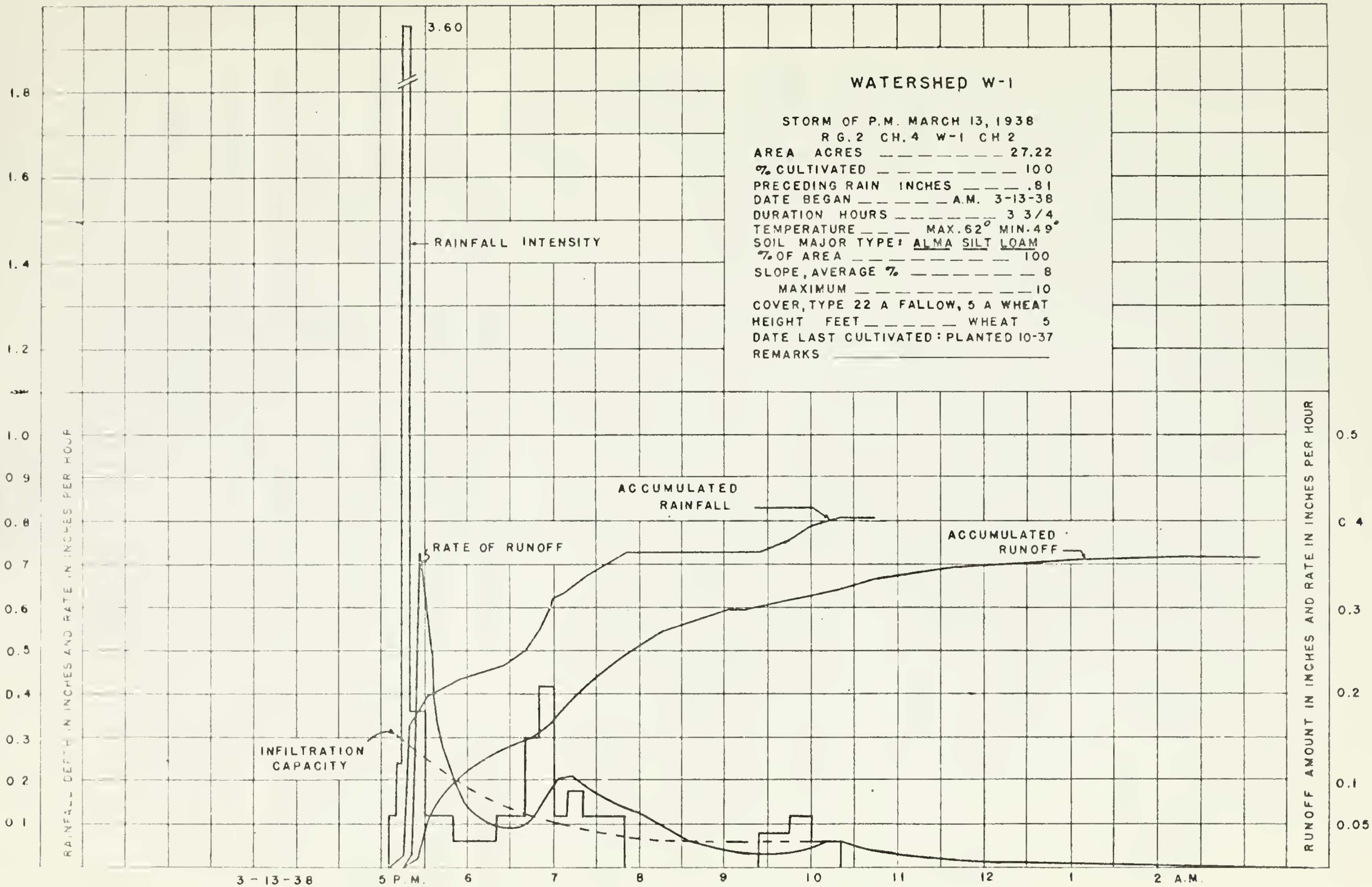

FIGURE 11—RAINFALL, RUNOFF AND INFILTRATION, EDWARDSVILLE ILL. W-1 MARCH 13, 1938—AFTERNOON

to take place near the ground surface. As soon as sufficient precipitation has fallen to satisfy this deficiency, the infiltration capacity rapidly drops to that which existed at the end of the preceding rain, and continues to fall as precipitation continues. The infiltration capacity determined for the period of rainfall between 9:23 and 10:20 is somewhat lower than expected. However, all quantitative values were so small and time of opportunity so short that any small error is magnified in the results.

STORM OF JULY 17, 1938

The accumulated depth of rainfall recorded during this storm was 4.60 inches. This was the heaviest storm during the entire year. Light rain occurred on several days in the latter part of June, 0.17 inches was recorded on July 1, and 0.06 inches on July 7.

Rainfall began at 4:50 A.M. (figure 12) and continued intermittently until 12:47 P.M. at intensities which ranged as high as 1.2 inches per hour. The accumulated depth during this period was .88 inch, and no runoff was produced. The rainfall which was effective in producing runoff obviously began at 12:47 P.M. with an intensity of 3.00 inches per hour. This storm serves as an excellent example of the difficulties encountered in the analysis in attempting to evaluate retention and time of opportunity. It

is safe to assume that all rainfall from 12:47 to 1:00 was at intensities above infiltration capacity, and that which occurred from 1:00 to 1:20 was below infiltration capacity. Runoff began at 1:03 P.M., and the first peak was produced at 1:27. From 12:47 to 12:50, .15 inch of rain fell. The question now arises as to what portion of the initial supply is necessary to satisfy the retention requirements. The retention was rather accurately determined in the storm of March 15, 1938, and found to be .06 inch. In the middle of the growing season, at which time this storm occurred, the retention requirement should be at least two to three times the March value. In view of this, rough computations based on the lag between the beginning of rainfall excess and runoff, and approximate infiltration losses during this time, the retention value established for this storm was .15 inches.

The total rainfall from 12:47 to 1:00 was .50 inches. The rain from 1:00 to 1:05 at .84 inches per hour was obviously less than the infiltration capacity during this time, but since it fell while there was still surface detention, this amount should be included in the computations. In view of the fact that the rain from 12:55 to 1:00 was probably very little above infiltration capacity, and the high infiltration capacity would have drawn rather heavily on surface detention, the period of opportunity should not be extended beyond 1:05. With opportunity and retention determined as accurately as possible, the average infiltration capacity from 12:47

to 1:05 is calculated as follows:

Rainfall, 12:47 to 1:05, .57 in.

Runoff to 1:30,	= .023		
after 4:30 (rec. curve)	= .03		
		.053	
		.517	inches of loss
	retention	.15	
		.367	inches infiltration loss

Opportunity period 12:47 to 1:05 = 18 min. or .3 hrs.

$$\frac{.367}{.3} = 1.23 \text{ in/hr. infiltration capacity}$$

From 1:05 to 1:20, which is apparently the time of beginning of the next period of rainfall excess, .08 inch of rain fell. Assuming that during this period the infiltration capacity had fallen to approximately .9 inches per hour, the retention value of .15 inch remaining at the end of the preceding period of excess rainfall would be just sufficient to meet the deficiency of supply during this period. However, the retention would not be entirely exhausted by the .23 inch infiltration requirement since a large portion would undoubtedly be held as capillary water between grass blades and other types of cover, and the depth in saucer-shaped depressions, which accounts for the greater part of the average areal value of .15, would be in excess of this depth. However, some allowance must be made in the beginning of the second period of rainfall excess to account for the lost retention. It is felt that .02 inch is a fair assumption of the additional requirement.

The average infiltration capacity for the second period of rainfall excess is computed by the following process:

1. The period of excess rainfall is taken as extending from 1:20 to 2:20.
2. The period of opportunity is assumed to have extended to 2:30, in view of the probable reduction in infiltration capacity demands on surface detention and the rainfall between 2:20 and 2:25. For the purpose of this calculation, rainfall is assumed to have ceased entirely at 2:25.
3. Rainfall 1:20 to 2:25, 1.17 in.

Runoff to 2:25	.2968 in.		
after 3:43	.1986		
	.4954		
due to prior rain	− .05	.445	
		.72	total losses
		.02	additional retention
		.70	infiltration loss

Opportunity 1:20 to 2:30, 1.17 hrs.

$$\frac{.70}{1.17} = .60 \text{ in. per hr. infiltration capacity}$$

The rain which fell between 1:20 and 1:30 presented a problem in that it is at first indefinite as to whether or not the intensity of this rainfall was in excess of the infiltration capacity during this period. Neglecting this rain and reducing the opportunity accordingly, reduces the computed infiltration

capacity by .04. This indicates that it was contributing to runoff. Had the intensity been just equal to the infiltration capacity, there would have been no effect on the computed value.

The third definite period of rainfall excess occurred between 2:27 and 3:24. The period of opportunity is considered to extend to 3:30. The additional time period is slightly less than that used in the other portions of the storm, but this seems justifiable in view of the lower intensities of post precipitation, reduced "lag time" between the center of mass of intense precipitation and hydrograph peaks, and the rather well defined point of inflection. The reduction in lag time may be due to the formation or cutting out of definite small channels over the area as runoff continues, thereby affording a less obstructed overland flow. Increased surface detention resulting from somewhat higher average rainfall intensities and decreased infiltration capacities produce greater discharge and increased velocities of flow.

Calculations for the average infiltration capacity during the third period are as follows:

Rainfall 2:27 to 3:30, 1.61 inches

Total runoff	1.61	
Due to prior rain	- .56	
		1.04
		.57 in. infiltration loss

Opportunity 2:27 to 3:30, 63 min. or 1.05 hrs.

$$\frac{.57}{1.05} = .54 \text{ in. per hr. infiltration capacity}$$

In order to obtain one additional value as a guide, the period from 1:20 to 3:30 is considered.

Rainfall 1:20 to 3:30		= 2.80 in.	
Total runoff	1.60		
Due to prior rain	- .05	1.55	
		1.25	in. infiltration loss

Opportunity 1:20 to 3:30 = 130 min. or 2.17 hrs.

$$\frac{1.25}{2.17} = .57 \text{ in. per hr. infiltration capacity}$$

Plotting the above computed values on the graph at the mid-point of the opportunity period of each defines the curve of varying infiltration capacities throughout the storm. Apparently the point computed for the second period of opportunity is somewhat lower than it should be, but the error is only about .03 inches.

This is the extent to which most of the analyses have been carried to-date. The calculations given here are the result of a number of initial trials made before the values can finally be adjudged the best obtainable.

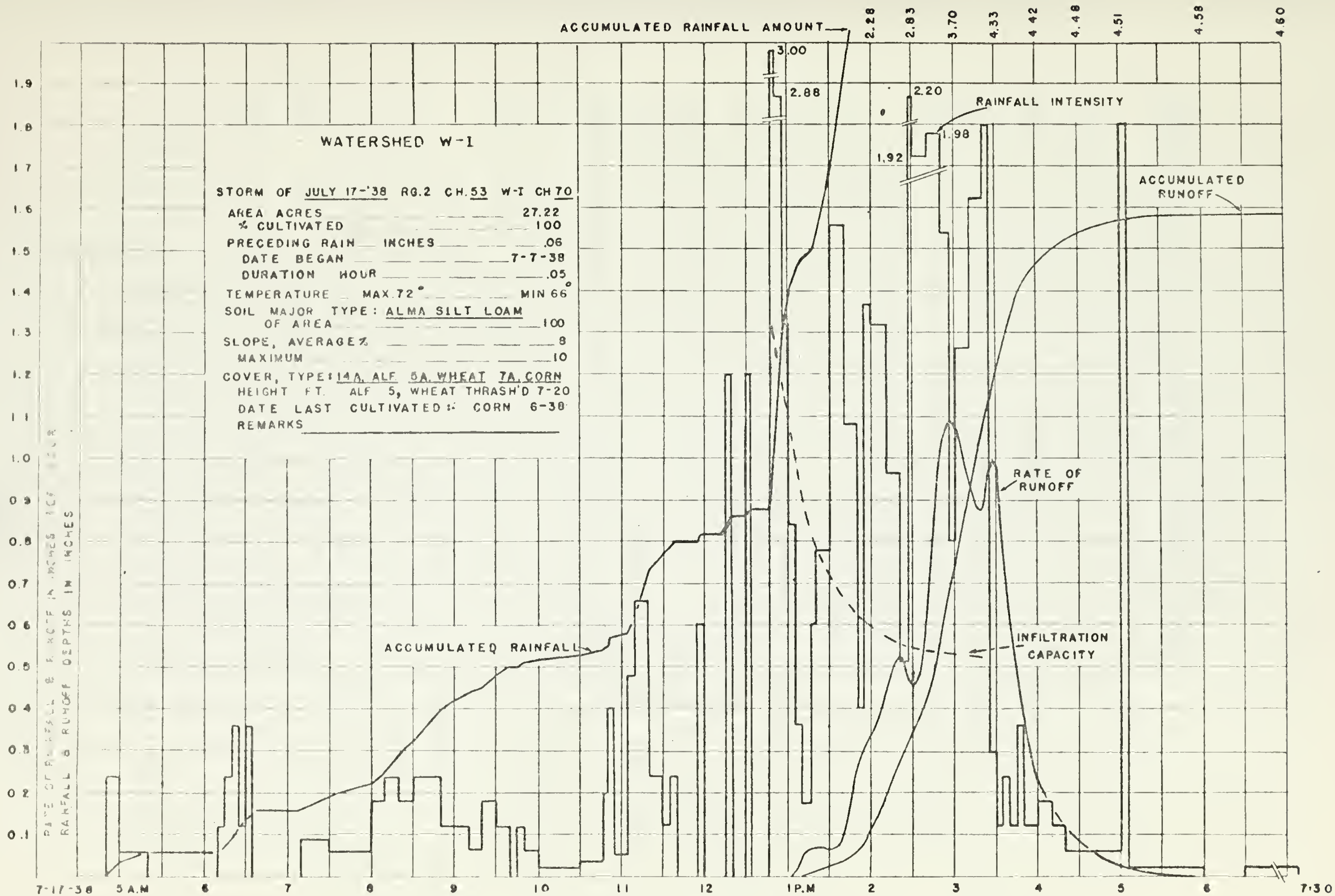

FIGURE 12 – RAINFALL, RUNOFF AND INFILTRATION, EDWARDSVILLE ILL. W-I, JULY 17, 1938

APPENDIX "A"

Characteristics of Infiltration-Capacity Curves::

The infiltration capacity that will be derived from small watershed data will generally have to pass through from two to six points, each related to a particular rise of the hydrograph. To the extent that the data are good and the analysis consistent, it should always be possible to draw a smooth curve through these points.

Quite often the first available point will be located at appreciable time distance after the beginning of intense rainfall. In the body of this paper it is suggested that the rise to the left of the first point may be extremely rapid, and that some better method of determining the probable value of initial infiltration capacity is desirable. It is also highly important, even where a detailed analysis of the data is not contemplated, to have some better idea of the characteristics of infiltration-capacity curves against which to measure the consistency of results.

For this reason there is abstracted in this appendix certain pertinent material from the paper on "Analysis of Run-off Plat Experiments with Varying Infiltration Capacity", by Robert E. Horton, Trans. Amer. Geophysical Union - 1939. This paper is an extremely important supplement to the material developed by Horton in his Bulletin No. 101, and materially extends and refines the conception of infiltration capacity as originally set out in that Bulletin.

The discussion in this paper is based on the results of run-off plat experiments conducted by Jesse H. Neal and published as Research Bulletin 280, Missouri Agricultural Experiment Station, April 1938. Neal's experiments were made on Putnam soil, taken from the surface five to six inches, from a timothy meadow. It was placed in a tank 12 feet long, and 26 inches deep. "Before each run the soil was dried and cultivated to a depth of 4 inches.... the surface soil was leveled off and worked down with a templet".

On the basis of Neal's data, Horton derived an equation for infiltration capacity. The following paragraphs are extracted from the Horton paper:

"RELATION OF INFILTRATION CAPACITY TO RAINFALL DURATION: As first noted by Horton[2] and subsequently by Neal[1], there is in general a decrease of infiltration capacity during the early stages of a storm. Exceptions will occur (1) where the soil is already at its minimum infiltration capacity; (2) in some regions, particularly on the western Great Plains, a moderate increase of infiltration capacity has been noted[3] in the earlier stages of application of water to sprinkled plats. This increase occurred on areas subject to dust storms and may have been due to washing away of fine dust deposited on the soil surface and into the entrances to soil pores.

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[1] Loc. cit.

[2] Loc. cit.

[3] From unpublished experiments.

"There are at least three reasons why infiltration capacity may decrease in the earlier stages of rain:

1. Swelling of colloids and closing of soil cracks and sun-checks.

2. Inwashing of fine material to the surface pores in the soil. Where surface erosion occurs, water entering the soil pores is charged with fine material in suspension, tending to clog the surface pores. Even though the surface soil is itself carried away, the clogging process still continues.

3. Rain packing. Especially in the earlier stages of intense rains, direct impact of raindrops on the soil compacts the soil surface and decreases the infiltration capacity.

"Except on flat areas, the soil surface is not as a rule wholly covered except with a thin film of water during rain, and on the portions not more deeply covered, rain packing continues until the soil surface reaches a maximum density.

"The first and third conditions partake of the nature of exhaustion phenomena and apparently follow the law of diminishing returns or the inverse exponential law in some form.

"The infiltration capacities derived from typical graphs of Neal's data are shown by circles on Fig. 2*. It was impossible to cover the interval from $t = t^1_o$, the beginning of run-off. However, the plotted points apparently belong to curves which

*(Fig. 2 showing 12 curves not reproduced here. See Fig. 3.)

start at some finite value f_o for $t = 0$. The infiltration capacity then decreases as the duration of application of water continues, the value of f approaching a constant minimum value of f_c asymptotically. These characteristics are common to exhaustion phenomena and suggest that the curves corresponding to the platted points can be represented by a general equation of relation of infiltration capacity to duration of rainfall of the form

$$f = f \quad + (f_o - f_c)\, e^{-K_f t} ,$$

where f = infiltration capacity, inches per hour, at time t, in hours: f_o = initial infiltration capacity at time $t = 0$; f_c = minimum constant infiltration capacity; K_f is constant for a given curve.[a]

"The experiments give f_c directly. To determine the other two constants, f_o and K_f, the following method was used. Smooth curves were drawn to represent the platted points within the range for which t and f were determined. From each curve two pairs of values, $t_1 f_1$ and $t_2 f_2$, were taken off. Then from equation (5),

$$f_1 = f_c + (f_o - f_c)e^{-K_f t_1} \qquad (6)$$

$$f_2 = f_c + (f_o - f_c)e^{-K_f t_2} \qquad (7)$$

from which, by transposition,

$$f_o - f_c = (f_1 - f_c)e^{K_f t_1} = (f_2 - f_c)e^{K_f t_2} \qquad (8)$$

---

[a] This equation has been found to fit accurately the results of ring infiltration experiments by Free, Browning and Musgrave, and sprinkled plot experiments on natural desert soils at Tucson, Ariz. by the U. S. Soil Conservation Service.

The only unknown quantity in the two right-hand terms is K_f. The values of the second and third terms of equation (8) were computed for each of a series of assumed values of K_f and the resulting numerical values of the second and third terms of equation (8) were platted in terms of K_f, as shown on Fig. 3. The point of intersection of the smooth curves drawn through the two series of platted points gives at once the value of K_f and also $f_o - f_c$. Since f_c is known, f_o can then be determined.

"On Fig. 2* the solid lines were computed from equation (5) with the constants appropriate to each curve. Aside from obvious discordancies in the data in some cases, due to lack of details of variation in rain intensity, there is good agreement between the platted points and the computed curves.

"While equation (5) may not actually represent the law governing the physical processes involved, this equation is rational in form, since it not only represents the observed data within the range of observation but also gives results in agreement with known facts for the limiting or boundary conditions.

The analysis of small watershed data for storms lasting more than two hours will often produce an approximation of the value of f_c, and the equation for the particular infiltration capacity curve can then be derived by the method shown in Horton's Fig. 3.

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*See Fig. 3.

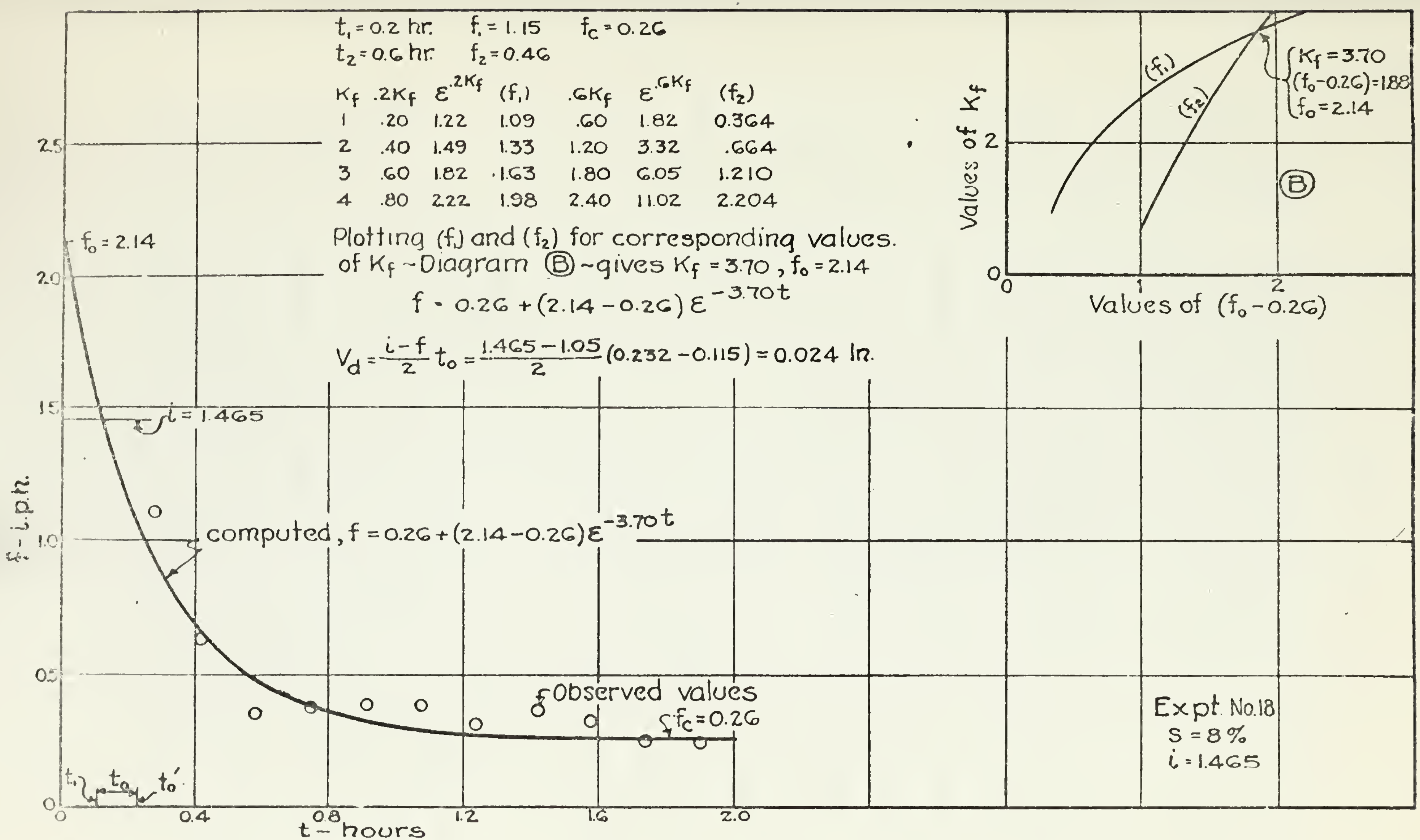

FIG. 3 – DETERMINATION OF CONSTANTS IN INFILTRATION-EQUATION AND COMPUTATION OF V_d

For shorter storms, the value of f_c may not be approximated but a curve of this type can still be fitted to the plotted points and extended in both directions to make available approximate values of both f_o and f_c.

Any one curve for a particular watershed derived from a single storm may contain an inconsistency with respect to one of the available points, but the preparation of several such curves for the same watershed under similar conditions of land use and cover will permit an adjustment as between the curves and the development of a master curve which may then be used in the further application of the data.

In the application of such curves to flood flow prediction, some method is needed by which the most probable value of f_o can be chosen. In the following paragraphs Horton has discussed the relation of infiltration capacity to soil moisture, the relation of initial infiltration capacity to antecedent rain; and the factors that determine minimum infiltration capacity.

"RELATION OF INFILTRATION CAPACITY TO SOIL MOISTURE--Neal found a close correlation between his computed average infiltration capacity for the first ten minutes of application of rain to the initial soil moisture. The validity of his results are, however, affected by the fact that depression storage and antecedent rainfall in which f exceeded i were not taken into account. A better basis of comparison of infiltration capacity with initial soil

moisture seems to be possible using f_o as a comparate.

"The initial soil-moisture to a depth of 1 inch, expressed in percentage of dry weight of soil, as given by Neal, was compared with the corresponding values of f_o, taking group means of experiments with closely similar initial soil moisture. The results are shown on Fig. 4. The curve is closely similar to that obtained by Neal.

"A similar platting of f_o in terms of initial soil moisture for a depth of 1 to 4 inches showed no definite evidence of correlation. This clearly indicates that the initial infiltration capacity, at least, is primarily a function of the condition of the soil surface.

"The data on Fig. 4 are well represented by the equation

$$f_o = f_w + (f_d - f_w)e^{-K_n \frac{n_o - n_d}{n_w}}, \qquad (13)$$

where n_w is the moisture content, percent dry weight of the soil in its initial surface condition but fully wetted (to field-moisture-capacity), f_w is the infiltration capacity of the soil in its initial surface condition but wetted at least to field-moisture capacity n_d and f_d are the moisture content and infiltration capacity, respectively, of soil in its initial condition when air-dry. n_o and f_o are, respectively, the actual initial moisture content and initial infiltration capacity. n_w and n_d correspond approximately to moisture content at field-moisture capacity and the hygroscopic

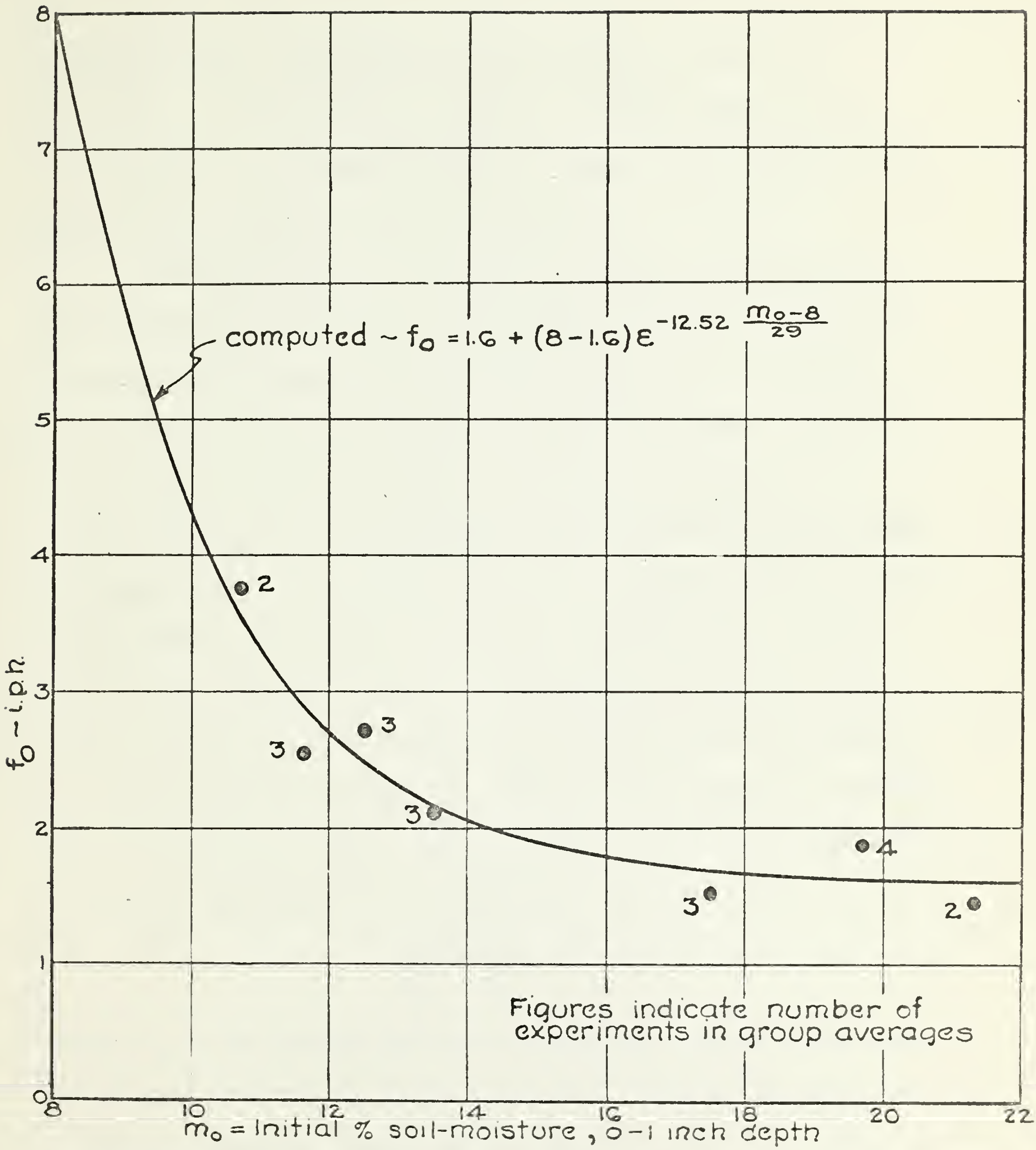

FIG. 4 ~ RELATION OF f_o TO INITIAL SOIL-MOISTURE CONTENT AT 0-1 INCH DEPTH

moisture content, respectively. Neal's experiments give f_d = 8 i.p.h., f_w = 1.6 i.p.h., K_m = 12.52. The difference, $f_d - f_w$ = 6.4 i.p.h., is the maximum effect of drying out of the soil surface for this soil and method of treatment.

"Since the soil was the same and the surface treatment the same in different experiments, the observed variations in f_o shown in column (4) of Table 2* are apparently due to (1) variation in soil moisture, (2) uncontrolled differences in surface compactness, (3) variation in rain intensity. The effect of variation of initial soil moisture can be largely eliminated by taking off from the curve on Fig. 4 the values of f_o for an assumed constant initial soil moisture m'_o. For this purpose m_o = 16% was used. For 16% soil moisture the curve gives f_o = 1.80 inches per hour. The observed values of f_o were reduced to the basis of 16% soil moisture by assuming that the observed f_o would have been changed by changing the initial soil moisture content to 16% in the same ratio that the corresponding values of f_o on the curve are changed, or,

$$\frac{f'_o}{f_o} = \frac{f_a}{f_b} ,$$

where f'_o is the initial infiltration capacity reduced to the basis of 16% soil moisture, f_a is the value of f_o given by the curve for

---

*Not reproduced. f_o varies from 1.4 to 4.4.

actual moisture content, and f_b = 1.80 in. per hour for 16% moisture. Consequently,

$$f'_o = 1.8 \frac{f_o}{f_a} \qquad (14)$$

The values of f'_o or the initial infiltration capacities for 16% moisture are shown in column (12) of Table 2. Correction to 16% moisture reduces the range and variability of f_o. The average of the observed values of f_o is 2.24; the average of the values of f'_o is 1.81; the average of the soil moisture 0 to 1 inch was 15.4%.

"The preceding discussion lays a foundation for the prediction of infiltration capacity on a soil of the type and with the method of cultivation used in Neal's experiments. For a large area, with the same soil and cultivation, it may be assumed that the average of f_c will apply in equation (5). From Table 2 this is 0.186; hence

$$f = 0.186 + (f_o - 0.186)e^{-K_f t}. \qquad (15)$$

"The constant K_f is an exponential parameter which measures the time required for the infiltration capacity to drop from its initial to its minimum value as the result of rain packing and inwashing, particularly the former. It is presumable that the rate of rain packing, and the consequent reduction of infiltration capacity thereby, increases with rain intensity, or the higher the rain intensity, the shorter the time t_c required to reduce the infiltra-

tion capacity from that corresponding to initial soil moisture, to the minimum value.

"The larger the value of K_f the shorter the time t_c. Hence K_f should increase as the rain intensity i increases. Neal's experiments afford an opportunity to test this hypothesis. The computed values of K_f were averaged by groups for the different rain intensities and the results have been plotted on Fig. 5#. While not highly consistent, the data are well represented by the equation:

$$K_f = 2.20\ i. \tag{16}$$

This expression is rational in form, since it makes f constant and equal to f_o for zero rain intensity and, on the other hand, the time required for the infiltration capacity to reach its minimum value f_c approaches zero as the limit as the rain intensity i increases.

"If the initial surface soil moisture percentage is known then equations (13), (15) and (16) provide a means of predicting the march of infiltration capacity during a subsequent rain. For example, let i = 3.0 i.p.h. for a soil the same as used by Neal, with m_d = 8%, m_w = 39% and f_w = 1.6 i.p.h. Let it be required to determine the infiltration capacity for an initial soil moisture m_o = 12%. From equation (13) f_o = 2.70 i.p.h. From equation (16) K_f = 6.60. Substituting these values of f_o and K_f in equation (15)

#Not reproduced.

gives

$$f = 0.186 + (2.10 - 0.186)e^{-6.60t}$$

for time t in hours. Solution of this equation for different values of t will give the march of infiltration during the subsequent rain.

"RELATION OF f_o TO ANTECEDENT RAIN--Ordinarily the initial surface soil moisture m_o is unknown. In order to make equations (13), (15), and (16), of the utmost practicable value, it is desirable to have some simple correlation between time elapsed since the last preceding rain and the soil surface moisture at the beginning of a given rain. Presuming that the antecedent rain penetrated the soil to a sufficient depth so that the rate of drying out would not be greatly affected by moisture condition below the depth of penetration, then it appears that at the end of the last antecedent rain, the soil surface moisture would have been equal to the field-moisture capacity m_f. At a time t_1 subsequent thereto the soil surface moisture will be reduced by an amount dependent on the evaporation rate. It appears probable that a fairly good correlation between initial moisture content and time elapsed since the last preceding rain could be worked out but thus far this has not been done. Quite probably it is an inverse exponential law of a form

$$m_o = m_h + (m_f - m_h)e^{-K_m t}, \tag{17}$$

where m_f = the field-moisture capacity, m_h = the hygroscopic moisture capacity, and m_o = moisture remaining at time t, and K_m depends on the evaporation rate.

"It is possible that a simple linear equation

$$m_o = m_f - (m_f - m_d) \frac{t_1}{t_d} \quad (18)$$

will meet practical requirements. In this equation t_d is the time required for the soil surface to become air-dry or to attain a condition of equilibrium with air of a given temperature and humidity. This is a function of the evaporation rate but since there is a high degree of correlation between evaporation and air temperature, and since temperature data are much more commonly available than evaporation data, it is possible that t_d can be expressed with sufficient accuracy in terms of air temperature alone.

"MINIMUM INFILTRATION CAPACITY -- Normal minimum infiltration capacity may be defined as the infiltration capacity of a soil surface free from sun-checks and biologic structures (earthworm, insect and root perforations) which has been wetted to field-moisture capacity long enough to permit full swelling of colloids and adjustment of the soil structure to a stable field condition. The author has closely duplicated determinations of f in such soils in repeated experiments and hence concluded that a given soil has a definite normal minimum infiltration capacity.[4]

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(4) Horton, Robert E., The role of infiltration in the hydrologic cycle. Trans. A.G.U., 1933, p. 451.

"A given soil surface may not fully meet these conditions during a rain because of under-or over-packing, puddling of the soil surface and inwashing of fine material, or because of the presence of biologic structures. Some variation of f_c in run-off plat experiments is therefore to be expected.

"The following tabulation shows the number of values of the constant or final infiltration capacity lying between given limits. For most of the experiments f_c lies between 0.15 and 0.30 and the variations from the average f_c = 0.186 may apparently be attributed to differences in compactness of the soil, as it is known that infiltration capacity is sensitive to variation of soil porosity.

Distribution of values of f_c

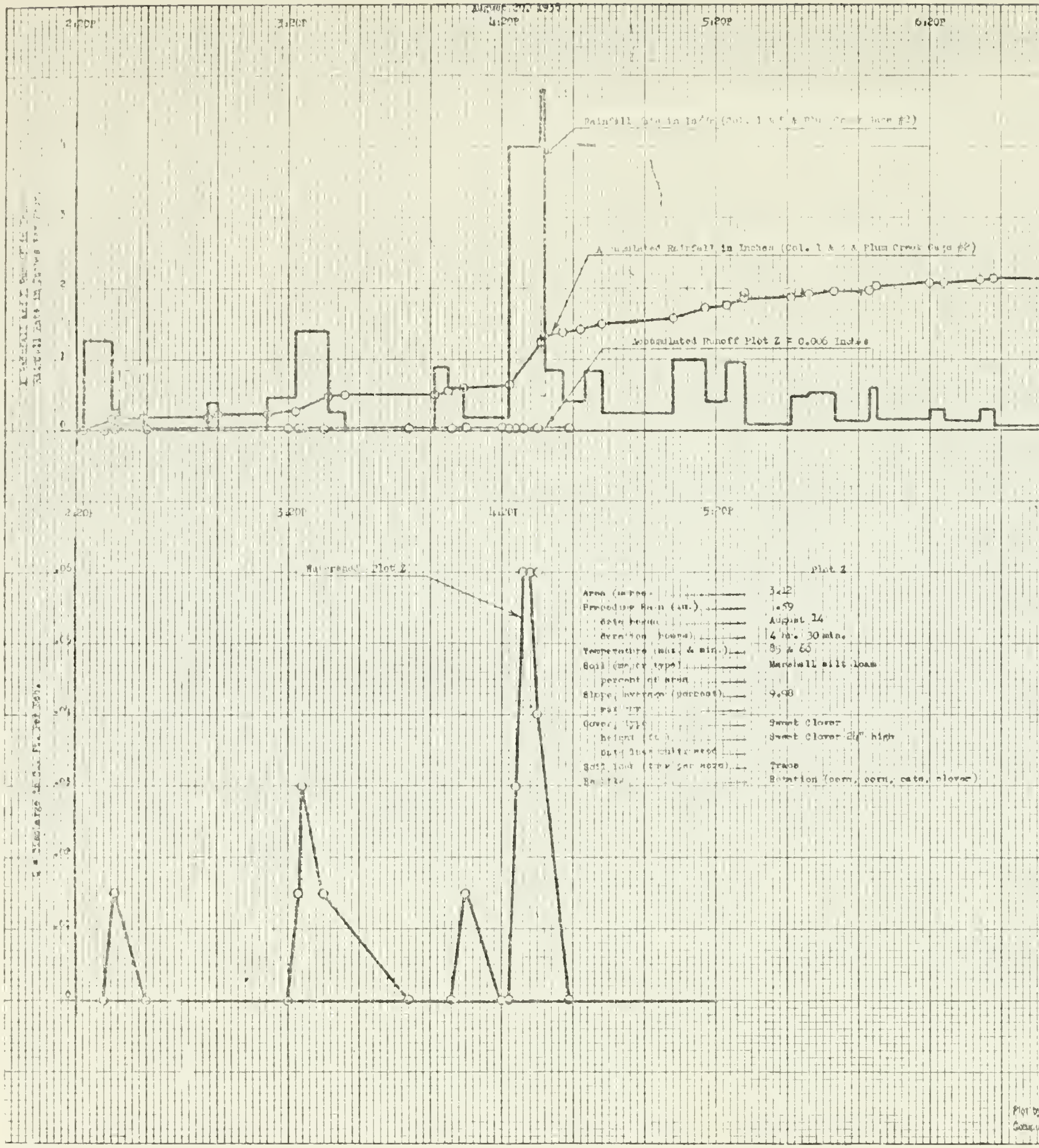
Limits		Number of values
<0.10		3
>0.10	<0.15	2
>0.15	<0.20	5
>0.20	<0.25	6
>0.25	<0.30	4

Compared with f_o, the variation of minimum infiltration capacity of a given soil is confined to a relatively narrow range. Also it is to be noted that the minimum initial infiltration capacity for loose soil, uncompacted by rain but fully wetted, as shown by Fig. 4, is 1.6 in. per hour. The difference between this and 0.186 in. per hour, the average f_c after prolonged rain, may be

attributed to rain packing or inwashing, or both."

While the greater part of this material is primarily important to a proper use of infiltration capacity curves, it is presented here with the suggestion that the infiltration capacity curves produced through the analysis of small watershed data be adequately annotated and referenced with respect to initial soil moisture, where available, and with respect to antecedent rainfall.

August 20, 1938
Watershed Plot Z



August 20, 1938
Clarinda, Iowa
Watershed Plot Z

(1) (t) (time)	(2) (Δt) (min)	(3) (ΣI) (in.)	(4) (ΔI) (in.)	(5) I = 60 ΔI/Δt (in./hr.)	(6) Int. on Act Z Col.5 × 2.18/2.15
2:22P					
	8		.17	1.28	1.29
2:30		.17			
	2		.01	.30	.30
2:32		.18			
	7		.01	.09	.09
2:39		.19			
	18		.00	.00	.00
2:57		.19			
	3		.02	.40	.40
3:00		.21			
	14		.00	.00	.00
3:14		.21			
	8		.06	.45	.45
3:22		.27			
	9		.21	1.40	1.41
3:31		.58			
	5		.02	.24	.24
3:36		.50			
	25		.00	.00	.00
4:01		.50			
	4		.06	.90	.90
4:05		.56			
	4		.04	.60	.60
4:09		.60			
	13		.04	.18	.18
4:22		.64			
	9		.60	4.00	4.04
4:31		1.24			
	1		.08	4.80	4.86
4:32		1.32			
	5		.07	.84	.84
4:37		1.39			
	6		.04	.40	.40
4:43		1.43			
	5		.07	.84	.84
4:48		1.50			
	20		.08	.24	.24
5:08		.58			
	9		.15	1.00	1.01
5:17		1.73			
	6		.04	.40	.40
5:23		1.77			
	5		.03	.36	.36
5:28		1.79			
	13		.02	.09	.09
5:41		1.87			
	5		.04	.48	.48
5:46		1.91			
	7		.06	.51	.51
5:53		1.77			
	10		.02	.12	.12
6:03		1.99			
	2		.02	.60	.60
6:05		2.01			
	15		.06	.24	.24
6:20		2.07			
	4		.02	.30	.30
6:24		2.09			
	10		.02	.12	.12
6:34		2.11			
	4		.02	.30	.30
6:38		2.15			
	17		.02	.07	.07
6:55		2.17			
					2.18*

* Rainfall on Watershed Plot Z determined by Horton's Method.

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SOIL CONSERVATION SERVICE
H. H. BENNETT, CHIEF
DIVISION OF RESEARCH, W. C. LOWDERMILK, CHIEF

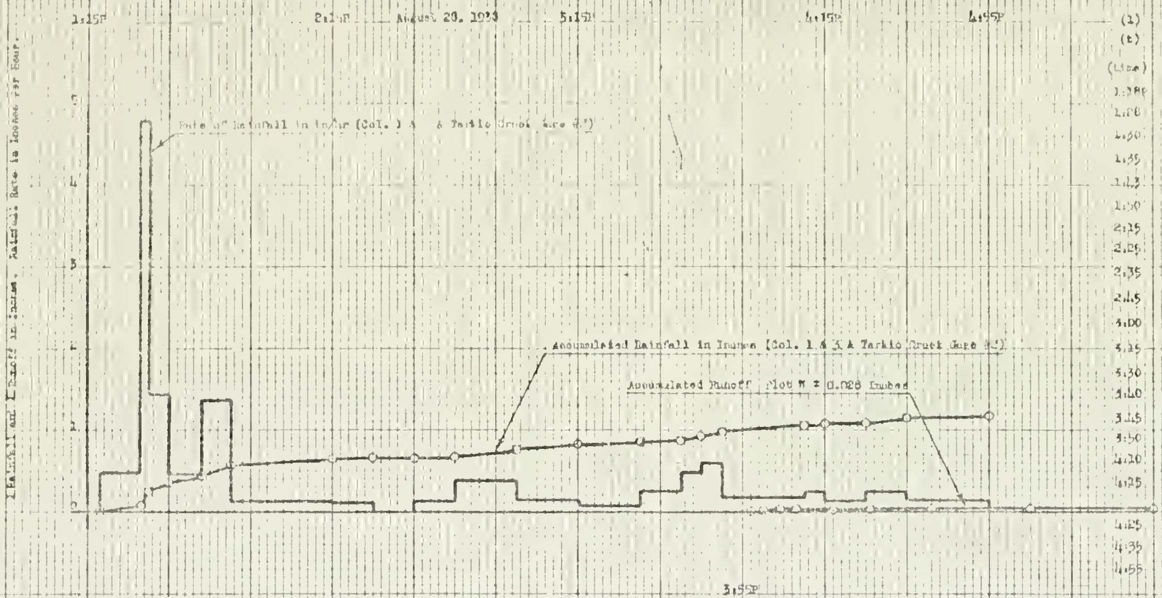
Clarinda, Iowa

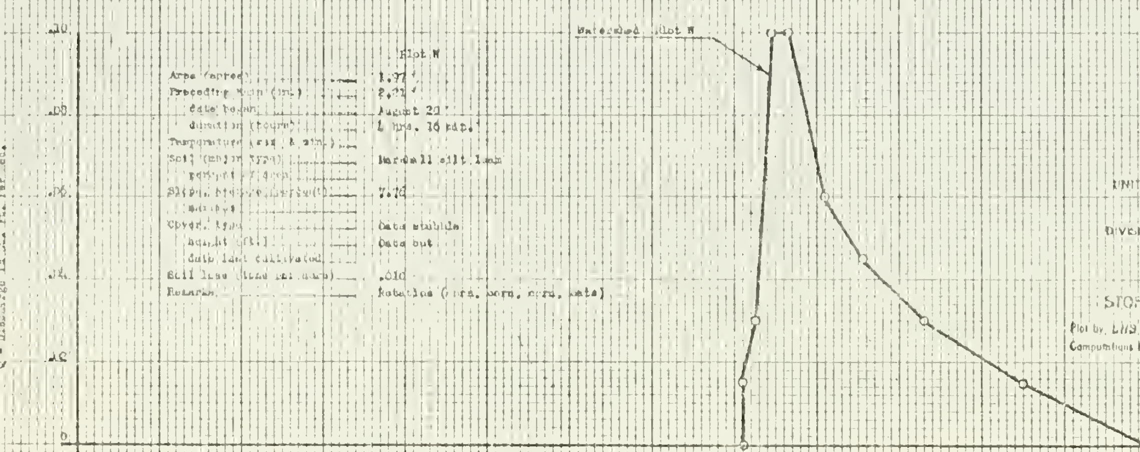
STORM NO. Aug. 20, 1938

Plot by L.H.S. date 7/28/38 checked by L.R.S. date 8/1/39
Computations by L.H.S. date 7/27/38 checked by L.R.S. date 7/27/39

Sheet 3 of 3 sheets

August 28, 1938
Watershed Plot W





August 28, 1938
Clarinda, Iowa
Watershed Plot W

(1)	(2)	(3)	(4)	(5)	(6)
(t)	(Δt)	(Σd)	(Δd)	i = 60 Δd/Δt	Int. on Plot W Col. 5 × 1.20/1.17
(time)	(min)	(in.)	(in.)	(in/hr)	
1:38P					
	10		.08	.48	.49
1:48		.08			
	2		.16	4.80	4.92
1:50		.24			
	5		.12	1.44	1.46
1:55		.36			
	8		.06	.45	.45
1:43		.42			
	7		.16	1.37	1.40
1:50		.58			
	25		.06	.14	.14
2:15		.64			
	10		.02	.12	.12
2:25		.66			
	10		.00	.00	.00
2:35		.66			
	10		.02	.12	.12
2:45		.68			
	15		.09	.36	.36
3:00		.77			
	15		.04	.16	.16
3:15		.81			
	15		.02	.08	.08
3:30		.83			
	10		.04	.24	.24
3:40		.87			
	5		.04	.48	.48
3:45		.91			
	5		.08	.96	.97
3:50		.99			
	20		.06	.18	.18
4:10		1.05			
	5		.02	.24	.24
4:15		1.07			
	20		.02	.12	.12
4:25		1.09			
	10		.04	.24	.24
4:35		1.13			
	20		.04	.12	.12
4:55		1.17			
					1.20*

* Rainfall on Watershed Plot W determined by Horton's Method.

	Plot W
Area (acres)	1.37
Preceding storm (in.)	2.21
date began	August 21
duration (hours)	4 hrs. 16 min.
Temperature (air & rain)	
Soil (major type)	Marshall silt loam
percent of area	
Slope, average percent	7.70
Slope, range	
Cover, type	Oats stubble
height (ft.)	Oats cut
date last cultivated	
Soil loss (tons per acre)	.010
Remarks	Rotation (corn, corn, corn, oats)

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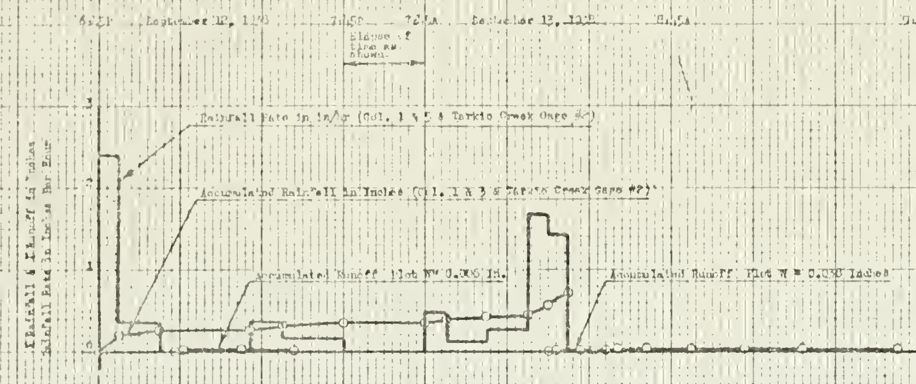
STORM NO. Aug. 28, 1938

Plot by LHS date 7/25/39 — LHS date 8/7/39
Computations by LHS date 7/17/39 — by LHS date 7/24/39

Sheet 1 of 1 sheet

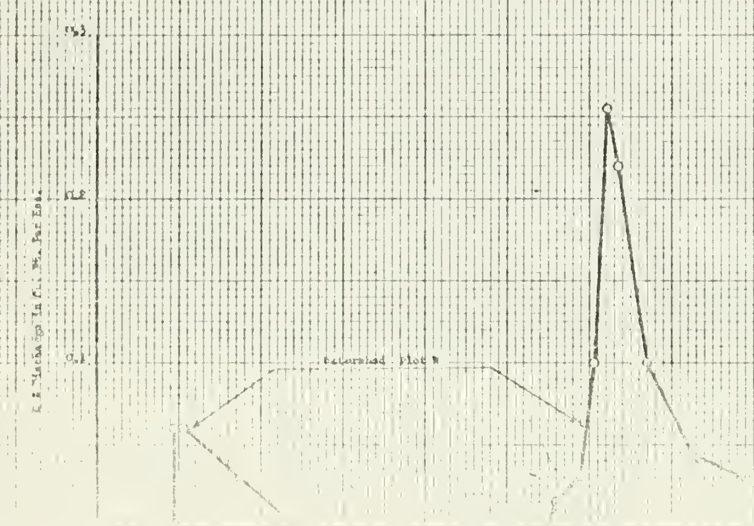
September 12 & 13, 1938
Watershed Plot W



September 12 & 13, 1938
Clarinda, Iowa
Watershed Plot W

	(1) (t) (time)	(2) (Δt) (min)	(3) (Σd) (in.)	(4) (Δd) (in.)	(5) i = 60 Δd/Δt (in/hr)	(6) Int. Plot W Col. 5 x .75/.71
9/12	6:45P					
		5		.20	2.40	2.52
	6:50		.20			
		10		.06	.36	.37
	7:00		.26			
		22		.00	.00	.00
	7:22		.26			
		8		.05	.38	.39
	7:30		.31			
		15		.04	.16	.16
	7:45 P		.35			
9/13	7:45A					
		5		.04	.48	.50
	7:50		.39			
		10		.02	.12	.12
	8:00		.41			
		10		.04	.24	.25
	8:10		.45			
		5		.14	1.68	1.76
	8:15		.59			
		5		.12	1.44	1.51
	8:20 A		.71			
						.75*

* Rainfall on Watershed Plot W Determined by Horton's Method.

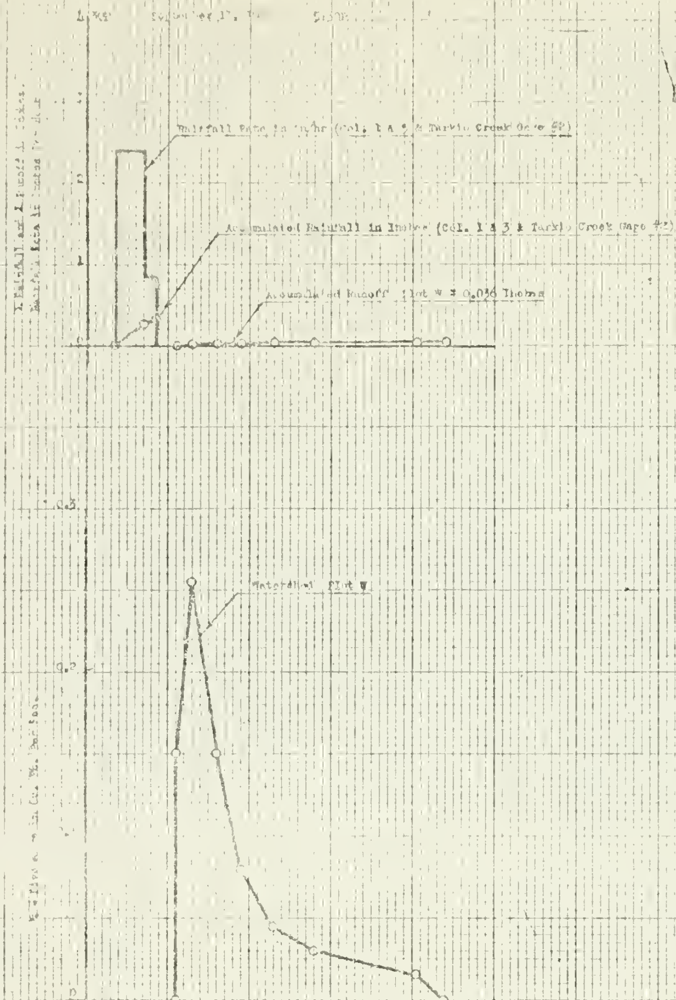


	Plot W
Area (acres)	1.97
Preceding Rain (in.)	1.06
Date began	September 10 & 11
Duration (hours)	10 hrs. 0 mins.
Temperature (max. & min.)	68 & 66
Soil (major type)	Marshall silt loam
percent of area	
Slope, average (percent)	7.76
maximum	
Cover, type	Oat stubble
Height (ft.)	Oats cut
Date last cultivated	
Soil loss (tons per acre)	.020
Remarks	Rotation (corn, corn, corn, oats)

Computed by L.H.S.

Sheet 1 of 1 sheet

September 13, 1938
Watershed Plot W



September 13, 1938
Clarinda, Iowa
Watershed Plot W

(1)	(2)	(3)	(4)	(5)	(6)
(t)	(Δt)	(Σd)	(Δd)	$i = 60 \frac{\Delta d}{\Delta t}$	Int. on Plot W
(time)	(min)	(in.)	(in.)	(in/hr)	Col. 5 x .34/.32
9/13 4:30					
	7		.20	2.40	2.54
4:37		.20			
	3		.04	.80	.34
4:40		.32			
					.34*

* Rainfall on Watershed Plot W determined by Horton's Method.

Plot W

Area (acres)	1.77
Preceding Rain (in.)	0.71
date began	September 12 & 13
duration (hours)	1 hr. 35 min.
Temperature (max. & min.)	62 & 66
Soil (major type)	Marshall silt loam
percent of area	
Slope, average (percent)	7.76
maximum	
Cover, type	Oat stubble
height (ft.)	Oats cut
date last cultivated	
Soil loss (tons per acre)	.014
Remarks	Rotation (corn, corn, corn, oats)

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Clarinda, Iowa

STORM NO. Sept. 13, 1938

Plot by LHS date 7/27/39 checked by LHS date 8/2/39
Computations by LHS date 7/24/39 checked by LHS date 7/25/39

Sheet 1 of 1 sheet

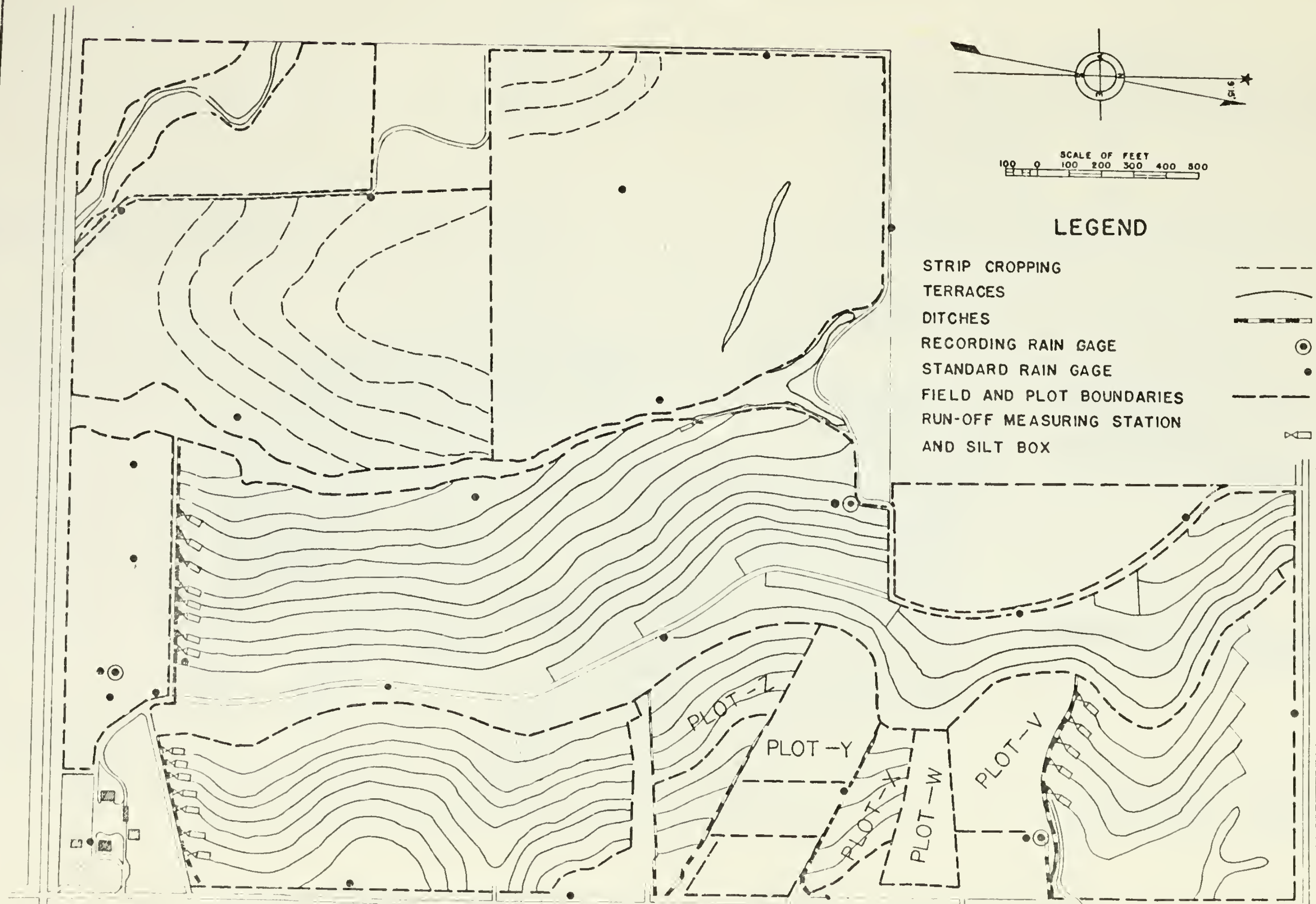

FIGURE 1.- MAP OF THE CONSERVATION EXPERIMENT STATION MISSOURI VALLEY LOESS REGION CLARINDA IOWA SHOWING LOCATION OF THE FIELDS AND EXPERIMENTAL AREAS

SOILS SURVEYED IN 1931

UPLAND SOILS

Marshall silt loam - 2"-3" inclusive ---------- 2
Marshall silt loam - 4"-9" inclusive ---------- 4
Marshall silt loam - 10"-14" inclusive ---------- 8
Marshall silt loam - 15" plus ---------- 9
Marshall silt loam Talus slope - bench like ---------- 40
Marshall silty clay loam ---------- 44
Shelby silt loam ---------- 14
Shelby silt loam deep phase (Drift 18"-28") ---------- 15
Shelby silty clay loam deep phase (Drift 18"-28") ---------- 31x

TERRACE SOILS

Judson silt loam - heavy subsoil phase ---------- 54x

BOTTOMLAND SOILS

Wabash silt loam - colluvial phase ---------- 27
Wabash silty clay loam - colluvial phase ---------- 30
Genesee silt loam - colluvial phase ---------- 24

CROP ROTATION

PLOT	1935 & 1939	1936 & 1940	1937 & 1941	1938 & 1942
V, Y, & Z	CORN RYE & VETCH COVER CROP	CORN	OATS	RED CLOVER
W & X	CORN RYE & VETCH COVER CROP	CORN	CORN	OATS

Corn listed on approximate contours on plots V, Y, & Z but without respect to contour on plots W & X.

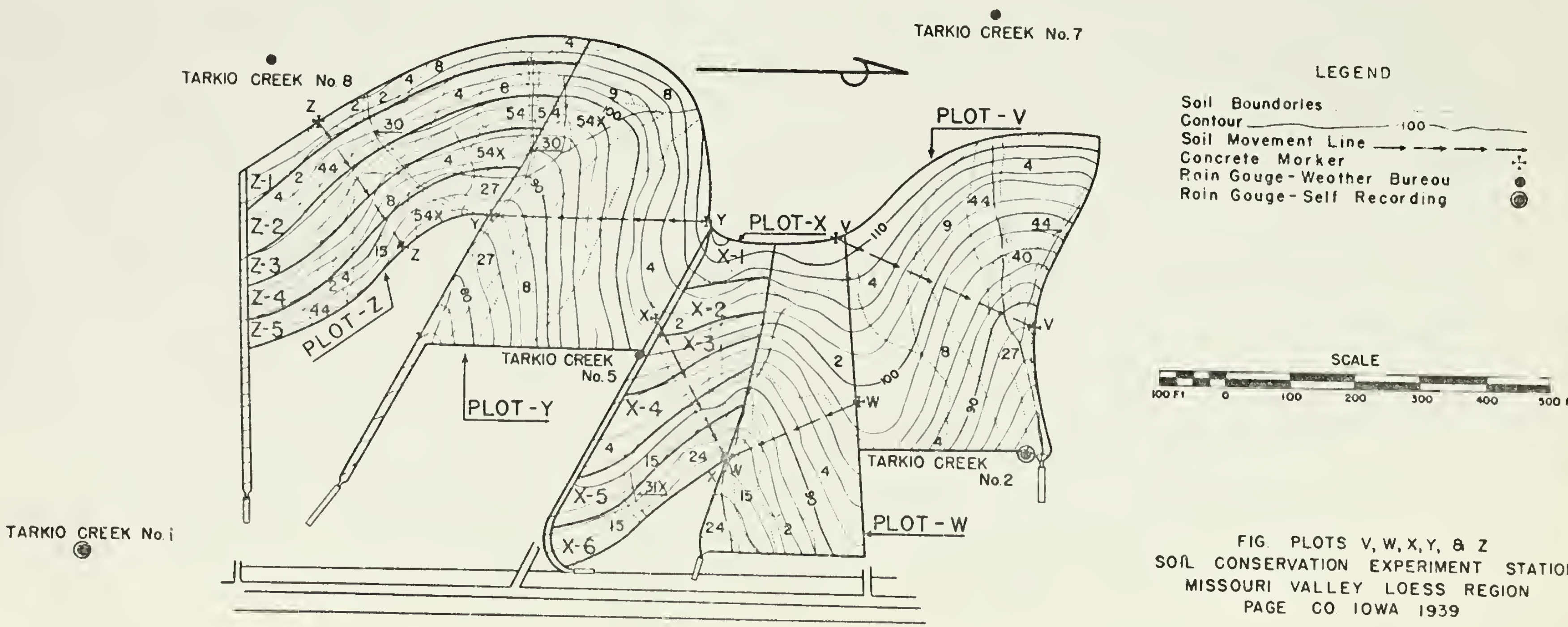

FIG. 2 MAP OF WATERSHEDS V,W,X,Y AND Z. CLARINDA, IOWA