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THE UNIT HYDROGRAPH - ITS CONSTRUCTION AND USES

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FOREWORD

The unit hydrograph theory has received the attention of eminent hydrologists since its introduction in 1932. A number of articles concerning the subject are to be found in the literature. The information contained herein regarding the unit hydrograph and its uses is presented with the hope that it will aid in engineering studies in the field of hydrology.

THE UNIT HYDROGRAPH - ITS CONSTRUCTION AND USES

INTRODUCTION

A hydrograph of a stream as defined by Wisler and Brater[8] is a graphical representation of its fluctuations in flow arranged in chronological order. A complete hydrograph shows every minor variation in flow and can therefore be obtained only from an instrument that continuously records these changes, for no stream is constant in flow even for short periods of time. Frequently, however, such continuous records are not available and either instantaneous, or mean daily readings, must be used in preparing the hydrograph. For instance, the stream discharge records as given in the U. S. Geological Survey Water Supply Papers are mean daily discharges. The beginning of the flood discharge during the 24 hour period, the amount of the peak discharge and the time the peak occurred are not commonly available in these records. Similarly the precipitation records as published by the U. S. Weather Bureau usually give the total precipitation for a 24 hour period. Thus it is not possible to tell from these records the time a rain commences, when it ended, or the rate at which it fell. Neither is it possible to tell with any degree of accuracy its direction of travel across a watershed.

Naturally, if all of the factors mentioned above were known, a much more accurate hydrograph could be produced. In constructing stream hydrographs, judgement and experience must sometimes be used to overcome this lack of information.

THE UNIT HYDROGRAPH

The unit hydrograph, or unit graph, as defined by Sherman[5] is a graph representing 1.00 inch of runoff from a watershed. This unit graph may be prepared from a known hydrograph, and may then be used to compute a hydrograph of runoff for this area for any particular storm or sequence of storms of any duration or intensity over any period of time.

Construction of the Unit Hydrograph

For simplicity of presentation the procedure for constructing the unit hydrograph will be given step by step, and the construction of a unit hydrograph for Richland Creek in Navarro County, Texas, will be used as an example. The steps in the construction of the unit hydrograph are as follows:

1. Selecting typical storm data.

Search the rainfall and stream discharge records of the watershed in question for an isolated 24 hour rain storm which covers the area fairly uniformly and which produces a rather large discharge. (Preferably, but not necessarily, over 1.00 inch of runoff over the watershed.) It is preferable that the flow of the stream be low, or normal, prior to the rain, and that no additional rain fell during the flood runoff. Sherman[5] gives methods for separating the runoff resulting from antecedent and subsequent rainfall, but these will not be presented in this simple discussion.

2. Obtaining the average rainfall over the area.

On a map, or map overlay, trace out the watershed in question. Locate the gaging station and the precipitation stations in, and surrounding, the area on the overlay. One of the standard methods of converting gage measurements to areal averages should be used to give the average depth of precipitation over the area. Most good hydrology books will give a discussion of these methods. Thiessens method was used on the Richland Creek area because it is more accurate than the arithmetical mean method, yet is simpler than the isohyetal map method. A Thiessen network is constructed by locating the stations on a map and drawing the perpendicular bisectors to the line connecting the stations. The polygons thus formed around each station are the boundaries of the effective area assumed to be controlled by that station. The area governed by each station is planimetered and expressed as a percentage of the whole area. In the Richland Creek watershed 25 percent of the area is closer to the Mexia gage than to any other station, 38 percent closer to the Hillsboro gage and 37 percent closer to the Corsicana gage as shown by Figure 1. It can be seen that in this method the gages at Waco and Waxahachie should not be considered. Weighted average rainfall for the basin is computed by multiplying each station's precipitation by its assigned percentage of area and totaling as shown in Table I. The use to be made of this weighted precipitation will be discussed later.

TABLE I

WEIGHTED RAINFALL OVER
RICHLAND CREEK DRAINAGE AREA FOR SELECTED STORMS

Gage	Rainfall in in.	Percent of area	Weighted Rainfall (in.)
	March 7, 1947		
Corsicana	1.36	37	.50
Mexia	2.00	25	.50
Hillsboro	1.15	38	.44
			1.44
	May 11-13, 1948		
Corsicana	5.86	37	2.17
Mexia	2.90	25	.73
Hillsboro	3.70	38	1.41
			4.31

FIGURE I
THIESSEN NETWORK FOR RICHLAND CREEK DRAINAGE AREA

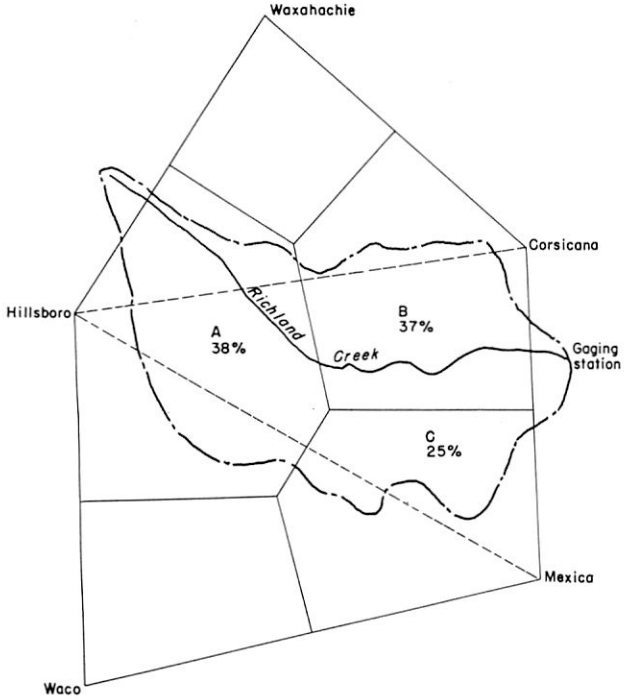


FIGURE 2
HYDROGRAPH FOR RICHLAND CREEK
CONSTRUCTED FROM WATER SURFACE REPORT

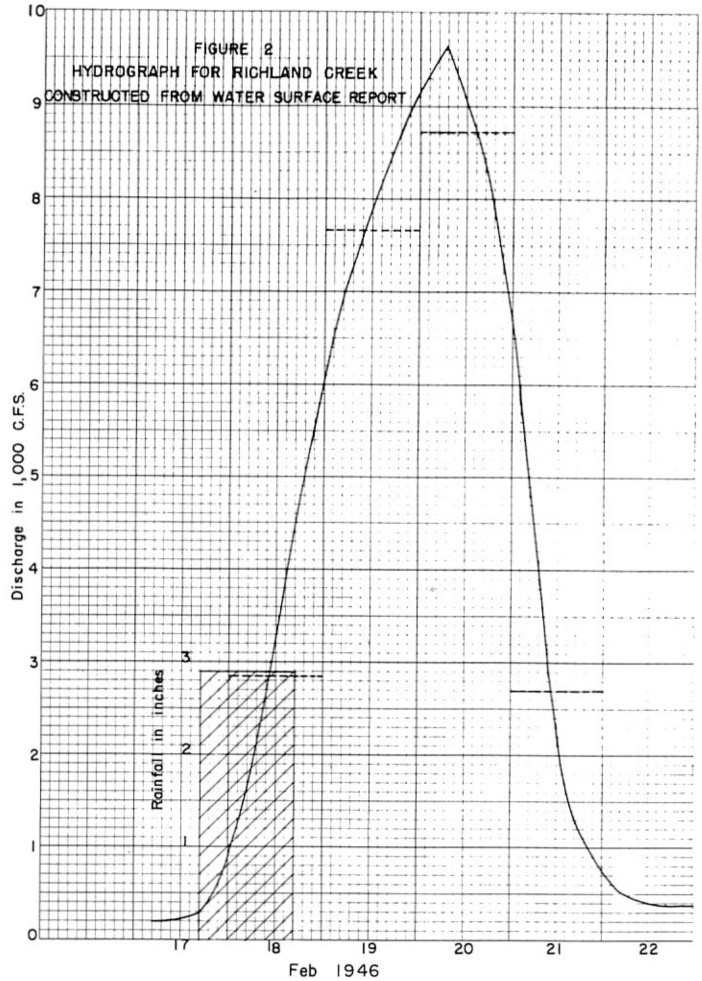


FIGURE 3
HYDROGRAPH CONSTRUCTED FROM DATA
FROM WATER LEVEL RECORDER CHART

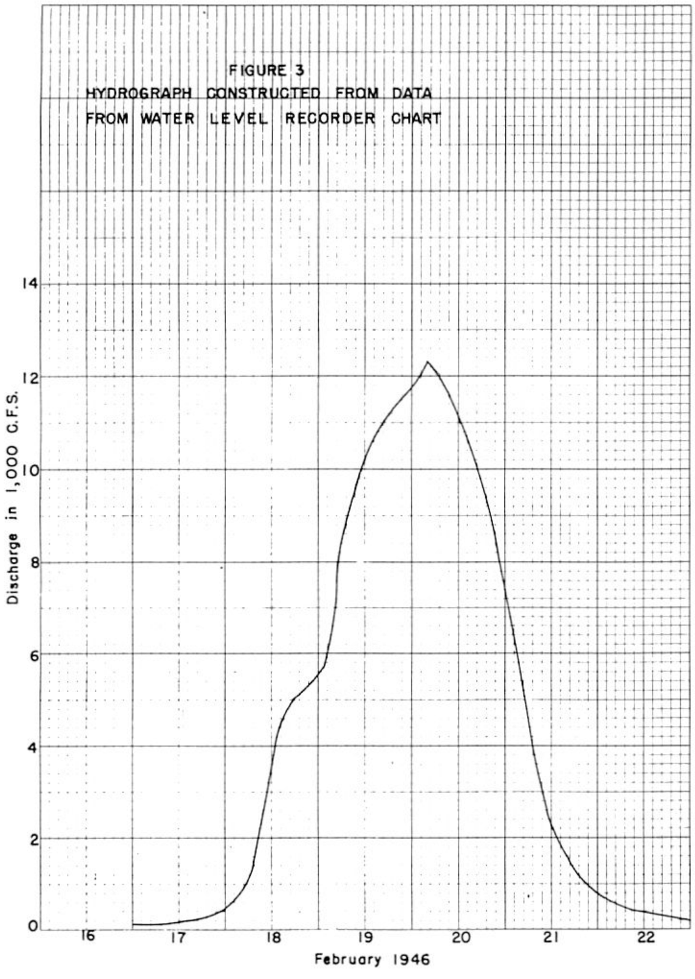
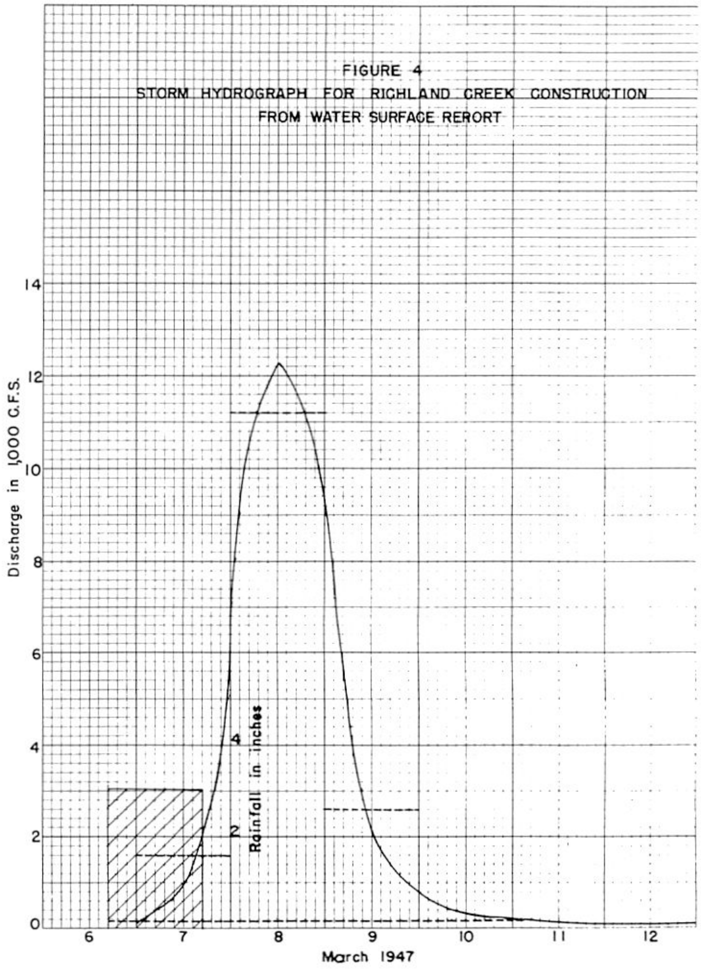


FIGURE 4
STORM HYDROGRAPH FOR RICHLAND CREEK CONSTRUCTION
FROM WATER SURFACE RERORT



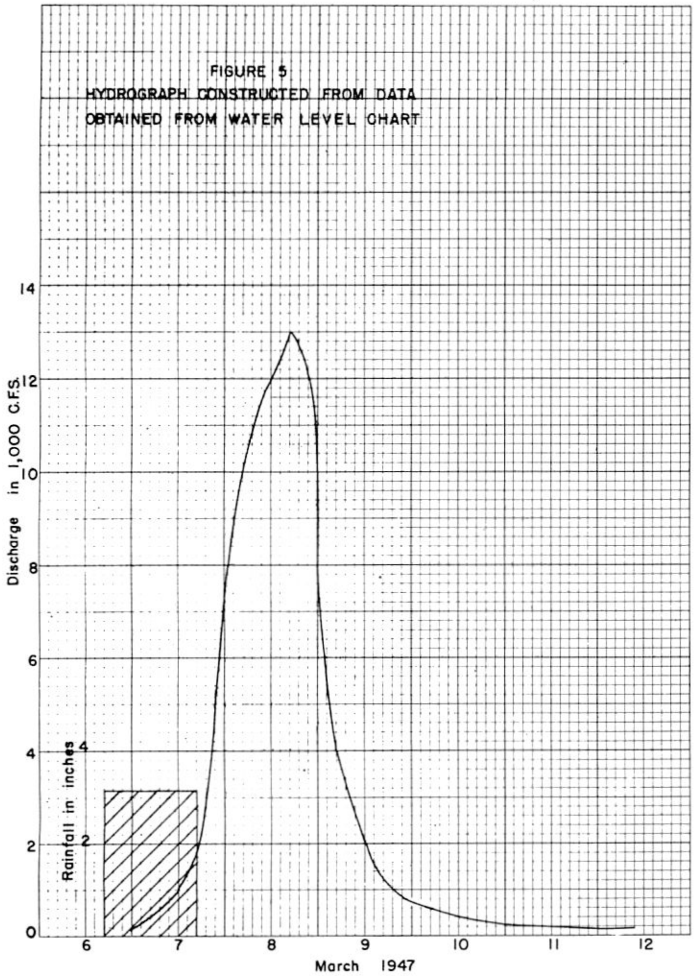


FIGURE 5
HYDROGRAPH CONSTRUCTED FROM DATA
OBTAINED FROM WATER LEVEL CHART
Discharge in 1,000 C.F.S.
Rainfall in inches
March 1947

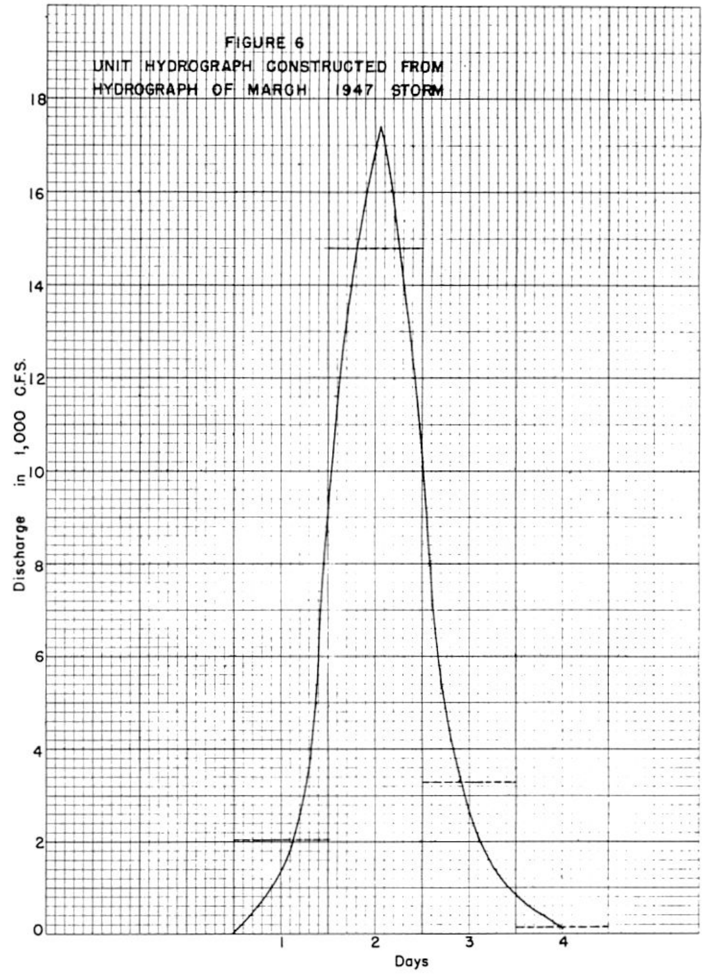


FIGURE 6
UNIT HYDROGRAPH CONSTRUCTED FROM
HYDROGRAPH OF MARCH 1947 STORM
Discharge in 1,000 C.F.S.
Days

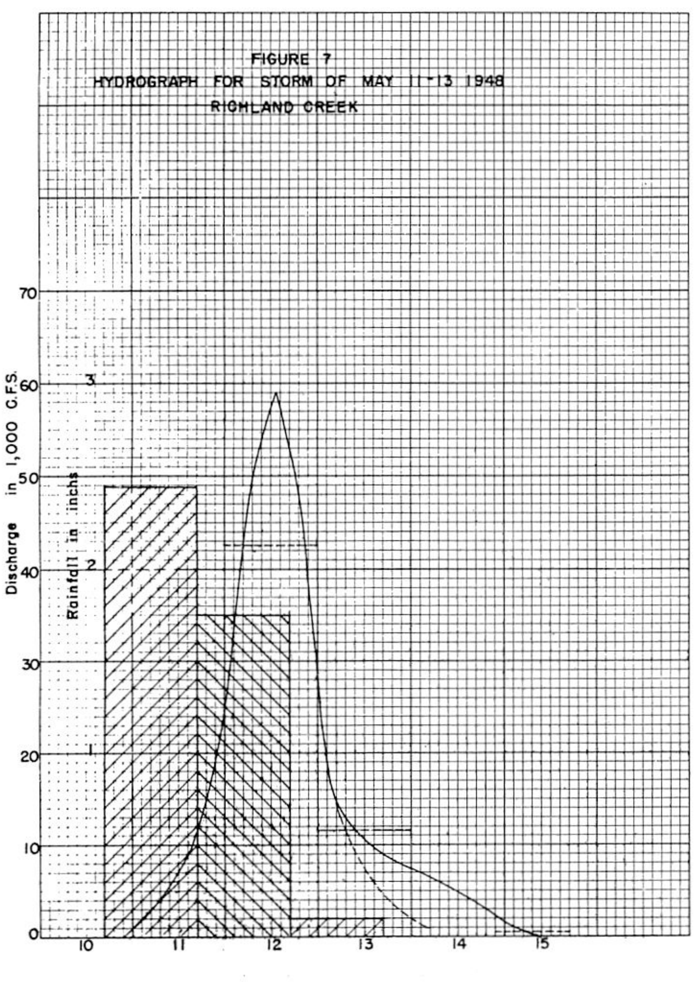


FIGURE 7
HYDROGRAPH FOR STORM OF MAY 11-13 1948
RICHLAND CREEK
Discharge in 1,000 C.F.S.
Rainfall in inchs

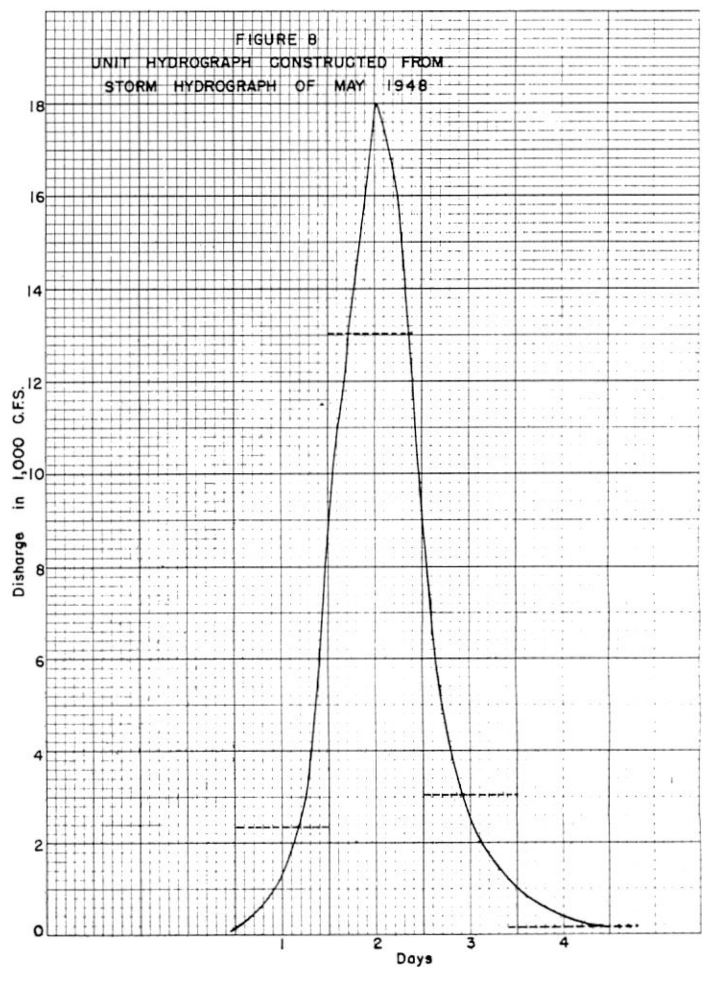


FIGURE 8
UNIT HYDROGRAPH CONSTRUCTED FROM
STORM HYDROGRAPH OF MAY 1948
Dishrge in 1,000 C.F.S.
Days

FIGURE 9
PERCENT RUNOFF CURVE FOR RICHLAND CREEK DRAINAGE AREA

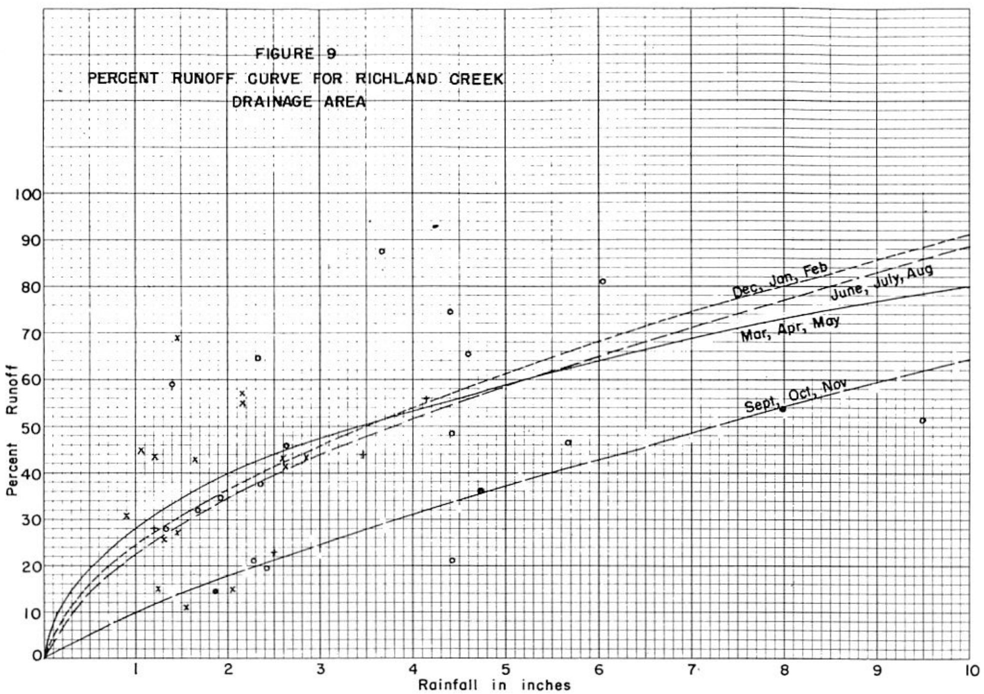


FIGURE 10
HYDROGRAPH RESULTING FROM ASSUMED 6 INCH RAINFALL ON RICHLAND CREEK DRAINAGE AREA

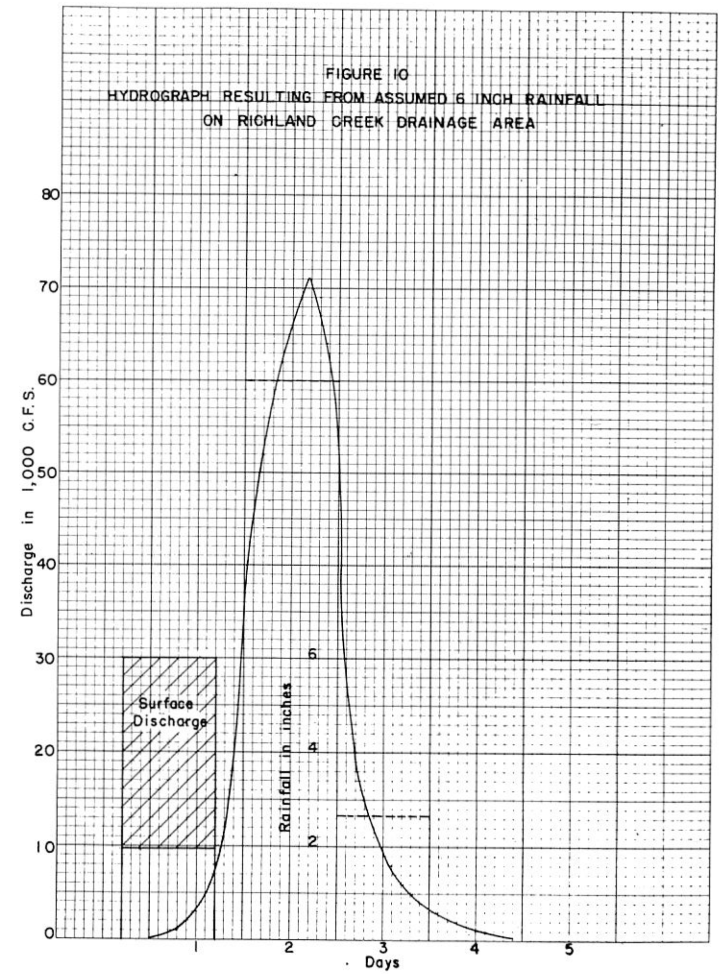
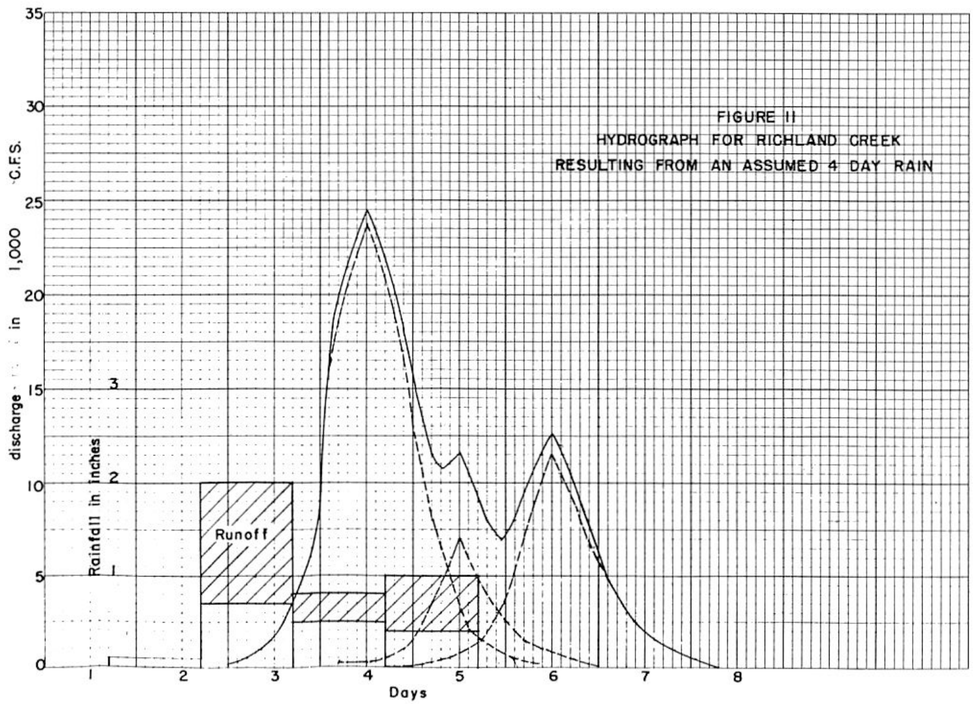


FIGURE 11
HYDROGRAPH FOR RICHLAND CREEK RESULTING FROM AN ASSUMED 4 DAY RAIN



3. Plotting the storm hydrograph.

On arithmetical cross section, or hydrograph paper, plot the storm hydrograph with flow in cubic feet per second as ordinates and days as abcissae. The first step is to decide what scale to use; next make a bar graph of the flow by drawing horizontal lines between the days representing the mean discharge for the day. The area under each bar then represents the total discharge for that day in second-feet days, and their sums would represent the total discharge during the storm. It can be readily seen that the rates during the day may vary appreciably from the mean daily discharge rate. The hydrograph of a stream shows instantaneous rates of flow; however, the area under the hydrograph represents the total flow and should equal the area under the bar graph. It follows that although the hydrograph will not necessarily cross the top of each bar graph at mid-day, the total area under each should be equal for any day. The process of drawing the hydrograph then becomes one of drawing a curve of best fit, representing instantaneous rates of flow such that the area under the curve represents total flow. The storm hydrograph obtained by the above method may not, in all cases, be identical with the actual hydrograph. Figure 2 is the hydrograph resulting from a rain storm occurring between late afternoon of February 17, 1946 and the same time February 18, 1946 on the Richland Creek watershed. This hydrograph was obtained by the method presented above. Figure 3 is the hydrograph of the same period obtained from the chart of the water level recorder.

When the above method is used in plotting the storm hydrograph the peak obtained may differ materially from the actual peak obtained from gaging records. This may be noted in Figures 2, 3, 4 and 5. Where the peak discharge for a given storm is not given in the water supply paper, it can usually be obtained by writing the U. S. Geological Survey. When the hydrograph must be plotted without information regarding the peak flow, the peak discharge for several storms, as given in the water supply paper, may be compared to their maximum mean daily discharges to obtain a ratio between the two, which then may be applied to the storm in question.

4. Constructing the unit hydrograph.

The first step in the construction of the unit hydrograph is to separate the normal or groundwater flow from the total flow. In cases where the flow was uniform prior to the storm this can be accomplished by drawing a line across the base of the graph representing this normal flow. All flow above this line could then be considered as flood flow. In cases where the flow was affected by an antecedent storm the storm and groundwater flow can be separated by reproducing across the hydrograph base the descending leg of the hydrograph from a point equal to the flow just prior to the storm in question.

The next step is the determination of the figures for a unit graph for this drainage area. It will have the same time base as the graph of the isolated storm in question. The ordinates will be in proportion to the ordinates of the storm hydrograph as 1.00 inch is to the depth of runoff from the area.

The storm runoff depth is found as follows:

The sum of the average runoff in Column 4 of Table II for period March 7-10, 1947, is 15,230 second-feet days. This total volume of run-off equals 567 inch miles.

$$\frac{15,230 \text{ sec. ft days} \times 3600 \text{ sec/day} \times 24 \text{ hrs/day} \times 12 \text{ in./ft}}{43560 \text{ sq. ft./acre} \times 640 \text{ acres sq. mi.}} = 567 \text{ in. miles}$$

The total volume of rainfall for this period was 1.55 in. X 760 sq. mi. = 1178 in. miles. The percentage of runoff = $\frac{567 \times 100}{1178}$ = 48.13 percent. The depth of runoff = 1.55 in. X 48.13 = .75 in. Column 5 in Table II is obtained by dividing the values in Column 4 by 0.75. These values are the ordinates for the unit graph. The total of Column 5 expressed as inch miles should equal the drainage area.

It is possible to construct a unit hydrograph from a storm hydrograph without going through the procedure of weighting the rainfall over the water-shed. In this procedure the depth of runoff over the area is determined from the volume of storm runoff. If the net runoff of 15,230 second feet days, as shown in column 4 of Table II, be converted to depth of runoff over the 760 square miles of the Richland Creek drainage area, it will be found to equal .75 inch which checks with the depth obtained by the other procedure. The longer procedure of studying the rainfall prior to drawing the unit graph will allow a more intelligent selection of uniform storms from which to construct the unit graph.

Figure 6 is the unit hydrograph for Richland Creek constructed from the storm hydrograph of March 6-10, 1947, as shown in Figure 5. As mentioned previously this storm hydrograph was plotted from readings taken off the water level recorder chart. Figure 8 is the unit hydrograph for this same watershed constructed from the storm hydrograph of May 11-15, 1948. This storm hydrograph was plotted from information as contained in the U. S. Geological Survey Water Supply Papers; that is, the average daily flows, and the peak discharge. The receding leg of this hydrograph was apparently affected by the rainfall on May 13. The runoff for this rainfall was separated by plotting the normal recession curve for this watershed as obtained from other hydrographs.

TABLE II

COMPUTATION OF UNIT GRAPHS FOR RICHLAND CREEK

Date	Observed runoff sec. ft.	Deduction of base flow sec. ft.	Net runoff sec. ft.	Unit graph sec. ft.
March - 1947				
6	48	48	---	---
7	1600	50	1550	2067
8	11200	100	11100	14800
9	2630	150	2480	3307
10	300	200	100	133
11	176	176	---	---
Total sec. ft. days			15230	20307
Total in. miles			567	

Total rainfall 1.44 X 760 = 1094 in. miles

$\frac{567}{1094}$ = 51.83 percent runoff

Depth of runoff - 1.44 X 51.83 = .75 in.

Date	Observed runoff sec. ft.	Deduction of base flow sec. ft.	Net runoff sec. ft.	Unit graph sec. ft.
May - 1948				
10	24	25	---	---
11	7890	50	7840	2676
12	42800	100	42700	14573
13	9000	150	8850	3020
14	600	200	400	137
15	200	200	---	---
16	187	187	---	---
Total sec. ft. days			59790	20406
Total in. miles			2224	

Total rainfall 4.31 X 760 = 3276

$\frac{2224}{3276}$ = 67.89 percent runoff

Depth of runoff = 4.31 X 67.89 = 2.93

It is to be noted that the two unit graphs thus compare very closely as to ordinate and base, but there is a small difference in their peaks.

If a number of suitable storm records can be found for the watershed in question, a unit hydrograph can be prepared from each set of records and then the peaks of the unit graphs averaged to give the peak of the average unit graph. In this regard Linsley, Kohler, and Paulhus[3] state, "The correct average unit graph should be obtained by locating the average peak height and time and sketching a mean graph having an area equal to 1 inch of runoff and resembling the individual graphs as much as possible. It will be noted that the peaks of the various unit graphs will not coincide nor will the bases be exactly identical." These discrepancies are due in the main to the inadequacy of the records, which have been mentioned previously. Rainfall distribution over the watershed will also affect the detailed shape of the hydrograph.

SYNTHETIC UNIT HYDROGRAPHS

Synthetic unit hydrographs, or hydrographs produced from rainfall and watershed characteristics rather than from actual stream gaging records, have two important uses. First, they may be used to check actual unit hydrographs. Second, and most important, the synthetic methods may be applied to the construction of unit graphs for areas where no gaging records are available.

In synthetic studies, the basic element is the time interval between rainfall and runoff. Snyder[7] has applied the term "lag" to this time interval and has defined it as the time between center of mass of rainfall excess and the resulting peak discharge at the location being studied. In certain other studies, such as that by Horner and Flynt[2], there has been used the time interval from the center of mass of rainfall excess to center of mass of runoff. This has also been called the "lag." For this discussion the definition as used by Snyder will be accepted. The lag for any area may be determined from a study of rainfall and stream gaging records if such are available; however, in the procedure to be presented herein it will be assumed that such records are not available and that the synthetic graph must be derived using only the information that is to be found on a topographic map.

The following symbols as used by Snyder[5] will be used in this presentation:

t_p = "Lag" in hours

t_r = Unit of duration of surface-runoff producing rain in hours.

t_R = Length of surface runoff producing rain in hours.

T = Time base of unit graph in days.

L = Length of area in miles, measured along the stream.

L_{ca} = Distance from station on the stream to center of area in miles.

A_p = Effective area contributing to the peak-flow in square miles.

q_p = Peak-rate of discharge of unit graph in cubic feet per second.

A = Drainage area in square miles.

C_t and C_p = Coefficients depending on units and drainage basin characteristics.

Procedure

1. Determine the center of area of the drainage basin. (A simple method is to trace the basin outline on stiff paper. Cut it out and suspend it by means of a string fastened to a pin through a point near the edge and extend the vertical

line through the area. A line formed by suspending from a second point gives an intersection, and a third suspension serves as a check.)

2. Determine the distance along the stream to the center of area. If the center of areas is not on the main channel then to a point opposite the center of area.

3. Determine the length of the stream from the station to its upper end.

4. Determine the lag, by means of formula $t_p = C_t\ (LcaL)^{0.3}$, as proposed by Snyder[5].

5. By formula $q_p = C_p\ 640/t_p$ determine peak flow per square mile of watershed.

6. Duration of surface runoff is next obtained from the following formula:

$$T = 3 + 3\ (t_p/24)$$

7. A graph is constructed showing the relation of basin-lag and the daily values of the distribution graph in percent.

8. From the information available a distribution graph and unit hydrograph are produced.

Example:

The procedure used in developing a synthetic unit graph for Jim Ned Creek above Colorado Camp dam site in Texas will be given.

From a map of the area the following information was obtained:

$L = 52$ miles
$L_{ca} = 24$ miles

The time lag for the watershed, $t_p = C_t\ (LcaL)^{0.3}$ can now be determined provided a value for C_t can be arrived at. Snyder states, "From a study of rainfall and gaging records of similar area this value can be determined." For the Jim Ned Creek the Corps of Engineers[1] arrived at a value of 1.0 for this coefficient. Using this value,

$$t_p = (1152 \times 24)^{0.3}$$

$$t_p = 8.5 \text{ hours (use 9.)}$$

The peak discharge of the unit graph in c.f.s. per square mile is,

$$q_p = C_p \; 640/t_p$$

For Snyder's studies C_p ranged from 0.56 to 0.69. From the Corps of Engineers' studies on Jim Ned Creek it appears that a value of 0.60 should be used for C_p.

Then,

$$q_p = \frac{.6\,(640)}{9}$$

$$q_p = 42.67 \text{ c.f.s. per square mile}$$

The contributing area in this case is 593 sq. miles; therefore,

$$Q_p = 42.67 \times 593 = 25{,}303 \text{ c.f.s.}$$

The duration of surface runoff according to Snyder's formula is,

$$T = 3 + 3(9/24) = 4.125 \text{ days}$$

(This value does not check with a unit hydrograph obtained from actual gaging records on Pecan Bayou, of which Jim Ned Creek is a tributary. The Pecan Bayou unit graph has a base of 48 hours.)

The time from the beginning of surface runoff to the peak of the unit graph is equal to $t_p + t_r/2$, and for a 3 hour rain on Jim Ned Creek should be 10.5 hours.

There is now available the peak discharge in c. f. s. for the unit graph, the time from the beginning of surface runoff to the peak in hours, the time for the base of the hydrograph and the total volume. (1 in runoff from 593 sq. mi.) From this information the unit hydrograph curve can be drawn. For further refinements in this procedure the reader is referred to Mr. Snyder's[7] article.

Accuracy of the Method

Mitchell[4] computed 58 synthetic unit hydrographs for Illinois streams and checked them against unit graphs computed from actual stream measurements. He found a probable error of 39.0 percent in magnitude of crest and 37.5 percent in timing.

The accuracy of the synthetic unit hydrograph is dependent to a large degree on the selection of proper coefficients. These coefficients are arrived at from consideration of measurements on other watersheds and are in the main dependent on the judgement and personal opinion of the individual doing the selecting.

The results obtained by Mitchell are none too good and in the hands of an inexperienced person the accuracy to be expected would be considerably lessened.

THE USE OF THE UNIT HYDROGRAPH

Constructing a Storm Hydrograph from the Unit Hydrograph

A hydrograph is developed from a unit graph through the following procedure:

(a) Daily rainfall properly weighted is listed by date.

(b) A coefficient is applied, reducing rainfall to runoff in inches of depth.

(c) The unit graph value for each day, multiplied by the runoff depth, gives the increment of stream flow attributable on that day to the daily rainfall so affected.

(d) The horizontal summation of the runoff increments, day by day, produces the total flow and becomes the ordinates of the graph.

This process may be used to:

(1) Develop hydrographs for areas where no records are available. These areas should be similar in drainage characteristics and size to the area from which the unit graph was developed.

(2) To develop hydrographs during periods where no records, or incomplete records are available for the watershed in question.

(3) To develop hydrographs for assumed or predicted rain storms over the subject watershed or similar watershed.

(4) To build a composite unit graph for large areas.

As mentioned above, one of the factors to be considered in developing a hydrograph from the unit graph is the percentage of runoff to be expected from the weighted rainfall over the watershed.

Sherman[5] points out that if our consideration be confined to surface runoff as compared with groundwater subflow seepage, or base flow, we find that the percentage of runoff increases with the rate and duration of precipitation. The percentage is also increased by the occurrence of previous precipitations. It varies with the season according to the temperatures and amount of vegetation, the topography, soil and conditions causing pocket storage and pondage.

Percentages of runoff for different watersheds, or the same watershed, under varying conditions, may vary greatly. However, if observations are confined to a sizable area and if they are segregated according to seasons, then the data will be quite consistent according to Sherman.[5] If, in addition, the effect of prior precipitation is considered, then the percentage of runoff will be in harmonious accord. From computations made of percent runoff of several storms of varying intensity occurring under similar conditions, a set of curves showing the percent runoff to be expected from storms of varying intensity occurring at different seasons of the year may be drawn. A set of such curves for Richland Creek is shown in Figure 9.

A procedure for estimating the volume of infiltration and surface runoff has been proposed by Sherman and Mayer[6], and has been used by Mitchell[4], and others in preference to the percent runoff concept. The procedure as proposed requires hourly precipitation and runoff records, which are not always available.

The infiltration approach has not been universally accepted by hydrologists. In this regard Linsley, Kohler and Paulhus[3] state as follows: "Basically the infiltration approach is exceedingly simple, and it is considered by many to be the rational approach. In practical application to natural drainage basins of sizable proportions, however, so many complications arise that the procedure is of little value." These authors further state, "The infiltration concept can be applied to the rational computation of surface runoff only when the following factors are essentially uniform throughout the area under consideration: (1) amount, intensity, and duration of rainfall; (2) infiltration characteristics; (3) surface storage characteristics. These drastic limitations naturally preclude direct application of the infiltration approach to any area other than a small plot or experimental basin."

It is not the intent in this paper to attempt to discredit either method but rather to point out that a universally acceptable method for determining abstractions from precipitation has not been presented at this time.

As an example of the use of the percent runoff curves and the unit hydrograph in constructing a storm hydrograph, assume a 6 inch rain to fall in 24 hours on the Richland Creek watershed during January. From Figure 9 it is found that approximately 68 percent, or 4.08 inches, of this rainfall would run off. The ordinates of the storm hydrograph are obtained by multiplying the ordinates of the unit graph by 4.08 and drawing the curve as previously explained. Table III gives these values and the hypothetical graph is shown in Fugure 10.

As another example in the use of the unit hydrograph in constructing a storm hydrograph, assume a four day rainstorm on the Richland Creek watershed, the weighted values for each day's rainfall being given in Figure II. For purpose of this illustration assume no runoff occurred from the first day's rain; 1.30 inch from the second, .3 inches from the third and .6 inch from the final day's rain. The storm graphs for each day's rain as obtained from the unit graph are shown in dotted lines in Figure II. The hydrograph for the entire storm is shown by the solid line. Ordinates for this hydrograph were obtained by adding the ordinates of the individual storm hydrographs.

As mentioned previously in this discussion, one of the major difficulties encountered in this procedure is the determination of abstractions from rainfall. Once a value for infiltration into the soil, or percent runoff, is arrived at, the construction of the hydrograph is relatively simple.

TABLE III

HYPOTHETICAL HYDROGRAPH FROM
AN ASSUMED RAINSTORM ON RICHLAND CREEK WATERSHED

Days	Unit graph sec. ft.	Net Hypothetical graph sec. ft.	Assumed base flow sec. ft.	Total flow sec. ft.
1	2067	8433	50	8483
2	14800	60384	100	60484
3	3307	13493	150	13643
4	133	543	200	743

Total rainfall.................... 6.00 inches
Runoff......................... 68.00 percent
Inches of runoff.................. 4.08 inches

COMPOSITE UNIT GRAPHS

Linsley, Kohler and Paulhus[3] have the following to say regarding the development and use of the composite unit graph:

"The problem of outflow from areas larger than can readily be handled by the ordinary unit graph may frequently be treated by use of a composite unit hydrograph. The composite unit graph is a tabular presentation of unit graphs for the important subdivisions of a larger area, with the time of beginning of rise appropriately lagged by the time of travel from the outlets of the subareas to the major gaging station. The runoff is computed independently for each subacre and multiplied by unit graph ordinates for that area. The sum of all flows thus computed in a vertical column, gives the flow to be expected at the outlet of the basin.

"The composite unit graph is obviously a simple application of the unit hydrograph principle combined with lagging of hydrographs in lieu of routing. It does not account for variations in travel time, which may be anticipated with widely varying patterns of runoff distribution. Hence, it must be expected to yield only a first approximation to outflow from areas far greater than those ordinarily treated by the unit graph method. Its simplicity makes it a useful tool for quick solutions such as may be required for preliminary design surveys or river forecasting."

SUMMARY

Construction of the Unit Hydrograph

The procedure for building a stream hydrograph may be summarized as follows:

(1) From a study of rainfall and stream gaging records select the storms to be used.

(2) Determine the average depth of precipitation over the area for the storms selected.

(3) Plot the storm hydrograph.

(4) Separate the normal flow from the flood flow.

(5) Determine the ordinates for the unit graph.

(6) In case more than one storm was selected, average the values for the peaks of the unit graphs obtained from each storm to obtain a more accurate unit graph peak for the area.

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