WEATHER BUREAU
Office of Hydrology
Washington, D.C.

October 1967

Elements of River Forecasting

Technical Memorandum WBTM HYDRO-4

U.S. DEPARTMENT OF COMMERCE / ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

U.S. DEPARTMENT OF COMMERCE
ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
WEATHER BUREAU

Weather Bureau Technical Memorandum WBTM HYDRO-4

ELEMENTS OF RIVER FORECASTING

Marshall M. Richards
Joseph A. Strahl

OFFICE OF HYDROLOGY

WASHINGTON, D.C.
October 1967

ELEMENTS OF RIVER FORECASTING

Page
No.

TABLES

Page No.

FIGURES

ELEMENTS OF RIVER FORECASTING

INTRODUCTION

The flow of a river is quite irregular when considered over long time periods. It is characterized by rises from rainfall and snowmelt followed by gradually receding flow when neither of these two contributing factors are present. The most elementary river forecasts are concerned with predicting the time and height of stages caused by peak flows. Other forecasts are made for the increasing flows before peaks and for the following recessions. Water supply forecasts attempt to predict the total flow for one year as early as possible during that year. During recent years, the trend has been toward more and more detailed forecasts with continuous flow forecasting required by more and more users.

This paper is chiefly concerned with forecasting storm hydrographs with emphasis on the crests. There are three major steps to forecasting the rise that results from a rainstorm or period of heavy snowmelt:

1. Making an accurate estimate of the volume of water that will run directly off the land surface into the stream. This step utilizes the rainfall runoff relation or snowmelt forecast.

2. Forecasting the distribution of this volume of water with time as it passes a forecast point. This is known as forecasting the hydrograph and the unitgraph is the tool most commonly used for this purpose.

3. Forecasting the change in shape of the hydrograph as the volume of water moves to points farther downstream. This is known as flow routing.

We have intended to provide a simple treatment of these subjects so that the paper can be used as an introductory course for new students in the field of hydrology.

1. Value of Forecasting Storm Runoff

The development of reliable procedures for the estimation of runoff that will result from storm rainfall has made possible an adequate system of river forecasting. Runoff is defined as the water that actually enters the stream channels draining a particular area and is thus carried out of the area.

Extension of Warning Times

Before adequate procedures were developed for estimating runoff from storm rainfall, the river forecaster was forced to wait until the end of the storm and could not issue specific forecasts until some of the upstream points in the river system had crested. Runoff estimates now make it possible to prepare flood warnings as the storm progresses, with the results that forecasts are much more timely.

In small headwater areas subject to flash floods, the crest of a flood may occur less than an hour after the end of flood-producing rains. In such a situation, warnings are possible only when based directly on rainfall and estimates of resultant runoff. Very often in such situations, procedures are required which short-cut the normal time-consuming steps in the forecast procedures and produce warnings in a minimum of time. Radar offers possibilities in this case, calling attention to areas currently receiving heavy rain and aiding in its evaluation.

For larger drainage areas, the time required to prepare forecasts is not generally as critical as for small headwater areas. This is particularly true for general rains of relatively uniform distribution in time and area. In this situation, however, much of the value of river forecasts lies in their making possible the evacuation of property before the flood strikes, and earlier warnings may have great monetary value.

There are cases when local inflow is an important factor. Even at points well downstream on a major river system, there are often situations where floods may occur within a few hours after the end of heavy rains. When the river stage has become high and nearly stationary, it is possible that a heavy rain in the portion of the drainage area immediately above a forecast point will cause a rapid rise to critical stages. In this situation the ability to estimate runoff is required to provide the needed forecasts.

More Efficient Operation of Water-Control Structures

Up to this point, the discussion has been limited to river forecasting on uncontrolled streams, where the purpose is to issue warnings to affected interests in the flood plain. River forecasts are of equal importance for the efficient operation of any sort of water control structure or water management program.

A few water control structures are self-regulating, that is, they have fixed openings and require no manual operations. For such structures, river forecasts have the same significance as in uncontrolled streams, serving as warnings to those affected. Most water-control structures, however, require varying degrees of manual control. Most levee systems have many openings which must be closed as rivers rise. If these closures are not made in time, the levee will not serve its intended purpose. Timely river forecasts are needed to give as much time as possible for making these closures. This is particularly true in cases where floods occur only rarely and crews making the closures are inexperienced. Conversely, river forecasts may indicate the river will stop rising before reaching stages requiring closures and much work can be avoided.

Efficient operation of a dam with movable gates is highly dependent upon accurate forecasts of inflow into the reservoir behind the dam. It is also necessary to have forecasts of river conditions downstream in order to minimize the effect of releases from the dam on critical points. This is particularly true for multi-purpose dams which are intended for many uses such as flood-control, generation of power, irrigation, navigation, and pollution abatement. Flood-control is most effective when the reservoir is kept nearly empty while most other uses are best served by holding as much water as possible behind the dam. Such conflicting interests create operational problems which can be handled effectively only with the forecast information required.

2. The Runoff Cycle

In order to understand the problems involved in the development of runoff relations it is first desirable to examine the runoff cycle--that part of the hydrologic cycle from the incidence of precipitation upon the land area to its subsequent discharge through stream channels or its direct return to the atmosphere through the process of evaporation or transpiration.

Discussion of Specific Processes Involved

Interception--When rain begins after a period of dry weather, much of the initial fall is stored temporarily on the vegetal cover as interception. Interception storage capacity is normally satisfied early in any storm. After that, interception practically ceases except for storage capacity that is recovered through evaporation from the wetted surfaces of the foliage. Interception is probably a significant percentage of the annual rainfall in most areas since it involves a large percentage of rain from a number of small storms. For large storms where runoff forecasts are most important, however, interception is relatively unimportant. Estimates of its value in well-developed forested areas are about 0.10 inch per storm. Its effect varies with basin cover and season in areas outside the tropics.

Depression storage--Also involved from the beginning of rain is depression storage. This is water temporarily stored in surface depressions which vary widely in area and depth. Whenever rainfall intensity exceeds the infiltration capacity these depressions begin to fill. As the depressions are filled, inflow into them must be balanced by outflow, infiltration, and evaporation. Small depressions fill rapidly after which overland flow begins, some of which ends up in larger depressions while some reaches stream channels. This process continues, with larger and larger depressions filling as the storm continues, resulting in more and more overflow reaching the streams. Between storms, water held in depressions is either absorbed by the soil through infiltration or evaporated into the atmosphere. Measurement of depression storage is almost impossible. Depressions of appreciable area, relative to the size of the drainage basin, should be excluded from the storm analysis. Common practice is for depression storage to be included with interception and treated as an initial loss with respect to storm runoff. Depression storage is a basin characteristic, subject to change with terracing, leveling or other contouring. In most basins it probably continues to be a small factor all through the storm period.

Infiltration, percolation, and soil-moisture storage--Infiltration is the passage of water through the soil surface into the soil and percolation is the movement of water within the soil. These two phenomena should be considered together since infiltration cannot continue to take place unless percolation has allowed water that infiltrated earlier to move out of the surface layer of the soil.

Once water has entered the ground, gravity tends to pull it downward, following paths of least resistance, toward the groundwater table. Capillary forces work against this, however, tending to divert this water into storage in capillary pore spaces. When the soil is dry, this diversion by capillary action is quite large. There is, of course, a limit to the capillary pore space in the soil and it is a function of soil types and conditions. This limit, the water the soil will retain against the force of gravity, is usually referred to as the field capacity during a storm, the capillary forces tending to divert water from its path of least resistance become progressively smaller. The rate at which water passing through the soil surface can be disposed of decreases and the end result is that the rate of infiltration decreases as a storm progresses. This also explains the reduced rates of infiltration in storms when all or part of the capillary pores have been filled during previous storms.

Infiltration rates tend to be highest for loose sandy soils and lowest for tight, clay soils. However, the sandy soils have much less field capacity than the clay soils. Quite obviously the soil types predominant in an area will have a great effect on runoff as will the initial moisture content of the soil.

The effect of various ground covers on infiltration and percolation is difficult to determine with any accuracy. Evaluation is complicated by the fact that ground cover affects interception as well as infiltration and runoff in several ways. The root system of vegetation makes soils more pervious, that is, the water can enter and flow through the soil more easily. Foliage shields the surface from the direct impact of raindrops and this reduces packing of the soil surface, which is an important factor, particularly in high intensity rainfall. Ground cover also retards water flow across the soil surface and thus gives the water more time to infiltrate the soil.

Relative Time Variations of Elements Throughout the Runoff Cycle

The phenomena discussed above, plus many others, are involved in the runoff cycle. A description of the relative time variations of pertinent runoff factors during a large storm of uniform intensity which falls on an initially rather dry basin is necessary.

At the onset of precipitation the only portion which will run off is that which falls directly into the river. This is a function of the area of the water surface of the stream and is usually a fairly small percentage of the total area. Though small, it is an element that continues throughout the storm, increasing as the river rises and spreads out.

Interception is another element that comes into play early in the storm. Its value is at its highest at the beginning, particularly during summer with dense ground cover. Its total effect is quite small in large storms and is of little consequence. Intercepted precipitation is usually returned to the atmosphere by evaporation.

Loss to depression storage begins early in the storm and decreases in effect as the storm progresses and small depressions are filled. It usually continues to have some effect throughout the storm, but this can vary greatly with slope and other factors. While usually treated as a loss, some of the water eventually infiltrates into the soil and may run off. The rest is returned to the atmosphere through evaporation.

As a general rule, the largest part of the precipitation that does not end up as runoff is taken to satisfy the soil-moisture deficiency. Its effect is greatest at the beginning of the storm. In general this deficiency must be nearly satisfied before appreciable surface runoff occurs, but it does continue to have considerable effect throughout the storm due to the relatively slow downward movement of water through soil profile. In the case of very intense storms, soil-moisture deficiency becomes less important, since the infiltration rate is usually the limiting factor in this situation.

Water which infiltrates the soil surface, but which is not retained as soil-moisture, must either move laterally and enter the stream as interflow or move down to the groundwater table. If the water table is deep enough, groundwater flow from it may not contribute to streamflow until well after the time under study, if ever. There is a great deal of disagreement as to the relative importance of interflow, and it is difficult to determine what percent of runoff it represents.

Surface runoff starts very slowly, gradually increases, and late in a long storm it becomes nearly a constant percentage of the rate of precipitation. As indicated above, its value relative to interflow is open to question. For most forecasting procedures it is not too important to determine the boundaries between interflow and surface flow on the one hand and base flow on the other. In this paper, hydrographs will be divided into 2 components; base flow and direct runoff or surface flow.

3. Possible Methods of Correlating Storm Runoff to Rainfall

Due to the many physical processes which affect runoff, as discussed in Section 2, and the complexities of even a small natural basin, any sort of a direct physical or analytic approach to the problem of forecasting runoff is not practical. Even if a modern computer could handle the problem it would probably be physically impossible - and certainly economically impractical - to make the measurements required. As a result, the usual solution is to analyze storms covering a wide range of conditions for drainage area above a point for which forecasts are desired. Rainfall and runoff for these storms are evaluated and procedures developed to correlate them.

The complexity of the correlation of runoff to rainfall makes the use of a graphical approach to the problem desirable. Each element of data retains its identity throughout the analysis. This allows the analyst to use the data not only to evaluate coefficients, and exponents, but also to help derive the structure of the graphical model which is made analogous to the processes which occur in nature.

Graphical Solutions

a. Direct correlation of runoff to rainfall - Plotting storm rainfall against resultant runoff cannot be expected to yield a usable product, but does indicate the nature of the problem. (Fig. 1)

b. Addition of a third variable - The amount of runoff resulting from a given rainfall in a given basin depends upon many things - such as vegetal cover, soil characteristics, initial moisture deficiencies, and storm characteristics such as areal distribution and intensity of the storm.

Vegetal cover and soil characteristics are to some extent automatically incorporated into the basic data for the basin. Storm characteristics can be reasonably well determined with an adequate network of precipitation stations. The real problem is some adequate and practical means of evaluating moisture deficiency in the study basin as it exists at the beginning of a storm event and the incorporation of it into the forecasting procedure. It is possible to make reasonably reliable evaluations of soil-moisture at certain points in the basin, but the necessary integration over a sizeable area introduces tremendous problems due to the infinite number and variety of soil profiles and surface conditions encountered in even a small drainage area. In addition, any quantitative method would necessarily have to consider the depression and interception storage above the surface of the soil.

A more practical solution to this problem is the use of some other measurable factor as an index to the initial soil moisture conditions.

Since the direct correlation of runoff to rainfall is quite poor, forecasters began to look for some variable - or variables - to improve it. An early approach was the use of a qualitative evaluation of soil conditions by the forecaster as shown in Fig. 2. This places a premium on the judgement of the forecaster and makes it difficult to evaluate past data.

One of the first measurable variables introduced in the correlation of runoff to rainfall was the number of days since the last significant rain. Each storm would be plotted as in Fig. 1 and labelled with this variable. This improved the correlation, but had many obvious deficiencies. No allowance was made for season of the year, duration of the storm, conditions before the last rain, and of course, the problem of how large the "last significant rain" had to be.

c. Use of multi-variable coaxial relation - The relatively crude attempts mentioned above led gradually to more sophisticated means for correlating runoff to rainfall. One of the important steps was the type shown in Fig. 7. This made practical the introduction of additional variables which were needed to adequately handle the problem.

The selection of parameters for use in a multi-variable graphical technique is of the greatest importance. Rainfall would certainly be the first and the problem here is in its evaluation which is discussed in some detail in Section 4.

Runoff is the factor required in making river forecasts and its evaluation is also discussed in Section 4. Actually the correlation described here is very often made, at least in its original form, in terms of basin recharge instead of runoff. Basin recharge is defined as that portion of the storm rainfall that is required to satisfy the demands of interception, depression storage, and soil-moisture. It is the difference between rainfall and runoff and is often referred to as "loss." Actually it is that part of the storm rainfall that replenished the moisture supply in the basin, hence: recharge. Advantages of its use in the development process are discussed in Section 5.

The selection of a parameter, or parameters, to adequately represent the effect of soil-moisture deficiency on the runoff process is the most difficult problem.

The index to soil moisture deficiency currently used in practically all forecasting operations of the United States Weather Bureau is an antecedent precipitation index which can be expressed by the equation

$$I = b_1P_1 + b_2P_2 + b_3P_3 \dots + b_iP_i \qquad (1)$$

where b_i is a constant and P_i is the basin precipitation which occurred i days before the storm under consideration. Such an equation is inconvenient for day-to-day use in river forecasting. A more stable form of this equation results if it is assumed that b decreases with time before the storm being considered according to a logarithmic recession. During times of no precipitation:

$$I_t = I_o k^t \qquad (2)$$

Where I_o is the initial value of the antecedent precipitation index (API), I_t is the reduced value t days later, and k is a recession factor. Letting t equal unity.

$$I_1 = kI_o \qquad (3)$$

The API for any day is equal to that of the day before multiplied by a factor of k. When rain occurs on any day, the amount is added to the index as illustrated in Fig. 5. The value of k should be a function of physiographic, climatic, and vegetative characteristics of the basin and the actual evapotranspiration. Normally, k is assumed to be a constant somewhere between 0.85 and 0.95, with 0.90 the most commonly used value.

When k=0.90 is used, the computation of the API value today is simply a matter of subtracting 10% from the API value for yesterday (on days when there is no rain).

The antecedent precipitation index described above gives some weight to precipitation falling over a period of about one month, with recent values having much effect and earlier rains less. It is a value that can easily be calculated and is independent of any judgement factor on the part of the forecaster.

The recession coefficient (k) used in computing the antecedent precipitation index essentially represents the process of drying out the basin. The drying rate will vary with season and an additional factor to account for this and other seasonal variations is needed. This is done by introducing the time of the year of the storm as a variable. This assumes that climatic factors affecting runoff conditions will vary the same way every year. This is not always the case and many ways of adjusting this variable have been suggested. Some of these are discussed in Section 6.

This gives us rainfall, antecedent precipitation index and time of year to use in a correlation with runoff (or recharge). None of these variables makes any allowance for the intensity of the storm. Some account can be made for this by adding the duration of the storm as a variable in the correlation. Evaluation of duration is sometimes a problem and means of computing it will be discussed in Section 4(d).

4. Collection of Basic Data for Development of Runoff Relation

The last section was merely a general discussion of factors to be considered and possible methods of approaching the rainfall runoff problem. Section 5 discusses graphical correlation procedure in more specific terms. Before the correlation can be accomplished, the collection of basic data must be considered. The initial phase of developing a forecast procedure for a basin involves selecting the specific past storms for the study and the evaluation of rainfall, runoff, antecedent conditions and duration for each of the storms selected. If this information is not available for the basin requiring a forecast procedure, it may be necessary to synthesize a procedure from those procedures used in nearby similar basins.

Requirements for the Basin to be Studied

In small basins, concentration times are normally shorter and the problem of relating streamflow to the storm which caused it is considerably simpler than for larger basins. In a large basin, direct runoff from one storm may still be appreciable at the time a subsequent storm occurs, making it difficult to assign runoff to the rainfall that caused it. In addition, a small basin should have less areal variations in rainfall, making estimates of basin precipitation simpler. Small basins, however, may reflect changes in land use which would not show up as much in larger areas. There is also the problem of abtaining adequate streamflow measurements on small basins where peak flows occur so soon after storms are over that it is difficult for stream gagers to make the necessary measurements of flow. No specific rules can be set down on the proper size for a basin to use in a runoff study, but in general basins having drainage areas of from 100 to 2,000 or more square miles can be developed if data limitations vs. forecast requirements make it desirable. When sufficient data is available, it is the usual practice to develop rainfall runoff procedures to forecast headwater points and then to use the routing techniques described in Section 8 to make forecasts for points further downstream.

It is desirable to have at least ten years of streamflow and precipitation records for the basin to be studied and to have 50 to 100 storms covering a wide range of conditions available for study. This ideal is not always attained and it is necessary to work with whatever records are available.

Selection of Storms to be Studied

After preliminary evaluation of available data, the next step is to pick the individual storms to be studied. As wide a range of conditions as possible should be represented by the storms selected and it is necessary to use precipitation as well as streamflow records to select the storms to study. Storms with significant rainfall but little runoff should be considered as well as those which produce appreciable runoff in order to avoid a bias in the resultant procedures.

Storms with very uneven areal distribution of precipitation should not be used, since in these cases estimates of average precipitation may be meaningless. Complex hydrographs resulting from long, sporadic rainfall should also be avoided since it becomes impossible to determine accurately the runoff to be attributed to a given rainfall.

Evaluation of Variables Required

Once the past storms have been selected for study, it remains to evaluate each of the variables selected for use in the correlation of each of the storms. It is important that this step be taken with as much accuracy as possible, since errors in the basic data, particularly for the few-of-a-kind storms (such as very large ones) may cause considerable bias in the resultant relation. It is particularly important to use the same rules in evaluating variables in development as will be used later in applying the procedure to forecasting. This will tend to minimize any bias that might result from a specific analysis. It is also necessary to use the same rules throughout the analysis for similar reasons.

a. Average basin precipitation - The first problem is to determine the average basin storm precipitation.

A basic rule is to be careful to include only the rainfall which actually produced the runoff to which it is to be related. Small amounts of precipitation falling after the hydrograph has started to recede should not be included if they obviously had little or no effect on the storm runoff. In addition, small amounts of precipitation falling before the main storm should be excluded and these amounts included in antecedent precipitation computations. Long, complex storms should be sub-divided if possible. Average basin rainfall for a specific storm period can be estimated in several ways. The arithmetic mean of the amounts measured in the basin is the simplest method. This gives good results in reasonably flat country if rain gages are uniformly distributed and the individual gage catches do not vary too widely from the mean.

A more complex means of estimating mean basin precipitation is the Thiessen[1] network. This system provides for the weighting of the precipitation value for each gage in or near the basin. The stations for which rainfall reports are available are plotted on a map (see Fig. 3) and these form polygons around each station. The sides of these polygons are the boundaries of the effective area attributed to each station. The area of each polygon is evaluated and then expressed as a percentage of the total area. For a given storm event the weighted average basin precipitation is determined by multiplying each station precipitation by its assigned percentage of area and totalling. This system in general will produce more accurate results than a simple arithmetic mean, but it does have limitations. One disadvantage is that any change in the gage network requires a revision of the gage weights. If a gage value is missing only occasionally, it is the usual practice to estimate its value for use in the computation. This method assumes linear variation of precipitation between stations and assigns each polygon of area to the nearest station. It makes no allowance for orographic effects.

The isohyetal method is the most accurate means for estimating average precipitation when properly handled. Precipitation amounts at individual stations are plotted on a map of the basin (Fig. 3). The analyst then draws lines of equal precipitation called isohyets. The areas between successive isohyets are measured and expressed as a fractional part of the total basin area. This fraction is then multiplied by the average precipitation between these isohyets, usually used as the average of the two isohyetal values. The total of these products is the estimated average basin precipitation.

The accuracy of this method depends on the skill with which the isohyets are drawn. The use of linear interpolation between stations would result in approximately the same results as the use of the Thiessen network. The analyst should, however, make use of his knowledge of orographic effects in the basin and storm morphology. In basins with decided orographic effects average monthly or seasonal basin precipitation patterns can be used to assist in drawing isohyets. One particular advantage of the isohyetal map is that all available knowledge and reports can be utilized. It also gives a useful display which points out centers of concentration which may affect the forecast.

b. Runoff (hydrograph separation) - For facility in forecasting, runoff is usually assumed to fall into two classes - (1) direct runoff, and (2) base or groundwater flow. The division of a hydrograph which results from a specific storm into its groundwater and direct runoff components is referred to as hydrograph separation. There obviously is no way of distinguishing between groundwater and direct flow in a stream at any time and

---

[1] A. H. Thiessen: "Precipitation for Large Areas"; Monthly Weather Review; U. S. Weather Bureau; Vol. 39; pp. 1082-1084; July, 1911.

the definition of these two components is rather arbitrary. As a result the method of separation is not as important as consistency throughout the study and in the application of its results.

A simple method of separation is based on the assumption that baseflow will continue as a constant throughout the storm (line AD in Fig. 4). This has the disadvantage of producing an extremely long time base for the direct runoff hydrograph. The time base will usually vary from storm to storm depending on the flow at the time the storm begins. (A in Fig. 4).

A commonly used method of hydrograph separation which does provide a relatively constant time base for direct runoff is shown by lines AB and BC in Fig. 4. The curve AB is the extension of the recession occurring at the time the storm began to a point B below the crest of the hydrograph. The line BC is then drawn to a point on the receding limb of the hydrograph n days after the crest. This value of n should theoretically be measured from the end of runoff-producing rainfall, but use of the crest is simpler and usually produces entirely acceptable results. The value of n is assumed to be a constant for a given basin, and generally varies with the drainage area. A method of estimating n is described in the unitgraph discussion of Section 7. Other factors, such as basin topography, can affect the value of n, but often they are not particularly critical. It is usually entirely adequate to estimate n after inspection of several storm hydrographs, so that the total time base is not too long or the rise in groundwater flow too great. The reasoning is that, as the stream rises, there is flow from the stream into the banks and groundwater flow should recede until river stages begin to fall.

If the runoff relation to be derived from the data is to be used in conjunction with a unit hydrograph, the same time base should be used for both the separation and the unit hydrograph.

The area bounded by the storm hydrograph and the line of separation (ABC in Fig. 4), converted to inches depth over the basin, is considered to be the direct runoff for the storm. This direct runoff is the usual value forecast in a rainfall-runoff relation and used in river forecasting for short periods.

At times it may be important to use total runoff, both direct and groundwater, in the forecasting procedure. To evaluate total storm runoff it is necessary to compute the volume of flow for a period beginning and ending with identical discharges, provided baseflow was essentially all groundwater flow at both these points. The total flow from time E to time F in Fig. 4 would represent total runoff.

c. Antecedent precipitation index - As was indicated in Section 3, a convenient means of approximating soil-moisture is the use of an antecedent-precipitation index such as the equation

$$I_1 = kI_0 + P_{(0-1)} \qquad (4)$$

where I_1 is today's index and k is a constant which varies with the basin characteristics. Rain which occurs during the intervening 24 hours $P_{(0-1)}$ is added to the current index. The calculation of a 10 day period is shown in Fig. 5.

The value of k must be determined by trial and error. Since this involves considerable work, it is customary to assume k=0.90 as a first approximation. No second approximation is usually undertaken unless there is a clear indication that this results in giving antecedent precipitation improper weighting. The use of a k of 0.90 is obviously convenient since the equation can then be expressed as:

$$I_1 = I_0 - (0.1)\, I_0 + P_{(0-1)} \qquad (5)$$

and this is an extremely easy computation.

The value of the API is normally computed for the entire period of record that is to be analyzed. It is necessary, however, to start the index somewhere, and theoretically the value for any day depends on the precipitation for an indefinite period beforehand. Satisfactory results can be obtained by assuming an initial API value of 1.20 inches about two months before the first storm to be considered.

There remains the problem of whether this computation should be made for individual stations or for the average precipitation over a basin. This can be done either way, but it is very often done by individual stations in areas where the areal distribution of precipitation is quite variable. The problem of determining the mean value of the antecedent precipitation index can then be handled by the same procedure as was discussed for determining mean basin precipitation. This is not usually a critical computation and it is the usual practice to use a simple weighting procedure or to plot individual values on a map and make estimates by inspection of the values for desired areas.

Since this is a process of accumulation, it is necessary to compute this index only at stations with reasonably complete records. Missing precipitation data should always be estimated before carrying the computation forward.

d. Storm duration - Storm duration can be defined for short, uniform storms, but becomes quite complicated for long, drawn-out storms. One approach, when six-hourly precipitation amounts are available currently is to take the sum of all six-hourly periods with .20 inch or more precipitation plus half the sum of intervening periods with less than .20 inches. An example of this computation is shown in Table 1.

e. Season of year - A convenient means of defining season is the use of the week of the year in which the storm begins. This is facilitated by the use of Table 2. A storm beginning on May 9 would be in the 19th week of the year.

5. Coaxial Graphical Correlation Analysis[2]

In the previous discussion, reasons were advanced for the selection of five variables to be included in the correlation - basin recharge,

---

[2] Linsley, Kohler & Paulhus, "Hydrology for Engineers" or "Applied Hydrology" (Appendix A) McGraw Hill, 1958 and 1949, respectively.

antecedent precipitation index, season or week of year, storm duration, and storm rainfall. Several numerical methods of correlation analysis have been programmed for solution on computers. The speed with which computations can be done makes practical the investigation of more parameters and many combinations of parameters. Thus the best possible analysis of the available data can be determined and new conceptual approaches can be tried rapidly. It is advisable, however, for the student to start with graphical analysis in order to gain more complete understanding of each step in the problem. Too much of the inter-relation between parameters is masked by the computer so that real understanding is suppressed. Fig. 6 shows the graphical correlation of the five variables listed above. In chart A, API is correlated to basin recharge with week number as the intermediate variable. In chart B, computed values of basin recharge from chart A are correlated with storm duration to obtain a new computed value of basin recharge. This new value is further modified, in chart C, by correlation with storm precipitation to get the best computation of basin recharge that can be forecast with the five variables. Finally, in chart D, the computed values are plotted versus the observed values to show how well the total procedure works. If use of the five variables could make perfect forecasts all storms would plot on the straight line in chart D. Such perfect correlation is extremely rare, partly because of errors in the basic data measurements. The arrangement used in Fig. 6 is preferred because it avoids the possibility of forecasting either negative recharge or recharge in excess of rainfall. Also, in actual forecast use, chart A is needed only once at the beginning of each storm.

Derivation of Initial Curves

It is helpful to tabulate all the storms and their variables before starting the analysis. Basin recharge is found by subtracting the storm runoff from the storm rainfall. The computed API for the first day of each storm is used. Week number and duration values are found in the manner just explained in the latter part of Section 4. Duration is a single value for the total storm during this analysis phase. (During a forecast operation the duration is a changing value while the beginning API is used until the storm ends or amounts to less than .50 inch during a 24 hour period).

Graphical correlation can be started as soon as the tabulation is completed. The poor correlation between the parameters in charts A and B makes their construction difficult. The work is simplified by sketching these two charts from Fig. 6 and using them as a first estimate for the new basin being studied. Chart C is then prepared from the actual data in the following manner:

1. For each storm, use its API, week number and duration in charts A and B to arrive at a computed basin recharge value for use in chart C.
2. Plot a point in chart C at the point described by this computed value and the observed value of basin recharge tabulated for this same storm.
3. Label this point with the storm precipitation for this same storm.

4. Repeat 1, 2 and 3 for each storm.
5. Draw lines that best fit the plotted data.

Refinement by Successive Approximation

Charts A and B should now be revised to show the relationship between the variables tabulated for the basin being studied. Chart A is revised in the following manner:

1. Assume charts B and C are correct while revising chart A.
2. For each storm use tabulated values of basin recharge, storm precipitation and duration to enter charts C then B in reverse order. This will give an "observed" recharge value for chart A.
3. Plot a point in chart A at the location indicated by the tabulated API and the "observed" recharge value obtained in step 2.
4. Label the point with the tabulated week number.
5. Repeat 1 thru 4 for all storms.
6. Adjust the lines to fit the plotted data.

Chart B should have straight parallel lines tilted at 45 degrees. The spacing can be refined by entering the chart sequence from both ends with "observed" values. Plot and label points indicated by these values then draw new lines with spacing indicated by the data.

Chart C can now be refined by entering A and B in the normal manner, using the original tabulated data. This whole "cut and try" procedure can be re-iterated as often as is required to define an accurate relationship. Complete chart D after each refinement so that improvement can be measured. If a point is persistently anomalous on chart D the original computation of all five variables for the storm should be checked for errors. The latest curves should be traced on new graph paper when the work sheet becomes too messy. It is also a good idea to develop the relation on large sheets of graph paper and transpose the final product to notebook size for use in forecasting.

Examination of Fig. 6 will show that the errors of the points with little runoff (recharge approaching precipitation) are considerably magnified when routed back through the chart sequence as described for the development of the second-approximation curves. Therefore, if this approach is used, it will be found that the curves can be more readily determined if low-runoff points are omitted in the original plotting. As an alternate approach, the required revisions of the curves can be determined qualitatively by labeling the points of chart D with week number or duration to determine if there is any residual correlation.

In preparing river forecasts, runoff is the controlling factor rather than basin recharge. Since rainfall and recharge determine runoff, the curves of chart C in Fig. 6 can be converted to read runoff directly as shown in Fig. 7. The final verification of the relation (chart D of Fig. 6) should also be made in terms of runoff since this is the element to be forecast.

Problems in Application

The runoff relation described above is derived on the basis of data for entire storms. In use it is necessary to estimate runoff increments throughout the storm proper for application of the unit hydrograph, or any other approach to the distribution of runoff. Mechanically this is accomplished by computing runoff for the accumulated rainfall for time increments required by the unit hydrograph, and obtaining runoff increments by the subtraction of each successive total value. Since the relation was developed on data from complete storms, there is some question as to the validity of its use for forecasts of incremental runoff. With sufficient data, however, there should be storms whose totals approximate the subtotals from larger storms, and the relation works reasonably well for determining time distribution as well as total volume of runoff.

Earlier it was suggested that storms with uneven areal distribution of rainfall should not be used in developing the forecasting procedure. It can be demonstrated that a storm with uniform areal distribution of rainfall will produce less runoff than a storm having the same average precipitation but with extremely uneven distribution. One solution is to compute runoff for each station rather than for the basin average. Runoff can then be averaged for the basin using the same procedure as described for rainfall. The same solution is also suggested when antecedent conditions vary widely throughout the basin.

It would be desirable to have a runoff relation in which it made no difference whether runoff was computed for an entire storm or the storm was broken into several increments and the runoff computed independently for each increment. The runoff procedure described here will not do this, primarily because it includes an initial loss which cannot be entirely compensated for by revision of the antecedent precipitation index. As a result there are times during a long, drawn-out storm when the problem arises as to whether the storm should be broken after a short break in the rainfall and a new runoff computation started using new antecedent conditions. Whenever there is a significant break in rainfall, handling the storm as one continuous event will result in a forecast of too much runoff. If the break is of less than two days duration, treating it as two storms will probably produce forecasts of too little runoff. One solution is to compute runoff treating it as one storm and then as two separate storms. The results are then weighted according to the length of the break in rainfall, assuming that a two day break will give full effect to treating the event as two storms. In general, it is common practice to break the storm whenever a 24-hour break in rainfall occurs in order to keep the computations from becoming too unwieldy.

When no records are available, about the only way to obtain a relation is to apply a procedure developed for an area assumed to have similar hydrologic characteristics. If a limited amount of data is available it is also necessary to start with the procedure for a similar area, making only minor adjustments if they are required. Actually this procedure is usually followed even where adequate data are available since it is much simpler to modify an existing procedure that is reasonably appropriate than to develop an entirely new relation. When using a coaxial correlation, it may be practical to use the same rainfall quadrant (chart C in

Fig. 6) for several basins, letting the season curves account for the differences in hydrologic characteristics from one area to the other.

Possibilities for Refinement of the Coaxial Graphical Correction

The coaxial graphical correlation of rainfall to runoff using antecedent precipitation index, season and duration as variables has proven to be a very practical and reasonably accurate means of estimating runoff. It has certain deficiences, however, which should be recognized. Some of these deficiences will be discussed and possible improvements suggested.

a. Use of recharge in place of rainfall - The use of rainfall in computing an index to soil-moisture conditions, such as the antecedent precipitation index, has a recognizable flaw. That portion of the rainfall that runs off leaves the basin rather quickly and has nothing to do with the moisture conditions of the basin. It is actually the recharge, precipitation less runoff, that effects the basin and it should be used to evaluate soil-moisture conditions. This involves a great deal of additional work in the use of the procedure, since the evaluation of runoff cannot be made with any accuracy until most of the storm hydrograph is available. As a result, recharge is rarely used in place of precipitation for evaluating soil-moisture conditions. It is possible, however, where the best possible estimates of runoff are required.

b. Variation of recession coefficient or use of dual values - It is obvious that the rate of drying in a basin varies from one season to another. The use of a constant value of k in computing the antecedent precipitation index is therefore, not entirely realistic. It might be better to vary this coefficient with season, making the value of k smaller in hot weather than in cold to reflect the faster drying conditions. This would be of particular importance if recharge were used in place of precipitation in computing the index. This adds additional complications in the development of the procedure and is not generally considered practical.

Another possible solution would be the use of two values of k in separate API calculations. One value of k is made rather low, say k=0.75 to 0.85, to represent rather short-range antecedent conditions. The second value of k is made quite high, k=0.93 to 0.99, and reflects long-term variations in antecedent conditions. The use of the two-value API helps to correct this deficiency in the relation.

c. Refinement of definition of season - The use of season in the rainfall-runoff correlation assumes that seasonal variations are constant from one year to the next. This obviously is not entirely correct and many attempts have been made to modify the season variable on the basis of current and past weather conditions. Most of these modifications have been only moderately successful. One promising solution has been the use of daily potential evapotranspiration values to compute an antecedent evapotranspiration index. When a recession coefficient of 0.98 to 0.99 is used, this index has a seasonal variation and can be used to replace season as a variable.

6. Alternate Methods for Estimating Runoff

The graphical correlation described in Section 5 has proven an extremely useful and reliable forecast tool. There are, however, several other approaches with particular advantages for certain situations. A few of the more well-known methods are discussed here.

Use of Index Basins

Another system of predicting runoff is to take advantage of the short time of concentration in a small basin. The runoff from the small index basin is evaluated as soon as enough of the hydrograph is available. The data thus obtained can then be used to aid in forecasting for larger areas nearby which are slower in reaching their peaks. Often the crest stage of the index basin is correlated directly to basin runoff, thus enabling an estimate to be made as soon as the crest is observed at the index station. Since, in even a small basin, there is some lag between the end of heavy rain and the crest stage, this wastes valuable time that can be saved by estimating runoff directly from rainfall. In addition there is also the problem of extrapolation of results in the index basin to fit the conditions in the area for which forecasts are desired. Adjustments can be made for differences in antecedent conditions, as well as storm precipitation, but they are usually of a subjective nature.

This procedure is to be recommended, however, in conjunction with conventional rainfall-runoff relations. Forecasts of runoff for the index basin can be compared to observed runoff and this information used to modify the runoff estimates for surrounding areas when necessary.

Initial Baseflow as an Index to Rainfall-Runoff

In humid areas where streams do not often go dry, groundwater discharge at beginning of a storm is often used as an index to initial basin conditions. An example of such a relation is shown in Fig. 8. This discharge reflects conditions throughout the entire area. Recent rains, particularly several small ones can alter basin moisture deficiencies without appreciably affecting streamflow. This could be handled by adding a variable of weighted precipitation for the past several days.

In some areas it is found necessary to vary this relationship with season. A common method is to develop a relation for summer and another for winter. This leads to the inevitable problem of storm events that occur between seasons. The usual solution is to make an estimate of runoff using each curve and then interpolate between these results.

The use of initial groundwater discharge as an index to runoff conditions is usually limited to small basins with rapid times of concentration. In larger areas during a rainy season one rise on the hydrograph tends to build on the last, making any satisfactory determination of initial groundwater discharge quite difficult. The usual approach is to determine initial groundwater discharge values for small index basins and apply them to other nearby areas having similar hydrologic characteristics.

Infiltration Approach

Many hydrologists consider the application of the infiltration theory to be the rational approach to the problem of estimating storm runoff. It is a rather direct approach and for studies of small, homogeous areas the method can often be used to advantage.

The infiltration capacity, f_p, was defined by Horton[3] as the maximum rate at which a given soil in a given condition can absorb rain as it falls. The value of f_p, starting at a maximum of f_o, is found to decrease rapidly at first and then approach some minimum f_c. The value of f_c would depend upon the permeability of the subsoil. Horton suggested that the relation of f_p to the duration of rainfall t_r can be expressed by the equation:

$$f_p = f_c + (f_o - f_c)\, e^{-Kt_r} \qquad (6)$$

where K is a positive constant and e is the Naperian base. While this equation was developed empirically it can be derived by assuming the processes that reduce f_p from f_o to f_c are exhaustive. Some of the physical processes causing the reduction are increasing channel length and decreasing permeability with depth, packing of the surface by rainfall, clogging soil pores by fine particles washed into them by the rain, swelling of colloids in the soil and a breaking down of the crumb colloids in the soil and a breaking down of the crumb structure of the soil. It is assumed that the infiltration capacity is equal to the observed infiltration rate f_i only when rainfall intensity i equals or exceeds f_p.

The application of the infiltration approach to estimating runoff is quite direct. The surface runoff is that portion of the rainfall from a specific storm which is not disposed of by interception, depression storage, evapotranspiration during the storm, and infiltration. If all of these losses but infiltration are either very small or can be reasonably evaluated the problem then becomes one of evaluating infiltration. Assuming Horton's equation is valid, that the values of f_o, f_c, K, and t_r are known, and that rainfall intensity is always greater than infiltration capacity f_p - the solution is shown in Fig. 9.

This approach is often applied in small homogeneous areas for use in the design of hydraulic structures. Soil profile characteristics over even a small basin are so variable that use of a single infiltration curve is difficult. Areal variations in storm rainfall over a basin make analysis a time consuming and, at times, almost impossible job unless an extremely dense network of recording rain gages is available. In addition there is the complicating fact that this handles only the surface runoff portion of the storm runoff. Since interflow is generally regarded to be a significant percentage of direct runoff, it must also be estimated and added in preparing river forecasts. These difficulties in the application of the infiltration theory have resulted in the development of various less rigorous applications of the theory.

---

[3] R. E. Horton, " The Role of Infiltration in the Hydrologic Cycle," Trans. Am. Geophys. Union, Vol. 14, pp 446-460, 1930.

Use of indices in solution - The ϕ index[4] has been defined as the rate of rainfall above which the rainfall volume equals runoff volume. The area below the ϕ value in Fig. 10 represents basin recharge and is a combination of infiltration, interception, and depression storage.

A slightly more complicated version is the use of the W-index which is the average infiltration rate during the period in which rainfall rate is greater than the capacity rate and can be expressed as

$$W=F/t=(P-Q-S)/t \tag{7}$$

where F is total infiltration, t is the time during which the rainfall rate exceeds the infiltration rate, P is the precipitation during time t, Q is surface runoff and S is surface retention. The W-index is about the same as the ϕ index less the average surface retention.

In a specific past storm it is quite easy to derive the value of either the ϕ or the W-index from rainfall data and discharge records. The application of either of these indices to forecasting runoff requires that the index itself be forecast. Since these indices vary in a manner comparable to runoff there is very little advantage to this approach in operation forecasting. In addition, the use of a constant rate tends to over-estimate runoff early in the storm and underestimate it late in the storm. It should be noted, however, that this approach is of considerable value for design studies for situations where a minimum infiltration rate may be assumed.

Possibilities of Soil-Moisture Accounting Approach

Soil-moisture deficiency is probably the most important factor involved in the relationship between rainfall and runoff. A practical means of estimating initial soil-moisture deficiencies for an area would provide a very useful variable for inclusion in a procedure for correlating storm rainfall to resultant runoff. Instruments for measuring soil-moisture for a specific soil profile have become reasonably practical, but the wide variety of soil profiles and moisture conditions existing in even a small basin make point measurements of soil-moisture of questionable value for use in a rainfall-runoff relation.

A more promising approach is the use of some sort of areal accounting technique which results in soil-moisture values more appropriate to the entire area. In such an approach precipitation is the inflow, and total runoff leaving the area by way of the stream channels plus evapotranspiration into the atmosphere from soil and plant surfaces throughout the area make up the outflow.

The means of estimating the mean precipitation over the area is the usual problem of deriving spatial averages from point values. Runoff from the area can be determined from streamflow records. Here, the problem becomes one of matching flow to the particular storm which caused it

---

[4] H. L. Cook, "The Infiltration Approach to the Calculation of Surface Runoff," Trans. Am. Geophys. Union, Vol. 27, pp. 726-747, October, 1946.

and is discussed in Section 4. The difference between rainfall and runoff is the water that remains in the area and is often referred to as recharge (R).

The third element, evapotranspiration, is the most difficult to evaulate. Most soil-moisture accounting techniques are based on the premise that actual evapotranspiration is either equivalent to the potential evapotranspiration rate (E) or bears a simple relation to potential evapotranspiration and soil-moisture deficiency.

A simple form of soil-moisture accounting is one in which the soil-profile is considered to have one capacity (S) over the entire area. Soil-moisture deficiency (d) is then determined by the equation:

$$d_{t+1} = d_t - R + E$$

where d_t is the soil-moisture deficiency at time t and d_{t+1} the value one time period later. R is the recharge and E the evapotranspiration which occurs between time t and t+1. The deficiency is allowed to vary between the limits of zero and S. It is possible to simplify this form of soil-moisture accounting by assuming the threshold approach. This assumes that all precipitation (P) is recharge (R) until the soil-moisture deficiency (S) is satisfied. After saturation is reached all the remaining precipitation is assumed to be runoff (Q_s). This eliminates the need for observed runoff values and permits soil-moisture computations to be made for any desired point or area.

A single value for soil-moisture capacity is not realistic, since even in small areas, there are differences in soil profiles and root structures which result in widely varying soil-moisture capacities. One solution is to assume the basin is made up of a range of soil-moisture capacities from S_1 to S_n. The threshold concept is applied to each of these assumed soil-moisture capacities in turn and for every rainfall event a runoff value is computed (Q_1 to Q_n). Observed runoff for each storm event (Q) is then correlated to the computed runoff values using the equation:

$$Q = aP + b_1 Q_{S_2} \dots + b_n Q_{S_n}$$

where a and b_1 to b_n are constants that can be determined using multiple correlation techniques. In the term aP in this equation P represents precipitation and aP is included to allow for areas characteristically having total runoff. Water falling on river or lake surfaces or on impervious areas adjacent to a stream channel would fall in this category.

This approach can be modified in many ways. One possibility is to make the smallest capacity (S_1) variable with season. Another would be to vary the constants a and b_1 to b_n with season.

In this form, soil-moisture accounting makes no allowance for rainfall intensity. A proposed solution is the establishment of maximum hourly rates, assuming that any rainfall above this maximum rate would run off directly and would not be treated as part of the storm rainfall. Determination of this maximum hourly rate would be undertaken after rainfall-runoff relations were developed in order to explain forecast deviations for storms having high hourly rates.

7. Development of Unit Hydrographs

After a satisfactory method of estimating the runoff that will result from a storm which we may wish to forecast has been determined, it is necessary to have quantitative knowledge of the hydrograph that will result at the forecast point. Runoff from the area near the forecast point will arrive soon after it occurs while runoff from progressively more distant areas will have progressively longer travel time. Runoff from uppermost portions of the drainage basin will arrive long after the flood crest has passed. The crest itself will be caused by runoff from an area near the center of the basin that consists of many points with nearly simultaneous travel times. It can readily be seen that runoff from a long, narrow basin will produce a different hydrograph than the same amount of runoff would produce from a short, wide basin. Other factors such as the slope of the terrain will affect the speed with which runoff reaches the forecast point.

A common method of predicting the flow hydrograph after the runoff has been forecast is by means of the unit hydrograph or unitgraph. The unitgraph can and should be tailored to fit uniquely each basin for which a forecast procedure is desired. Most unitgraphs developed for actual use will be developed by professional hydrologists at the proper River Forecast Center.

The aim here is to convey some knowledge of the physical principles involved and to show a simple method of unitgraph development that can be easily done with manual computations. Many more complicated methods exist, but most of them require considerably more work unless they are done on a computer.

A unit hydrograph is the hydrograph of a unit of runoff from a rain storm of unit duration. The unit of runoff is usually one inch, and the unit of duration is commonly taken as 12 hours of rain. Of course, very few rains produce exactly one inch of runoff and last exactly 12 hours. But this circumstance can be overcome by the very fact that makes the unit-hydrograph method valid: Two inches of runoff from a 12-hour storm will have a hydrograph which corresponds to the hydrograph from a one-inch 12-hour storm in that it will be just twice as high. To get a unit hydrograph from the two inches of runoff, divide runoff values by two.

This general consistency in shape is a characteristic of each drainage area. The explanation is simply that regardless of how much water runs off the time is about the same for its movement over the soil and through the soil. After the water reaches a channel, this is no longer true, and different rates of flow for different amounts of water are accommodated in flow-routing, which is explained later.

Because storms do not have uniform intensity throughout their duration, because they are not uniformly distributed over the drainage area, and because of the fact that the amount of runoff does have some effect on the shape of the unit hydrograph, it is necessary to derive the basin unit hydrograph by studying several storms, converting their runoff to a one-inch basis, and averaging the unit hydrographs in a special manner.

Unit Time Period

The unit time period for each storm studied is the same as the runoff duration which can be obtained from the rainfall-runoff relation already developed and the mass curve (see Mass Curve Section). Thus, unitgraphs may be developed from several storms, each with a different unit time. Each storm would need to be converted to a common unit time if this simple approach were used to develop a final operational unitgraph. The most desirable final unit time is dictated by the following considerations:

1. It should be a simple fraction of 24 hours such as 2, 3, 6, 12, or 24 hours to simplify later computations.
2. It should be related to rainfall reporting periods. For example, reports received each 6 hours will be used to forecast 6-hour amounts of runoff so a 6-hour unitgraph would be convenient.
3. It should not be too long to accurately describe the storm by hydrographs. For the inexperienced, it is helpful to compute the actual volume described by a hydrograph and compare this with the value obtained by addition of the values for ordinates spaced by unit time periods. If these two values do not agree within 10%, a shorter unit time period should probably be used. For example, the total direct runoff in Fig. 12 is computed in Table 4 to be 74,500 1/2dsf. If the area between the curve and the base flow line in Fig. 12 were found by planimeter to represent a volume of between 67,000 and 82,000 1/2dsf, one could assume that the unit time of 12 hours is short enough.

(The term "ordinate" will be used frequently in this discussion. An ordinate is the value along a vertical scale. To illustrate its meaning, refer to Fig. 12. The ordinate value of the total flow at midnight between the 4th and 5th is 27.0 cfs/1000. At the same time the ordinate value of base flow is 2.0 cfs/1000. The difference between the two is direct runoff and its ordinate value is 25.0 cfs/1000.)

The basic data needed for <u>each storm</u> used to develop a unitgraph is:

1. Precipitation record (preferably hourly) for several stations in the basin.
2. Rating curve for the forecast point.
3. Stage hydrograph (with readings taken frequently enough to adequately define the hydrograph).
4. Rainfall runoff relation.

Storm Selection

Storms selected for the development of a unit hydrograph should preferably contain at least .75 inch of runoff. The first step is to plot a discharge hydrograph for each storm, using the stage hydrograph and converting stage readings to discharge in cubic feet per second (cfs) with the use of the rating curve for the forecast point (see Rating Curves).

Then, a Base Flow Separation line must be drawn so that the direct runoff can be computed (see Section 4 for Hydrograph Separation). Values for ordinates of surface flow spaced a unit time (for example, 6 hours) apart are determined by subtracting the base flow value from the total hydrograph value at each ordinate. These values are summed to give the total volume of direct runoff. With a unit time of 6 hours, the answer will be in quarter-day second-feet or dsf/4. To convert this to inches of runoff, we need to know the square-mile area of the drainage basin in question. One inch of runoff from one square mile produces 26.9 dsf or 107.6 dsf/4. (See Table 4.)

$$\frac{\text{Storm total runoff in dsf/4}}{107.6 \times \text{square mile area}} = \text{storm runoff in inches}$$

In addition to the size requirements of storms selected, they should also be simple storms of reasonably uniform intensities with the period of runoff lasting as near 6 hours (or the unit time period) as can be found. Runoff from a simple storm has a single peak with a smooth rising limb and a smooth recession. A minor peak on the recession can be separated from the main storm as in Fig. 17, but care must be taken to avoid using the runoff that produced this minor peak in any computations.

Rating Curves

Rating curves are needed to convert stage to discharge when working with recorded data and vice versa when making forecasts. This is usually a curvilinear relation which must have been determined for low, medium and high flows several times during the past several years before we can attempt to develop a unit hydrograph or other forecast tools. Since there is apt to be some difference between ratings made during different storms, it is helpful to plot all available information on a stage versus discharge graph with special emphasis on known peaks. The results will probably show a scatter of points along a curve that is approximately parabolic in shape. The scatter may be real due to shifting controls, scour, etc., or to errors made during some of the actual rating determinations. For future forecasting, it is desirable to draw a best fit curve while considering all the points, Fig. 11. The rating curve can be extended beyond the highest flood of record through the use of log-log paper. To do this, plot stage versus flow on log-log paper for known data. Draw the straight line best fitting this data. Then extend the line with dashes to show what stages would be most likely if larger flows should ever occur. It is helpful to use tables from the values on the curve such as those in Table 3. Any extensions in the curve or the table which have been extrapolated beyond known data should be clearly marked as approximations.

Base Flow Separation

As noted in the discussion of Fig. 4, it is important to be consistent in drawing base flow separation lines. That is, the same method should be used throughout the development of a forecast procedure as well as when forecasting for the same basin.

As a guide to the time that surface flow has ended (point C, Fig. 4), several total flow values should be listed for points 6 hours apart in the area where the recession is rapidly becoming flatter. When one of these values is found to be 85 to 90% of its preceding value, it is safe to assume that surface flow has virtually ended and the base flow separation line should end here. This point should be determined for several storm hydrographs and an average time from peak to this point should be computed. This time in either hours or unit time periods is called the "n" value. The same straight line procedure with the same n value should be used consistently in all computations made on any basin being studied.

Mass Curves

When preparing data for the development of a unit hydrograph, it is helpful to plot mass curves of precipitation for several rainfall stations that are likely to indicate average conditions in the basin as a visual aid to the relation between rainfall and streamflow. The runoff period begins when the hydrograph starts to rise and ends when significant precipitation ends. The runoff period will be the unit time period while developing a unit hydrograph with this particular storm.

The mass curve should be plotted on the same sheet that is used for the storm hydrograph being studied. The scale should be in inches and start at the top of the sheet (see Fig. 12). If data is available from a recording rain gage, the amounts taken at 2-hour intervals should be accumulated and plotted on the depth versus time scale. If only longer time interval readings are available, they will have to be accumulated and adjusted to fit all information that is known with regard to beginnings, endings or changes in rate of rainfall. Observer's notes and knowledge of frontal passages are good sources for this type of information. After several mass curves are plotted for the basin in different colors, an average curve for the basin should be drawn.

Development

At this stage all the basic data has been reduced to a form that is convenient for the final development of the unit hydrograph. River stage readings have been converted to discharge and plotted on graph paper (see Fig. 12). The base flow separation has been made and the unit time period determined. The total volume of direct runoff has been found by adding the ordinates and this total has been converted to inches of runoff for the storm. The period of runoff is known from the mass curve and the rainfall runoff relation.

Next the ordinate values in cfs for the storm hydrograph should be divided by the total direct runoff in inches. Computations based on Fig. 12 are shown in Table 4.

The results are the ordinates of the desired unitgraph. Its unit time is 12 hours and its unit amount one inch. The unitgraph for this basin and a different unit amount is easily obtained by multiplication. To produce the unitgraph for 1/2 inch of runoff in 12 hours, one would multiply each of the ordinates in Table 4 by 0.5; for a unit amount of 0.67 inch multiply by 0.67. Similarly, to get a unitgraph to represent the flow from 2.38 inches of runoff during a unit time period, one should multiply each ordinate of the derived one inch unitgraph by 2.38. Changing the unit time is much more complicated and will not be discussed in this paper.

The final one inch unit hydrograph should be adjusted so that the total volume is equivalent to one inch of runoff for the basin. Unitgraphs, especially one developed in this manner, should be tested on other historical storms before being put into use. Careful subjective adjustments can be made in the unit hydrograph if it does not forecast a peak near that of the actual peak. The forecast volume should match the actual volume rather closely if runoff used for testing matches the actual computed runoff for the storm.

Several unitgraphs can be derived from different storms that occurred in the same basin but a note of warning is in order. An arithmetic average of all the first ordinates, then all the second ordinates, etc. cannot be used for a satisfactory unitgraph. Instead, both the peaks and the times from end of significant runoff to peaks should be averaged. The average unitgraph is then sketched to conform to the general shape of the other graphs, passing through the computed peak at the computed average time of peak. The sketched unitgraph should have a volume of one inch.

8. Flow Routing

It is frequently necessary to forecast points where it is unnecessary or impractical to use the rainfall runoff and unitgraph approach. These points are usually downstream from headwater forecast points or from reservoirs with release information that can be obtained or forecast. In some cases lead time is short and forecasts must be made from forecasts of upstream flow that will pass a headwater point or reservoir. At points further downstream it is usually necessary to issue a preliminary estimate from forecast data but the final forecast should be delayed until upstream crests are known. Forecasts for key points, which involve routing, will usually be made by the appropriate River Forecast Center while intermediate points that can be forecast using stage relations are often handled by the RDO.

A flood wave normally changes its shape as it moves downstream. The rising side of the wave is steeper than the recession side, and hence moves faster. This effect, plus channel storage and other influences, generally causes the wave to flatten out as it proceeds downstream. The degree of flattening, and the shape of the hydrograph are determined by relatively stable channel characteristics. Thus the relationship of hydrograph shape at some point to hydrograph shape downstream from this point can be determined empirically, by analysis of past floods. Forecasting the changing shape of the wave is known as flood or flow routing.

Among the many factors that can cause attenuation or distortion of the flood wave are tributary inflow, friction, bank losses, difference in river bed slope, backwater, change in cross sectional area, channel storage, overbank storage and natural controls that differ with the volume of flow. Depending on the number and the complexity of these effects, forecasts are made by using stage relations or routing techniques.

Stage Relations

A good method of determining whether stage relations will render good forecasts is to plot on graph paper upstream versus downstream stage data from numerous storms which have occurred during the past several years. If the points fall on or very near a smooth curve it is very likely that this crest relation is a reliable forecast tool (see Fig. 13). Simultaneous stages during periods of low steady flow can be used for the lower end of the curve. For higher storm flows only the crests at each point should be used. The travel time of the crest from the upper gage to the lower should be entered for each point on the graph so that one can see if this time varies with stage height. If the first plotting shows an unacceptable scatter of points it may be possible to introduce another parameter (such as the crest on a large representative tributary) into a more complex stage relation. It is necessary to be alert for changes such as channel improvement or new reservoirs which may have changed the relation. As the complexity increases there is more incentive to use a routing technique.

Routing

Routing techniques are normally developed and used by professional hydrologists at an RFC. Many different methods are employed as dictated by the needs of the area and the preference of the hydrologists. A simple graphical method that is adequate in many forecast situations is described here in order to convey some basic knowledge of the problem. This method deals with the time lag that inflow at the upstream point(s) experiences before it becomes outflow at the downstream point. It also deals indirectly with the storage that occurs within the reach between forecast points. This graphical method makes use of two factors called K and L.

K is a coefficient which, when it is multiplied times the change in outflow (dO) with the change in time (dt) gives the change in storage (dS) with change in time (dt). The formula reads:

$$K\frac{dO}{dt} = \frac{dS}{dt}$$

$\frac{dS}{dt}$ is simply the inflow minus the outflow or I-O. Hence, the formula could just as well read:

$$K\frac{dO}{dt} = I-O \qquad \text{or} \qquad \frac{I-O}{K} = \frac{dO}{dt}$$

The last formula reads: The inflow minus the outflow divided by K equals the change in outflow with the change in time. Graphical determination of these values will be explained after L is defined.

L is the lag time. It is found as follows:

1. Plot both the inflow and outflow hydrographs of an actual storm on one sheet of paper as has been done in Fig. 14a.
2. Note the time difference in hours between A and B.
3. The value found in step 2 is L.

An inflow hydrograph which is lagged L hours, as shown in Fig. 14b, passes through the crest of the outflow hydrograph at point P. At this point d0/dt is zero and the lagged inflow equals the outflow. To find K as a function of outflow at points along the outflow curve we perform the graphics indicated in Fig. 14c:

1. Select point A on the rising side of the inflow hydrograph.
2. Draw a vertical line downward through point A to a point, B, on the outflow hydrograph.
3. Draw a horizontal line through point A to the right, until it hits the outflow hydrograph.
4. From point B, draw a line tangent to the outflow hydrograph, upward until it hits the horizontal line at a point, C.
5. The distance in hours from A to C is the value of K for the value of outflow at point B.
6. A similar construction can be performed on the recession sides of the inflow and outflow hydrographs.

After computing K for several points along the outflow hydrograph one can construct a curve to show how K varies with outflow as has been done in Fig. 14d. In order to find values for the L curve in 14d, one must look at several historic floods of different magnitudes. Along some reaches L may have the same value for all outflows. K and L curves should be convenient to or plotted on hydrographs that will be used as forecast work sheets.

After K and L have been established for a reach, inflow values are the only information that is needed to forecast the outflow hydrograph. The following procedure for drawing the outflow hydrograph is shown in Fig. 15a:

1. The inflow should be lagged L hours and plotted on hydrograph paper. (Forecast inflow can also be lagged and plotted if needed for timely forecasts, but it should be clearly marked as such and revised as observed values become available.)
2. A point is plotted K hours from I_2 with the same flow value.
3. A straight edge from this point to 0_1 gives the slope at 0_2.
4. A short segment of the outflow hydrograph should be drawn at time 0_2.
5. This procedure is repeated as often as is found by experience to be adequate for a good description of the outflow.
6. The lagged inflow and graphically derived outflow for an entire storm is shown in Fig. 15b.

9. Operational Problems in River Forecasting

Collection of Basic Data

Successful operation of a river forecasting service can be made possible only by the availability of adequate basic data. This includes the historical data required for the development of forecast procedures and a basic network of current reporting stations to support forecasting operations. The need for historical data in the development of rainfall-runoff relations was covered in Section 4 and this discussion will be confined to operational requirements.

a. Network Design - Preparation of timely and accurate river forecasts requires timely and accurate information about hydrologic conditions in the drainage areas involved. This includes enough rainfall reports to adequately define the areal precipitation pattern and enough hourly or six-hourly information to make a reasonable time distribution of the rainfall. The density of rainfall reports required to evaluate the areal pattern will vary with the type of precipitation which produces floods. Areas subject to thunderstorm type precipitation require a greater density than those with relatively uniform precipitation patterns. A distance of 20-25 miles between rain gages is usually satisfactory for all but thunderstorms. For thunderstorms it is almost impossible to maintain a network dense enough to adequately define the areal precipitation pattern. Radar offers a means for dealing with high intensity storms covering a small area. Radar information can be used with observed rainfall information to construct isohyetal patterns of great value in estimating mean basin precipitation.

In areas where there are no available observers or no reliable communications facilities it may be necessary to use automatic equipment to obtain reports. Gages are now available that automatically measure precipitation or river stage and transmit it by radio to the collection point. This equipment can be constructed to report at regular time intervals, using built-in timing devices, but this system does not allow for cutting this interval down during critical periods. Another solution is to construct the equipment to report whenever an activating signal is sent from the collection point, but this requires both a sending and receiving radio set at each gage. This equipment is rather expensive and is normally used only when it is the only way to obtain reports.

The river gage network required is dictated primarily by the area for which forecasts are needed and where records are available for use in the development of procedures. Often locations requiring river forecasts due to the local flood problem are not particularly suitable for making streamflow measurements. When this is the case it may be necessary to prepare the basic forecast for a nearby rated station and use an auxiliary relation to forecast for the location in question.

b. Reporting procedures - Hydrologic data is of no use in forecasting unless it is collected regularly and reaches the forecaster promptly.

(1) Rainfall reports - It is the usual practice to have a few rainfall observers report daily regardless of whether or not there has been precipitation. These reports form a basic network which is supplemented by additional data during rainy periods. These added reports are obtained whenever some predetermined criterion occurs. This criterion may be a fixed amount of rain in a given time interval and may vary with the season of the year. It should be determined by the amount required to produce a significant rise in river stages.

Once the reporting criterion has been reached, the observer reports until the storm is over. It is desirable to have the observer report one period of no rain at the end of the storm before terminating his report. Otherwise, when reports stop it may be difficult to tell whether the report is missing or the rain has actually ceased.

The interval at which the observer reports rainfall is a function of the time of concentration of the area involved and how critical the flood problem is. In most cases, reports are required at six hour intervals - morning, noon and evening. It is usually not practical to attempt to collect reports during the night unless flood emergency is particularly critical. In some downstream areas, twelve-hour reports are adequate and in some cases reports can be collected once a day. An area subject to flash flooding will probably require a specially designed network with some means of getting data more often, sometimes as frequently as once an hour.

(2) River reports - River observers are instructed to report on the same basis as rainfall observers. A few key stations should report every day. The remainder of the network is usually set up to start reporting whenever the stage reaches a specified value and to continue to report at a predetermined interval until the stage goes below the specified stage. Here, too, it is desirable to have the observer make one report after the stage falls below the criterion value.

The reporting interval is determined in the same way as was described for rainfall observers.

Observed discharge data from dams along the river are usually furnished by the agency operating the structure along with anticipated changes in discharge. Close coordination is required because a decision on how to operate the dam depends upon forecasts of inflow into the dam.

In the case of both rainfall and river observers it is the usual practice to require them to make daily readings even though they are below reporting criteria and to mail these data to the river forecaster. This will enable him to keep track of current river and antecedent precipitation conditions.

(3) Other hydrologic information - Additional, more specialized data may be required at certain times and places such as depth of frost in the soil, soil moisture, evaporation, wind, and temperature. Such data are usually obtained from the most convenient source with special arrangements to fit each case.

(4) Rainfall data at night - It was mentioned earlier that it is difficult to obtain rainfall reports with any regularity at night. In areas where dangerous flood conditions can develop during the night it is often necessary to make special arrangements to obtain a skeleton network of rainfall reports at any time. Utility plants, police stations, fire stations, or other stations which work around the clock are possible sources of this information. Remote reading gages may be used to facilitate this. These gages have their collectors mounted on the roof. A tube leads from the collector down to a measuring tube located at some convenient spot in the building, making it easy for an observer to obtain readings whenever they are requested. One problem is to be sure the gage is emptied regularly. It is best to have the gage read daily at a certain hour and emptied only then. All measurements after that can be relied upon to be the total since the regular observation time. This is particularly important in a location where observations may be made by a number of different people.

Methods of Preparing Forecasts

The steps taken to prepare a river forecast are illustrated here by a simple example. A hypothetical river basin is shown in Fig. 16 in which river forecasts are required by Stations A and B. Unit hydrographs[5] are utilized for the distribution of runoff and the Muskingum routing[6] technique is used for the routing from A to B.

It is assumed that a storm began at about 7:00 pm on May 17 and that a forecast is being prepared on the basis of rainfall reported up to 7:00 am on May 19.

The computation of runoff is shown in Table 5. The antecedent precipitation index (API) for 7:00 am May 17 is used. This is the value for the first day of the storm but it does not include any storm rainfall. The week of the year is determined by the date of the beginning of the storm, May 17, which falls in week 20 (Table 2). The average rainfall amounts above Station A and between Stations A and B for 12-hour increments are entered in lines 5 and 14.

Dashed lines on the runoff relation (Fig. 7) indicate the computation of runoff for the area above Station A for 7:00 am on May 18 as follows:

1. Enter the relation with the API (1.89).
2. Move left to the week of the year (20), down to storm duration (12).
3. Move to the right to storm precipitation (1.02).
4. Move up to obtain storm runoff (.38).
5. This process is repeated at the end of each 12-hour period using precipitation accumulated to that time.
6. The 12-hour increments of runoff (Table 5 lines 9 & 18) are determined by subtracting the previous storm runoff total from the storm runoff total at the time in question and are entered in lines 1 and 12 of the forecast sheet (Table 6).
7. The 12-hour runoff increments are converted to discharge using the 12-hour unit hydrograph for Station A (Table 7).
8. Each 12-hour ordinate of the unit hydrograph is obtained for the first runoff increment (.38 inch) by interpolation and entered in line 2 of Table 6, with the first value in the same column as the runoff increment (this is the ending time of the 12-hour period when the runoff occurred).
9. This process is repeated on lines 3 and 4 for the other increments of runoff and the total for each time entered in line 6.
10. Baseflow (line 7) includes all flow from events preceding the storm.
11. The "computed" forecast, the sum of total runoff (line 6) and baseflow (line 7), is entered on line 8.
12. These values are plotted (as crosses) on the hydrograph (Fig. 17).

---

[5] L. K. Sherman, "Streamflow from Rainfall by the Unit-graph Method," Eng. News-Record, Vol. 108, pp. 501-505, 1932.

[6] R. K. Linsley, M. A. Kohler, and J. L. H. Paulhus, "Applied Hydrology," pp. 228-229, McGraw-Hill, New York, 1958.

This "computed" forecast is the unadjusted result of the forecast procedures, and the forecaster must then draw an "adjusted" forecast reconciling the "computed" forecast with available observed data. The "adjusted" forecast is shown as a solid line when based on observed values and as a dashed line in the forecast period. The "adjusted" values are entered in line 9 for routing to Station B.

The final step in preparing the forecast is the conversion of forecast discharge to stage using the rating curves (Fig. 18). The forecast for Station A could be given as "crest of 23 ft. at 11 pm on May 19" or as "crest of 23 to 24 ft. near midnight." Giving a specific figure, such as 23 ft. may give the impression to the recipient of the forecast that is likely to vary within 1/10 foot, which may not be the case.

The "adjusted" flows for Station A (line 9) are routed to Station B using the routing diagram in Fig. 19 rather than a K and L method.

The forecast outflow of 6.4 cfs for 7:00 pm on the 19th is made in the following manner:

1. Add the inflow for 7:00 am (7.5) to the inflow for 7:00 pm (10.4). The result is I_1 plus I_2 which equals 17.9.
2. Enter Figure 19 with 0_1 which is 4.1 at 7:00 am as entered on line 11.
3. Move to the right and find an I_1 plus I_2 value of 17.9.
4. Move down to an 0_2 value of 6.4 and enter this value on line 11 under 7:00 pm.

Dashed lines in Fig. 19 are used to indicate this forecast.

The forecast of flow from the local area is made in the same manner as for Station A using the unitgraph in Table 8. The "computed" forecast is the sum of the routed value (line 11), the total runoff (line 17), and the baseflow (line 18). These values are plotted on the hydrograph and "adjusted" on the basis of observed data (Fig. 20). Convert to stage with Fig. 18.

The forecast for Station B might be given as "crest of 36 ft. at 2 am on May 20" or as "crest of 35 to 36 ft. early on May 20." It is a good practice to maintain a record of these forecasts on a tabulation sheet such as Table 9 in order to minimize the chance of errors in transmitting the forecast to the user.

Computing Runoff from Melting Snow

The estimation of runoff is sometimes complicated by snowmelt. When heavy rain occurs on a relatively light snow cover, the water equivalent of the snow is added to the rainfall and the total used in computing runoff. This assumes the snow will be completely melted during the rain.

When rain falls on deeper snow packs the problem becomes much more complicated. Part of the snow may melt and become a part of the total runoff. Part of the rain may be absorbed and retained by the snow pack so that this rain does not contribute to runoff. In mountainous areas this situation is harder to define if the freezing level is changing during the storm. As of 1967, much more research and instrumentation is needed before completely objective forecasts can be made under such conditions.

Another problem arises when runoff is primarily a result of the snowmelt alone. Snowmelt rates depend upon many meteorological elements such as temperature, humidity, wind and radiation. In addition the condition of snow on the ground and its water equivalent must be considered. This is a complicated problem which cannot be treated thoroughly here. A common solution is to compute melt by multiplying the average of the degree-days above 32°F for the area by a factor which usually varies from .05 to .15 inch with .10 inch probably the most commonly used value. This degree-day factor is often correlated with calendar date or accumulated degree-days as is shown in Fig. 21. This obviously does not take into account many of the factors influencing melt, but does produce usable estimates of runoff. Further refinements require observations of meteorological elements such as humidity, radiation and wind that are usually not available in the area requiring forecasts. It should be noted that the relation shown in Fig. 21 estimates snowmelt as such, and it is necessary to use a rainfall-runoff relation to compute runoff for use in forecasting.

Seasonal Flow or Water Supply Forecasts

In areas where snow accumulates during the winter and is melted during the spring thaw, seasonal runoff computations[7] can be made. A plotting of annual precipitation against annual runoff may show considerable correlation. Additional refinement can usually be made by the adjustment of the runoff value for such factors as storage changes in reservoirs and diversions for irrigation. The effectiveness of precipitation in producing runoff depends upon when it occurs. It is the usual practice to apply monthly weights to precipitation amounts and also to assign weights to the various stations observing precipitation. These weights can be derived using least-square analysis. Due to the high intercorrelation of observed precipitation values within a limited area it is the usual practice to smooth both the seasonal and station weights.

Flash Flood Warning Procedures

At points where there is a very short time between the occurrence of heavy rain and the peak stage at a forecast point, it is often necessary to use special short cut procedures in place of the conventional approach described earlier in this section. An example of one form this can take is shown in Table 10. These tables were based on a conventional rainfall runoff relation and unit hydrograph. The table is intended for use by a representative in the area subject to flash flooding. The "index" is given to the representative regularly and represents current runoff conditions in the area.

Warning procedures can take many forms, depending upon available data for development and many other factors. In general the procedures will be used by forecasters with a limited knowledge of hydrology and simplicity is more important than extreme accuracy.

---

[7] M. A. Kohler and R. K. Linsley, "Recent Developments in Water Supply Forecasting," Trans. Am. Geophys. Union, Vol. 30, pp. 427-436, June 1949.

For example, a local flash-flood representative has been given a Runoff Index of 4 by the river forecasting office. At 4 pm, rainfall observers report rainfall of 4.30 inches in the preceding 6 hours. The duration is 6 hours so the left side of Table 10 applies as follows:

1. Move down the runoff index column to the current value (4).
2. Move to the left and interpolate between 3.85 inches (21 ft.) and 4.60 inches (24 ft.).
3. This gives a forecast of a crest stage of 22.8 ft. The table indicates the crest for a 6-hour rain will occur 7 hours after the end of heavy rain - at 11 pm.
4. The forecast issued might read - "crest stage of 22 to 23 ft. late this evening."

TABLE 1. COMPUTATION OF STORM DURATION

Date	4	4	4	5	5	5
Hour	12	18	24	6	12	18
6 Hourly Rainfall in Inches	.62	.40	.14	.24	.09	.22
Estimated Storm Duration in Hours	6	12	15	21	24	30

(Table 1 is referred to on Page 11.)

TABLE 2. WEEK NUMBER

Date		Week No.	Date		Week No.
Jan.	1- 7	1	July	2- 8	27
	8-14	2		9-15	28
	15-21	3		16-22	29
	22-28	4		23-29	30
	29- 4	5		30- 5	31
Feb.	5-11	6	Aug.	6-12	32
	12-18	7		13-19	33
	19-25	8		20-26	34
	26- 4	9		27- 2	35
Mar.	5-11	10	Sept.	3- 9	36
	12-18	11		10-16	37
	19-25	12		17-23	38
	26- 1	13		24-30	39
Apr.	2- 8	14	Oct.	1- 7	40
	9-15	15		8-14	41
	16-22	16		15-21	42
	23-29	17		22-28	43
	30- 6	18		29- 4	44
May	7-13	19	Nov.	5-11	45
	14-20	20		12-18	46
	21-27	21		19-25	47
	28- 3	22		26- 2	48
June	4-10	23	Dec.	3- 9	49
	11-17	24		10-16	50
	18-24	25		17-23	51
	25- 1	26		24-31	52

(Table 2 is referred to on Pages 11 and 29.)

TABLE 3. EXAMPLE RATING TABLE

DISCHARGE $\frac{\text{cfs}}{1000}$

Stage	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
4	.8	.9	1.0	1.2	1.3	1.4	1.5	1.6	1.8	1.9
5	2.0	2.2	2.4	2.6	2.8	3.0	3.1	3.3	3.5	3.7
6	3.9	4.1	4.3	4.6	4.8	5.0	5.2	5.4	5.7	5.9
7	6.1	6.4	6.6	6.7	7.2	7.5	7.7	8.0	8.3	8.5
8	8.8	9.1	9.4	9.6	9.9	10.2	10.5	10.8	11.0	11.3
9	11.6	11.9	12.2	12.5	12.8	13.1	13.4	13.7	14.0	14.3
10	14.6	14.9	15.3	15.6	16.0	16.3	16.6	17.0	17.3	17.7
11	18.0	18.4	18.8	19.1	19.5	19.9	20.3	20.7	21.0	21.4
12	21.8	22.2	22.7	23.1	23.6	24.0	24.4	24.9	25.3	25.8
13	26.2	26.6	27.1	27.5	28.0	28.4	28.8	29.3	29.7	30.2
14	30.6	31.1	31.6	32.2	32.7	33.2	33.7	34.2	34.8	35.3
15	35.8	36.3	36.8	37.3	37.8	38.4	38.9	39.4	39.9	40.4
16	40.9	41.5	42.0	42.6	43.1	43.7	44.2	44.8	45.3	45.9
17	46.4	47.0	47.6	48.2	48.8	49.4	49.9	50.5	51.1	51.7
18	52.3	52.9	53.5	54.1	54.7	55.4	56.0	56.6	57.2	57.8
19	58.4	*59.1	59.9	60.6	61.4	62.1	62.8	63.6	64.3	65.1
* BEGINNING OF EXTRAPOLATED DATA										
20	65.8	66.6	67.5	68.3	69.2	70.0	70.8	71.7	72.5	73.4
21	74.2	75.0	75.8	76.5	77.3	78.1	78.9	79.7	80.4	81.2
22	82.0	83.7	85.4	87.1	88.8	90.5	92.2	93.9	95.6	97.3
23	99.0									

(Table 3 is referred to on Page 22.)

TABLE 4. UNITGRAPH DEVELOPMENT (SEE FIG. 12)

A. DATE	3	4		5		6		7
B. TIME	12	00	12	00	12	00	12	00
C. TOTAL FLOW ORDINATE (cfs/1000)	2.7	5.8	14.3	27.0	23.0	12.4	9.1	6.7
D. BASE FLOW ORDINATE (cfs/1000)	2.0	2.0	2.0	2.0	2.8	4.0	5.3	6.4
E. DIRECT RUNOFF ORDINATE (cfs/1000)	.7	3.8	12.3	25.0	20.2	8.4	3.8	.3

1 square mile = 27,878,400 $ft.^2$

for 1 inch depth over 1 square mile $\frac{27,878,400}{12} = 2,323,200\ ft.^3$

$\frac{1\ \text{cubic foot}}{\text{sec.}} \times \frac{86,400\ \text{sec.}}{\text{day}} = 86,400$ dsf

$\frac{2,323,200}{86400} = 26.9$

Therefore 1 inch of runoff from 1 square mile produces 26.9 dsf.

IN THIS STORM TOTAL DIRECT RUNOFF = 74,500 dsf/2

26.9 x 400 sq. mi. = 10,760 dsf/1" R. O.

= 21,520 1/2 dsf/1" R. O.

74,500 1/2 dsf/21,520 = 3.46" R. O.

DERIVED UNITGRAPH ORDINATES (each direct runoff ordinate was divided by total storm rainfall);

.2 1.1 3.6 7.2 5.8 2.4 1.1 .1

(Table 4 is referred to on Pages 21, 22, and 23.)

TABLE 5. COMPUTATION OF STORM RUNOFF

Month...............May.....Year...			Date	16		17		18		19	
			Hour	7a	7p	7a	7p	7a	7p	7a	7p
Drainage Area Above A	1	0.9 of yesterday's API..........		2.10		1.89					
	2	Precipitation in past 24 hours..		0		0					
	3	API for today..............		2.10		1.89					
	4	Week of year...............				20					
	5	12 hour precip increment (in.)..						1.02	.67	1.88	
	6	Total storm precipitation (in.).						1.02	1.69	3.57	
	7	Durations (hours)...........						12	24	36	
	8	Total storm runoff (in.)........						.38	.76	1.90	
	9	12 hour runoff increments (in.).						.38	.38	1.14	
Drainage Area Between A and B	10	0.9 of yesterday's API..........		2.46		2.21					
	11	Precipitation in past 24 hours..		0		0					
	12	API for today..............		2.46		2.21					
	13	Week of year...............				20					
	14	12 hour precip increments (in.).						.91	.71	2.12	
	15	Total storm precipitation (in.).						.91	1.62	3.74	
	16	Duration (hours)..........						12	24	36	
	17	Total storm runoff (in.)........						.36	.64	1.86	
	18	12 hour runoff increments (in.).						.36	.28	1.22	

(Table 5 is referred to on Page 29.)

TABLE 6.

FORECAST COMPUTATION SHEET

STATION A		17		18		19		20		21		22		23	
		7a	7p	7a	7p	7a	7p	7a	7p	7a	7p	7a	7p	7a	7p
1 Fcst 12-hr RO(in.)				.38	.38	1.14									
2 Distribution of RO	(cfs)/(1000)			.7	1.5	1.9	1.3	.8	.4	.2	.1				
3 ''''					.7	1.5	1.9	1.3	.8	.4	.2	.1			
4 ''''						2.1	4.6	5.6	4.0	2.4	1.3	.7	.2	.1	
*5 ''''															
6 Total (line 2+3+4)				.7	2.2	5.5	7.8	7.7	5.2	3.0	1.6	.8	.2	.1	
7 Baseflow		1.2	1.1	1.0	.9	.8	.8	.9	1.0	1.2	1.4	1.5	1.5	1.5	
8 "Computed" Fcst (line 6+7)	(cfs)/(1000)	1.2	1.1	1.7	3.1	6.3	8.6	8.6	6.2	4.2	3.0	2.3	1.7	1.6	
9 "Adjusted" Fcst	(cfs)/(1000)	1.2	1.1	1.8	3.6	7.5	10.4	9.7	7.1	4.5	3.0	2.3	1.7	1.6	
10 $I_1 + I_2$		3.3	3.3	2.9	5.4	11.1	17.9	20.1	16.8	11.6	7.5	5.3	4.0	3.3	
11 A routed to B		4.0	3.0	2.5	2.5	4.1	6.4	8.4	8.3	7.3	5.5	4.2	3.1	2.5	
STATION B															
12 Fcst 12-hr RO(in.)				.36	.28	1.22									
13 Distribution of RO	(cfs)/(1000)			1.4	2.4	2.3	1.3	.6	.2						
14 ''''					1.1	1.9	1.8	1.0	.5	.2					
15 ''''						4.9	8.2	7.9	4.4	2.1	.7	.1			
*16 ''''															
17 Total (line 13+14+15)				1.4	3.5	9.1	11.3	9.5	5.1	2.3	.7	.1			
18 Baseflow		.9	.8	.8	.7	.7	.7	.9	1.1	1.3	1.4	1.5	1.5	1.5	
19 "Computed" Fcst (line 11+17+18)	(cfs)/(1000)	4.9	3.8	4.7	6.7	13.9	18.4	18.6	14.5	10.9	7.6	5.8	4.6	4.0	
20 "Adjusted" Fcst	(cfs)/(1000)	4.9	3.8	4.4	6.4	13.0	17.3	17.6	14.0	10.5	7.6	5.8	4.6	4.0	

* Lines 5 and 16 are reserved for the next forecast period.

(Table 6 is referred to on Page 29.)

TABLE 7. STATION A 12-HOUR UNITGRAPH

Flow $\frac{(\text{cfs})}{(1000)}$ at end of:

Runoff	Hours: 12	24	36	48	60	72	84	96	108
.05	.1	.2	.2	.2	.1	.1			
.10	.2	.4	.5	.4	.2	.1	.1		
.15	.3	.6	.8	.5	.3	.2	.1		
.20	.4	.8	1.0	.6	.4	.2	.1		
.25	.5	1.0	1.2	.9	.5	.3	.2	.1	
.30	.6	1.2	1.5	1.1	.6	.3	.2	.1	
.35	.7	1.4	1.7	1.2	.7	.4	.2	.1	
.40	.8	1.6	2.0	1.4	.8	.4	.2	.1	
.45	.9	1.8	2.2	1.6	.9	.5	.3	.1	
.50	1.0	2.0	2.5	1.8	1.0	.6	.3	.1	.1
.55	1.1	2.2	2.7	2.0	1.1	.7	.3	.1	.1
.60	1.1	2.4	2.9	2.1	1.3	.7	.4	.1	.1
.65	1.2	2.6	3.2	2.3	1.4	.7	.4	.1	.1
.70	1.3	2.8	3.4	2.5	1.5	.8	.4	.1	.1
.75	1.4	3.0	3.7	2.6	1.6	.8	.5	.2	.1
.80	1.5	3.2	3.9	2.8	1.7	.9	.5	.2	.1
.85	1.6	3.4	4.2	3.0	1.8	.9	.5	.2	.1
.90	1.7	3.6	4.4	3.2	1.9	1.0	.5	.2	.1
.95	1.8	3.8	4.7	3.3	2.0	1.0	.6	.2	.1
1.00	1.9	4.0	4.9	3.5	2.1	1.1	.6	.2	.1
1.25	2.4	5.0	6.1	4.4	2.6	1.3	.8	.3	.1
1.50	2.9	6.0	7.4	5.3	3.2	1.7	.9	.3	.2
1.75	3.3	7.0	8.6	6.1	3.7	1.9	1.1	.4	.2
2.00	3.8	8.0	9.8	7.0	4.2	2.2	1.2	.4	.2
3.00	5.7	12.0	14.7	10.5	6.3	3.3	1.8	.6	.3

(Table 7 is referred to on Page 29.)

TABLE 8. STATION B LOCAL AREA 12-HOUR UNITGRAPH

Flow $\frac{(cfs)}{(1000)}$ at end of:

Hours:	12	24	36	48	60	72	84
Runoff							
.05	.2	.3	.3	.2	.1		
.10	.4	.7	.7	.4	.2	.1	
.15	.6	1.0	1.0	.5	.3	.1	
.20	.8	1.3	1.3	.7	.3	.1	
.25	1.0	1.7	1.6	.9	.4	.2	
.30	1.2	2.0	2.0	1.1	.5	.2	
.35	1.4	2.3	2.3	1.3	.6	.2	
.40	1.6	2.7	2.6	1.4	.7	.2	
.45	1.8	3.0	2.9	1.6	.8	.3	
.50	2.0	3.4	3.2	1.8	.8	.3	.1
.55	2.2	3.7	3.6	2.0	.9	.3	.1
.60	2.4	4.0	3.9	2.2	1.0	.4	.1
.65	2.6	4.4	4.2	2.3	1.1	.4	.1
.70	2.8	4.7	4.6	2.5	1.2	.4	.1
.75	3.0	5.0	4.8	2.7	1.3	.5	.1
.80	3.2	5.4	5.2	2.9	1.4	.5	.1
.85	3.4	5.7	5.5	3.1	1.4	.5	.1
.90	3.6	6.0	5.9	3.2	1.5	.5	.1
.95	3.8	6.4	6.2	3.4	1.6	.6	.1
1.00	4.0	6.7	6.5	3.6	1.7	.6	.1
1.25	5.0	8.4	8.1	4.5	2.1	.8	.1
1.50	6.0	10.1	9.8	5.4	2.6	.9	.2
1.75	7.0	11.7	11.4	6.3	3.0	1.1	.2
2.00	8.0	13.4	13.0	7.2	3.4	1.2	.2
3.00	12.0	20.1	19.5	10.8	5.1	1.8	.3

(Table 8 is referred to on Page 30.)

TABLE 9. FORECAST RECORD SHEET

Forecast Point	Forecast				Time forecast issued			Latest stage available when fcst prepared			Based on precip up to		Remarks
	Crest	Hour	Date	By	Hour	Date	By	Stage	Hour	Date	Hour	Date	
1 Station A	23	11 pm	19	MR	9 am	19	MR	21.5	7 am	19	7 am	19	
2 Station B	36	2 am	20	MR	9 am	19	MR	31.4	7 am	19	7 am	19	
3													

(Table 9 is referred to on Page 30.)

TABLE 10. FLASH-FLOOD WARNING PROCEDURE

Precipitation (in.)	Duration of heavy rain -- 6 hours Time to crest after end of heavy rain -- 7 hours. Crest stage in ft.			Runoff index *	Duration of heavy rain -- 12 hours Time to crest after end of heavy rain -- 5 hours Crest stage in ft.			
18	21	24	27		18	21	24	27
2.80	3.40	4.15	4.75	1	3.30	4.00	4.50	5.40
2.95	3.55	4.30	5.00	2	3.45	4.15	4.70	5.60
3.10	3.70	4.45	5.20	3	3.60	4.30	4.90	5.80
3.25	3.85	4.60	5.40	4	3.75	4.45	5.10	6.00
3.40	4.00	4.75	5.60	5	3.90	4.60	5.30	6.20
3.55	4.15	5.00	5.80	6	4.05	4.75	5.50	6.40

* Provided by the responsible river forecast office.

(Table 10 is referred to on Pages 31 and 32.)

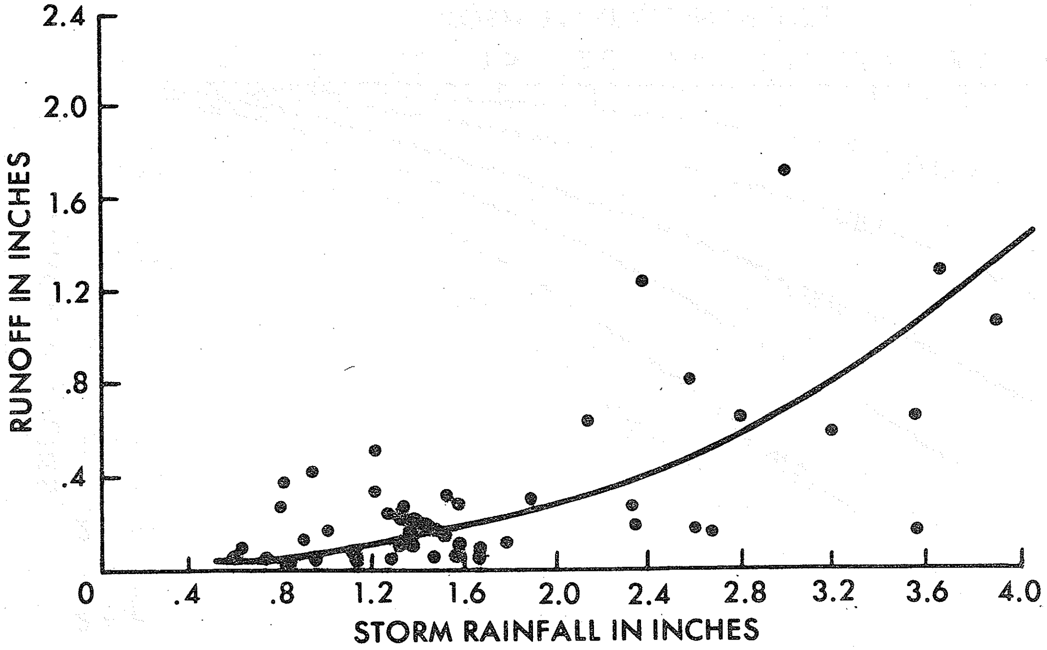


FIG. 1. RAINFALL-RUNOFF RELATION FOR WHITEOAK BAYOU AT HOUSTON, TEXAS

(Fig. 1 is referred to on Page 5.)

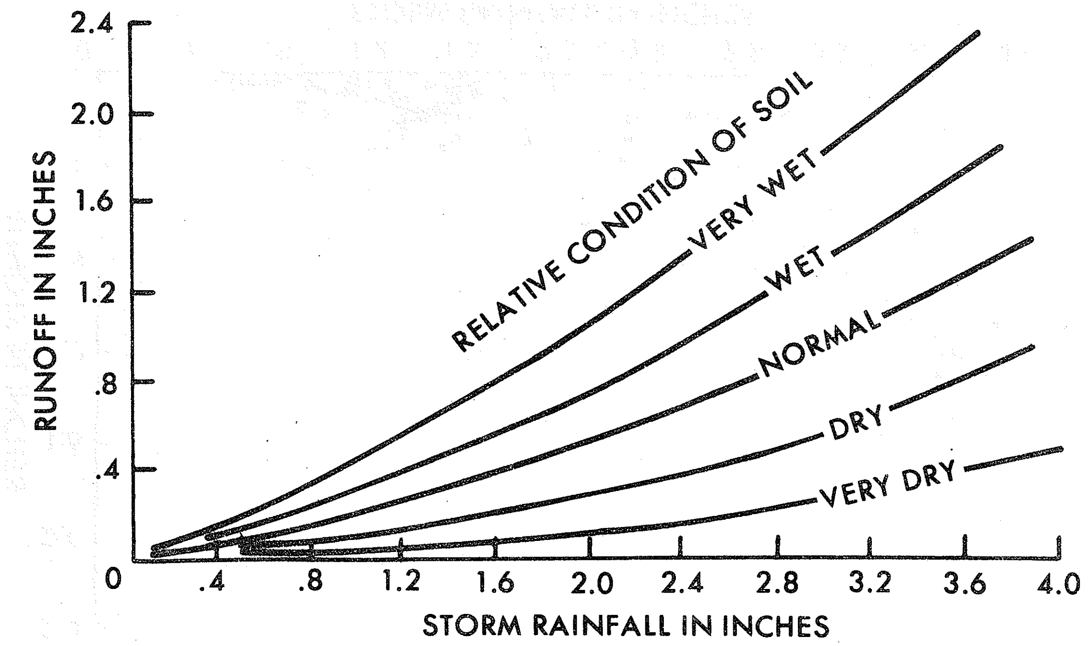
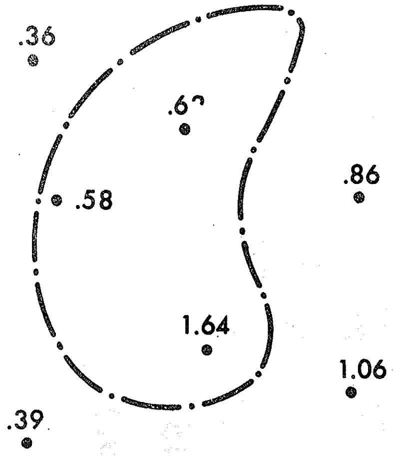


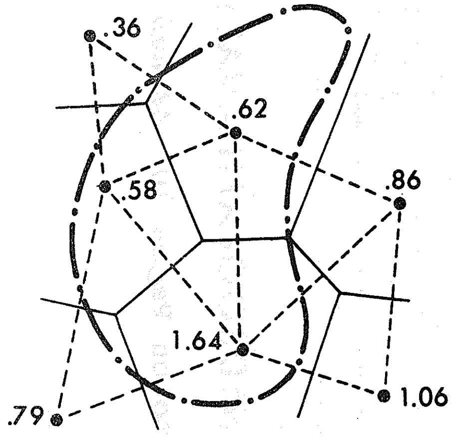
FIG. 2. RAINFALL-RUNOFF RELATION USING SOIL CONDITION AS A PARAMETER

(Fig. 2 is referred to on Page 5.)



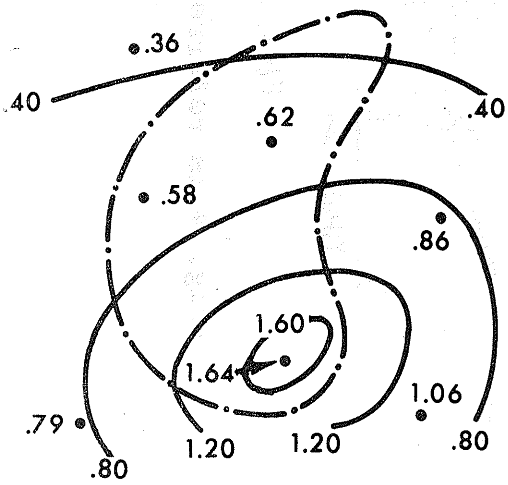
$$\frac{.58 + .62 + 1.64}{3} = \underline{\underline{.95 \text{ IN.}}}$$

ARITHMETIC MEAN



OBSERVED PRECIPITATION (IN.)	POLYGON AREA	PERCENT TOTAL AREA	WEIGHTED PRECIP. (IN.)
.36	2	1	0
.58	77	24	.14
.62	132	40	.25
.79	4	1	.01
1.64	112	34	.56
	327	100	.96 IN.

THIESSEN METHOD



ISOHYET LIMITS	AREA ENCLOSED	PERCENT TOTAL AREA	AVE. PRECIP. (IN.)	WEIGHTED PRECIP. (IN.)
>1.6	19	6	1.64	.10
1.2 - 1.6	60	18	1.40	.25
.8 - 1.2	87	27	1.00	.27
.4 - .8	139	42	.60	25
< .4	22	7	.36	.03
	327	100		.90 IN.

ISOHYETAL METHOD

FIG. 3. AREAL AVERAGING OF PRECIPITATION

(Fig. 3 is referred to on Page 9.)

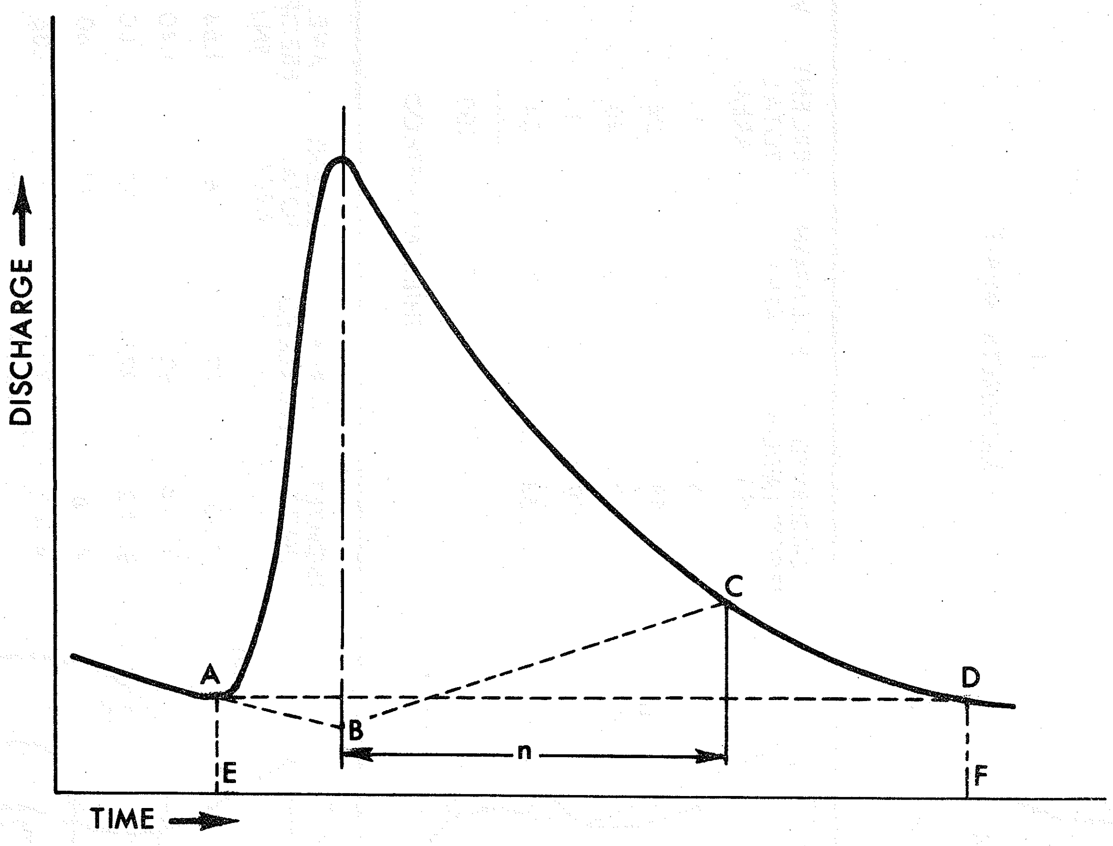
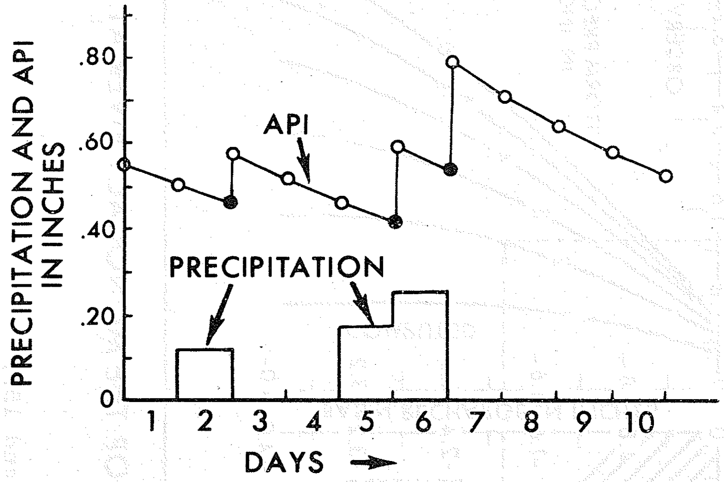


FIG. 4. HYDROGRAPH ANALYSIS

(Fig. 4 is referred to on Pages 10, 22 and 23.)



DATE →	1	2	3	4	5	6	7	8	9	10
0.9 OF YESTERDAY'S API	.50	.45	.51	.46	.41	.52	.69	.62	.56	.50
PRECIPITATION IN PAST 24 HRS.	0	.12	0	0	.17	.25	0	0	0	0
API FOR TODAY	.50	.57	.51	.46	.58	.77	.69	.62	.56	.50

FIG. 5. COMPUTATION AND PLOTTING OF ANTECEDENT PRECIPITATION INDEX (API)

(Fig. 5 is referred to on Pages 6 and 10.)

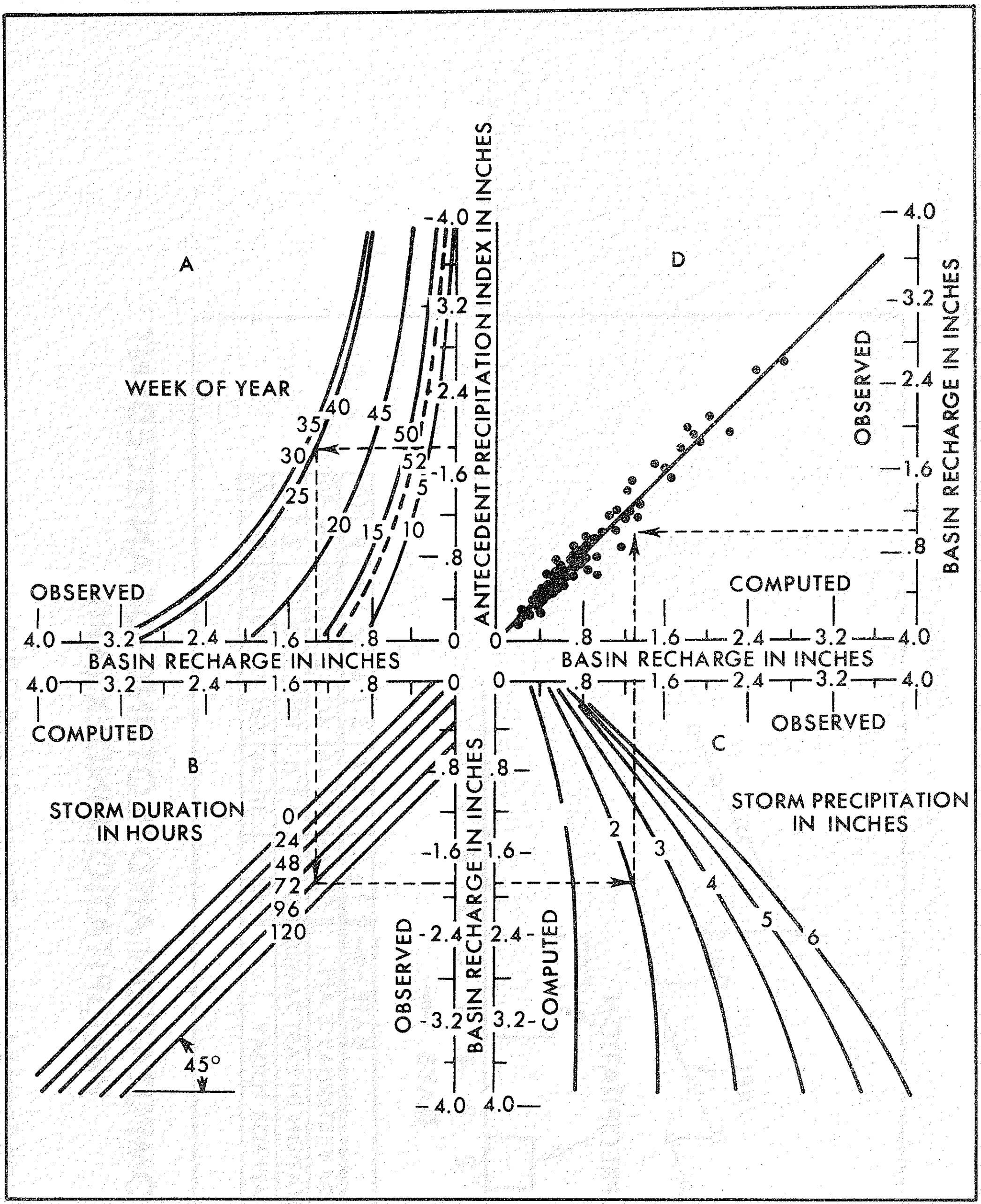


FIG. 6. BASIN RECHARGE RELATION FOR THE MONOCACY RIVER AT JUG BRIDGE, MD.

(Fig. 6 is referred to on Pages 12, 13 and 15.)

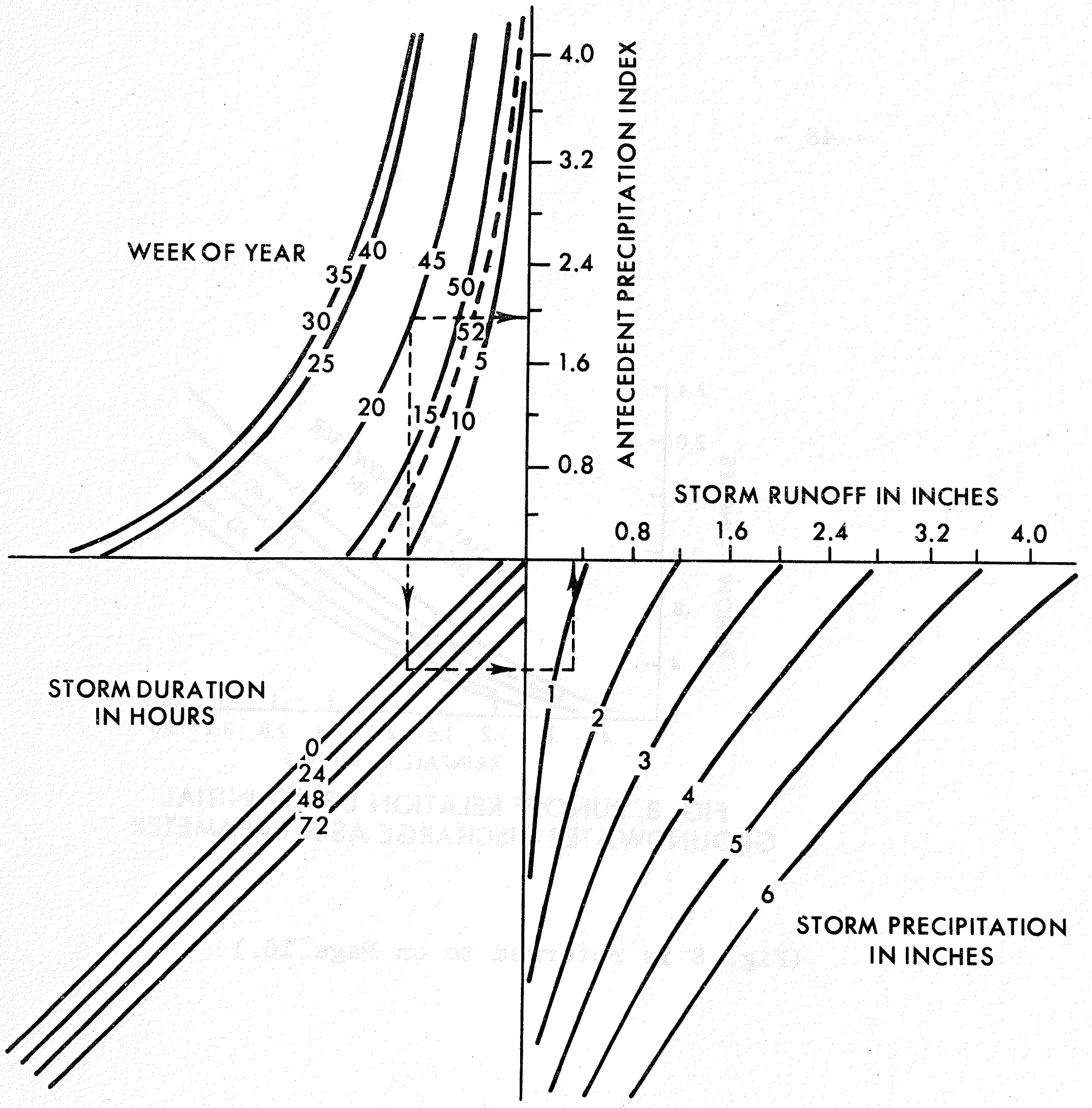


FIG. 7. RUNOFF RELATION FOR MONOCACY RIVER AT JUG BRIDGE, MD.

(Fig. 7 is referred to on Pages 6, 13, and 29.)

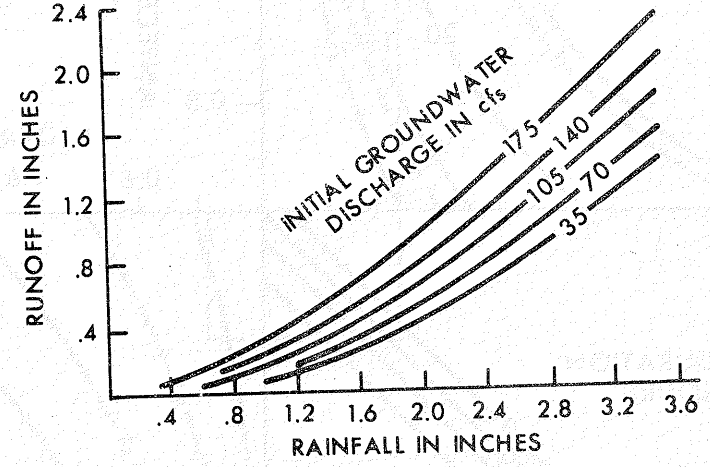


FIG. 8. RUNOFF RELATION USING INITIAL GROUNDWATER DISCHARGE AS A PARAMETER

(Fig. 8 is referred to on Page 16.)

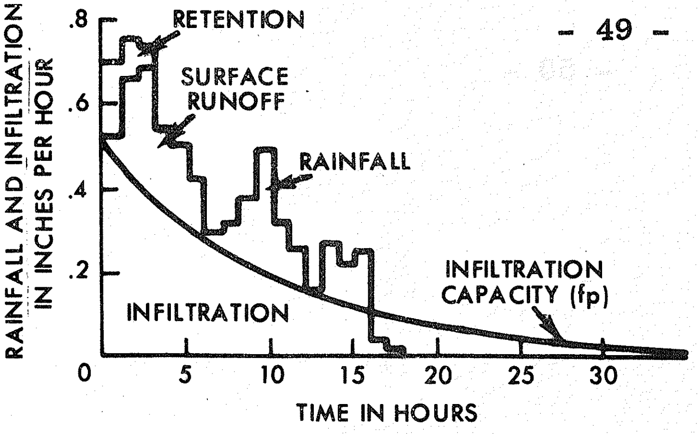


FIG. 9. APPLICATION OF INFILTRATION - CAPACITY CURVE

(Fig. 9 is referred to on Page 17.)

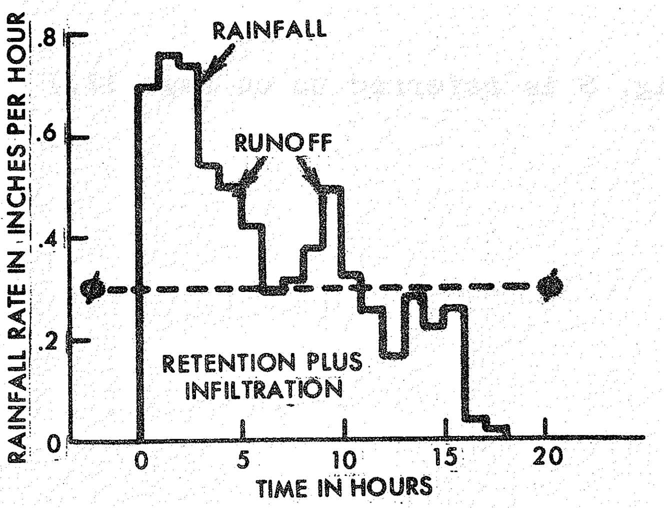
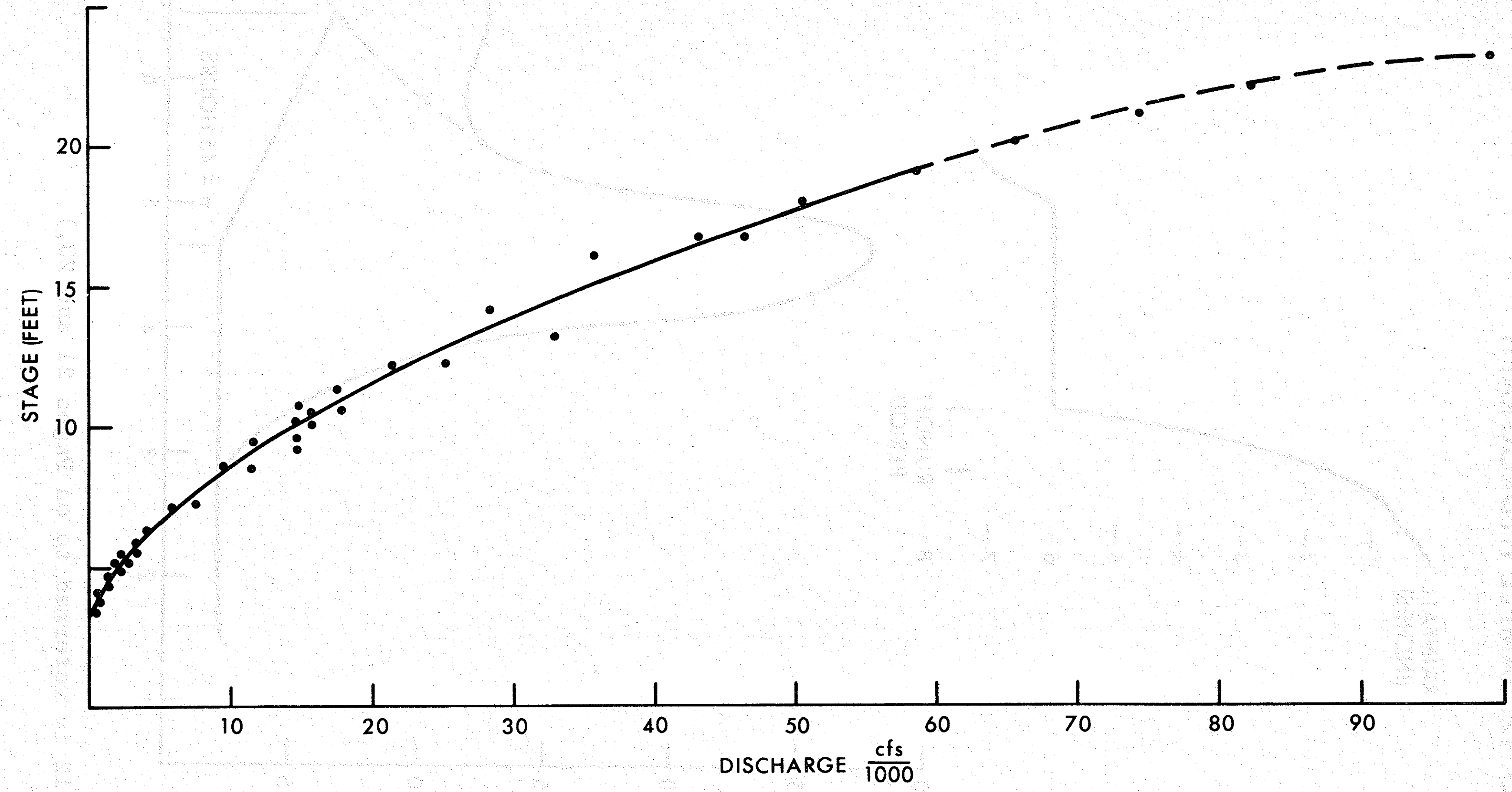


FIG. 10. APPLICATION OF ϕ INDEX IN ESTIMATING RUNOFF

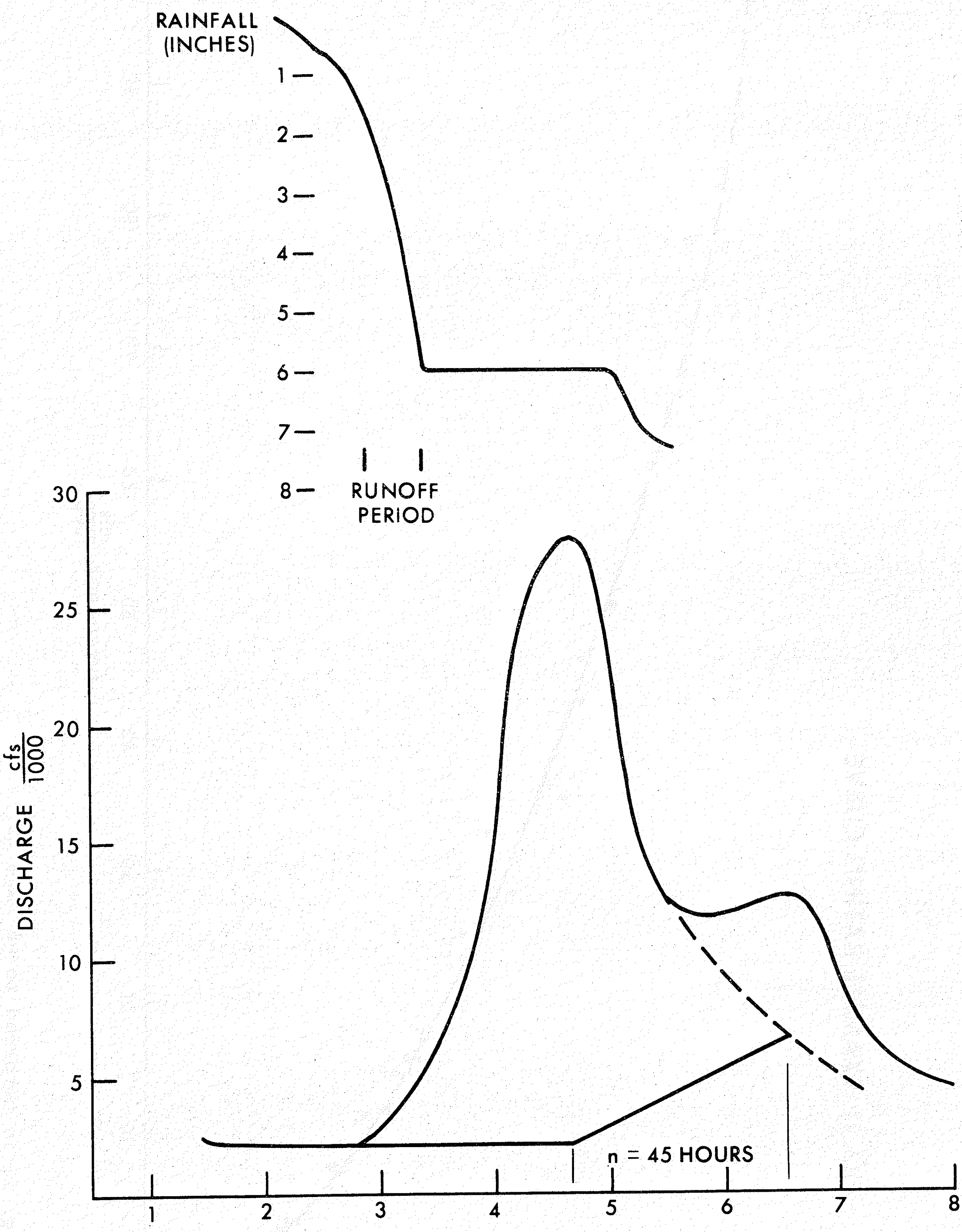
(Fig. 10 is referred to on Page 18.)

FIG. 11. EXAMPLE RATING CURVE



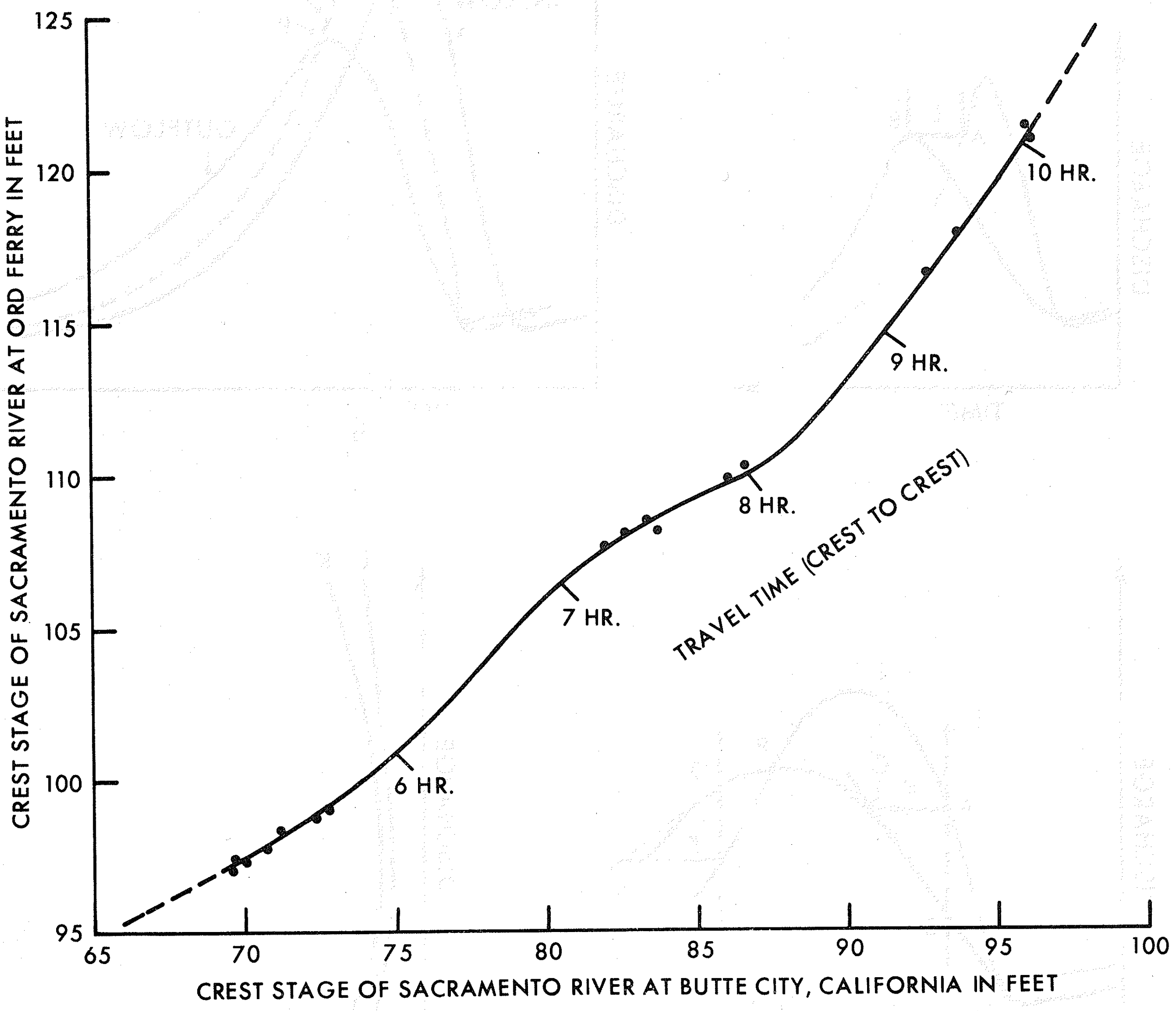
(Fig. 11 is referred to on Page 22.)

FIG. 12. SAMPLE HYDROGRAPH



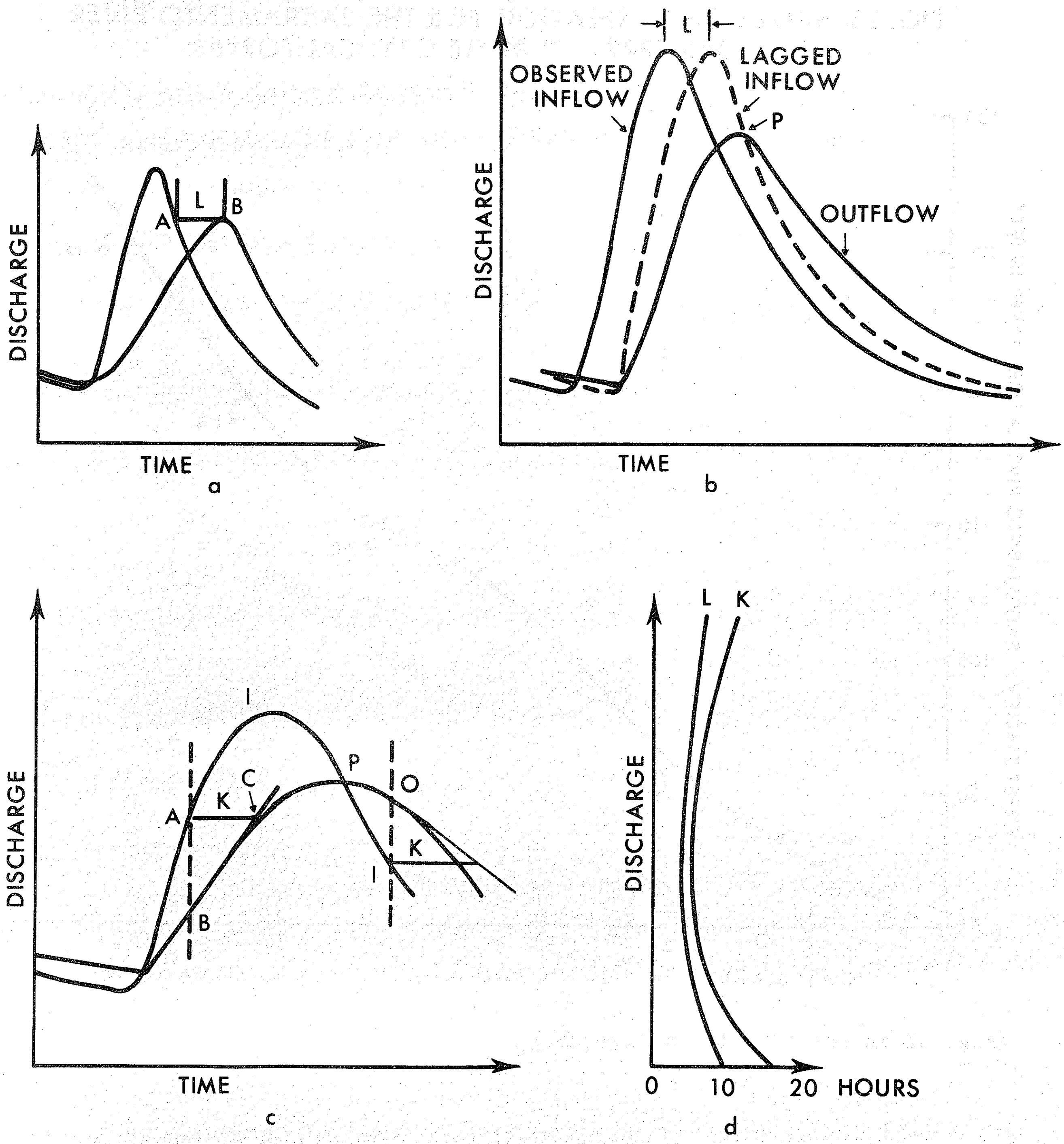
(Fig. 12 is referred to on Pages 21 and 23.)

FIG. 13. SIMPLE GAGE RELATION FOR THE SACRAMENTO RIVER FROM ORD FERRY TO BUTTE CITY, CALIFORNIA



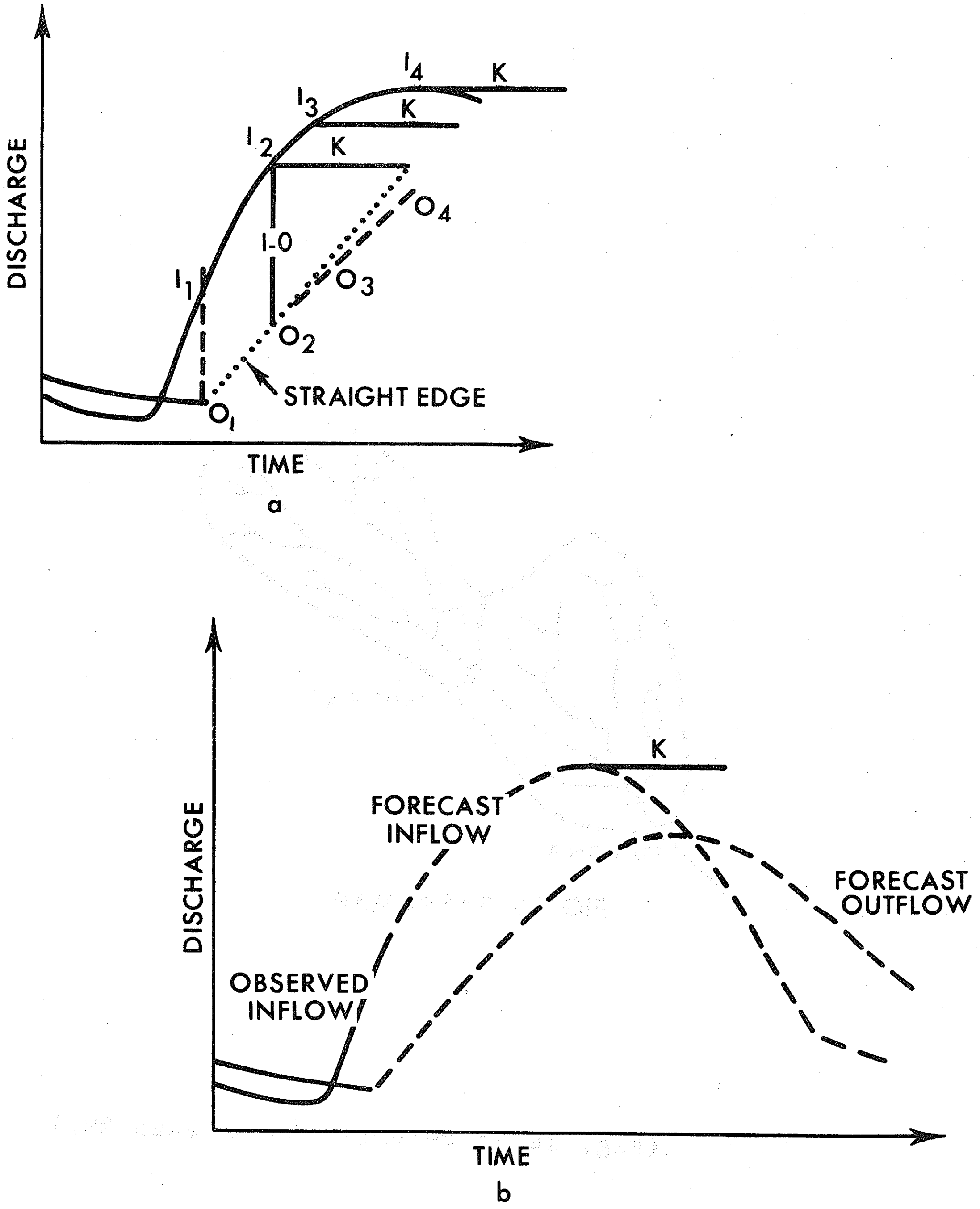
(Fig. 13 is referred to on Page 25.)

FIG. 14. DETERMINING K AND L



(Fig. 14 is referred to on Pages 25 and 26.)

FIG. 15. K AND L ROUTING



(Fig. 15 is referred to on Page 26.)

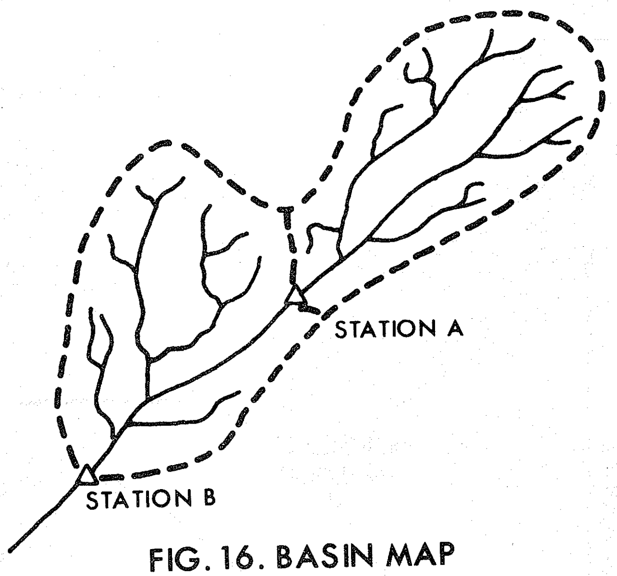
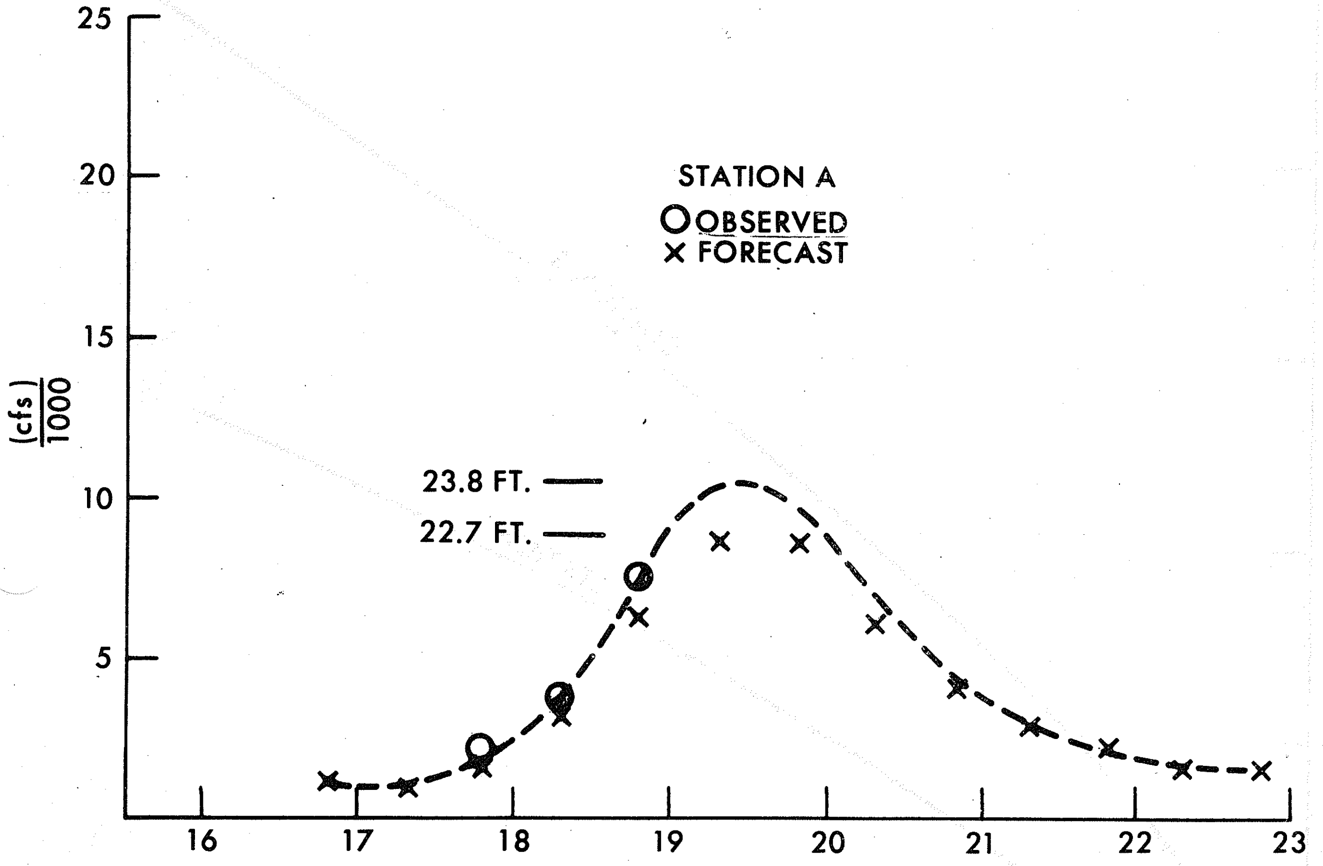


FIG. 16. BASIN MAP

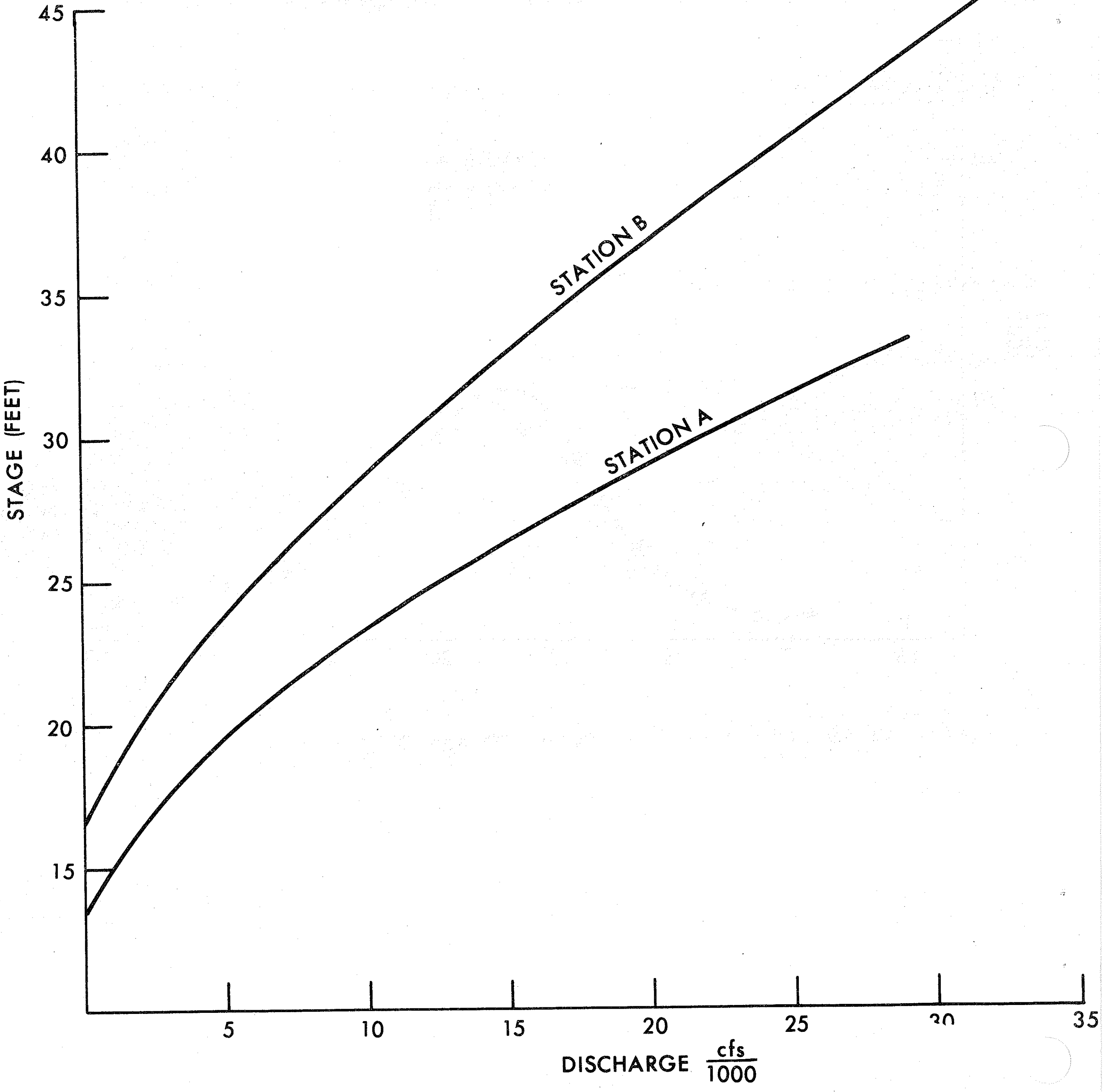
(Fig. 16 is referred to on Page 29.)

FIG. 17. FORECAST HYDROGRAPH



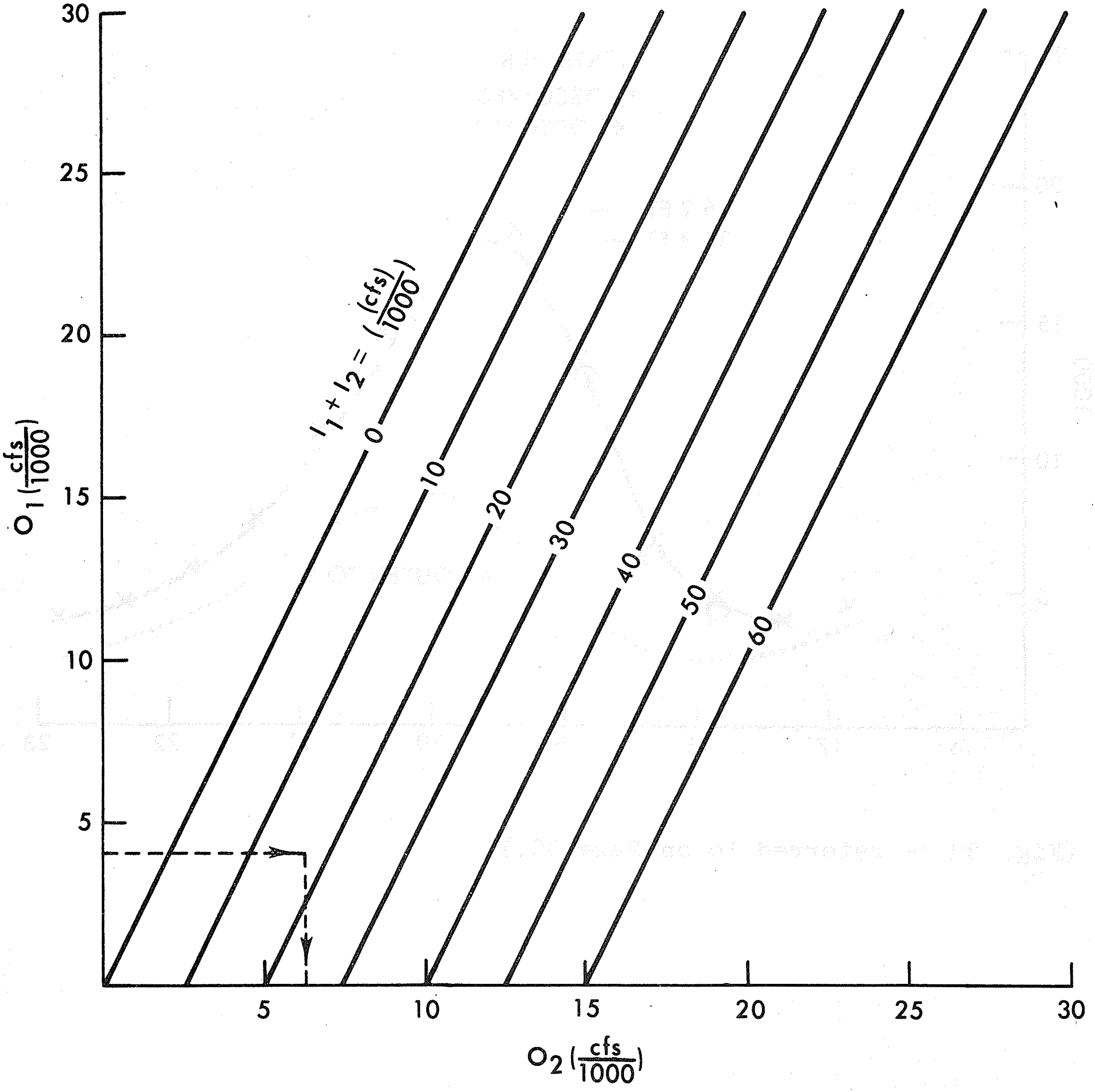
(Fig. 17 is referred to on Pages 22 and 29.)

FIG. 18. RATING CURVES



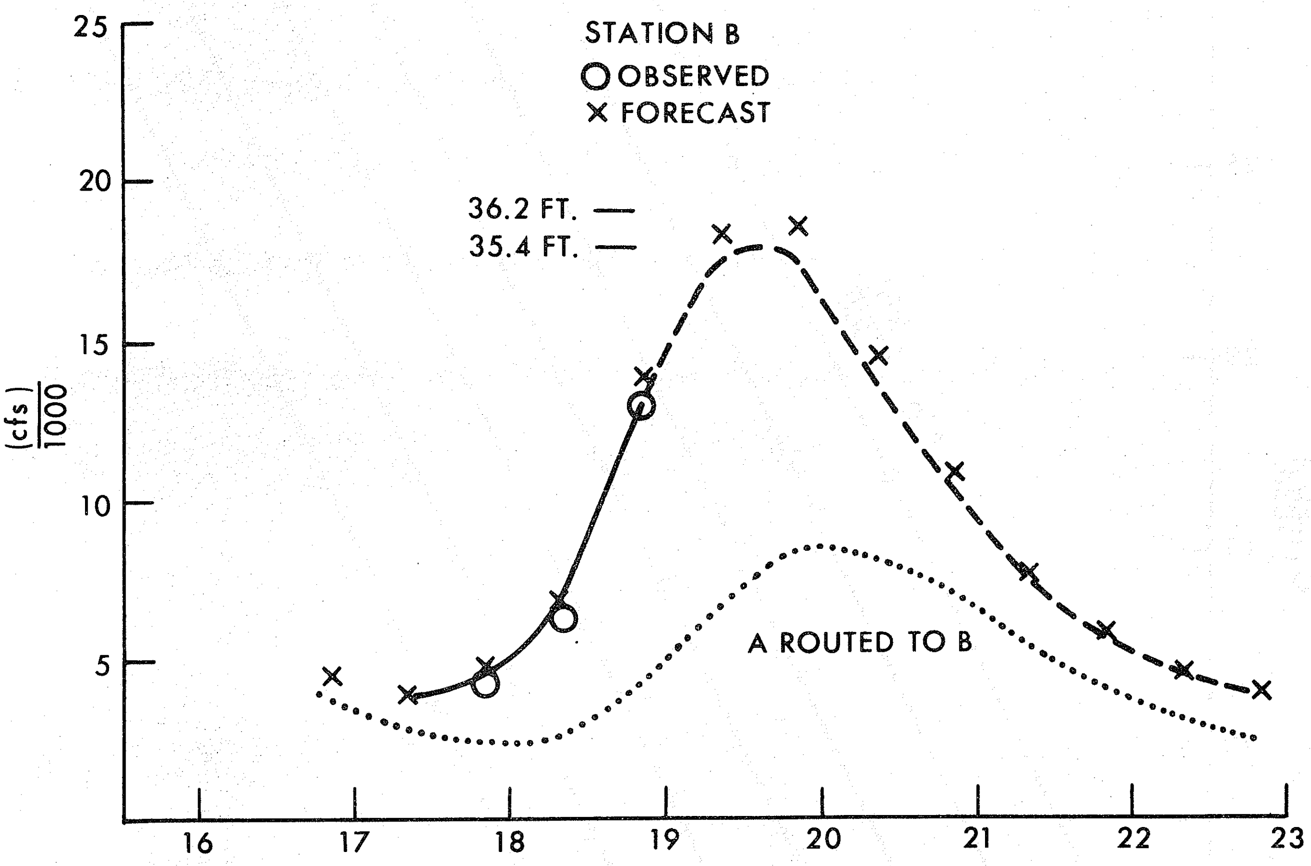
(Fig. 18 is referred to on Page 30.)

FIG. 19. MUSKINGUM ROUTING DIAGRAM



(Fig. 19 is referred to on Page 30.)

FIG. 20. FORECAST HYDROGRAPH



(Fig. 20 is referred to on Page 30.)

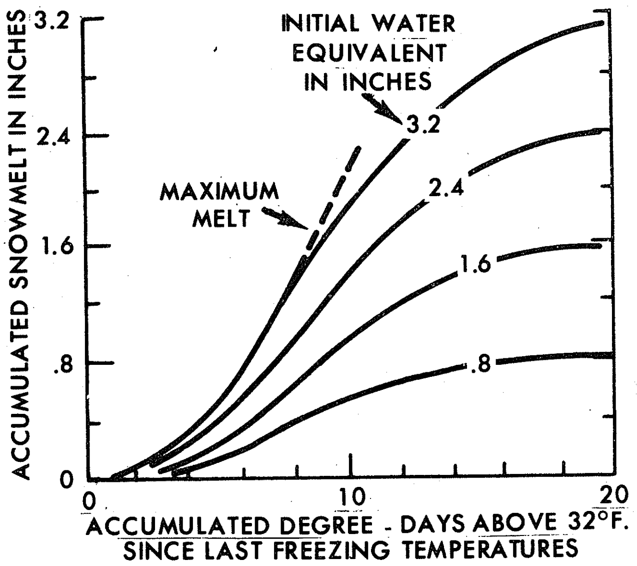


FIG. 21. TYPICAL SNOWMELT RELATION

(Fig. 21 is referred to on Page 31.)