A United States Contribution to the International Hydrological Decade

IHD 1965 1974

HEC-IHD-0400

Hydrologic Engineering Methods For Water Resources Development

Volume 4
Hydrograph Analysis

October 1973

Approved for Public Release. Distribution Unlimited.

IHD-4

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the date needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** October 1973	**3. REPORT TYPE AND DATES COVERED** IHD Volume 4	
4. TITLE AND SUBTITLE Hydrologic Data Management			**5. FUNDING NUMBERS**
6. AUTHOR(S) Edward F. Hawkins, Warren Sharp, Dale Burnett, Ken Brooks			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center 609 Second Street Davis, CA 95616-4687			**8. PERFORMING ORGANIZATION REPORT NUMBER** IHD-4
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER** N/A
11. SUPPLEMENTARY NOTES			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for Public Release. Distribution of this document is unlimited.			**12b. DISTRIBUTION CODE**

13. ABSTRACT *(Maximum 200 words)*

This is Volume 4 of the 12 volume report prepared by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers as a contribution to the International Hydrological Decade.

This volume describes practical techniques for analyzing precipitation, snowmelt, infiltration, and runoff processes as they relate to the computation of flood hydrographs. Topics discussed include: estimation of the areal depth and distribution of precipitation; calculation of runoff from snowmelt; determination of loss rates by linear and nonlinear functions; unit hydrograph theory and derivation; hydrograph reconstitution; and, the estimation of unit hydrograph and loss rate coefficients for ungaged areas. Descriptions of generalized computer programs "Basin Rainfall and Snowmelt Computations" and "Unit Hydrograph and Loss Rate Optimization" are included as appendices.

14. SUBJECT TERMS International Hydrological Decade, Storm Runoff, Effective Precipitation, Snowmelt, Hydrographs, Unit Hydrographs, Rainfall-Runoff Relationships			**15. NUMBER OF PAGES** 160 **16. PRICE CODE**
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	**18. SECURITY CLASSIFICATION OF THIS PAGE** UNCLASSIFIED	**19. SECURITY CLASSIFICATION OF ABSTRACT** UNCLASSIFIED	**20. LIMITATION OF ABSTRACT** UNLIMITED

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

Hydrologic Engineering Methods for Water Resources Development

Volume 4
Hydrograph Analysis

October 1973

US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center
609 Second Street
Davis, CA 95616

(530) 756-1104
(530) 756-8250 FAX
www.hec.usace.army.mil

IHD-4

FOREWORD

This volume is part of the 12-volume report entitled "Hydrologic Engineering Methods for Water Resources Development," which is being prepared by the Hydrologic Engineering Center (HEC) as a part of the U. S. Army Corps of Engineers participation in the International Hydrological Decade. Volume 4 describes methods and procedures for analyzing precipitation, snowmelt, infiltration and the runoff process for the purpose of computing flood hydrographs. Emphasis is placed on selected practical procedures for analyzing flood hydrographs rather than on the underlying theory behind the procedures. Although many of the methods and procedures described herein have been used successfully in Corps of Engineers studies, the volume should not be construed to represent the official policy or criteria of the Corps.

This volume was prepared primarily from technical material developed by the U. S. Army Corps of Engineers during the past few years. Many individuals from the HEC have contributed to its contents including Messrs. Edward Hawkins, Warren Sharp, Dale Burnett, and Ken Brooks. Helpful comments were received from the HEC reviewers Messrs. Augustine J. Fredrich, John Peters, Darryl Davis, Leo R. Beard (HEC Director until July 1972) and Bill S. Eichert (present HEC Director).

CONTENTS

CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

Chapter 1

Introduction

CHAPTER 1. INTRODUCTION

Various hydrologic processes contribute to the formation of a runoff hydrograph resulting from rainfall and snowmelt on a watershed. The study of these processes and the determination of the key parameters affecting them give insight to hydrograph production. This volume will describe certain methods of deriving fundamental hydrologic parameters from observed events, and will suggest techniques of utilizing these deduced parameters in the hydrologic design of water resource developments. It presents some highly useful and up-to-date procedures concerned with hydrograph analysis, with emphasis devoted to areas where the quantity of hydrologic data is limited. Several of these procedures are illustrated in sufficient detail to facilitate a thorough understanding, not only of the principles and procedures, but of application and the management of the basic data as well. Although the emphasis in this volume is placed on computer-oriented techniques, it is recognized that these same techniques may not be as useful when electronic computers are not readily available. Accordingly, Appendix 1 describes some techniques that are oriented toward desk calculator use. Where pertinent, certain generalized hydrologic engineering computer programs that have been found to be useful to the engineer engaged in water resource studies are described, and two of them are included as appendices to this volume.

This volume is not intended to be a compendium of available methods. The methods presented have been selected for their applicability to the more frequent types of problems encountered in hydrograph analysis. While it is known that many of these techniques contain assumptions (such as linearity) that do not accurately describe the processes actually occurring in nature, experience has shown that these assumptions need not be a major handicap, considering the quality of the basic data that are usually available, and provided that the techniques are applied with judgment and understanding of the assumptions. In addition, many of the functions described in this volume are based in part on the fact that the hydrologic quantities utilized in hydrograph analysis are averaged or "lumped" for computation purposes. This assumption can severely limit the techniques in some cases; while in others, the limitation can be relatively minor. The governing limitations of each technique are indicated and their effect on the technique is discussed in more detail in the following chapters.

Chapter 2

Analysis of Precipitation

CHAPTER 2. ANALYSIS OF PRECIPITATION

Section 2.01. Introduction

Precipitation is the general term for all forms of moisture emanating from clouds and falling to the ground. The principal forms are dew, rain, hail, sleet and snow. Estimates of intensity, depth and areal distribution of precipitation will be discussed in this chapter.

Limitations in the application of precipitation data are largely related to statistical sampling inadequacies. The existing precipitation network in the United States and most other countries is ordinarily not sufficiently dense to define storm precipitation for average depth over areas of the size suited for hydrograph analysis. In fact, it is known that many "cloudbursts" occur that are not recorded at any observation station.

The nature of storm precipitation and the uses for which precipitation data are intended should determine network density, since the probability that a storm center will be defined adequately varies with network density. A relatively sparse network of stations will often suffice for studies of large general storms or for determining long-term averages over large areas of level terrain, but a dense network is required to delineate the rainfall pattern in small-area storms.

In this regard, it should be noted, however, that no feasible means of accounting for all the effects of random variations in the areal distribution of rainfall have been devised, nor is information on precipitation (and other hydrologic variables) sufficient to define areal variations accurately. Accordingly, some assumptions of uniformity in precipitation patterns in subareas are necessary, and the maximum subarea size feasible for hydrograph analysis is limited by the degree of random precipitation variation. This limitation can be relatively minor in areas of general storms where precipitation is highly correlated from point to point. On the other hand, it can be highly restrictive where precipitation is erratic, as in areas that experience cloudbursts.

Section 2.02. Estimating Missing Precipitation at a Point

It is often necessary or desirable to supplement incomplete precipitation records by estimating values that are missing at one or more stations. One procedure that can be used is to estimate the precipitation from that observed at stations as close to and as evenly spaced as possible around the station with the missing record. Experience has indicated that at least three stations should be used. If the average annual precipitation at each of these stations is about equal, a simple arithmetic average of the precipitation at the three selected stations provides the estimated amount. If there is a significant difference in the average annual precipitation of the stations, then further adjustments should be made or another technique should be used.

Another method of estimating missing data is by means of regional analysis, as discussed in Volume 2 of this report. This method determines by multiple-linear regression the correlation between the station with the missing data and all other nearby stations for the period when they have coincident records. By using the resultant regression equation and adding a random component, the missing record can then be estimated.

A more commonly used technique is the mass precipitation curve, illustrated in fig. 2.01. Mass precipitation curves are determined by plotting accumulative precipitation versus time. Curves are first plotted for continuous recording stations within and around the study area, and then similar curves are constructed for nonrecording stations in the same area, using the recording station curves as a guide. Stations should be compared for possible similarities of topographic influences and meteorological conditions during the storm and grouped accordingly. The mass precipitation curves should be completed in accordance with these groupings by interpolating the curves between established points in such a manner as to reflect reasonable consistency with the period of precipitation at neighboring stations. Incremental values can then be extracted from the curves for use in determining mean precipitation over an area. Care must be used in this procedure, however, because minor smoothing of mass curves could change intensities greatly.

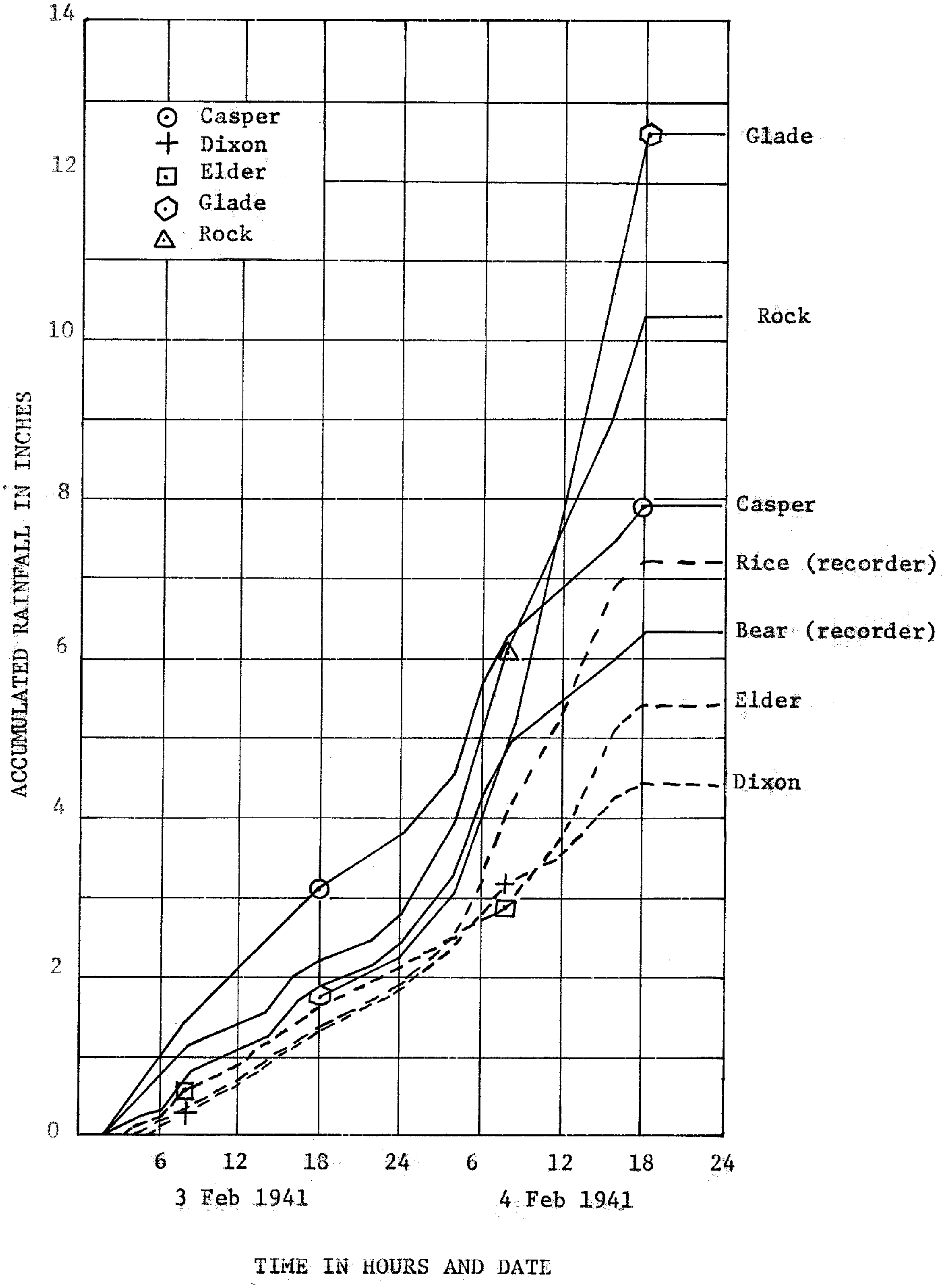


Fig. 2.01. Mass precipitation curves

Section 2.03. Estimating Areal Depth of Precipitation

The average depth of precipitation over a specified area is required in many hydrologic problems. The three most commonly used methods for computing mean precipitation over an area are: (1) the station-average method, (2) the Thiessen method and (3) the isohyetal method. These methods are illustrated in fig. 2.02. In each of the methods, the accuracy with which rainfall depth over an area can be estimated depends on the number and spacing of precipitation stations. In general, the larger the area, the greater the number of sampling points included within the area, and the greater the resulting accuracy of average depth determinations.

Station-Average Method

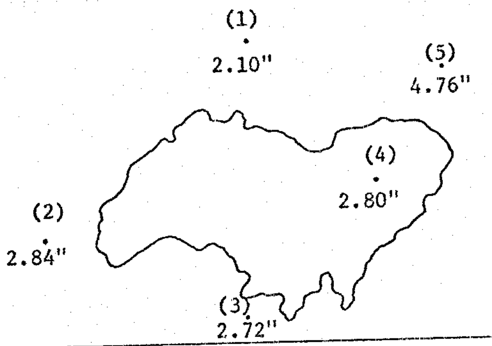
The simplest method to obtain the mean areal depth is to compute the arithmetic mean by dividing the sum of the depths at all stations by the number of stations, as illustrated in fig. 2.02. This often is as accurate as is justified for the purpose or by the basic data. If stations are spaced with reasonable uniformity and the individual gage catches do not vary widely from the mean, the arithmetic average will usually suffice. In most cases, however, the gages are not uniformly spaced, and topographic and other influences produce a large variation in the areal distribution of precipitation. In such cases, more precise methods are required.

Thiessen Method

In the Thiessen method, it is assumed that the amount of precipitation at any station can be applied halfway to the next station in any direction. A weighting process is used by determining the area of influence associated with each station and assuming the occurrence of uniform precipitation over each of these areas is equal to the measured station precipitation. The area of influence of each station is obtained by constructing polygons determined by drawing perpendicular bisectors to lines connecting the stations, as shown in fig. 2.02b. The bisectors are the boundaries of the effective area for each station. The area inclosed by each polygon is measured, and weighted average precipitation for the total area is computed by multiplying the precipitation at each station by the proportion of the total area within its polygon and adding the products. The results are usually considered to be more accurate than those obtained by simple arithmetic averaging. However, this method may require extensive computation, since a new Thiessen diagram is required for each change of station network, and the method does not account for orographic influences or the erratic nature of precipitation.

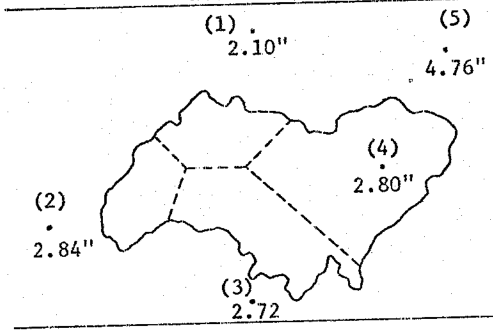
Isohyetal Method

A more accurate method of averaging precipitation over an area and, at the same time, showing the areal variation, is the isohyetal method. A precipitation-depth contour map is determined by plotting station precipitation and constructing lines of equal precipitation called isohyets, as illustrated in fig. 2.02c. Average depths are obtained by measuring the areas between adjacent isohyets. Each increment of area is multiplied by the estimated average precipitation depth for that area. The separate terms are then added and the sum is divided by the total area to obtain the average depth. The isohyetal method permits the use and interpretation of all available data and is well adapted for display and examination. In constructing an isohyetal map, the engineer can make full use of his knowledge of orographic effects and storm morphology, and in this way the final map should represent a more realistic precipitation estimate than could be obtained from the gaged amounts alone. The accuracy of the isohyetal method is, to a large degree, dependent upon the skill of the engineer performing the analysis. If linear interpolation between stations is used, the results will be essentially the same as those obtained with the Thiessen method. In mountainous areas, systematic



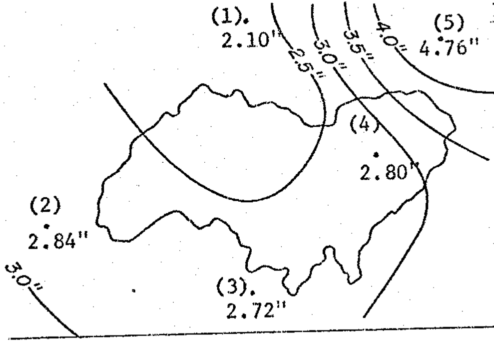
$$\frac{2.10 + 2.84 + 2.72 + 2.80 + 4.76}{5} = \underline{\underline{3.04 \text{ in.}}}$$

(a) ARITHMETIC MEAN



Polygon	Observed Precip.	Area (sq mi)	Percent Tot.Area	Weighted Precip.
(1)	2.10	174.4	15.6	.33
(2)	2.84	154.3	13.8	.39
(3)	2.72	328.7	29.4	.80
(4)	2.80	460.6	41.2	1.15
		1,118.0	100.0	2.67 in

(b) THIESSEN METHOD



Isohyet	Average Precip.	Area Isohyet	Percent Tot.Area	Weighted Precip.
2.0-2.5	2.30	335.4	30.0	.69
2.5-3.0	2.70	679.7	60.8	1.64
3.0-3.5	3.25	71.6	6.4	.21
3.5-4.0	3.70	31.3	2.8	.10
		1,118.0	100.0	2.64 in

(c) ISOHYETAL METHOD

Fig. 2.02. Estimating areal depth of precipitation

sampling errors usually result because of the preponderance of stations at low elevation. Their average usually represents less precipitation than occurs on the basin as a whole. In such regions, an isohyetal map can still be employed to advantage if the effect of topography is taken into consideration in locating isohyetal lines.

Where average annual precipitation varies appreciably over a basin and storm precipitation usually reflects such variation (as in mountainous regions), an adjustment by use of long-term averages can be made. The average storm precipitation for a basin is determined by multiplying the weighted storm precipitation at each station by the ratio of the average annual precipitation of the basin to the weighted average annual precipitation at that station. The long-term average for the basin is determined by one of the methods previously discussed, using all stations having appreciable record. Where average annual precipitation is not a good indicator of the areal variation of storm precipitation, average precipitation for the rainy season, average storm precipitation, or storm precipitation amounts exceeded with a specified frequency (such as once in 10 years) can be used for this adjustment. The principal advantage of this type of adjustment is that some information on normal area patterns is obtained from stations that do not have records for a particular storm.

Computer program number 723-G1-L2260, "Basin Rainfall and Snowmelt Computation," described in Appendix 2, is designed to accept precipitation gage rainfall data for a specific storm period and time interval for an entire region, and to compute basin-mean values for any number of basins in the region with output time intervals that are specified multiples or fractions of the input time interval. These routines are also incorporated into computer program, HEC-1, "Flood Hydrograph Package," which is described in Volume 1 of this report.

Chapter 3

Runoff from Snowmelt

CHAPTER 3. RUNOFF FROM SNOWMELT

Section 3.01. Introduction

Snow is hydrologically important in many parts of the world. Generally, snowmelt is an important factor in hydrograph analysis in mountainous and high plains basins where the snowpack accumulates throughout the snowfall season and causes flooding during the melt season. Also, the presence of snow can greatly influence the short-term runoff characteristics of a basin under certain conditions of air temperature and rainfall. The evaluation of snowmelt quantities contributing to runoff can be important for (a) the determination of floods for planning and design purposes, (b) operational flood forecasting, and (c) hydrograph analysis for determining unit hydrograph and loss rate characteristics.

A snowpack can be considered a frozen reservoir for which the water equivalent can be measured quantitatively if given enough time and effort. The problem, however, is to be able to adequately predict energy supplies so that an estimate can be made of the melt rate or the rate of delivery of liquid water to the snow-soil interface. As opposed to rainfall, snowmelt quantities cannot be measured directly, but must be estimated from meteorological parameters. The rate of overall basin snowmelt is governed by the transfer of energy involving radiation, convection, advection, and conduction. The relative importance of each of these processes of heat transfer is highly variable, depending upon conditions of weather and local environment. The natural sources of heat energy in melting snow are absorbed solar radiation, net longwave (terrestial) radiation, convection and advection heat transfer from the air, latent heat of vaporization by condensation from the air, conduction of heat from the ground and from rain water. Since heat from the ground is usually minor in relation to the other sources of heat where the snowpack is significant, it is usually neglected in determining snowmelt quantities during floods.

Section 3.02. Snowfall

Snowfall is that part of precipitation that forms and reaches the ground as ice crystals. If air temperatures near the surface are warmer than those aloft, snow crystals may melt as they descend and occur as rainfall at the surface. In mountainous watersheds, snow may accumulate in the higher elevations while rain occurs at lower elevations. Whether precipitation falls as rain or snow can be estimated from records of air temperatures at the surface, assuming that snowfall occurs wherever surface temperatures are below 34°F to 36°F (1°C to 2°C). In mountainous regions, the elevation above which snowfall occurs at any particular time can be determined by applying a lapse rate to surface air temperatures. This is a common practice since most air temperature stations are located in the more accessible,lower elevation areas.

Section 3.03. Snowpack Measurement

Where spring snowmelt floods are of particular concern, it is usually practical to evaluate the areal extent, water equivalent and depth of the snowpack at specified times before and during the early melt period. The measurements of water equivalent at selected points in the basin and estimates of the areal extent of the snow covered area are of particular importance. In a manner very similar to the isohyetal analysis of storm rainfall, the amount of water in the snowpack and its areal extent can be mapped. Such mapping must consider elevation and exposure in a mountainous terrain. Where there is appreciable variation of snowpack within the basin, the snowpack water equivalent should be measured at various elevations and exposures. If direct measurement of the snowpack is not made, some approximation of seasonal snow accumulation can be made from rainfall and temperature measurements.

Section 3.04. Sources of Heat Energy

Solar Radiation

Solar (or shortwave) radiation is the prime source of all energy at the earth's surface. The amount of heat energy transferred to the snowpack by solar radiation varies with latitude, season, time of day, atmospheric conditions, forest cover, basin orientation, and reflectivity (albedo) of the snow. Cloud cover significantly affects the transmission of solar radiation and is the cause of the largest variations in solar radiation incident to the snow surface. The direct measurement of solar radiation at the snow surface, therefore, reflects the influence of clouds. Inasmuch as residual solar radiation measurements are not generally available, it is usually necessary to estimate incoming radiation indirectly from observations of duration of sunshine, observations of cloud conditions, or in some cases, daily air temperature fluctuations.

Local conditions, such as basin slopes and orientation, and forest type and cover, have a marked effect upon the amount of solar radiation received on the snow surface. Solar radiation incident on south-facing slopes in the northern hemisphere is much greater than on north-facing slopes. Similarly, the amount of solar radiation incident on a snowpack is greater in a nonforested area than in a dense forest. The percentage of transmitted solar radiation is related to forest composition, density, and condition of trees. Determination of the amount of sunshine transmitted through the forest is, at best, an approximation. For basin application, the transmission factor and forest canopy density can be combined into a single factor, usually termed the effective forest cover.

The albedo of a snowpack varies considerably with time, and is, therefore, important in estimating the amount of solar energy absorbed by the snowpack. Albedo is expressed as the percent of reflected shortwave radiation incident on the snow surface. Values range from more than 80 percent for new-fallen snow to as little as 40 percent for an older, ripe snowpack. Since reflectivity depends on the angle of incidence as well as on snow surface characteristics, the albedo will vary with season, latitude, and basin slope for the same surface characteristics.

Terrestial Radiation

Snow is considered to be an almost perfect "black body" with respect to terrestial (or longwave) radiation. Therefore, snow absorbs all such radiation incident upon it and emits the maximum possible radiation. For clear skies, the heat gain from longwave radiation from the atmosphere and forest cover is generally less than the heat loss. The presence of cloud cover has a marked effect on the longwave energy exchange at the snow surface. Since a cloud is also considered to be a "black body" with respect to longwave radiation, temperature differences between a cloud base and the snow surface govern the energy exchange. Evaluation of longwave radiation exchange with the snowpack is usually simplified by assuming a linear relationship between longwave radiation and air temperature. This assumption is valid for the limited range of temperatures that are normally experienced in snowmelt computations.

Convection-Condensation

The vertical and horizontal fluxes of heat energy between the air mass and snowpack are usually of secondary importance to radiation. However, significant amounts of sensible heat energy can be transferred from an overlying air mass to a colder snowpack. Similarly, if vapor pressure gradients are such that condensation occurs on the snow surface, the latent heat of vaporization (approximately 600 calories per gram of water) is released to the snowpack. The importance of these sources of energy depends upon not only the atmospheric or storm conditions, but also on the basin exposure to wind and the related topographic and forest characteristics.

Minor Sources of Heat Energy

In addition to the previously discussed sources of heat energy for snowmelt, the conduction of heat from the ground and the heat content of rainfall provide, in most instances, rather minor amounts of heat energy for snowmelt. The conduction of heat energy from the underlying ground to the snowpack has little effect on daily snowmelt quantities, however, this process may be important in terms of priming the soil surface prior to the actual melt season. The amount of heat yielded to the snowpack by rain water is largely dependent upon the temperature of the rainwater. Also, the freezing of rain water in the snowpack releases heat energy (latent heat of fusion,80 calories per gram) to the snowpack.

Section 3.05 Snowpack Condition

Snowmelt at any point in time is highly dependent upon the condition of the snowpack as well as the heat energy flux. The snowpack condition is generally identified in terms of its "cold content" and its water-holding capacity or liquid-water deficiency. Basically, energy is required to raise the snowpack temperature to 32°F (0°C) and to melt enough snow to satisfy the water-holding capacity of the snowpack before liquid water can reach the soil surface. Once these conditions are met, the snowpack is considered to be "ripe" and any additional energy input to the snowpack causes snowmelt runoff. Although these properties of a snowpack are difficult to quantify in a practical sense, some assessment of snowpack condition is needed to predict the proper timing of snowmelt runoff.

Section 3.06 Snowmelt Equations

The complexity of the snowmelt process coupled with a general lack of energy budget data, necessitates the use of rather simplified mathematical equations to estimate snowmelt. The type of equation used in most instances is determined as much by data availability as by the basin and storm characteristics. Numerous snowmelt equations, their development, and examples of application are presented in references 3.04 and 3.05.

When energy-budget data are available in sufficient quantity and quality, the generalized snowmelt equations can be used. For example, snowmelt during a rainstorm for an open or partly forested basin can be computed by the following equation if English units are used:

$$M = .09 + (.029 + .0084kW + .007R)(T-TF) \quad (3\text{-}1)$$

The modified equation for metric units is:

$$M = 2.286 + (1.326 + .2134kW + .125R)(T-TF)$$

where:

M = Snowmelt in inches (or mm)

k = convection-condensation melt constant for a basin which represents the mean exposure of the basin; k would range from 1.0 for an unforested basin to 0.3 for a densely forested basin

W = Wind speed in miles per hour (or kph) at 50 feet (15m) above the snow

R = Rainfall in inches (or mm) per day

T = Air temperature in degrees F (or degrees C) at the 10-foot level (assumed to equal the temperature of rainwater)

TF = Temperature of the snowpack in degrees F (or degrees C), usually assumed to be 32°F (0°C) for a melting snowpack

Equation 3-1 can be further modified by adding a dimensionless coefficient to account for undetermined variation in basin snowmelt. This modification results in the following equation:

$$M = C\ (.09 + (.029 + .0084kW + .007R)(T-TF)) \quad (3\text{-}2)$$

or $$M = C\ (2.286 + (1.326 + .2134kW + .125R)(T-TF))$$

for English and metric units, respectively.

When rainfall is not occurring, snowmelt can be computed for a partly-forested basin by the following equation with English units:

$$M = k'(1-F)(.004S)(1-A) + k(.0084W)(.22T' + .78TD') + F(.029T') \quad (3\text{-}3)$$

When metric units are used, equation 3-3 becomes:

$$M = k'(1-F)(.1015S)(1-A) + k(.2134W)(.22T' + .78TD') + F(1.326T')$$

where:

k' = Basin shortwave radiation melt factor, indicative of average exposure of open areas to shortwave radiation in comparison with an unshielded horizontal surface (usually 0.9 to 1.1), A horizontal basin would have a $k' = 1.0$

F = Basin average forest canopy cover, expressed as a decimal fraction

S = Observed or estimated solar radiation at the snow surface in langleys per day

A = Albedo of snow surface expressed as a decimal fraction (varies from over .8 for new snow to .4 for ripe snow)

T' = Difference between air temperature measured at 10 feet (3m) and the snow surface, in degrees F (or degrees C)

TD' = Difference between dewpoint temperature measured at 10 feet (3m) and at the snow surface, in degrees F (or degrees C)

A dimensionless coefficient C can again be applied to equation 3-3 to correct for undetermined variations in basin snowmelt, resulting in the following equation:

$$M = C[k'(1-F)(.004S)(1-A) + k(.0084W)(.22T' + .78TD') + F(.029T')] \qquad (3\text{-}4)$$

where:

A = Albedo of snow determined by $.75/(D^{.2})$ and constrained above .4

D = Days since last snowfall

A similar equation with the appropriate constants could be used for metric units.

The coefficient C contained in equations 3-2 and 3-4 is theoretically 1.0. However, because of the difficulty of evaluating many factors such as albedo and wind patterns, the coefficient can be used to calibrate the equations to a particular basin.

The preceding equations are generally useful for study purposes or for design flood derivations where it is desirable to obtain a rational evaluation of factors affecting snowmelt. The energy budget approach, however, is usually not practical for operational usage because of the data requirements. A useful, although simplified approach for computing snowmelt on forested watersheds, is the temperature index or degree-day method. Snowmelt (M) is computed by this method as follows:

$$M = MR\ (T-TB) \qquad (3\text{-}5)$$

where

MR = Melt rate coefficient or degree-day factor in inches (or mm) of melt per degree-day

T = Air temperature in degrees F (or degrees C), above which snowmelt is assumed to occur.

The value of the base temperature depends on whether mean daily or maximum daily temperatures are used. Base temperature values are typically 32°F (0°C) and 40°F (4.4°C) for mean daily and maximum daily temperatures, respectively. Equation 3-5 must be applied with discretion since it is not generally applicable to unforested or open areas.

Section 3.07 Snowmelt Computation

The average snowmelt in a basin can be computed directly for relatively flat regions, by applying one of the preceding equations to the total basin area. In mountainous regions, the selected equation should be applied in turn to each of a number of elevation zones. It is usually adequate to use zones that are 1,000 feet (or 300 meters) in height and to apply a lapse rate (average rate of decline of temperature with elevation) to observed temperature data which are usually available from low elevation stations. Lapse rates can vary considerably with time but usually average about 3°F per 1000 feet (approximately .6°C per 100 meters). It is desirable to use actual variations of surface temperatures with elevation when temperature data are available at different elevations. For each computation interval, the melt in each elevation zone is then multiplied by the area of that zone. The sum of the cross products from all zones can be divided by the total basin area to obtain the basin-mean snowmelt. An example of snowmelt computations is described in Section 3.08.

Several computer programs of varying complexity have been developed with the capability of computing snowmelt. Snowfall and snowmelt computations are made automatically by use of computer programs 723-X6-L2010 and 723-G1-L2260. The first program (HEC-1, Flood Hydrograph Package) will compute snowmelt by use of equations 3-2 or 3-4 and 3-5, and the program is described in Volume 1 of this report. Computer program 723-G1-L2260 (Basin Rainfall and Snowmelt Computation) will compute snowmelt by use of equation 3-5 only, and is attached to this volume as Appendix 2. The SSARR Model (reference 3.06) and the Stanford IV Model (reference 3.02) have capabilities for computing runoff from snowmelt, with the former being used in operational streamflow forecasting. Also, a computer program of the US Forest Service has recently been developed which utilizes a comprehensive energy budget approach for computing snowmelt in mountainous watersheds (ref. 3.03).

Section 3.08 Example of Snowmelt Determination

The example presented is a typical problem encountered in hydrograph analysis where snowmelt quantities must be determined. In this particular problem, adequate data are available so that the energy-budget approach can be used. The metric unit equivalents of equations 3-2 and 3-4 are used in this example.

Selected snowmelt characteristics and coefficients are:

a. Temperature lapse rate of 0.6°C per 100 meters of elevation,

b. Freezing temperature of 0°C for all elevations zones,

c. Rain-freeze temperature (for determining if rainfall or snowfall is occurring) of 1°C,

d. Snowmelt coefficient, C, of 0.70; basin shortwave radiation melt factor k', of 1.0; and convection-condensation melt constant, k, of 0.6 (in equations 3-2 and 3-4), and

e. Basin average forest canopy cover, F, of 0.5 (50 percent cover).

The initial conditions and basin characteristics are given in table 3.01 and climatological data are given in table 3.02.

Table 3.01 Initial conditions
(as of 1 April) and basin characteristics

	Zone 1	Zone 2	Zone 3
Elevation (meters)	900 - 1200	1200 - 1500	1500 - 1800
Area (sq km)	260	1820	780
Snowpack (mm)*	178	330	457

*Snowpack is expressed in equivalent mm of water content

Table 3.02 Meteorologic data

Date	Precipitation (mm)	Air Temperature *(degrees C)	Dew Point *(degrees C)	Average Wind (km/hr)	Solar Radiation (ly per day)
1 April	1	5.0	-2.2	13.9	397.9
2 April	0	4.4	-2.2	11.0	556.5
3 April	0	9.7	-0.6	15.8	469.9

*Temperature and dew point at bottom of lowest elevation zone, i.e. at elevation 900 meters.

The total melt that will occur in the first day (1 April) can be computed using the metric equivalent of equation 3-2 (precipitation is occurring). The melt in each of the three zones is:

Zone 1

$$M_1 = 0.7[2.286 + (1.326 + .2134(.6)(13.9) + .125(1))(4.1-0)]$$

$$M_1 = 11 \text{ mm}$$

Zone 2

$$M_2 = 0.7[2.286 + (1.326 + .2134(.6)(13.9) + .125(1))(2.3-0)]$$

$$M_2 = 7 \text{ mm}$$

Zone 3

$$M_3 = 0.7[2.286 + (1.326 + .2134(.6)(13.9) + .125(1))(0.5-0)]$$

$$M_3 = 3 \text{ mm}$$

The weighted basin average snowmelt for 1 April is:

$$M = \frac{11(260) + 7(1820) + 3(780)}{2860}$$

$$M = 6 \text{ mm}$$

The snowmelt from each zone must be subtracted from the snowpack and any snowfall added in that zone to determine the snowpack water equivalent for the next day.

Table 3.03 Status of the snowpack at the end of the first day

	Zone 1	Zone 2	Zone 3
Elevation (m)	900 - 1200	1200 - 1500	1500 - 1800
Snowpack at beginning of first day (mm)	178	330	457
Melt for the day (mm)	11	7	3
Snowfall during the day (mm)	0	0	1
Snowpack at end of the first day (mm)	167	323	455

In table 3.03, note that both snowmelt and snowfall occurred during the first day (1 April) in zone 3. This is because the lapsed temperature (0.5°C) for zone 3 exceeded the snowpack temperature (assumed to be 0°C), yet was less than the rain-freeze temperature of 1.0°C.

To compute snowmelt that will occur during 2 April, equation 3-4 is used since precipitation is not occurring. For the purposes of this example, it is assumed that snowfall occurred in all zones on 31 March. The melt computations for each zone are as follows:

Zone 1

$$M_1 = 0.7[(1.0)(.5)(.1015)(556.5)(1-0.75/2^{.2}) + 0.6(.2134)(11)(.22(3.5) + .78(-3.1)) + 0.5(1.326)(3.5)]$$

$$M_1 = 7 \text{ mm}$$

Zone 2

$$M_2 = 0.7[(1.0)(.5)(.1015)(556.5)(1-0.75/2^{.2}) + 0.6(.2134)(11)(.22(1.7) + .78(-4.9)) + 0.5(1.326)(1.7)]$$

$$M_2 = 4 \text{ mm}$$

Zone 3

$$M_3 = 0.7[(1.0)(.5)(.1015)(556.5)(1-0.75/1^{.2}) + 0.6(.2134)(11)(.22(-.1) + .78(-6.7)) + .5(1.326)(-.1)]$$

$$M_3 = 0$$

The weighted basin-average snowmelt for 2 April is:

$$M = \frac{7(260) + 4(1820) + 0(780)}{2860}$$

$$M = 3 \text{ mm}$$

The resultant status of the snowpack is indicated in table 3.04 for each elevation zone.

Table 3.04 Status of the snowpack at the end of the second day

	Zone 1	Zone 2	Zone 3
Elevation (m)	900 - 1200	1200 - 1500	1500 - 1800
Snowpack at beginning of 2nd day (mm)	167	323	455
Melt for the day (mm)	7	4	0
Snowpack at end of 2nd day (mm)	160	319	455

Chapter 4

Infiltration and Excess

CHAPTER 4. INFILTRATION AND EXCESS

Section 4.01. Introduction

Precipitation is subjected to a number of losses before it eventually appears as flow in a stream. In hydrograph analysis, losses are considered to be the difference between the total amount of precipitation that produced a hydrograph and the volume of water in that hydrograph. Precipitation will be lost by vegetation interception, evaporation, transpiration, and infiltration into the soil. Infiltration is the largest of these processes diverting precipitation from immediate streamflow, and usually more than half of the water which infiltrates is retained in the soil until it is returned to the atmosphere by evapotranspiration. Since infiltration has such a major effect on precipitation contributing to immediate streamflow and all the other losses are relatively minor, infiltration is ordinarily the only loss that is considered in detail in hydrograph analysis. This simplification will have some effect on the analysis, but considering the inconsistencies and inaccuracies in precipitation and streamflow measurements, the effect is relatively minor.

The basic approach to determining loss-rate functions for use in analyzing hydrographs is to develop techniques that approximate the physical processes that are occurring and still be mathematically tractable. Traditionally, the techniques are based on representing an infiltration capacity curve, such as the typical curve illustrated in fig. 4.01. The infiltration capacity is defined as the maximum rate at which a soil will accept water and it is a function of soil characteristics, land slopes, vegetation, and soil moisture content. However, in applying any loss-rate technique to natural basins the following factors must be considered:

a. Since the infiltration capacity of a given soil at the beginning of a period of rainfall is related to antecedent field moisture and the physical condition of the soil, the infiltration capacity for the same soil can vary appreciably.

b. The infiltration capacity of a soil is normally highest at the beginning of rainfall and, since rainfall frequently begins at moderate rates, a substantial period of time may elapse before the rainfall intensity exceeds the infiltration capacity. It is generally accepted that a fairly definite quantity of water loss by infiltration is required to satisfy initial soil moisture deficiencies before runoff will occur, the amount of initial loss depending on antecedent moisture conditions. Practical applications of estimating runoff from moderate rainfall intensities ordinarily include an allowance for these initial losses corresponding to various antecedent soil-moisture conditions.

c. Rainfall does not usually cover an entire drainage basin during all the time a storm is occurring with intensities exceeding infiltration capacities. Furthermore, soils and infiltration capacities vary throughout a drainage basin. Therefore, any loss-rate technique must consider varying rainfall intensities in various portions of the basin in order to determine the area covered by effective runoff-producing rainfall.

It can be seen that loss rates vary both areally and temporally. Furthermore, areal variations of precipitation, soils, and vegetation also affect the relationship of area rainfall to area losses. Both effects tend to cause increased basin-mean losses with increased basin-mean rainfall. Time intervals adopted in the analysis and basin sizes should, therefore, be limited so that neglecting these variations will not be serious. However, the limitation recommended for basin size can be somewhat relaxed by the use of loss-rate functions that reflect areal rainfall distribution and variations of soils, vegetation, and other pertinent factors within a given basin.

Section 4.02. Initial Loss

Initial loss, denoted as f_i in fig. 4.01, is defined as the maximum amount of precipitation that can occur without producing runoff. Initial loss values for basins may range from a minimum value of a few tenths of an inch during relatively wet seasons to several inches during dry summer and fall months. The initial loss for conditions conducive to major floods usually ranges from about 0.2 to 0.5 inch (5 to 15 mm) and is relatively small in comparison with flood runoff volume. Consequently, in computing loss rates from data for major floods, allowances for initial loss may be estimated approximately without introducing important errors in the results.

Section 4.03. Infiltration Index

In view of the difficulties encountered in determining actual infiltration capacities (f), especially for large heterogeneous areas, average loss rates are usually computed from rainfall and runoff data and are referred to as infiltration indices, f_{av} (see fig. 4.01). The infiltration index, f_{av}, is defined as an average rate of loss such that the volume of rainfall in excess of that rate will equal the volume of direct runoff. (See Chapter 5 for a discussion of direct runoff.) This volume of rainfall is commonly called the rainfall excess. Often an initial loss is accounted for before computing the infiltration index on the basis of remaining rainfall.

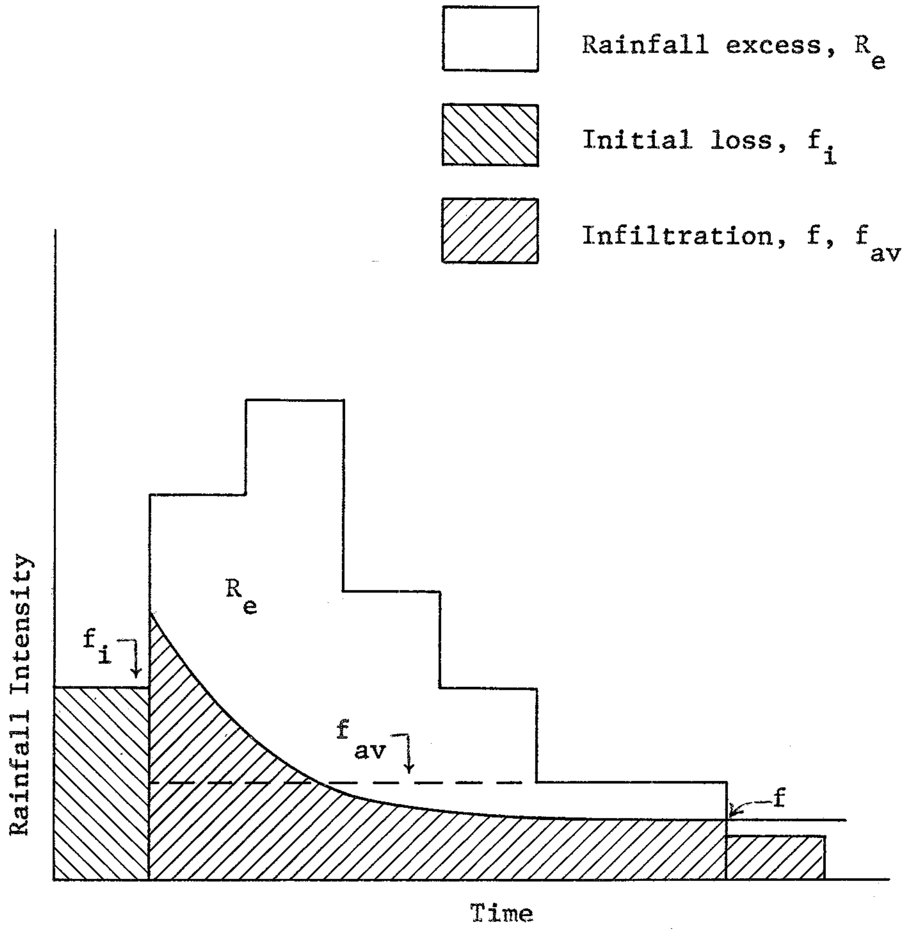


Fig. 4.01. Infiltration **analysis**

Section 4.04. Nonlinear Loss Relation

A great many studies relating basin-average rainfall amounts for short intervals in a storm to observed runoff indicate a distinctly nonlinear relationship between basin-mean rainfall intensity and basin-mean infiltration rate. Considering the heterogeneity of soils, vegetation, and precipitation throughout a drainage basin, this nonlinearity is logical. The following equation has been used in many of these types of studies, with a constraint that loss does not exceed precipitation for each time interval:

$$LR = KP^{E} \qquad (4\text{-}1)$$

where:

LR = loss rate in inches (mm) per hour
K = coefficient decreasing with increased ground wetness
P = rainfall rate in inches (mm) per hour
E = exponent between zero and 1.0, depending on the variation of factors within the basin

It will be noted that a value of zero for E would correspond to loss rates independent of rainfall intensity (the traditional assumption), and that an exponent of 1.0 would correspond to loss rates directly proportional to rainfall intensity. Hydrograph reconstitution studies have indicated that the exponent will ordinarily range from 0.3 to 0.9, and frequently in regional studies a value of 0.7 has been adopted for purposes of uniformity.

The loss coefficient, K, in equation 4-1 decreases with ground wetness during a storm in general accord with the following equation:

$$K = K_{o}C^{-(L/10)} \qquad (4\text{-}2)$$

where:

K_o = loss coefficient at start of storm (different for snow-free and snow-covered areas)

C = coefficient controlling rate of decrease of K (different for snow-free and snow-covered areas)

L = accumulated loss during storm

To account for initial soil moisture deficiency, equation 4-1 is usually modified as follows:

$$LR = (K + K') \cdot P^E \tag{4-3}$$

where:

K' = $0.2D\,(1 - L/D)^2$ where L/D is constrained to 1.0 or less

D = Initial soil moisture deficiency in inches or mm

Figure 4.02 illustrates this general loss rate function, and an example of its use is shown in Section 5.06 of this volume.

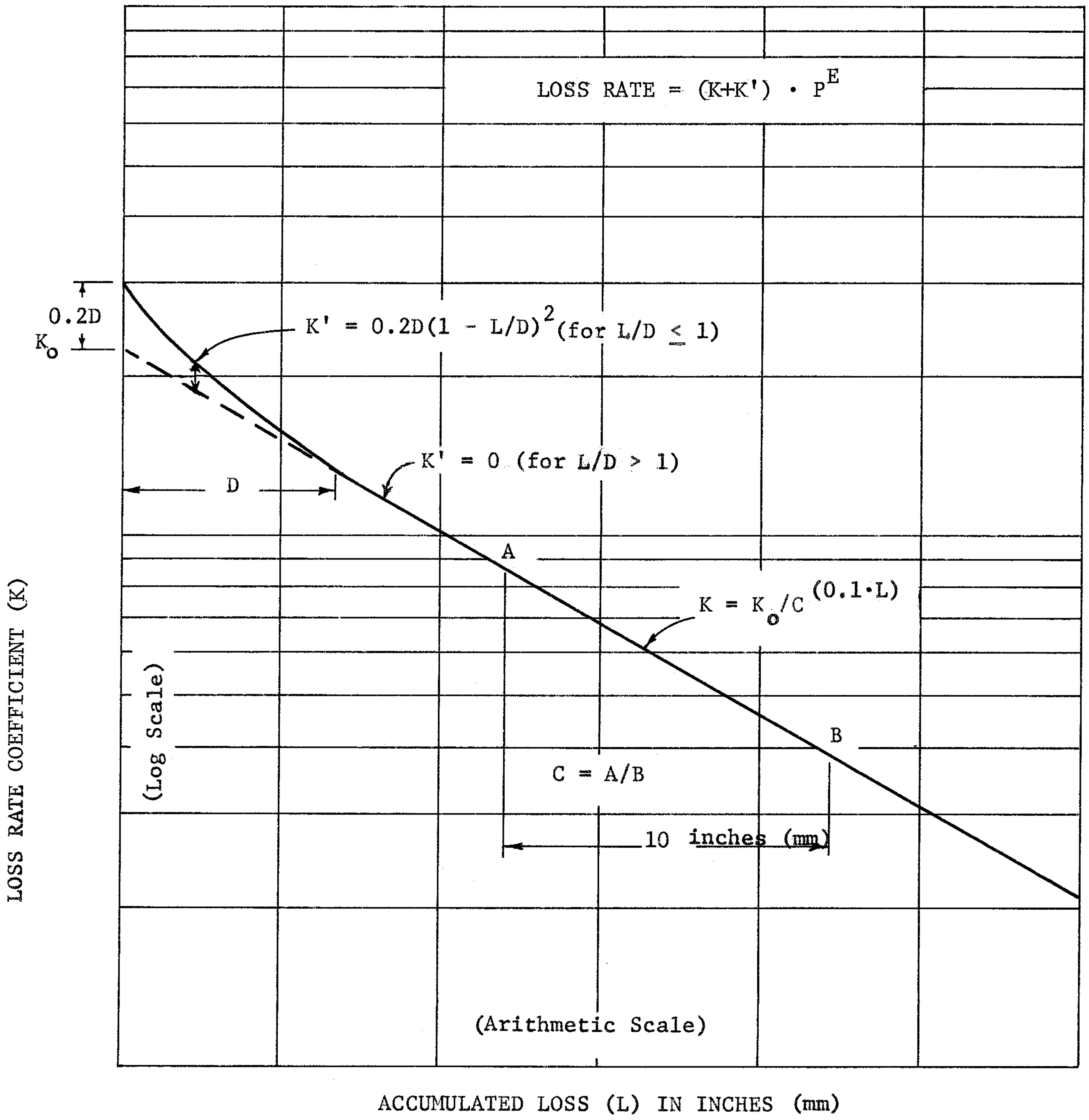


Fig. 4.02. General loss rate function (snow-free ground)

Chapter 5

Hydrographs of Direct Runoff

CHAPTER 5. HYDROGRAPHS OF DIRECT RUNOFF

Section 5.01. Introduction

There are numerous occasions in the planning, design, and operation of water resources projects when estimates of flood flows that will result from rainfall and snowmelt are necessary. The general technique that is used by virtually all water resources development organizations in the United States for transforming rainfall and snowmelt to direct surface runoff is the unit hydrograph technique. However, the characteristics of direct and subsurface runoff differ so greatly that, in most cases, they are analyzed separately in problems involving storm runoff. Direct runoff is that water which travels over the land surface or laterally in the surface soil to a stream channel. The stream channels allow this flow to travel rapidly. Therefore, the direct runoff is ordinarily the most important element in the formation of flood peaks. Subsurface flow or "base flow" into a stream results when the ground-water table is higher than the stream surface. Ground water contribution to streamflow does not ordinarily fluctuate rapidly due to the medium through which it travels. Up to several weeks, or even a few months, may be required for the effect of a given accretion to ground water to be discharged into the streams.

There is no practical method of differentiating between base flow and direct runoff after they have been intermixed in the stream, and the techniques of hydrograph separation are rather arbitrary. For this reason, the technique recommended in this volume consists simply of separating recession runoff of preceding floods from the current hydrograph, as illustrated in fig. 5.01. This accounts for the principal volume of base flow and permits the application of the unit hydrograph technique to the remaining flow with reasonable accuracy.

In an effort to minimize the subjective judgment in hydrograph analysis, computer programs developed in The Hydrologic Engineering Center include all components of streamflow in the direct derivation of the unit hydrograph except the following, which are calculated separately:

a. Recession flow from antecedent runoff that would occur in the absence of the current storm.

b. Recession flow from the current runoff computed from the unit hydrograph (after the end of the current storm). Figure 5.01 illustrates this quantity.

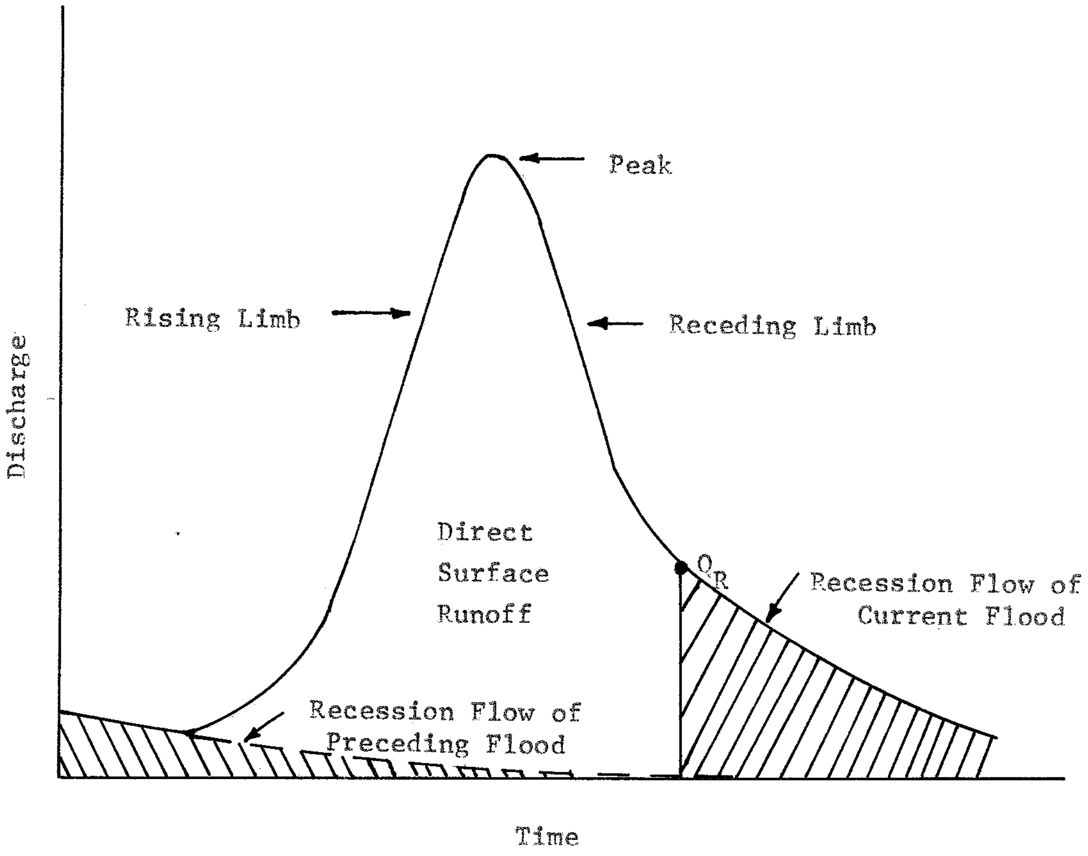


Fig. 5.01. Typical flood hydrograph separation

Both of these quantities are computed as identical exponential decay functions (receding straight lines on semilog paper) defined as the ratio (B) of flow at a given time to flow 10 time intervals later. Thus, the recession flow at the end of any period (Q_i) is computed from the recession flow at the start of that period (Q_{i-1}) as follows:

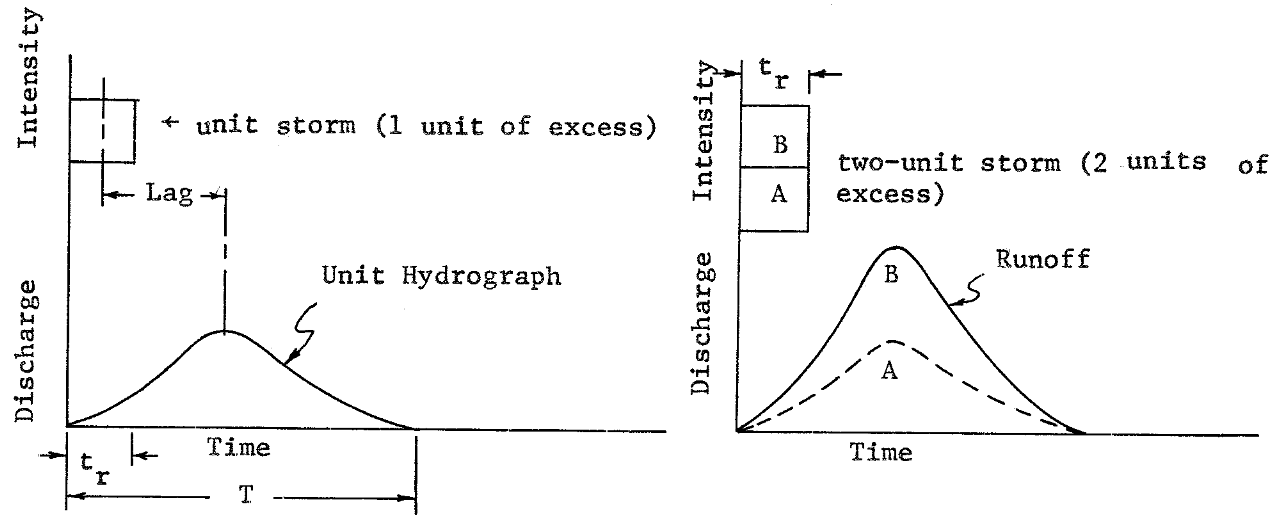
$$Q_i = Q_{i-1}/B^{0.1} \tag{5-1}$$

Recession of antecedent flow computed in this manner is added to runoff computed from the unit hydrograph. After the total flow recedes below a specified threshold value, Q_R, it is computed by use of the recession equation (equation 5-1) in lieu of continuing the unit hydrograph computation. The threshold flow, Q_R and B, are obtained by plotting observed recession curves on semilog paper, selecting Q_R as the upper limit of the portion that is sensibly a straight line and B as the ratio (always greater than 1.0) of flow 10 time intervals apart on that straight line. Since this recession is considered to be characteristic of a basin, these values should be the same for different flood hydrographs at the same location.

Section 5.02. Unit Hydrograph Theory

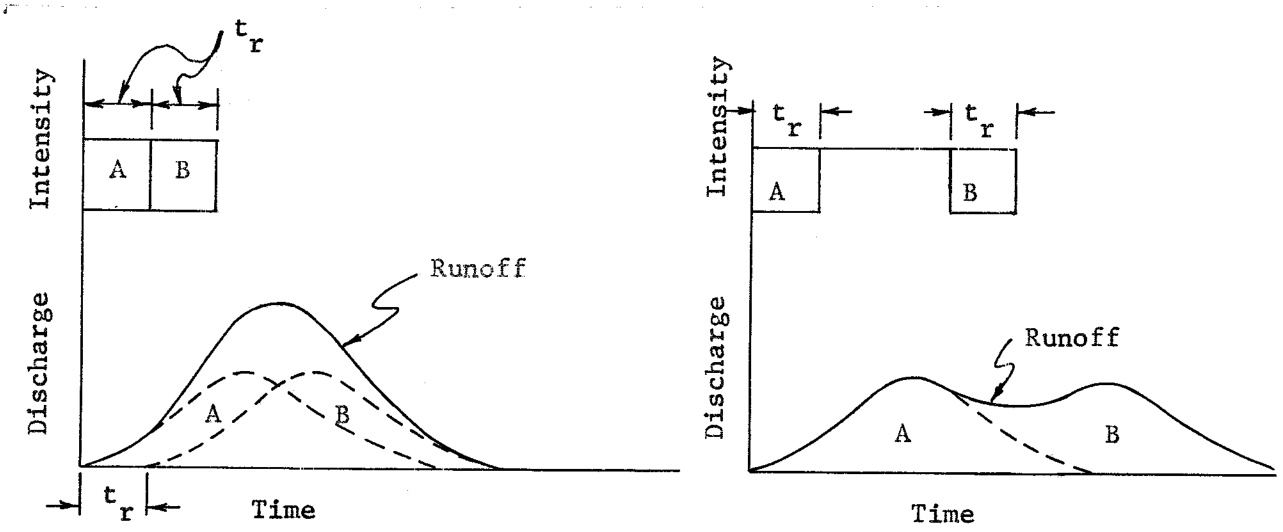
A unit hydrograph is the direct runoff that would be observed at the downstream limit of the drainage area as a result of 1 unit of rainfall plus snowmelt excess occurring within the unit time interval with a given areal pattern (fig. 5.02a). The unit of excess is normally taken as equal to 1 inch or 1 mm. Since the physical features of the basin (shape, size, slopes, soils, etc.) do not vary from storm to storm, hydrographs from storms of like duration and pattern are assumed to have the same shape, but with ordinates of flow in proportion to the runoff volumes. Thus, if 2 units of excess occurred in 1 unit time interval, then it would be expected that the resulting hydrograph would have the same shape as the hydrograph from 1 unit of excess in the same time, except that all of the ordinates would be twice as large (fig. 5.02b). As another example (fig. 5.02c), if 1 unit of excess occurred in each of 2 consecutive unit time intervals, the resulting hydrograph would simply be the sum of the two unit hydrographs, but with the second unit hydrograph beginning 1 time unit later.

While it is known that some assumptions of linearity involved in the unit hydrograph technique do not accurately apply, extensive experience indicates that the limitations of the technique are not a major handicap, considering the quality of rainfall and snowmelt data that are usually available, provided that the procedures involved are applied with appropriate knowledge and judgment.



(a) Unit hydrograph

(b) Hydrograph for a 2-unit storm



(c) Hydrograph from consecutive unit storms.

(d) Hydrograph from intermittent rainfall periods.

Fig. 5.02. Unit hydrograph relationships

Section 5.03. Factors Causing Variations in Unit Hydrographs

From the preceding discussion it can be seen that it would be erroneous to assume that one unit hydrograph would suffice for any basin. Although the physical characteristics of natural basins may remain relatively constant, variations in storm characteristics will have a significant effect on the shape of resulting hydrographs. The primary variations in unit hydrographs are due to variations (a) in areal distribution of rainfall and snowmelt, (b) rainfall and snowmelt duration, and (c) time intensity patterns.

In general, a hydrograph resulting from precipitation concentrated in the lower part of a basin will have a rapid rise, a sharp peak, and a rapid recession, while precipitation concentrated in the upper part of the same basin will have a slower rise and recession and a lower, broader peak. It can be seen that unit hydrographs developed from these different areal distributions of runoff would have very different shapes. On occasions, unit hydrographs have been developed for upstream, uniform, or downstream concentrations of runoff. However, this is not wholly satisfactory due to the subjectivity involved, and a better solution is to limit the application of the unit hydrograph technique to basins small enough so that the differences in spatial distribution of rainfall and snowmelt do not significantly affect runoff. This limitation does not ordinarily apply to rainfall variations caused by topographic effects, since the effects can be considered as relatively fixed characteristics of the basin. It is variations from the normal areal pattern of precipitation that cause the differences in unit hydrographs.

By definition, a unit hydrograph contains 1 unit of runoff from rainfall and snowmelt occurring in a specified unit time. If the amount of runoff remains constant (1 unit) and the duration is increased, the time base of the unit hydrograph will be lengthened (T_r in fig. 5.02a) and the peak will be lowered. A separate unit hydrograph is theoretically necessary for each possible duration of rainfall and snowmelt. Actually, a few unit hydrographs for short durations will serve most requirements, and a unit hydrograph for a short duration of rainfall and snowmelt can be used to develop unit hydrographs for storms of longer duration (see Appendix 1 and Section 5.06).

Time-intensity patterns of rainfall can have a significant effect on unit hydrographs and the effect is directly related to basin size. On large basins, changes in storm intensity must last for several hours to cause distinguishable effects on the hydrograph. On the other hand, clearly defined peaks in the hydrographs may be caused by short bursts of rainfall lasting only a few minutes in very small basins. For large basins, valley storage tends to eliminate the effects of short-time intensities and only major changes in the time-intensity pattern are reflected in the hydrograph. The effects of changes in the time-intensity pattern can usually be lessened by selecting the computation interval to be used in developing a unit hydrograph short enough that the changes are not great from one computation interval to the next.

Up to this point, it has been assumed that the physical characteristics of a basin have remained relatively constant. But it is known that changes in the physical characteristics can and do occur from natural and manmade causes. A typical example is the drastic changes that can occur in the shape of hydrographs and unit hydrographs developed over a period of time for basins that are being urbanized. In this case, because of the reduction of natural valley storage, the unit hydrographs will tend to have higher peaks and shorter times of concentration. Under natural conditions, changes in physical characteristics can occur due to seasonal and long-term changes in vegetation or to other causes, such as fires. It should be noted that these variations also affect loss rates. For example, the increase in impervious area caused by urbanization will not only reduce the natural valley storage of a basin, but will also lower the average loss rates, since some rainfall will contribute directly to streamflow with no loss.

There is no prescribed set of rules for solving this problem, but the engineer should be aware that many factors cause variations in unit hydrographs.

Section 5.04. Hydrograph Computation Using the Unit Hydrograph

Since the ordinates of a unit hydrograph represent the distribution by time and magnitude of 1 unit of runoff from a drainage basin, the unit hydrograph may be applied to rainfall and snowmelt excess of any magnitude to determine the resulting hydrograph, provided the duration of excess coincides with the unit duration of the unit hydrograph. For a storm with only one period of excess, the ordinates of the hydrograph are computed as follows:

$$Q_i = U_i \cdot E \qquad (5\text{-}2)$$

where:

Q_i = the hydrograph ordinate for any period, i
U_i = the unit hydrograph ordinate for the same period, i
E = the rainfall plus snowmelt excess

For complex storms in which excess occurs in more than one period (the normal case), the resulting hydrograph can be determined by computing the individual hydrographs resulting from the various excess periods in their proper time sequence and adding the individual components. The individual components need not be tabulated separately, but accumulatively multiplied until all excess periods have been used, to obtain a total hydrograph ordinate. A general equation for the total hydrograph ordinate for any period, i, is:

$$Q_i = U_1 \cdot E_i + U_2 \cdot E_{i-1} + U_3 \cdot E_{i-2} + \ldots + U_n \cdot E_{i-n+1} \qquad (5\text{-}3)$$

where:

i = sequence number of excess
Q_i = the hydrograph ordinate for period, i

U = the unit hydrograph ordinates in order from 1 through n

E = the rainfall plus snowmelt excess in reverse order from i through i-n

n = total number of unit hydrograph ordinates or i, whichever is smaller

When the computation is made on a desk calculator, the above process can be simplified by constructing a template, as illustrated in Appendix 1.

Section 5.05. Unit Hydrograph Derivation from Flood Hydrographs

A theoretically simple method of deriving a unit hydrograph involves the analysis of runoff resulting from isolated precipitation that produces reasonably uniform excess rates for a period approximately equal to the desired unit duration. Base flow is separated from the direct runoff, and the individual ordinates of the direct runoff hydrograph are divided by the volume of direct runoff. The resulting ordinates form a unit hydrograph for the specified duration of unit excess. The occurrence of floods resulting from single bursts of uniform precipitation rates are rare and, therefore, the data required to develop unit hydrographs in the above manner seldom exists. However, if individual bursts of rain in the storm result in well-defined peaks, it is sometimes possible to separate the hydrographs produced from the various bursts by estimating the recession of runoff from each burst. These hydrographs may then be used as runoff from independent storms for the development of unit hydrographs in the manner described above.

The result of the above derivation, or where unit hydrographs from different storms at the same location are derived, is a series of unit hydrographs with differences due to observation errors and other factors as described previously. For the convenience of dealing with only one unit hydrograph, and to minimize any errors due to separation of the hydrographs in the above procedure, the unit hydrographs are normally averaged. All unit hydrographs to be averaged must have the same unit duration, which may require converting to a common unit duration (see Appendix 1). The averaging is usually done graphically to prevent reducing the peak incorrectly which is the likely result when an arithmetic average is applied to concurrent ordinates. The instantaneous peak flows should be averaged, regardless of differences in lag time (fig. 5.02a) and plotted at the average lag time. The average unit hydrograph can then be sketched to conform to the shape of the graphs, passing through the computed average peak, and having a volume of 1 unit of runoff.

However, it usually is not possible or practical to separate the hydrograph according to bursts of rain. Sometimes it is possible to obtain a first-trial unit hydrograph by reversing the procedure described in Section 5.04 (see Appendix 1). But probably the most common procedure for deriving a unit hydrograph from a complex storm is by successive approximations, as described below.

By inspection of the heaviest rainfall and snowmelt excesses that caused the peak flows of the flood hydrograph, unit hydrograph ordinates around the peak are first estimated. The remainder of unit hydrograph is then estimated so that the volume is equal to 1 unit of runoff. In estimating the overall shape of the unit hydrograph, consideration is given to the rate of rise and recession of the flood hydrograph and the estimated lag time from the heaviest excess period to the peak of the flood hydrograph. This first-trial unit hydrograph is then applied to the excess estimates, and the resulting computed hydrograph is checked against the observed flood hydrograph. The unit hydrograph is then adjusted as needed, and the process is repeated until the computed hydrograph approximates the observed hydrograph to the desired accuracy.

The computation of a hydrograph requires not only developing a unit hydrograph but estimating rainfall and snowmelt losses as well, and ordinarily the analysis involves both procedures at the same time. This is normally required since it is not always obvious whether the unit hydrograph or the loss rates should be adjusted to obtain a better fit between the computed and observed hydrographs.

The reconstitution of historical flood hydrographs involves the estimation of base flow, loss rates, and unit hydrographs; and it becomes clear that many combinations of these three items can reconstitute the same flood hydrograph equally as well. Consequently, a considerable amount of engineering judgment will be required to establish reasonable estimates for each of these items. Some subjectivity can be eliminated by techniques such as the base flow separation discussed in Section 5.01. However, there is no way to completely eliminate all of the subjectivity involved. Consistency in approach can be gained through the use of computer programs such as the one shown in Appendix 3. This program, Unit Hydrograph and Loss Rate Optimization, will automatically derive "best fit" unit hydrograph and loss rate coefficients based on least-square differences between observed and computed flows. Care must still be exercised by the engineer, however, to evaluate the computed coefficients for reasonableness. The program uses the nonlinear loss rate function discussed in Section 4.04 and the base flow separation technique discussed in Section 5.01. The unit hydrograph is computed by use of the Clark method discussed in Section 5.06.

Section 5.06. Derivation of Unit Hydrographs by the Clark Method

As discussed previously, there are many possible unit hydrographs for the same basin, since the shape of the hydrographs vary with different unit durations and other factors. To define a unique unit hydrograph for a basin that can be adjusted to account for some of the factors, C. O. Clark developed a technique (reference 5.03) which uses the concept of the instantaneous unit hydrograph (IUH). This is conceptually the hydrograph that would result from 1 unit of excess occurring over the basin in a specified areal pattern and zero time. The IUH can then be used to compute a unit hydrograph for any unit duration equal to or greater than the time interval used in the computations.

The Clark method uses two parameters and a time-area relation to define the instantaneous unit hydrograph. The first parameter, time of concentration (t_c) is the travel time of a water particle from the most upstream point in the basin to the outflow location. An estimate of this lag time is the time from the end of effective rainfall plus snowmelt over the basin to the inflection point on the recession limb of the surface runoff hydrograph (fig. 5.06). The time of concentration is used in developing the time-area relation.

The second parameter is the attenuation constant, R, which has the dimension of time. This parameter is used to account for the effect that storage in the river channel has on the hydrograph. This parameter can be estimated by dividing the flow at the point of inflection of the surface runoff hydrograph by the rate of change of discharge (slope) at the same time (fig. 5.06). Another technique for estimating R is to compute the volume remaining under the recession limb of the surface runoff hydrograph following the point of inflection and divide by the flow at the point of inflection. In either case, R should be an average value determined by using several hydrographs.

The other necessary item to compute an IUH is the time-area relation. When t_c has been determined, the basin is divided into incremental runoff-producing areas that have equal incremental travel times to the outflow location (fig. 5.03). The distance from the most upstream point in the basin is measured along the principal watercourse to the outflow location. Dividing this distance by t_c gives an estimate of the rate of travel. Isochrones representing equal travel time to the outflow location are laid out using the rate of travel to establish the location of the lines. The areas between the isochrones are then measured and tabulated in upstream sequence versus the corresponding incremental travel time for each incremental area.

The increment of time used to subdivide the basin need only be small enough to adequately define the areal distribution of runoff while the time period selected as the computation interval must be equal to or less than the unit duration of excess. Since the former is frequently larger than the latter, a plot percent of time of concentration versus accumulative area is useful in determining time-area relationships (fig. 5.04). Such a curve facilitates rapid development of unit hydrographs for various computation intervals and unit durations of excess. This is especially helpful when making flood predictions and for basins where t_c is not firmly established at the outset, since unit hydrographs may be easily modified to reflect subsequent changes in t_c. Also, it is possible to refine the curve by considering the variation of velocity from stream reach to stream reach and specified contributions of excess (as ratios of basin-mean contribution) in different portions of the basin. Another advantage is that the unit duration can be changed without requiring a new time-area relation to be developed.

The runoff from the contributing areas (between the isochrones) which has been translated to the outflow location is in units of volume (in-mi^2 or mm-km^2). The conversion to proper units of discharge is made through the relationship:

$$I_i = K\, a_i / \Delta t \tag{5-4}$$

where:

I_i = ordinate in proper units of discharge (cfs, cms, etc.) of the translation hydrograph at the end of period i

a_i = ordinate in units of area-depth of excess (in-sq mi, mm-sq km, etc.) of the translation hydrograph at the end of period i

K = conversion factor to convert a_i to I_i (to convert in-sq mi to cfs, K = 645; to convert mm-sq km to cms, K = .278 etc.)

Δt = time period of computation interval in hours

The routing of the translation hydrograph through storage at the outflow location is accomplished as follows:

$$O_i = C\, I_i + (1-C)\, O_{i-1} \tag{5-5}$$

where:

O_i = outflow from the basin at the end of period i

I_i = inflow or runoff from each area at the end of period i

C = dimensionless routing constant

The routing constant, C, is determined for prism type storage as:

$$C = \frac{2\Delta t}{2R + \Delta t} \qquad (5\text{-}6)$$

where: Δt = time period of computation interval

R = attenuation constant having the dimension of time

It can be shown that when inflow into the principal storage reach has ceased:

$$R = \frac{Q}{dQ/dt} \qquad (5\text{-}7)$$

and the time of this basin characteristic is depicted by the point of inflection of the recession limb of the observed hydrograph after base flow separation. The above ratio decreases to a minimum at the point of inflection and remains constant thereafter.

The hydrograph that results from routing these flows from the incremental areas is the instantaneous unit hydrograph. The IUH can be converted to a unit hydrograph of unit-rainfall duration Δt by simply averaging two instantaneous unit hydrographs spaced an interval Δt apart as follows:

$$0_i = 0.5\ (0_i + 0_{i-1}) \qquad (5\text{-}8)$$

The IUH can be converted to a unit hydrograph of some unit-rainfall duration other than Δt (provided that it is an exact multiple of Δt) by the following equation:

$$Q_i = \frac{1}{n}\left[(.5)\ 0_{i-n} + 0_{i-n+1} + \ldots + 0_{i-1} + .5\ (0_i)\right] \qquad (5\text{-}9)$$

where:

Q_i = ordinate at time i of unit graph of duration D and tabulation interval Δt

$n = \frac{D}{\Delta t}$

D = unit graph duration

Δt = tabulation interval

General Procedure

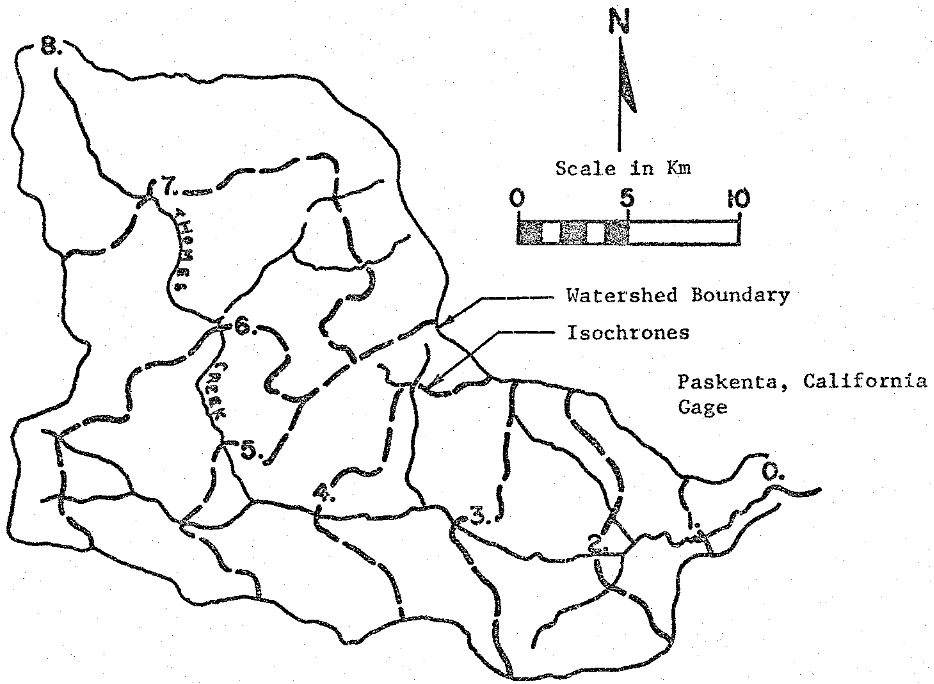
The complete procedure can be illustrated by a typical problem. In this case, a unit hydrograph is to be derived to reconstitute the observed hydrograph for Thomes Creek at Paskenta, California, on 31 January-3 February 1963. So that the unit hydrograph derivation can be illustrated more directly, it is assumed that a loss rate function that is applicable has been previously derived (fig. 5.05). Also, it is assumed that a map of the basin showing the principal watercourses has been developed (fig. 5.03). The complete procedure for deriving the unit hydrograph by the Clark method is as follows:

a. Draw lines (isochrones) which subdivide the basin into a chosen number of parts as illustrated in fig. 5.03. These isochrones are constructed so that the travel time along a watercourse is the same from one isochrone to another. For simplicity, they are usually drawn equal distances apart from the outflow location to the uppermost head of the basin. The number of isochrones used is ordinarily chosen so that a convenient scale may be used and a reasonably good definition of the time-area relation is obtained. In the example, seven isochrones were constructed to divide the basin into eight subareas. This was convenient since the estimated t_c is 8 hours and the distance along the main watercourse is 51.5 km.

b. Measure the area between each pair of isochrones (fig. 5.03). If a nonuniform pattern of excess is assumed, multiply each area by the average excess within that subdivision. These are tabulated on fig. 5.03.

c. Plot the curve of time versus area (or excess) as shown on fig. 5.04. Note that the absicissa was expressed in percent of t_c. Tabulate increments between points that are 1 computation interval (Δt) apart, as illustrated on table 5.01.

d. Convert the units of inflow (columns 2 and 3 of table 5.01) using equation 5-4.



Travel Time from "8" to gage is 8.0 Hours for the 51.5 Km

Map Area Number (1)	Planimeter Values from Map Incremental Unit (2)	 Accumulated Unit (3)	Accumulated Area (KM) (Col 3)·(152.6) (4)	Travel Time in Percent [(1/8)·(100)] (5)
1	0.08	0.08	12	12.5
2	0.15	0.23	35	25.0
3	0.40	0.63	96	37.5
4	0.36	0.99	151	50.0
5	0.45	1.44	220	62.5
6	0.45	1.89	288	75.0
7	0.66	2.55	389	87.5
8	0.68	3.23	493	100.0
Total	3.23			

Sq. Km/Planimeter unit = 493/3.23 = 152.6

Drainage Area = 493 square Km

Fig. 5.03. Computation of the time-area relation

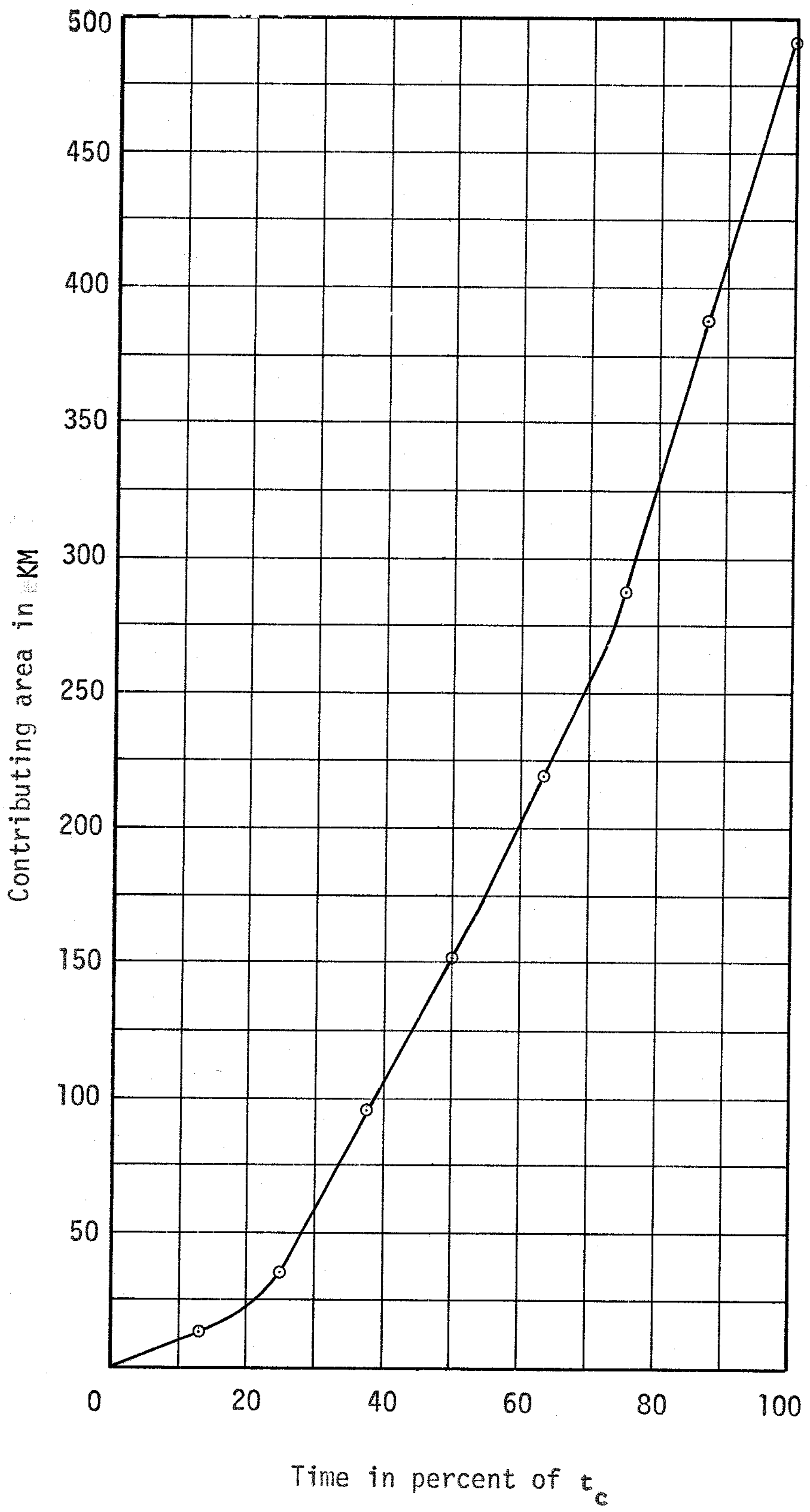
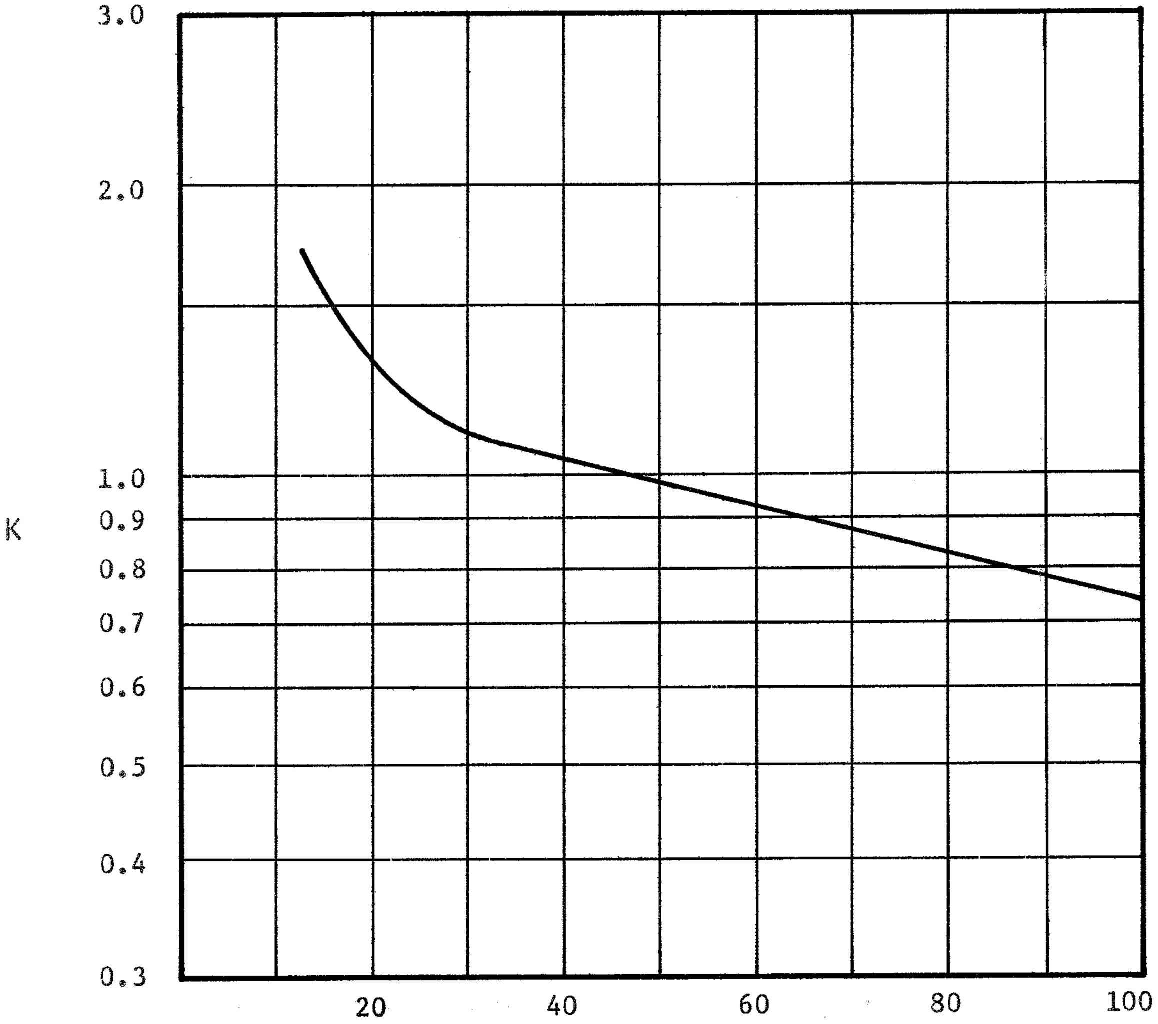


Fig. 5.04. Watershed time-area relation



Accumulated loss in mm

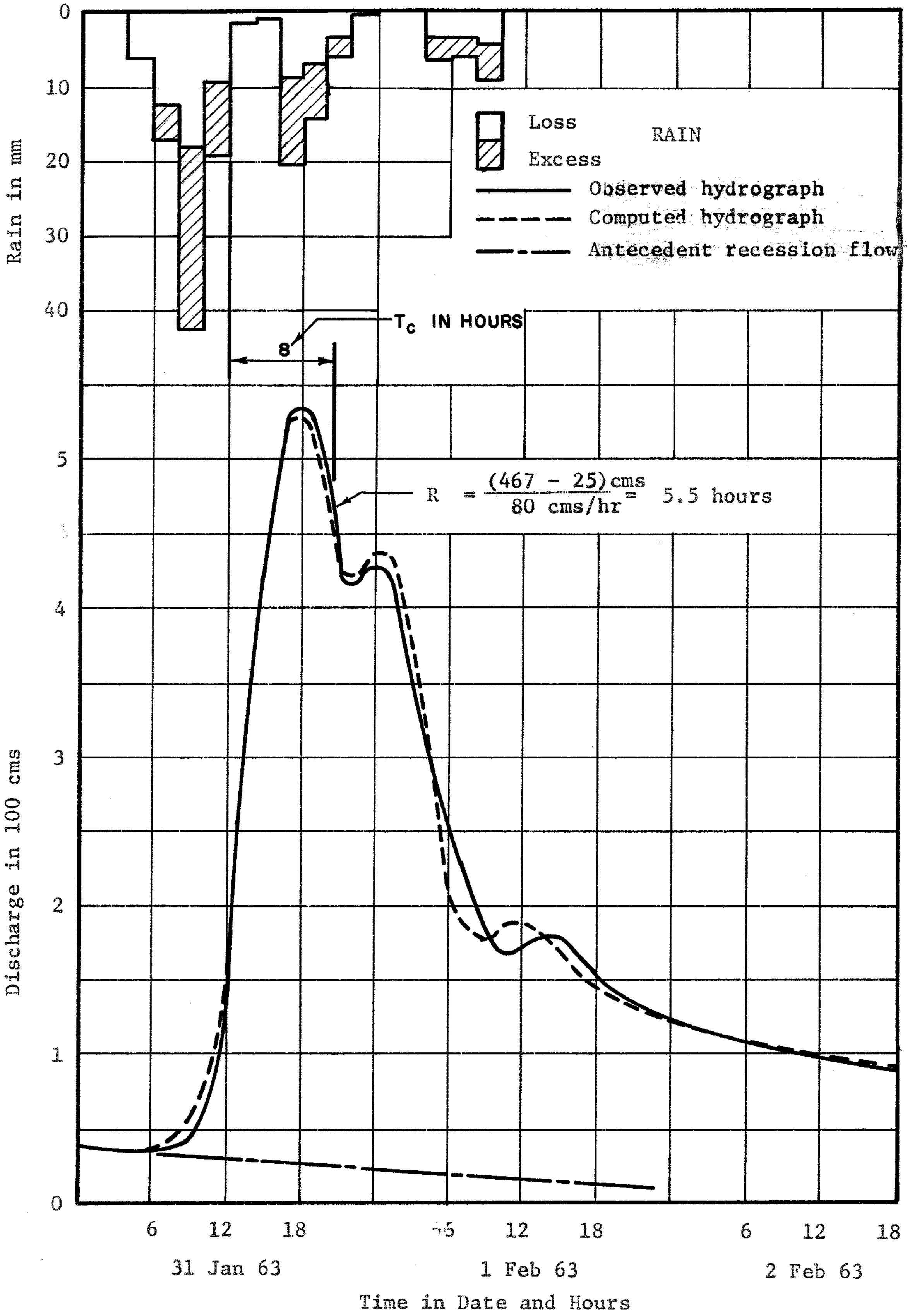
Loss Rate Function:

$$L = KP^{E}$$

where:

L = loss rate in mm per hour
K = value from curve
P = rainfall in mm per hour
E = constant for watershed area

Fig. 5.05. Loss rate function



Drainage Area: 493 sq km

Fig. 5.06. Determination of Clark coefficients and flood reconstitution

Table 5.01. Unit graph computation Clark method
Thomes Creek at Paskenta, California

DRAINAGE AREA = 493 SQUARE KILOMETERS
TIME OF CONCENTRATION (t_c) = 8.0 HOURS (See Figure 5.06)
ATTENUATION VALUE (R) = 5.5 HOURS (See Figure 5.06)
TIME INTERVAL (Δt) = 2.0 HOURS

EQUATIONS (Subscript i refers to current period)

$$I_i = a_i \ .278/\Delta t$$

$$C = \Delta t/(R + .5\Delta t) = 0.308$$

$$O_i = C I_i + (1-C)O_{i-1}$$

$$Q_i = .5(O_{i-1} + O_i)$$

TIME hr (1)	INFLOW (FIG. 5.04) a_i SQ.KM.-mm/Δt (2)	 I_i cms (3)	INSTANTANEOUS UNIT GRAPH O_i cms (4)	2-HOUR UNIT GRAPH Q_i cms (5)
0	0	0	0	0
2	35	5	1.55	.78
4	116	16	5.97	3.76
6	137	19	10.01	7.99
8	205	29	15.69	12.85
10	0	0	10.85	13.27
12			7.50	9.17
14			5.19	6.35
16			3.59	4.39
18			2.49	3.04
20			1.72	2.11
22			1.19	1.45
24			.82	1.00
26			.57	.70
28			.39	.48
30			.27	.33
32			.18	.22
34			.13	.16
36			.09	.11
38			.06	.08
40			.04	.05
42			.03	.03
44			.02	.02
46			.02	.02

Table 5.02. Thomes Creek at Paskenta, California flood hydrograph computation (31 January - 2 February 1963)

DRAINAGE AREA = 493 SQUARE KM
RECESSION FLOW BELOW 115 cms = $0.95(Q_{i-1})$

DATE *Day/Mo/Year* *1*	TIME *hour* *2*	PERIOD RAIN *mm* *3*	RAIN RATE *mm/hr* *4*	K VALUE *fig 5.05* *5*	LOSS RATE $L=KP^{.7}$ *mm/hr* *6*	PERIOD LOSS *mm* *7*	ACCUMULATED LOSS *mm* *8*	RAIN EXCESS Col 3 - Col 7 *mm* *9*	UNIT GRAPH TABLE 5.01 *cms* *10*	RUNOFF *cms* *11*	ANTECEDENT BASE FLOW $0.95(Q_{i-1})$ *cms* *12*	FLOOD HYDROGRAPH Col 11+Col 12 *cms* *13*
	INITIAL						12.7				37	37
31 JAN 63	0600	6.2	3.1	1.72	3.1	6.2	18.9	0	0	0	35	35
	0800	17.8	8.9	1.41	6.4	12.8	31.7	5.0	.78	34	33	37
	1000	42.8	21.4	1.09	9.1	18.2	49.9	24.6	3.76	38	32	70
	1200	19.8	9.9	.95	4.8	9.6	59.5	10.2	7.99	140	30	170
	1400	1.6	.8	.90	.8	1.6	61.1	0	12.85	299	29	328
	1600	1.0	.5	.90	.5	1.0	62.1	0	13.27	462	27	489
	1800	20.8	10.4	.90	4.6	9.2	71.3	11.6	9.17	510	26	536
	2000	14.8	7.4	.87	3.6	7.2	78.5	7.6	6.35	441	25	466
	2200	6.2	3.1	.85	1.8	3.6	82.1	3.6	4.39	399	23	417
	2400	.6	.3	.82	.3	.6	82.7	0	3.04	407	22	429
1 FEB 63	0200	0	0	.82	0	0	82.7	0	2.11	402	21	423
	0400	0	0	.82	0	0	82.7	0	1.45	331	20	350
	0600	6.6	3.3	.82	1.8	3.6	86.3	3.0	1.00	242	19	261
	0800	6.2	3.1	.79	1.8	3.6	89.9	2.6	.70	179	18	197
	1000	9.2	4.6	.79	2.3	4.6	94.5	4.6	.48	152	17	169
	1200	0	0						.33	156	16	172
	1400	0	0						.22	164	15	179
	1600	0	0						.16	157	15	172
	1800	0	0						.11	129	14	143
	2000	0	0						.08	89	13	136
	2200	0	0						.05			129
	2400	0	0						.03			123
2 FEB 63	0200	0	0						.02			116
	0400	0	0						.02			$(0.95)(Q_{i-1})$

*RUNOFF + ANTECEDENT BASE FLOW IS LESS THAN 115 cms SO ANTECEDENT RECESSION FLOW IS COMPUTED FOR HYDROGRAPH.

e. Route the inflows (column 3 of table 5.01) to the outflow location (column 4 of table 5.01) using equations 5-5 and 5-6. The attenuation constant, R, is 5.5 hours, as illustrated in figure 5.06.

f. Average the ordinates of the routed hydrograph with those of an identical hydrograph 1 computation interval, Δt, later using equation 5-8. The result (column 5 of table 5.01) is the unit hydrograph from a unit of rainfall plus snowmelt excess of duration equal to the computation interval.

Conclusion

The Clark method has two advantages that make it particularly attractive:

a. It provides a means of direct computation of unit hydrographs for electronic computer applications, whereas most other procedures require successive adjustments of the computed unit hydrographs.

b. It provides a means of adjusting objectively for changes in drainage patterns resulting from urbanization or construction of reservoirs, channels, or diversions without requiring that the basin be subdivided into many subareas. This is accomplished simply by constructing a time-area curve that corresponds to new travel times through reaches and reservoirs.

Section 5.07. Derivation of Clark Coefficients

The Clark unit hydrograph coefficients, t_c and R, discussed previously were related to observed characteristics of a surface runoff hydrograph. But, in practice, uncertainties of the concepts and of recorded data usually preclude their reliable determination in a simple fashion. It is known that t_c and R are not rigid and, by analyzing several different storms on the same basin, different values will probably be obtained for different storms. For instance, t_c for a storm centered over the head of the basin will probably be larger than t_c for a storm centered over the foot of the basin.

If discharge and precipitation records are available, t_c and R can be estimated from observed events. As is illustrated on fig. 5.06, t_c can be estimated as the time from the end of the heavy excess to the inflection point on the recession limb of the flood hydrograph. Likewise, R can be estimated by dividing the discharge at the inflection point by the rate of change of flow at that point on the hydrograph. However, the shapes of hydrographs reflect many irregularities of rainfall, snowmelt, and stream patterns, and estimates obtained in this manner are usually satisfactory only for the first approximations.

It is best, if the data are available, to derive the unit hydrograph and loss coefficients by successive approximations by applying trial unit hydrographs to the excess computed from trial loss functions. If snowmelt is occurring, the problem is even more involved, since trial values of the snowmelt coefficient, freezing level, and lapse rate may also have to be evaluated. The computations for the case where snowmelt is not involved is illustrated in table 5.01 and figs. 5.05 and 5.06. The duration of unit excess and computation interval, Δt, must be shorter than t_c and preferably shorter than one-third of t_c. Storms selected for study should be several times longer than the computation interval in order to provide representative basin coverage of rainfall and snowmelt.

Section 5.08. Synthetic Unit Hydrographs

Synthetic unit hydrographs are often required at locations where hydrologic records are not available, and as a means of correlating and supplementing observed data. Several methods of computing synthetic unit hydrographs have been presented in technical publications, but most of these methods were developed to serve special purposes and may not constitute the most suitable procedure for all uses. For instance, in flood forecasting the need for speed in calculations may justify approximations that are not warranted in estimating design flood hydrographs. In estimating critical hydrographs of runoff, conditions favorable to high concentrations of runoff must be assumed, whereas the assumption of average conditions may be more reasonable in other problems. In developing unit hydrographs for use in estimating critical hydrographs of runoff, conservative determinations of peak discharge, the degree of concentration of runoff near the peak, and the time of concentration are of primary importance. The shape of the rising and recession limbs, and the length of the base of the unit hydrograph are usually of secondary importance if the three components enumerated above are fixed. The empirical relations presented in reference 5.08 have proved to be useful in the study of runoff characteristics of drainage areas where streamflow records are not available, as well as in modifying or supplementing available runoff records to serve specific purposes.

Regional analysis has proved useful in relating unit hydrograph coefficients to drainage basin characteristics. The unit hydrograph coefficients for a region, such as Clark's t_c and R are correlated with such drainage basin characteristics as drainage area size, stream slope, basin slope, median stream length, soils, and vegetation. The resulting regression equations can be used to estimate t_c and R for ungaged areas in the region where hydrologic data are sparse.

Since changes in t_c and R produce similar changes on the unit hydrograph, about equally good hydrograph reconstitutions can be obtained by decreasing one coefficient and increasing the other. Accordingly, since the two coefficients are interdependent, the results obtained are not ordinarily as dependable for individual values as for some combination of the two. For this reason, and to make the coefficients as independent as possible, ordinary practice for regional studies consists of adopting an average value of R/t_c or $R/(R + t_c)$ for the entire region and correlating only the sum, $R + t_c$, with the drainage basin characteristics. Volume 2 of this report gives detailed procedures used in regional analysis.

Section 5.09. Computer Programs

Several computer programs have been developed in The Hydrologic Engineering Center that can be used in hydrograph analysis. Computer programs 723-X6-L2010 (HEC-1, Flood Hydrograph Package) and 723-G2-L2230 (Unit Hydrograph and Loss Rate Optimization) will automatically determine "best-fit" unit hydrograph and loss rate coefficients that will reconstitute observed hydrographs. The former program is described in Volume 1 of this report and the latter program, 723-G2-L2230, is described in Appendix 3 of this volume. Another computer program, 723-G1-L2280 (Unit Graph and Hydrograph Computation) will compute unit hydrographs and hydrogrphs if the unit hydrograph and loss rate coefficients are given. This program is described in Volume 5.

Section 5.10. Adjustments for Refinements

In most cases, use of the Unit Hydrograph and Loss Rate Optimization program will give acceptable results when an average of several flood hydrograph reconstitutions can be utilized. However, as pointed out in Section 5.05, each optimization run must be evaluated visually to confirm the acceptability of the reconstitution and the rationality of the optimized unit hydrograph and loss rate functions.

Usually, some improvement in reconstitutions can be obtained by modifying the loss rate functions, base flow recession coefficient or unit hydrograph coefficients obtained from the computer-optimized values, or the computer can be forced into a better solution by a technique explained in paragraph 4e of Appendix III. The engineer must always be aware of sources of data errors as well as data deficiencies. Seldom does one have as much data as desirable. Recording rain gages may be located too far from the basin to properly reflect the distribution of rainfall; rain gages may be too far apart to result in a reasonably accurate estimate of total storm rainfall over the basin; stage-discharge relations may have been extrapolated so far from measurements that errors in peak discharge and volume of runoff results. Reconstitution studies must take all of these possibilities into account when evaluating the applicability of a derived unit hydrograph or reconstituted discharge hydrograph.

When making trial reconstitutions of observed discharge hydrographs by the desk calculator technique outlined in Appendix I, adjustments are generally made to loss rates until the rainfall or rainfall plus snowmelt excess is equal to the direct surface runoff. The time of the first values of excess should coincide with the initial rise of the hydrograph.

Often some compromise must be reached when recorded rainfall patterns do not fully substantiate the runoff pattern. If the reconstituted peak consistently occurs before or after the observed peak, this normally indicates the unit hydrograph should be adjusted to peak sooner or later as indicated by the observed and computed differences. Similarly, if the computed hydrograph consistently has a peak value greater than the observed value, the unit hydrograph can be modified by decreasing the peak of the unit hydrograph by the same percentage as the difference between the peak discharges of the observed and computed hydrographs. The recession side of the computed hydrograph is relatively insensitive to changes in the recession characteristics of the unit hydrograph, but the trends are naturally in the same direction. If rainfall excess is rather uniform throughout the storm period, the computed hydrograph is much less responsive to adjustments in the unit hydrograph than it is when the rainfall distribution displays intense bursts of storm rainfall. As pointed out in Section 5.03, the areal distribution of rainfall has a marked effect on the runoff hydrograph and hence the resultant unit hydrograph which may be derived from reconstitution studies of that storm event. It is important to keep these characteristics in mind when selecting the unit hydrograph to apply to a design storm. If a major storm event and discharge hydrograph are not available for analysis in developing the unit hydrograph, or when future basin development or channel improvements are anticipated which will significantly influence the runoff characteristics of a basin, it is advisable to modify the unit hydrograph which is to be applied to the design storm to reflect these more intense storms and/or basin changes. This usually takes the form of decreasing the t_c and R by as much as 25 to 50 percent, depending on the forecast basin conditions. It is advisable in studies of this kind to make sensitivity tests by changing each variable a reasonable amount and observing the magnitude of its effect on the computed hydrograph. Only in this way can an engineer gain the judgment necessary in making rational decisions when selecting parameters required in design flood estimates.

Selected Bibliography

SELECTED BIBLIOGRAPHY

Chapter 2

2.01. American Society of Civil Engineers, "Hydrology Handbook," pp. 5-26, New York, 1949.

2.02. Butler, Stanley S., "Engineering Hydrology," pp. 39-65, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1957.

2.03. Gilman, Charles S., "Rainfall," in Chow, V.T., Handbook of Applied Hydrology," Section 9, pp. 9-1 through 9-68, McGraw-Hill Book Company, New York, 1958.

2.04. Linsley, Roy K. and Franzini, Joseph B., "Water Resources Engineering," pp. 12-18, McGraw-Hill Book Company, New York, 1964.

2.05. Linsley, Roy K., et al., "Hydrology for Engineers," pp. 23-51, McGraw-Hill Book Company, New York, 1958.

2.06. Thiessen, A. H., "Precipitation for Large Areas," Monthly Weather Review, v. 39, U. S. Weather Bureau, Washington, D.C., July 1911.

Chapter 3

3.01. Garstka, Walter U., "Snow and Snow Survey," Section 10 in Chow, V.T., "Handbook of Applied Hydrology," pp. 10-1 through 10-57, McGraw-Hill Book Company, New York, 1958.

3.02. Crawford, Norman H. and Linsley, Ray K., "Digital Simulation in Hydrology: Stanford Watershed Model IV," Technical Report No. 39, Department of Civil Engineering, Stanford University, Stanford, California, July 1966.

3.03. Leaf, Charles F. and Brink, Glen E., "Computer Simulation of Snowmelt within a Colorado Subalpine Watershed," USDA Forest Service Research Paper RM-99, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, February 1973.

3.04. U. S. Army Corps of Engineers, "Runoff from Snowmelt," Engineering Manual 1110-2-1406, Washington, D.C., January 1960.

3.05. U. S. Army Corps of Engineers, North Pacific Division, "Snow Hydrology," Portland, Oregon, June 1965.

3.06. U. S. Army Corps of Engineers, North Pacific Division, "Program Description and User Manual for SSARR, Streamflow Synthesis and Reservoir Regulation," Portland, Oregon, September 1972.

Chapter 4

4.01. Beard, Leo R., "Hypothetical Flood Computation for a Stream System," International Association of Scientific Hydrology, publication No. 80, Tuscon, Arizona, December, 1968.

4.02. Butler, Stanley S., "Engineering Hydrology," pp. 95-109, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1957.

4.03. U. S. Army Corps of Engineers, "Flood-Hydrograph Analyses and Computations," Engineering Manual 1110-2-1405, pp. 5-6, Washington, D.C., 1959.

Chapter 5

5.01. American Society of Civil Engineers, "Hydrology Handbook," pp. 65-115, New York, 1949.

5.02. Butler, Stanley S., "Engineering Hydrology," pp. 287-336, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1957.

5.03. Clark, C.O., "Storage and the Unit Hydrograph," Transactions of the American Society of Civil Engineers, v. 110, New York, 1943.

5.04. Johnstone, Don and Cross, W. P., "Elements of Applied Hydrology," The Ronald Press Company, New York, 1949.

5.05. Linsley, Roy K., et al., "Hydrology for Engineers," pp. 193-215, McGraw-Hill Book Company, New York, 1958.

5.06. Sherman, L. K., "Streamflow from Rainfall by the Unit-Graph Method," Engineering News Record, v. 108, pp. 501-505, New York, April 1932.

5.07. Snyder, Franklin F., "Synthetic Unit Graphs," Transations, American Geophysical Union, pt. 1, 1938.

5.08. U. S. Army Corps of Engineers, "Flood-Hydrograph Analyses and Computations," Engineering Manual 1110-2-1405, pp. 7-16, Washington, D.C., 1959.

5.09. U. S. Army Corps of Engineers, The Hydrologic Engineering Center, "Unit Hydrograph and Loss Rate Functions," HEC Training Document, Sacramento, California, May, 1969.

Appendix 1

Unit Hydrograph Techniques For Desk Calculators

APPENDIX I. UNIT HYDROGRAPH TECHNIQUES FOR DESK CALCULATORS

Hydrograph Computation By Use Of The Unit Hydrograph Template

In Section 5.04 of this volume, the general equation is presented for computing the hydrograph ordinate at any time i, given the unit hydrograph and rainfall and snowmelt excess (equation 5-3). However, in computing ordinates for all possible values of i by a desk calculator, the process can be simplified by constructing a template consisting of the unit hydrograph ordinates tabulated in reverse order.

The template is placed alongside the excess on a computation sheet with the first unit hydrograph ordinate, U_1, opposite the first excess value, E_1. Compute the first hydrograph ordinate, which is equal to U_1 times E_1. Slide the template down 1 period and accumulatively multiply U_1 by E_2 and U_2 by E_1. Note that if there is no excess during the second period, the second hydrograph ordinate would simply by U_2 times E_1. Repeat this process until the last unit hydrograph ordinate has been applied to the last excess value. This procedure is applicable to a storm having any number of excess periods regardless of the time lapse between excess values. The procedure is illustrated by the simple example shown in table I-01.

Table I-01. Hydrograph computation using a unit hydrograph template

Computation Period	Unit Hydrograph Ordinate	Excess	(Template)	Hydrograph Ordinate for Period 1		Hydrograph Ordinate for Period 6
			100			
			150			
			320			
			400			
			190		(Template)	
1	100	.10	100	10*	100	
2	190	.10			150	
3	400	0			320	
4	320	.40			400	
5	150	.05			190	
6	100	0			100	194.5**

* $Q_1 = 100\ (0.10) = 10$

** $Q_6 = 100\ (0) + 190\ (0.05) + 400\ (0.40) + 320\ (0) + 150\ (0.10) + 100\ (0.10) = 194.5$

Unit Hydrograph Determination By The Inverse Procedure

Since a hydrograph is computed by multiplying a unit hydrograph by the excess, then theoretically the unit hydrograph may be computed by the inverse of that procedure. However, practical considerations of the procedure usually restrict its application to the development of the rising limb and 1 or 2 periods past the peak of the unit hydrograph.

In order to apply the technique, it is necessary to perform an analysis of rainfall and snowmelt, loss, and excess. After estimating the excess, the rising limb of the unit hydrograph is determined by applying equation 5-2 in reverse order as follows:

a. Rearrange equation 5-3 to solve for U; for instance:

$$U_1 = Q_1/E_1 \tag{I-1}$$

$$U_2 = (Q_2 - (E_2 \cdot U_1))/E_1 \tag{I-2}$$

$$U_3 = (Q_3 - (E_3 \cdot U_1) - E_2 \cdot U_2)/E_1 \tag{I-3}$$

b. Tabulate the rainfall excess in a column in sequence.

c. Tabulate the hydrograph (after base flow separation) in the following column corresponding to rainfall excess values.

d. Set the edge of a second sheet alongside the rainfall excess. The unit hydrograph ordinates are to be tabulated on the second sheet.

e. Using equation 1, tabulate the resulting unit hydrograph ordinate opposite E_1.

f. Slide the sheet down 1 period and determine U_2 using equation I-2.

g. Repeat the process through 1 or 2 periods past the peak of the unit hydrograph.

Although this procedure may seem simple, there are certain difficulties involved. Since the computation of each unit hydrograph ordinate depends on all preceding computations, large negative ordinates sometimes develop. This may be due to a number of things, but the greatest source of error usually occurs in the determination of rainfall excess. Due to the likelihood of cumulative errors occurring, the technique described below is usually used to determine the recession limb of the unit hydrograph:

a. Sketch the unit hydrograph ordinates computed thus far and compute the remaining volume, V_r, required to produce 1 unit of runoff. Compute the ordinates of the recession limb using the equation:

$$U_{i+1} = K \cdot U_i \qquad \text{(I-4)}$$

where:

U_i = the last ordinate determined by the inverse procedure

$K = 1 - \frac{U_i}{U_i + V_r}$, the slope of the recession limb of the unit hydrograph.

It may be necessary to adjust the rising limb and recompute the slope of the recession limb to produce a reasonably shaped unit hydrograph due to the fact that there may be cumulative errors and that the rising limb of the unit hydrograph must be sketched to compute the remaining volume. The procedure is not ordinarily used except to determine a "first-trial" unit hydrograph. After the unit hydrograph has been tested against the hydrograph, it is usually simpler to adjust the first-trial unit hydrograph than to repeat the process. Also, there is considerable uncertainty whether to adjust the unit hydrograph or loss rates, as discussed in Section 5.05.

Unit Hydrograph Adjustment For Various Durations

Since a unit hydrograph by definition contains 1 unit of runoff, increasing the duration of the rainfall and snowmelt lengthens the time base and lowers the peak of the unit hydrograph. Any unit hydrograph can be easily converted to represent a longer duration, provided the desired duration is a multiple of the original duration. Figure I-01 shows the development of a 12-hour unit hydrograph from a 6-hour unit hydrograph. If a unit hydrograph of duration t_r is added to an identical unit hydrograph lagged by t_r, the resulting hydrograph represents the hydrograph from 2 units of excess occurring in $2t_r$ time. The ordinates of this hydrograph can then be divided by 2 to obtain a unit hydrograph for a unit duration of $2t_r$.

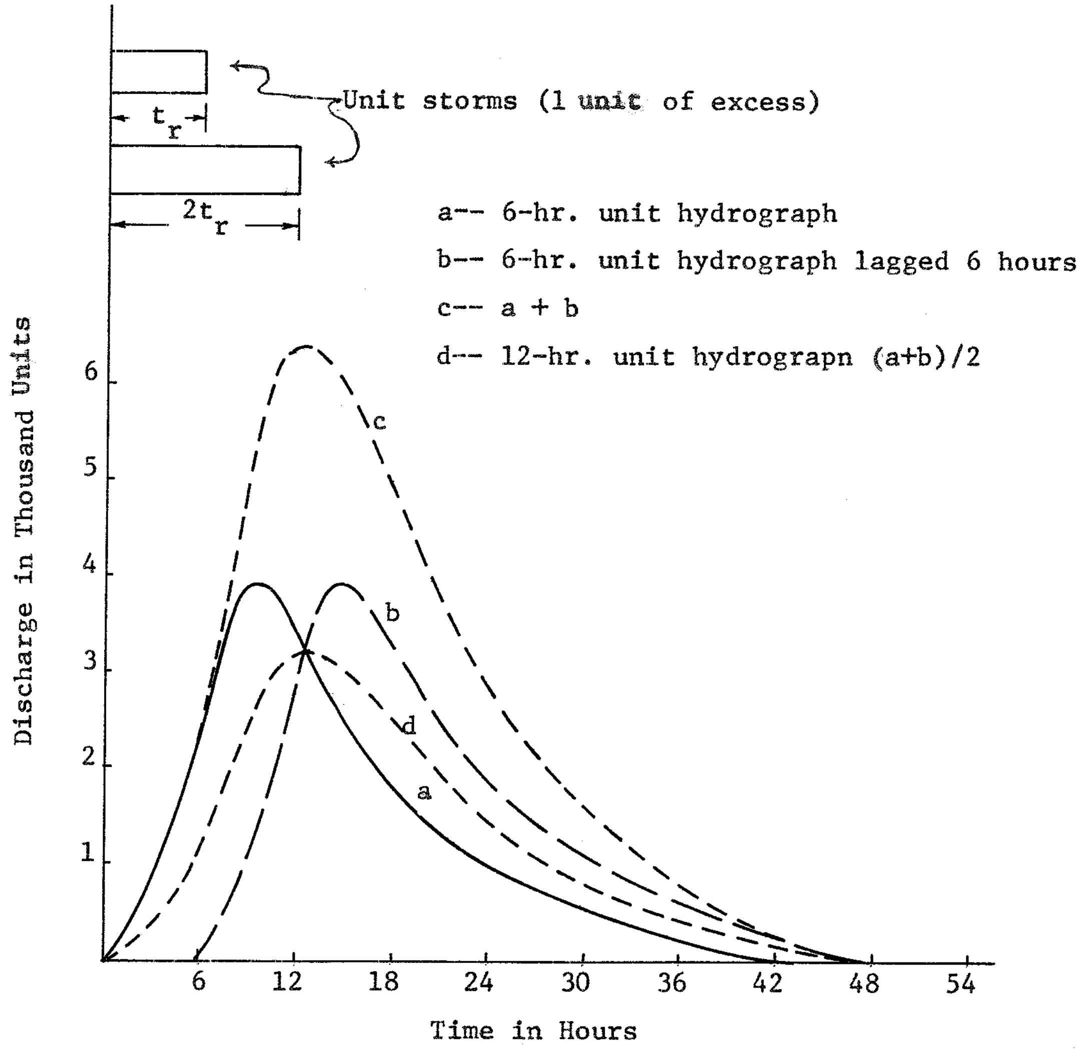


Fig. I-01. Conversion of a unit hydrograph to duration $2t_r$

TIME IN HOURS	COMPUTATION OF S-CURVE HYDROGRAPH FROM KNOWN 12-HOUR UNIT HYDROGRAPH			COMPUTATION OF 6-HOUR UNIT HYDROGRAPH FROM 12-HOUR S-CURVE HYDROGRAPH		
	12-HOUR UNIT HYDROGRAPH ③ Fig. I-013 IN C.F.S.	12-HOUR S-CURVE HYDROGRAPH ② Fig. I-013 IN C.F.S.	12-HOUR S-CURVE HYDROGRAPH ① Fig. I-013 IN C.F.S.	12-HOUR S-CURVE HYDROGRAPH ① SHIFTED SIX HOURS	RUNOFF FROM 0.5 INCH R_e IN 6 HOURS (COL.4-COL.5)	6-HOUR UNIT HYDROGRAPH [2 (COL.6)] IN C.F.S.
1	2	3	4	5	6	7
6	900		900		900	1,800
12	3,400		3,400	900	2,500	5,000
18	6,900	900	7,800	3,400	4,400	8,800
24	10,100	3,400	13,500	7,800	5,700	11,400
30	12,300	7,800	20,100	13,500	6,600	13,200
36	13,600	13,500	27,100	20,100	7,000	14,000
42	13,900	20,100	34,000	27,100	6,900	13,800
48	13,200	27,100	40,300	34,000	6,300	12,600
54	11,800	34,000	45,800	40,300	5,500	11,000
60	10,300	40,300	50,600	45,800	4,800	9,600
66	8,950	45,800	54,750	50,600	4,150	8,300
72	7,650	50,600	58,250	54,750	3,500	7,000
78	6,400	54,750	61,150	58,250	2,900	5,800
84	5,250	58,250	63,500	61,150	2,350	4,700
90	4,200	61,150	65,350	63,500	1,850	3,700
96	3,200	63,500	66,700	65,350	1,350	2,700
102	2,280	65,350	67,630	66,700	930	1,860
108	1,580	66,700	68,280	67,630	650	1,300
114	1,100	67,630	68,730	68,280	450	900
120	750	68,280	69,030	68,730	300	600
126	500	68,730	69,230	69,030	200	400
132	300	69,030	69,330	69,230	100	200
138	150	69,230	69,380	69,330	50	100
144	50	69,330	69,380	69,380	0	0

*ALL DISCHARGES ARE INSTANTANEOUS VALUES AT THE END OF THE HOUR DESIGNATED IN COLUMN 1. DRAINAGE AREA EQUALS 1290 SQUARE MILES.

Fig. I-02. Relation of unit hydrographs to S-curve hydrographs (after EM 1110-2-1405, reference 5.08)

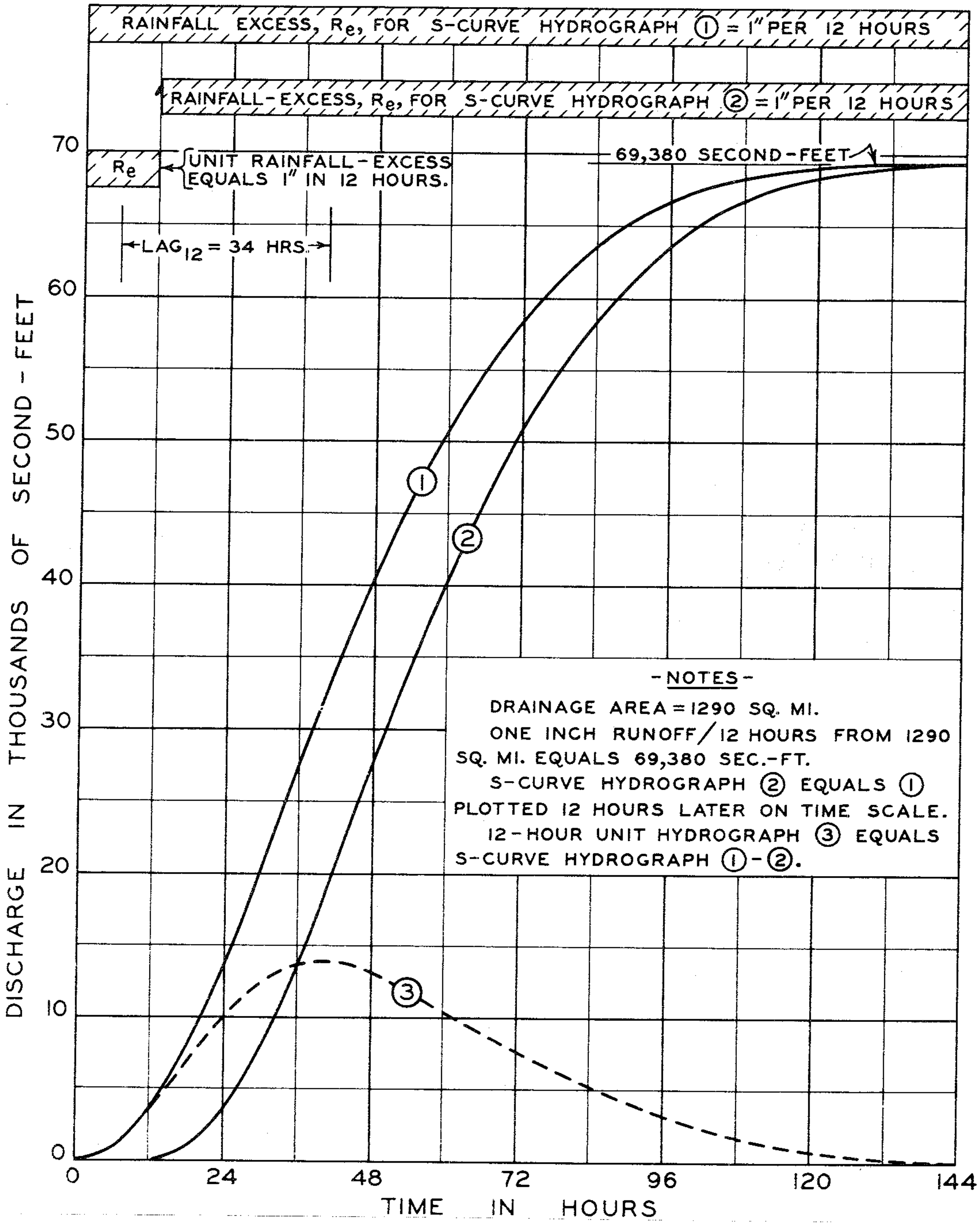


Fig. I-03. Relation of unit hydrograph to S-curve hydrograph (after EM 1110-2-1405, reference 5.08)

A more general technique to convert unit hydrographs to different unit rainfall durations is by use of S-curve hydrographs. The S-curve hydrograph is the hydrograph that would result if the unit rate of excess should continue indefinitely with the same areal distribution and intensity characteristics. The S-curve hydrograph is constructed by adding together a series of unit hydrographs, each lagged the unit duration, t_r, with respect to the preceding one. If the time base of the unit hydrograph is T, then a continuous rainfall plus snowmelt of 1 unit of runoff every t_r would develop a constant outflow at time T. (T and t_r are illustrated in fig. 5.02a of the main text.)

A convenient technique for computing an S-curve hydrograph and then determining a unit hydrograph of different unit duration is illustrated in figs. I-02 and I-03. In this particular example, it is desired to compute an S-curve hydrograph so that a 12-hour unit hydrograph can be used to determine a 6-hour unit hydrograph. Note that the 12-hour unit hydrograph must be tabulated in 6-hour (or less) time intervals. The computation of the 6-hour unit hydrograph is illustrated in columns 5-7 of fig. I-02.

Appendix 2

Basin Rainfall and Snowmelt Computations

This program is furnished by the Government and is accepted and used by the recipient upon the express understanding that the United States Government makes no warranties, express or implied, concerning the accuracy, completeness, reliability, usability, or suitability for any particular purpose of the information and data contained in this program or furnished in connection therewith, and the United States shall be under no liability whatsoever to any person by reason of any use made thereof.

The program herein belongs to the Government. Therefore, the recipient further agrees not to assert any proprietary rights therein or to represent this program to anyone as other than a Government program.

BASIN RAINFALL AND SNOWMELT COMPUTATION

COMPUTER PROGRAM 723-G1-L7260

JULY 1966

THE HYDROLOGIC ENGINEERING CENTER
U.S. ARMY ENGINEER DISTRICT, SACRAMENTO
609 SECOND STREET
DAVIS, CALIFORNIA 95616

BASIN RAINFALL AND SNOWMELT COMPUTATION

HYDROLOGIC ENGINEERING CENTER
723-G1-L7260

CONTENTS

EXHIBITS

BASIN RAINFALL AND SNOWMELT COMPUTATION

HYDROLOGIC ENGINEERING CENTER

1. ORIGIN OF PROGRAM

This program was prepared in the Hydrologic Engineering Center, Corps of Engineers, 650 Capitol Mall, Sacramento, California, principally by Leo R. Beard. Up-to-date information and copies of source statement cards for various types of computers can be obtained from the Center upon request by Government and cooperating agencies.

2. PURPOSE OF PROGRAM

a. This program written in Fortran II is designed to compute basin input (rainfall plus snowmelt) values for a storm. It will (a) compute basin mean precipitation from station precipitation weighted in any designated proportion and on the basis, if desired, of normal seasonal precipitation; (b) determine, if desired, whether each period of precipitation is rain or snowfall in each of as many as ten 1000-foot elevation zones, subtracting snowfall from precipitation and adding to snowpack; and (c) determine, if desired, snowmelt during each period in each of as many as ten 1000-foot elevation zones, adding to basin input and subtracting from snowpack.

b. The features of snowfall and snowmelt computation are bypassed, as are station weighting and normal seasonal precipitation routines, when not desired. Consequently, the program is efficient for the simpler applications as well as for those that are complex.

c. The program is designed to accept station rainfall data and storm temperatures for a specific storm period and tabulation interval for an entire region, then compute basin-mean values for any number of basins or sub-basins in the region with output intervals that are exact multiples or fractions of the input interval.

d. A listing of the source program is given in exhibit 4.

3. DESCRIPTION OF EQUIPMENT

a. This program was prepared for use in the IBM 1620 computer with 40,000 digit memory and the GE 225 and RCA 301 computers having comparable memory.

b. Source decks for various computers are available in the Hydrologic Engineering Center.

4. METHODS

a. Basin mean storm precipitation (ASP) is determined from station storm precipitation (STASP), if not supplied, on the basis of station normal seasonal precipitation (STANP) and basin normal seasonal precipitation (ANP) using any station weighting (WT) desired as follows:

$$ASP = \frac{(STASP \cdot WT)}{(STANP \cdot WT)} \quad ANP \tag{1}$$

If either weights or normal seasonal precipitation or both are not used, values of 1.0 are automatically substituted, thus nullifying their influence.

b. Precipitation by input periods is derived from station data by periods (STAP) as follows:

$$P = \frac{(STAP \cdot WT)}{(STASP \cdot WT)} \quad ASP \tag{2}$$

Here STASP and ASP are storm precipitation. If data for any period at any station is missing, a negative quantity must be entered for that station and period. Storm totals that include all storm precipitation for each station must be given, however.

c. The output period can be any exact multiple of the input period. If larger, successive values are added. If smaller, input-period values are divided uniformly.

d. Precipitation in each elevation zone falling as snow (whenever temperature at that mid-zone elevation is below $34^{o}F$) is added to the snowpack, whereas melt is subtracted. The coefficient for snowmelt (CSNOW in the above equation) should be in the order of .02 to .04. A lapse rate of $3^{o}F$ per 1000 feet is used. Snowmelt is computed by use of the equation below:

$$MELT = CSNOW\ (TMP-32)\ (PRECIP) \tag{3}$$

5. INPUT

Input is summarized in exhibits 5 and 6. Only those cards and items of input necessary to any particular run are required. All data are entered consecutively on each card, using 8 columns (digits, including decimal point, if used) per variable and 10 variables per card, unless fewer variables are called for. At the end of each run, data for the next run will be accepted.

6. OUTPUT

a. Input

b. Basin mean rainfall plus snowmelt by periods and total for storm.

c. If a positive value is entered for IPRNT, basin mean precipitation values and their sum, and other data will be printed.

d. If a positive value for IPNCH is entered, the final input amounts for each period at each basin will be punched on cards to the nearest hundredth of an inch in ten 8-column fields per card.

7. OPERATING INSTRUCTIONS

Standard Fortran II operating instructions. No sense switches used. Program is acceptable to Fortran IV with input-output conversion routine.

8. DEFINITION OF TERMS

Terms used in this program are defined in exhibit 3.

9. EXAMPLES

Examples of various applications of this program are given in exhibits 1 and 2.

10. PROPOSED FUTURE DEVELOPMENT

It is anticipated that additions to or revisions of this program may be desirable from time to time. It is requested that any user who finds an inadequacy or desirable addition or modification notify the Hydrologic Engineering Center.

SAMPLE INPUT

```
                          TEST NO 1
                SAMPLE HYETOGRAPH COMPUTATION
                        FULL ROUTINE
     2     10      2     65    120      1      1             1
     1  16.68  53.70
     2  20.19  62.70
     3  16.51  61.90
     4  21.74  66.90
     5  23.75  76.50
     6  18.99  47.70
     7   8.92  25.40
     8   5.67  22.00
     9  17.93  69.30
    10   9.15  39.70
     3    .31    .36    .48    .79    .49    .19    .08    .01    .08
     0    .06    .03     -1     -1     -1     -1     -1     -1     -1
    -1     -1     -1     -1     -1    .44    .40    .47    .34    .36
   .47    .35    .30    .22    .25    .13    .15    .22    .06    .09
   .14      0    .01    .06    .02    .01    .33    .18    .05    .37
   .66    .60    .35    .36    .38    .62    .50    .81    .48    .39
   .33    .22    .13    .06      0    .01
     5    .05    .15    .30    .60    .67    .45    .15    .17      0
   .02    .01      0    .10     -1    .05    .24    .39    .17    .46
   .33    .28    .25    .41    .55    .48    .52    .61    .46    .63
   .61    .66    .69    .57    .48    .76    .33    .25    .14    .06
   .02    .06    .10    .16    .01    .07    .09    .21    .25    .54
   .76    .74    .68    .66    .60    .93   1.21    .48    .70    .67
   .59    .64    .28    .14    .02    .05
    47     46     47     50     51     52     52     52     53     54
    54     54     54     54     53     54     55     56     56     57
    58     58     58     58     58     58     58     59     61     63
    63     63     63     62     61     60     60     60     60     59
    60     62     63     62     62     62     61     60     60     60
    61     62     65     66     66     66     67     65     65     65
    65     64     64     64     65     65
     1     10      2     60           .02     61
     1      1      2      1      3      1      4      1      5      1
     6      1      7      1      8      1      9      1     10      1
     3      2      5      2
  .000   .075   .147   .159   .131   .191   .225   .072
  1.00  43.50  54.00  61.90  66.50  67.70  63.90  56.70   1.00   1.00
```

EXHIBIT 1

PAGE 1 OF 2

```
                                     .80    2.00    2.70    2.50
       2               2     360    18.5     .02      61
       3       1       5       1
    .000    .075    .147    .159    .131    .191    .225    .072
    1.00   43.50   54.00   61.90   66.50   67.70   63.90   56.70    1.00    1.00
                                     .80    2.00    2.70    2.50
```

EXHIBIT 1
PAGE 2 OF 2

SAMPLE OUTPUT

```
1
                               TEST NO 1
                     SAMPLE HYETOGRAPH COMPUTATION
                              FULL ROUTINE

NLOC NSTA NSTAR  NP IPER SNOW INAP PNCH PRNT
   2   10     2  65  120    1    1    0    1

     STA   STANP   STASP
       1   16.68   53.70
       2   20.19   62.70
       3   16.51   61.90
       4   21.74   66.90
       5   23.75   76.50
       6   18.99   47.70
       7    8.92   25.40
       8    5.67   22.00
       9   17.93   69.30
      10    9.15   39.70

STATION PRECIPITATION AMOUNTS BY PERIOD
       3     .31     .36     .48     .79     .49     .19     .08     .01     .08
    0.00     .06     .03   -1.00   -1.00   -1.00   -1.00   -1.00   -1.00   -1.00
   -1.00   -1.00   -1.00   -1.00   -1.00     .44     .40     .47     .34     .36
     .47     .35     .30     .22     .25     .13     .15     .22     .06     .09
     .14    0.00     .01     .06     .02     .01     .33     .18     .05     .37
     .66     .60     .35     .36     .38     .62     .50     .81     .48     .39
     .33     .22     .13     .06    0.00     .01
       5     .05     .15     .30     .60     .67     .45     .15     .17    0.00
     .02     .01    0.00     .10   -1.00     .05     .24     .39     .17     .46
     .33     .28     .25     .41     .55     .48     .52     .61     .46     .63
     .61     .66     .69     .57     .48     .76     .33     .25     .14     .06
     .02     .06     .10     .16     .01     .07     .09     .21     .25     .54
     .76     .74     .68     .66     .60     .93    1.21     .48     .70     .67
     .59     .64     .28     .14     .02     .05
```

EXHIBIT 2
PAGE 1 OF 4

```
TEMPERATURES BY PERIOD
    47.     46.     47.     50.     51.     52.     52.     52.     53.     54.
    54.     54.     54.     54.     53.     54.     55.     56.     56.     57.
    58.     58.     58.     58.     58.     58.     58.     59.     61.     63.
    63.     63.     63.     62.     61.     60.     60.     60.     60.     59.
    60.     62.     63.     62.     62.     62.     61.     60.     60.     60.
    61.     62.     65.     66.     66.     66.     67.     65.     65.     65.
    65.     64.     64.     64.     65.

LC=  1  NSTAB= 10  NSTRB=  2  JPER= 60  ASP=  0.00  CSNOW=   .02  ANP=  61.0
     1    1.00       2    1.00      3    1.00      4    1.00      5    1.00
     6    1.00       7    1.00      8    1.00      9    1.00     10    1.00
     3    2.00       5    2.00
RTIOA =       0.00    .07    .14    .15    .13    .19    .22    .07   0.00   0.00
ZONNP =       1.00  43.50  54.00  61.90  66.50  67.70  63.90  56.70   1.00   1.00
SNOW  =       0.00   0.00   0.00   0.00    .80   2.00   2.70   2.50   0.00   0.00
NO DATA FOR PERIOD 14

REMAINING SNOW
   0.00    0.00    0.00    0.00    0.00    0.00    1.90    3.72     .08     .17

TOTAL PRECIP= 18.47  COMPARED WITH ASP= 18.50
    .17     .23     .36     .64     .53     .29     .11     .08     .04     .01
    .03     .01     .08    0.00     .04     .19     .30     .13     .36     .26
    .22     .19     .32     .43     .42     .42     .50     .37     .46     .50
    .46     .46     .36     .34     .41     .22     .22     .09     .07     .07
    .03     .05     .10     .01     .04     .19     .18     .14     .42     .65
    .62     .47     .47     .45     .71     .79     .59     .54     .49     .42
    .40     .19     .09     .01     .03
```

EXHIBIT 2
PAGE 2 OF 4

```
 65 BASIN INPUT VALUES, STA      1 120-MINUTE INTERVAL
TOTAL= 19.07

     .06     .08     .12     .32     .39     .22     .08     .06     .03     .01
     .03     .01     .08    0.00     .03     .19     .31     .13     .36     .28
     .24     .22     .36     .48     .47     .47     .55     .41     .52     .58
     .52     .51     .41     .37     .45     .24     .24     .10     .08     .08
     .03     .06     .11     .02     .04     .22     .20     .15     .46     .72
     .68     .53     .54     .52     .83     .88     .65     .58     .53     .46
     .43     .20     .10     .01     .03

130 BASIN INPUT VALUES, STA      1  60-MINUTE INTERVAL
TOTAL= 19.34

     .03     .03     .04     .04     .06     .06     .16     .16     .20     .20
     .11     .11     .04     .04     .03     .03     .02     .02     .01     .01
     .02     .02     .01     .01     .04     .04    0.00    0.00     .02     .02
     .10     .10     .16     .16     .07     .07     .18     .18     .14     .14
     .12     .12     .11     .11     .18     .18     .24     .24     .24     .24
     .24     .24     .28     .28     .21     .21     .26     .26     .29     .29
     .26     .26     .26     .26     .21     .21     .19     .19     .23     .23
     .12     .12     .12     .12     .05     .05     .04     .04     .04     .04
     .02     .02     .03     .03     .06     .06     .01     .01     .02     .02
     .11     .11     .10     .10     .08     .08     .23     .23     .36     .36
     .34     .34     .27     .27     .27     .27     .26     .26     .42     .42
     .44     .44     .33     .33     .29     .29     .27     .27     .23     .23
     .22     .22     .10     .10     .05     .05     .01     .01     .02     .02
```

EXHIBIT 2
PAGE 3 OF 4

```
LC=  2  NSTAB=  0  NSTRB=  2  JPER=360  ASP= 18.50  CSNOW=   .02  ANP=  61.0
     3    1.00         5    1.00
RTIOA =      0.00    .07    .14    .15    .13    .19    .22    .07   0.00   0.00
ZONNP =      1.00  43.50  54.00  61.90  66.50  67.70  63.90  56.70   1.00   1.00
SNOW  =      0.00   0.00   0.00   0.00    .80   2.00   2.70   2.50   0.00   0.00
NO DATA FOR PERIOD 14

REMAINING SNOW
    0.00    0.00    0.00    0.00    0.00    0.00    1.90    3.72     .08     .17

TOTAL PRECIP= 18.45  COMPARED WITH ASP= 18.50
      .17     .23     .36     .64     .53     .29     .11     .08     .04     .01
      .03     .01     .08    0.00     .04     .19     .30     .13     .36     .26
      .22     .19     .32     .43     .42     .42     .50     .37     .45     .50
      .46     .45     .36     .34     .41     .22     .22     .09     .07     .07
      .03     .05     .10     .01     .04     .19     .18     .14     .42     .65
      .62     .47     .47     .45     .71     .79     .59     .54     .49     .42
      .40     .19     .09     .01     .03

 65 BASIN INPUT VALUES, STA     2 120-MINUTE INTERVAL
TOTAL= 19.04

      .06     .08     .12     .32     .39     .22     .08     .06     .03     .01
      .03     .01     .08    0.00     .03     .19     .31     .13     .36     .28
      .24     .22     .35     .48     .47     .47     .55     .41     .52     .58
      .52     .51     .41     .37     .45     .24     .24     .10     .08     .08
      .03     .06     .11     .02     .04     .22     .20     .15     .46     .72
      .68     .53     .54     .52     .82     .88     .65     .58     .52     .46
      .43     .20     .10     .01     .03

 22 BASIN INPUT VALUES, STA     2 360-MINUTE INTERVAL
TOTAL= 19.04

      .26     .93     .17     .05     .11     .63     .88    1.05    1.49    1.51
     1.44    1.06     .42     .17     .17     .57    1.86    1.59    2.35    1.56
      .73     .04
```

EXHIBIT 2
PAGE 4 OF 4

DEFINITIONS - 723-G1-L7260

AI(I) - Basin mean rainfall plus snowmelt in inches for period I
AJ - J
AM - M
AMELT - Basin total melt in inches during given period
AMLT - Zone melt in inches during given period
ANP - Basin mean normal precipitation (usually normal annual precipitation in inches)
AP(I) - Basin mean precipitation in inches for period I
ASP - Basin mean storm total precipitation in inches
ATMP - Mid-zone temperature in degrees fahrenheit above 34° (and later, above 32°)
CMELT - Degree-day coefficient of snowmelt
CSNOW - Snowmelt coefficient ranging from .02 to .04
I - Index for period of storm
INAP - Positive value causes normal seasonal precipitation to be used
IPER - Duration of input unit period in minutes
IPNCH - Positive value calls for punch-out
IPRNT - Positive value causes supplementary print-out
ISNOW - Positive value calls for snowfall and snowmelt data and computation
IST(KX) - Identification number of non-recording gage
ISTR(KK) - " " " recording gage
ITMP - Temporary variable
J - Index of elevation zone
JPER - Duration of output unit interval in minutes
K - Station number and miscellaneous index
KPER - Maximum number of precipitation intervals
KSTA - Maximum number of stations
KSTAR - Maximum number of recording stations
KX - Index of station
L - Index for period of storm
LC - Identification number of basin
M - Ratio of put and output intervals and other items
N - Number of basins or sub-basin
NLOC - Number of basins or sub-basins for which hyetographs are to be computed
NP - Number of input periods
NPX - Number of output periods
NREM - Number of remaining input periods
NSTA - Number of stations in region
NSTAB - Number of stations used to determine basin mean storm total precipitation
NSTAR - Number of recorder stations in region

EXHIBIT 3
PAGE 1 OF 2

NSTRB - Number of recorder stations used to determine basin mean hyetograph
P(K,I) - Precipitation in inches for period I at station K
RTIOA(J) - Ratio of area in 1000-ft elevation zone J to total basin area
RTIOP - Ratio of rain area to total basin area
RTIOZ(J) - Ratio of normal precipitation in elevation zone J to that for basin
SNOW(J) - Water equivalent of snowpack in inches, average for elevation zone J
STANP(K) - Station normal precipitation (usually normal annual in inches) for station K
STASP(K) - Station storm total precipitation in inches for station K
SUM1 - Total basin precipitation
SUM2 - Total basin rain plus snowmelt
SUMNP - Sum of station normal precipitation
SUMP - Sum of station precipitation in inches for period
SUMSP - Sum of station storm precipitation in inches
TEMP - Temporary variable
TMPR(I) - Temperature in degrees fahrenheit at bottom of lowest elevation zone (usually sea level) during period I
WT(KX) - Relative station weight for non-recording station
WTR(KX) - Relative station weight for recorder station
ZONNP(J) - Normal precipitation (usually annual in inches), average for elevation zone J

EXHIBIT 3

SOURCE PROGRAM LISTING

```
C     723-GI-L7260 BASIN RAINFALL AND SNOWMELT COMPUTATION
C     HYDROLOGIC ENGINEERING CENTER      JULY 1966
C     INDEXES I=PER  J=ELEV ZONE  K=STA
C     FUNCTIONS USED - NONE
      DIMENSION AI(500),AP(500),IST(100),ISTR(100),
     1P(25,500),RTIOA(10),RTIOZ(10),SNOW(10),STANP(100),STASP(100),
     2TMPR(500),WT(30),WTR(20),ZONNP(10)
      KSTA = 100
      KSTAR = 25
      KPER = 500
    1 FORMAT (1X,I7,9I8)
    2 FORMAT (1X,F7.0,9F8.0)
    3 FORMAT (10F8.2)
    4 FORMAT (1X,I7,F8.0,I8,F8.0,I8,F8.0,I8,F8.0,I8,F8.0)
    5 FORMAT(5(I8,F8.2))
  100 PRINT 110
  110 FORMAT (1H1)
      READ 120, (TMPR(I),I=1,120)
  120 FORMAT (1X,A1,39A2)
      READ 1, NLOC,NSTA,NSTAR,NP,IPER,ISNOW,INAP,IPNCH,IPRNT
      IF (NLOC) 122,122,124
  122 STOP
  124 IF (NSTA-KSTA) 125,125,127
  125 IF (NSTAR-KSTAR) 126,126,127
  126 IF (NP-KPER) 129,129,127
  127 PRINT 128
  128 FORMAT (19H DIMENSION EXCEEDED)
      STOP
  129 PRINT 120, (TMPR(I),I=1,120)
      PRINT 130, NLOC,NSTA,NSTAR,NP,IPER,ISNOW,INAP,IPNCH,IPRNT
  130 FORMAT (/45H NLOC NSTA NSTAR  NP IPER SNOW INAP PNCH PRNT/9I5//
     1 24H     STA   STASP   STANP)
      DO 150 KX=1,NSTA
      READ 160, K,STASP(K),STANP(K)
      PRINT 161, K,STASP(K),STANP(K)
  150 CONTINUE
  160 FORMAT (1X,I7,9F8.0)
  161 FORMAT (I8,9F8.2)
      PRINT 170
  170 FORMAT (/40H STATION PRECIPITATION AMOUNTS BY PERIOD)
      DO 180 KX=1,NSTAR
```

EXHIBIT 4
PAGE 1 OF 6

```
      READ 160, K,(P(K,I),I=1,9)
      IF (KSTAR-K) 127,172,172
  172 PRINT 161, K,(P(K,I),I=1,9)
      IF(NP-9)180,180,175
  175 READ 2,(P(K,I),I=10,NP)
      PRINT 3,(P(K,I),I=10,NP)
  180 CONTINUE
      IF (ISNOW) 205,205,190
  190 READ 2, (TMPR(I),I=1,NP)
      PRINT 200,(TMPR(I), I=1,NP)
  200 FORMAT (/23H TEMPERATURES BY PERIOD/(10F8.0))
  205  DO 750 N=1,NLOC
      PRINT 110
      READ 207, LC,NSTAB,NSTRB,JPER,ASP,CSNOW,ANP,CMELT
  207 FORMAT (1X,I7,3I8,4F8.0)
      PRINT 210, LC,NSTAB,NSTRB,JPER,ASP,CSNOW,ANP,CMELT
  210 FORMAT (/4H LC=I3,8H  NSTAB=I3,8H  NSTRB=I3,7H  JPER=I3,6H  ASP=
     1 F6.2,8H  CSNOW=F6.2,6H  ANP=F6.1/7H CMELT=F7.4)
      IF (INAP) 211,211,213
  211 DO 212 K=1,KSTA
      STANP(K) = 1.
  212 CONTINUE
      ANP = 1.
  213 IF (ASP) 215,215,218
  215 READ 4, (IST(KX),WT(KX),KX=1,NSTAB)
      PRINT 5, (IST(KX),WT(KX),KX=1,NSTAB)
  218 READ 4, (ISTR(KX),WTR(KX),KX=1,NSTRB)
      PRINT 5, (ISTR(KX),WTR(KX),KX=1,NSTRB)
      IF (ISNOW) 255,255,220
  220 READ 2, (RTIOA(J),J=1,10)
      PRINT 230, (RTIOA(J),J=1,10)
  230 FORMAT (10H RTIOA =  10F7.2)
      READ 2, (ZONNP(J),J=1,10)
      PRINT 240, (ZONNP(J),J=1,10)
  240 FORMAT (10H ZONNP =  10F7.2)
      READ 2, (SNOW(J),J=1,10)
      PRINT 250, (SNOW(J),J=1,10)
  250 FORMAT (10H SNOW =   10F7.2)
  255 SUM1 = .005
      SUM2 = .005
      IF (ASP) 260,260,310
```

EXHIBIT 4
PAGE 2 OF 6

```
  260 SUMSP = 0.
      SUMNP = 0.
  290 DO 300 KX=1,NSTAB
      K = IST(KX)
      SUMSP = SUMSP+STASP(K)*WT(KX)
      SUMNP = SUMNP+STANP(K)*WT(KX)
  300 CONTINUE
      ASP = SUMSP*ANP/SUMNP
  310 IF (ISNOW) 345,345,315
  315 DO 340 J=1,10
      IF (INAP) 320,320,330
  320 RTIOZ(J) = 1.
      GO TO 340
  330 RTIOZ(J) = ZONNP(J)/ANP
  340 CONTINUE
  345 DO 490 I=1,NP
      SUMP = 0.
      SUMSP = 0.
      DO 360 KX=1,NSTRB
      K = ISTR(KX)
      IF (P(K,I)) 360,350,350
  350 SUMP = SUMP+P(K,I)*WTR(KX)
      SUMSP = SUMSP+STASP(K)*WTR(KX)
  360 CONTINUE
      IF (SUMSP) 370,370,390
  370 PRINT 380, I
  380 FORMAT (19H NO DATA FOR PERIOD I3)
      SUMSP = 1.
  390 AP(I) = SUMP*ASP/SUMSP
      IF (ISNOW) 470,470,400
  400 AMELT = 0.
      RTIOP = 1.
C             * * INPUT = PRECIP-SNOWFALL+SNOWMELT
      DO 460 J=1,10
      AJ = J
      ATMP = TMPR(I)-3.0*AJ-32.5
      IF (ATMP) 410,420,420
  410  SNOW(J) = SNOW(J)+AP(I)*RTIOZ(J)
      RTIOP = RTIOP-RTIOA(J)*RTIOZ(J)
  420 ATMP = ATMP+2.
      IF (ATMP) 460,460,430
```

EXHIBIT 4
PAGE 3 OF 6

```
  430 AMLT = CSNOW*ATMP*AP(I)*RTIOZ(J)+ CMELT*ATMP
      IF (AMLT-SNOW(J)) 450,450,440
  440 AMLT = SNOW(J)
  450 SNOW(J) = SNOW(J)-AMLT
      AMELT = AMELT+AMLT*RTIOA(J)
  460 CONTINUE
C     AI(I) = BASIN INPUT FOR PERIOD I  * * *
      AI(I) = AP(I)*RTIOP+AMELT
      GO TO 480
  470 AI(I) = AP(I)
  480 M = AP(I)*100.+0.5
      AP(I) = M
      AP(I) = AP(I)*0.01
      SUM1 = SUM1+AP(I)
      M = AI(I)*100.0+0.5
      AI(I) = M
      AI(I) = AI(I)*0.01
  490 SUM2 = SUM2+AI(I)
      IF (ISNOW) 520,520,500
  500 PRINT 510, (SNOW(J), J=1,10)
  510 FORMAT (/15H REMAINING SNOW/10F8.2)
  520 PRINT 530, SUM1,ASP
  530 FORMAT (/14H TOTAL PRECIP= F6.2,20H  COMPARED WITH ASP= F6.2)
      IF (IPRNT) 550,550,540
  540 PRINT 3, (AP(I),I=1,NP)
C            CHANGE TABULATION INTERVAL
  550 NPX = NP
      IF(JPER)552,552,554
  552 JPER=IPER
  554 IF(JPER-IPER)555,680,555
  555 IF (IPRNT) 570,570,560
  560 PRINT 690, NP,LC,IPER
      PRINT 700, SUM2
      PRINT 3, (AI(I),I=1,NP)
  570 IF (JPER-IPER) 640,680,590
  590 M = JPER/IPER
      ITMP = M*IPER
      IF (JPER-ITMP) 720,600,720
  600 NPX = NP/M
      NREM = NP-M*NPX
      K = 0
```

EXHIBIT 4

```
      DO 610 L=1,NPX
      K = K+1
      AI(L) = AI(K)
      DO 605 I=2,M
      K = K+1
  605 AI(L) = AI(L)+AI(K)
  610 CONTINUE
      IF (NREM) 680,680,620
  620 NPX = NPX+1
      AI(NPX) = 0.
      DO 630 I=1,NREM
      K = K+1
      AI(NPX)=AI(NPX)+AI(K)
  630 CONTINUE
      GO TO 680
  640 M = IPER/JPER
      AM = M
      J = IPER/M
      IF(JPER-J)720,650,720
  650 K = NP*M+1
      SUM2 = 0.
      DO 660 KX=1,NP
      DO 655 L=1,M
      I = NP-KX+1
      K = K-1
      J = AI(I)*100./AM+0.5
      TEMP = J
      AI(K) = TEMP*0.01
      SUM2 = SUM2+AI(K)
  655 CONTINUE
  660 CONTINUE
      NPX = NP*M
  680 PRINT 690, NPX,LC,JPER
  690 FORMAT (/I4,24H BASIN INPUT VALUES, STA I6,I4,16H-MINUTE INTERVAL)
      PRINT 700, SUM2
  700 FORMAT (7H TOTAL= F6.2/)
      PRINT 3, (AI(I),I=1,NPX)
      IF(IPNCH)750,750,705
  705 PUNCH 3, (AI(I),I=1,NPX)
      GO TO 750
  720 PRINT 730
```

```
730 FORMAT (29H UNACCEPTABLE OUTPUT INTERVAL)
750 CONTINUE
    GO TO 100
    END
```

EXHIBIT 4
PAGE 6 OF 6

INPUT DATA 723-G1-L7260

A Three output title cards. Leave first column of each blank

B Job data card (All integers right justified without decimal points)

1. NLOC - Number of basins and sub-basins for which input values are to be computed.
2. NSTA - Number of recording and non-recording stations used in job.
3. NSTAR - Number of recording stations used in job.
4. NP - Number of input precipitation intervals in storm.
5. IPER - Input interval in minutes
6. ISNOW - Positive value calls for snowfall and snowmelt data and computation
7. INAP - Positive value calls for use of normal annual precipitation in computation of basin storm precipitation.
8. IPNCH - Positive value calls for punched cards with basin rainfall plus snowmelt amounts.
9. IPRNT - Positive value call for print-out of basin precipitation and rainfall plus snowmelt for input interval as well as rainfall plus snowmelt for output interval.

C Station cards, one for each station in any order (NSTA Cards)

1. IST - Station number, integer less than 60, right justified without decimal point.
2. STASP - Station storm precipitation in inches.
3. STANP - Station normal seasonal precipitation in inches. May be omitted if not used.

D Recorder station data, set for each recorder station (NSTAR Cards)

1. ISTR - Recorder station number, integer less than 20, right justified without decimal point.
2. P - Precipitation amounts in inches for respective periods of the storm in successive fields, 9 on first card and 10 on each succeeding card up to NP values.

E Temperature data (required only when ISNOW is positive)

TMPR - Temperature in degrees fahrenheit at bottom of lowest elevation zone (usually sea level), ten per card up to NP values.

EXHIBIT 5

F.* Basin data card, first four values integers right justified without decimal point

1. LC - Basin or sub-basin location number.
2. NSTAB - Number of stations used for computing basin mean storm total precipitation.
3. NSTRB - Number of recorder stations used for computing basin mean period precipitation.
4. JPER - Output interval in minutes, must be exact multiple or fraction of IPER.
5. ASP - Basin mean storm precipitation, specified only if determined separately, otherwise leave blank.
6. CSNOW - Snowmelt coefficient between .02 and .04.
7. ANP - Basin mean normal seasonal precipitation in inches.
8. CMELT - Degree-day coefficient of snowmelt

G. Storm total station identification (NSTAB pairs), omit if ASP is positive

1. IST - Station number, integer right justified without decimal point.
2. WT - Corresponding relative weight for station

H. Recorder station identification (NSTRB pairs)

1. ISTR - Recorder station number, integer right justified without decimal point.
2. WTR - Corresponding relative weight for station

I. Areas of elevation zones, up to 10 values. Omit if ISNOW is not positive

RTIOA - Ratio of area in each 1000-ft. elevation zone (starting with lowest) to total basin area.

J. Normal seasonal precipitation for elevation zones, up to 10 values. Omit if ISNOW is not positive.

ZONNP - Normal seasonal precipitation in inches in each 1000-foot elevation zone starting with the lowest.

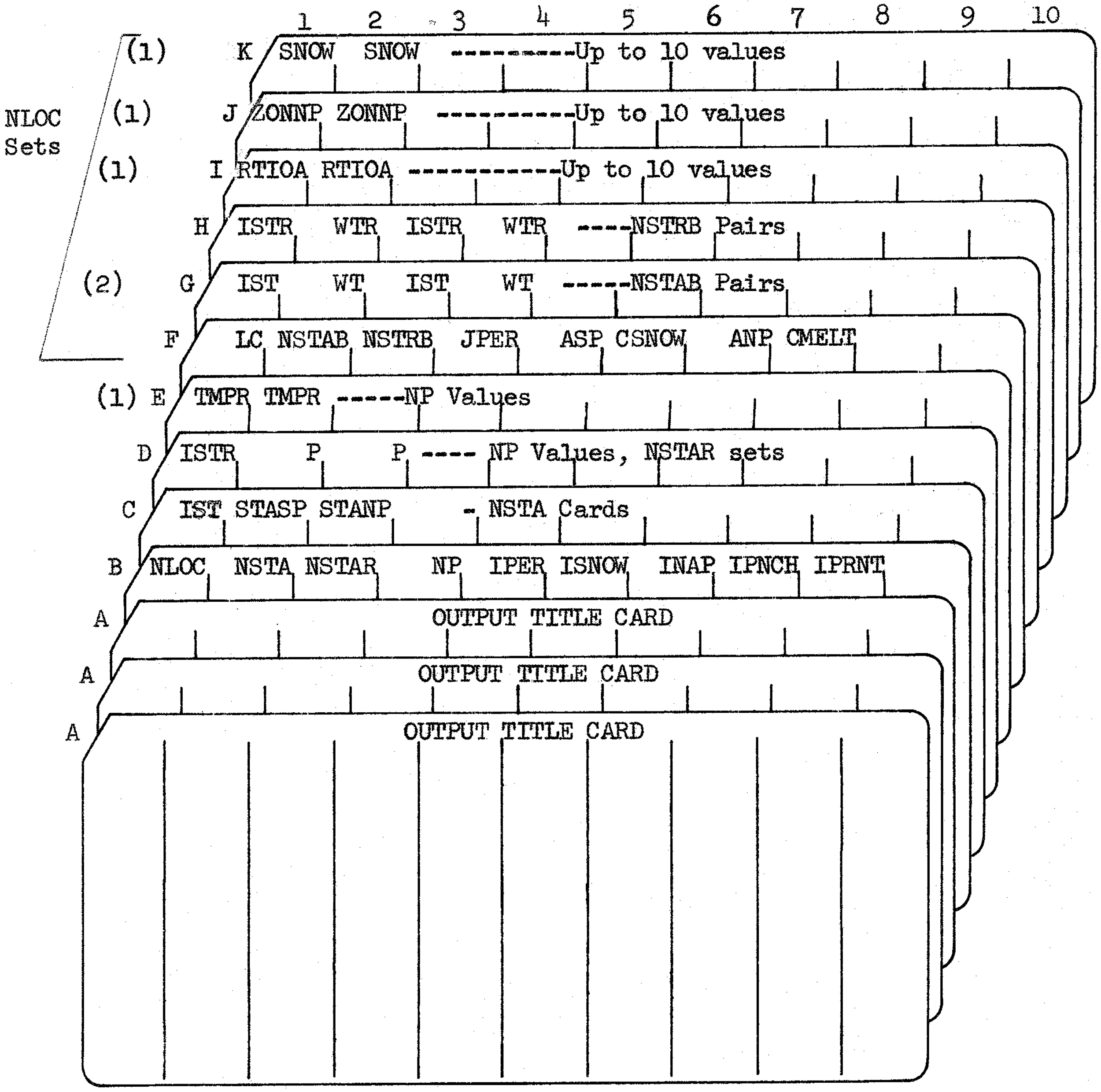
K. Initial snow pack in elevation zones, up to 10 values, omit if ISNOW is not positive.

SNOW - Water equivalent in inches of snowpack in each elevation zone (starting with the lowest) at start of storm.

* Items F through K repeated in same sequence for each sub-basin.

723-G1-L7260

SUMMARY OF REQUIRED CARDS



(1) Omit if ISNOW is zero or negative

(2) Omit if ASP is positive

EXHIBIT 6

Appendix 3

Unit Hydrograph and Loss Rate Optimization

This program is furnished by the Government and is accepted and used by the recipient upon the express understanding that the United States Government makes no warranties, express or implied, concerning the accuracy, completeness, reliability, usability, or suitability for any particular purpose of the information and data contained in this program or furnished in connection therewith, and the United States shall be under no liability whatsoever to any person by reason of any use made thereof.

The program herein belongs to the Government. Therefore, the recipient further agrees not to assert any proprietary rights therein or to represent this program to anyone as other than a Government program.

UNIT GRAPH AND LOSS RATE OPTIMIZATION

HYDROLOGIC ENGINEERING CENTER
COMPUTER PROGRAM 23-J2-L211

AUGUST 1966

U. S. ARMY ENGINEER DISTRICT
650 CAPITOL MALL
SACRAMENTO, CALIFORNIA

UNIT GRAPH AND LOSS RATE OPTIMIZATION

HYDROLOGIC ENGINEERING CENTER
COMPUTER PROGRAM 23-J2-L211

CONTENTS

EXHIBITS

UNIT GRAPH AND LOSS RATE OPTIMIZATION

HYDROLOGIC ENGINEERING CENTER
COMPUTER PROGRAM 23-J2-L211

1. ORIGIN OF PROGRAM

This program was prepared in the Hydrologic Engineering Center, Corps of Engineers, 650 Capitol Mall, Sacramento, California, by Leo R. Beard. Up-to-date information and copies of source statement cards can be obtained from the Center upon request by Government and cooperating organizations.

2. PURPOSE OF PROGRAM

a. This program, written in Fortran II, will determine the best unit hydrograph and loss coefficients, within the limits of the mathematical model, to reproduce a number of flood hydrographs at a given location from specified rainfall amounts. Best reproduction is defined as that which gives the least-squares of differences between computed and observed flows, with greater weight given to errors associated with higher flows, as discussed in paragraph 4e.

b. The unit hydrograph is computed from the Clark coefficients, time of concentration TC and routing coefficient R, and given time-area tabulation. An artificial time-area tabulation in the program can be used if desired. After the best TC and R are determined, Snyder's T_p and C_p for the unit graph are computed.

c. Losses are a complex function of rain intensity and accumulated loss (as an index of ground wetness), as described in Exhibit 5. Five loss-rate variables represent average loss, initial loss, rate of decrease of loss with wetness, relation of loss to rain intensity, and rate of recovery of loss-rate between storm periods. Any of these can be specified and held constant in order to simplify the analysis, but probably at the expense of less adequate results. In addition, one variable (no. 4) represents ratio of imperviousness, the proportion of basin rainfall that is considered to run off without any losses.

d. While it is advantageous to suggest approximate values for variables to begin each analysis, the program will initiate any or all of them, if not supplied. It is best to supply at least an initial estimate of time of concentration.

e. A complete listing of the source program is given in Exhibit 3.

3. DESCRIPTION OF EQUIPMENT

While it may be possible to modify this program for use on medium computers such as IBM 1620 and GE 225 with large memory capacity, it is far more economical to use this program only on high speed computers of the 7090 class.

4. METHODS OF COMPUTATION

a. All variables to be changed for optimization purposes are designated VAR with a subscript. The first two are Clark's TC and R/TC. The given time-area curve expressed in any units of area at uniform time intervals is converted to a base length of TC and ordinates of cfs by linear interpolation. If an artificial time-area curve is to be used, VAR(3) represents the exponent of a parabolic time-area curve for each half of the area as follows:

$$A = kT^{E} \quad (0 < T < .5) \qquad (1)$$

$$1\text{-}A = k(1\text{-}T)^{E} \quad (.5 < T < 1) \qquad (2)$$

where A is area as ratio to total drainage area and T is time as ratio to time of concentration. These are routed through basin storage by the following standard Clark equations, **which is equivalent to the Muskingum routing with R = K and X = O:**

$$C1 = TRHR/(R+.5\ TRHR) \qquad (3)$$

$$C2 = 1\text{-}C1 \qquad (4)$$

$$O_2 = C1(I_2) + C2(O_1) \qquad (5)$$

$$QUNGR_2 = .5(O_1+O_2) \qquad (6)$$

where TRHR is the tabulation interval in hours.

b. Losses for each period are computed by the following equation **(see illustration in Exhibit 5):**

$$ALOSS = AK(RAIN)^{E} \qquad (7)$$

The coefficient AK is a function of 4 variables (average value and initial loss increment, which differ from flood to flood, and recovery rate and exponential recession rate, which are uniform for all floods). If the first ordinate of the time-area curve (at zero time) is not zero, its value is considered to be reservoir area and contributing 100 percent runoff.

c. No return flow is added to the computed flow except an exponential recession of flow that existed at the start of the storm. Thus, the unit hydrograph obtained includes subsurface flow as well as surface runoff. After flow recedes to a specified value, the recession flow each period is computed and used whenever flow computed from the unit hydrograph falls below that recession value. This exponential recession rate is the same as that used for recession from antecedent runoff.

d. After initializing all variables, the program will start optimizing with the loss rate variable E (VAR 7) unless directed to start elsewhere. Each approximation is accomplished by computing all flood hydrographs and over-all standard error of reproduction with all variables fixed and then with the one variable decremented by 10 and 20 percent, respectively. The standard error differences indicate the direction in which the variable should be changed to improve the reproduction. The amount of change is computed as follows:

$$X' = X(.95+DSER1/DIF2) \qquad (8)$$

Where X stands for any variable, DSER1 is the difference in standard error in the second and first computation and DIF2 is the increase in this difference for the third and second computations. If DIF2 is negative, divergence is indicated, and a maximum change in the direction of improvement is made. All changes are limited to a factor of 1.5 and are checked to assure that the standard error is being reduced by the change and that the new value is logical. If the standard error increases, the change is reduced 70 percent. If divergence still exists, it is reduced 70 percent of the remainder. If the standard error still increases, it is set to where it was and the next variable considered.

e. In order to improve the reproduction of peak flows, errors associated with high flows are weighted heavier than those associated with low flows. Each error squared is multiplied by $(Q+\bar{Q})/(2\bar{Q})$. Also, if a reproduction is not satisfactory, considerable improvement can be made in a second run by a routine that artificially changes 1 or 2 flows in each flood temporarily to force a better reproduction without impairing the validity of the results. For example, a portion of a reconstituted hydrograph that is too low can be fitted better by increasing a key flow (using input items G6-9) by about double the discrepancy. Since the reconstituted hydrograph is derived from the known unit hydrograph and loss rate functions, the only test of validity is its comparison with the observed hydrograph.

f. After all variables have been optimized 3 times (after the 4th cycle), the program continues optimizing, selecting each time the variable that made the greatest change in its latest test. When the greatest change is less than 1 percent of the remaining standard error, all variables are reviewed once more and the routine of selecting variables causing maximum improvement is repeated, after which optimization is declared and results printed out.

5. INPUT

a. Input is summarized in Exhibits 6 and 7. All data are entered consecutively on each card, using 8 columns (digits, including decimal point, if used) per variable and 10 variables per card unless fewer are called for. Column 1 on all cards is reserved for identification and is not read by the computer. Hence, the first field on each card has only 7 usable columns.

b. At the end of each job, data for the next job will be accepted. An exit routine will call for a normal exit if 5 blank cards are added to the end of the data deck.

6. OUTPUT

a. Input, except time-area table.

b. Standard error for each and for all floods for each iteration.

c. All changes of input data and each variable change.

d. Values of optimized variables and of Snyder's coefficient and of STRTK.

e. Unit hydrograph tabulation.

f. Summary tabulation of rain, loss, excess, recession, computed flow and observed flow and the column totals.

7. OPERATING INSTRUCTIONS

Standard Fortran II or Fortran IV operation. No sense switches used.

8. DEFINITION OF TERMS

Terms used in this program are defined in Exhibit 3.

9. EXAMPLE

An example of input and output is shown in Exhibits 1 and 2.

10. PROPOSED FUTURE DEVELOPMENT

It is requested that any user of this program who finds an inadequacy or desirable addition or modification notify the Hydrologic Engineering Center.

SAMPLE INPUT

```
                            ST MARIES RIVER AT LOTUS
                             UNIT HYDROGRAPH STUDY
                                 18-21 FEB 1961
       1                      11
     437     180       8                                              .7    2000
                       1       1               1       1                     1.3
       0     1.9     7.4    14.2    21.5    34.6    51.7    68.6    78.1    95.1
     100
      25                    1100      62
    1165    1165    1165    1165    1165    1143    1099    1085    1113    1136
    1188    1316    1527    1890    2326    2777    2958    2986    2986    2958
    2958    3540    4099    5608    6918    8820    9244    8995    8311    7512
    6832    6102    5376    4760    4312    3868    3540    3240    3000    2818
    2628    2482    2362    2235    2158    2081    2000    1930    1900    1830
    1780    1734    1689    1644    1599    1572    1554    1492    1468    1396
    1348    1308
     .01     .02     .04     .07     .06     .02     .12     .11    0.00     .03
     .20     .22     .17     .01     .10    0.00    0.00    0.00     .06     .08
     .45     .13     .38     .21     .09
```

EXHIBIT 1
PAGE 1 OF 1

SAMPLE OUTPUT

```
                              ST MARIES RIVER AT LOTUS
                               UNIT HYDROGRAPH STUDY
                                   18-21 FEB 1961

 INPUT DATA

       NET        M    IPNCH   NCLRK
         1       -0       -0      11

        DA       TR     VAR1     VAR2     VAR3     VAR4     VAR5     VAR6     VAR7   QRECSN
    437.00      180     8.00      -0.      -0.      -0.      -0.      -0.      .70     2000

     FLAG1    FLAG2    FLAG3    FLAG4    FLAG5    FLAG6    FLAG7   FLGNH1   FLGNH2    RTIOR
        -0       -0        1        1       -0        1        1       -0       -0     1.30

 INPUT DATA

        NP  VARNH1   VARNH2    STRTQ      NQO      IQA      RQA      IQB      RQB        N
        25     -0.      -0.     1100       62       -0      -0.       -0      -0.        1

 MODIFIED INPUT DATA

        NP  VARNH1   VARNH2    STRTQ      NQO      IQA      RQA      IQB      RQB        N
        25     .50      .50     1100       62       -0      -0.       -0      -0.        1

        DA       TR     VAR1     VAR2     VAR3     VAR4     VAR5     VAR6     VAR7   QRECSN
    437.00      180     8.00     1.00     1.50      -0.     2.00      -0.      .70     2000

     FLAG1    FLAG2    FLAG3    FLAG4    FLAG5    FLAG6    FLAG7   FLGNH1   FLGNH2    RTIOR
        -0       -0        1        1       -0        1        1       -0       -0     1.30

 OUTPUT

 M=VAR NO,NC=COMP NO,STDERR GIVEN IN TURN FOR EACH HYDROGRAPH AND TOTAL
 VAR  8 ADJ FROM     .50 TO     .14
 VAR  9 ADJ FROM     .50 TO     .14
 VAR  8 ADJ FROM     .14 TO     .13
 VAR  9 ADJ FROM     .14 TO     .13
 M= 8  NC=1 STDERR=     3405     3405
 M= 8  NC=2 STDERR=     3564     3564
 M= 8  NC=3 STDERR=     3729     3729
 VAR  8 ADJ FROM    .13 TO     .19
 M= 9  NC=1 STDERR=     2729     2729
 M= 9  NC=2 STDERR=     2729     2729
 M= 9  NC=3 STDERR=     2730     2730
 VAR  9 ADJ FROM    .13 TO     .19
 M= 1  NC=1 STDERR=     2727     2727
 M= 1  NC=2 STDERR=     2975     2975
 M= 1  NC=3 STDERR=     3279     3279
 VAR  1 ADJ FROM   8.00 TO   11.18
 M= 2  NC=1 STDERR=     1836     1836
 M= 2  NC=2 STDERR=     2001     2001
 M= 2  NC=3 STDERR=     2187     2187
 VAR  2 ADJ FROM   1.00 TO    1.50
 M= 5  NC=1 STDERR=     1259     1259
 M= 5  NC=2 STDERR=     1260     1260
 M= 5  NC=3 STDERR=     1262     1262
 VAR  5 ADJ FROM   2.00 TO    2.67
 M= 8  NC=1 STDERR=     1256     1256
 M= 8  NC=2 STDERR=     1359     1359
 M= 8  NC=3 STDERR=     1513     1513
```

EXHIBIT 2

```
VAR  8 ADJ FROM     .19 TO     .22
M= 9  NC=1 STDERR=     1196      1196
M= 9  NC=2 STDERR=     1197      1197
M= 9  NC=3 STDERR=     1198      1198
VAR  9 ADJ FROM     .19 TO     .29
M= 1  NC=1 STDERR=     1187      1187
M= 1  NC=2 STDERR=     1432      1432
M= 1  NC=3 STDERR=     1691      1691
VAR  1 ADJ FROM   11.18 TO   16.77
M= 2  NC=1 STDERR=      915       915
M= 2  NC=2 STDERR=      846       846
M= 2  NC=3 STDERR=      807       807
VAR  2 ADJ FROM    1.50 TO    1.07
M= 5  NC=1 STDERR=      811       811
M= 5  NC=2 STDERR=      822       822
M= 5  NC=3 STDERR=      834       834
VAR  5 ADJ FROM    2.67 TO    4.00
M= 8  NC=1 STDERR=      769       769
M= 8  NC=2 STDERR=      750       750
M= 8  NC=3 STDERR=      847       847
VAR  8 ADJ FROM     .22 TO     .21
M= 9  NC=1 STDERR=      742       742
M= 9  NC=2 STDERR=      747       747
M= 9  NC=3 STDERR=      752       752
VAR  9 ADJ FROM     .29 TO     .43
M= 1  NC=1 STDERR=      713       713
M= 1  NC=2 STDERR=      878       878
M= 1  NC=3 STDERR=     1183      1183
VAR  1 ADJ FROM   16.77 TO   17.90
M= 2  NC=1 STDERR=      660       660
M= 2  NC=2 STDERR=      695       695
M= 2  NC=3 STDERR=      778       778
VAR  2 ADJ FROM    1.07 TO    1.09
M= 5  NC=1 STDERR=      656       656
M= 5  NC=2 STDERR=      663       663
M= 5  NC=3 STDERR=      673       673
VAR  5 ADJ FROM    4.00 TO    6.00
M= 8  NC=1 STDERR=      628       628
M= 8  NC=2 STDERR=      632       632
M= 8  NC=3 STDERR=      735       735
VAR  8 ADJ FROM     .21 TO     .20
M= 9  NC=1 STDERR=      617       617
M= 9  NC=2 STDERR=      628       628
M= 9  NC=3 STDERR=      638       638
VAR  9 ADJ FROM     .43 TO     .65
M= 1  NC=1 STDERR=      553       553
M= 9  NC=1 STDERR=      553       553
M= 9  NC=2 STDERR=      573       573
M= 9  NC=3 STDERR=      593       593
VAR  9 ADJ FROM     .65 TO     .97
M= 1  NC=1 STDERR=      489       489
M= 9  NC=1 STDERR=      489       489
M= 9  NC=2 STDERR=      496       496
M= 9  NC=3 STDERR=      516       516
VAR  9 ADJ FROM     .97 TO     .98
M= 1  NC=1 STDERR=      489       489
VAR  9 ADJ FROM     .97 TO     .98
M= 1  NC=1 STDERR=      489       489
VAR  9 ADJ FROM     .97 TO     .97
M= 1  NC=1 STDERR=      489       489
M= 1  NC=1 STDERR=      489       489
M= 1  NC=2 STDERR=      564       564
```

EXHIBIT 2

```
 M= 1   NC=3  STDERR=       822       822
 VAR   1 ADJ FROM   17.90 TO   17.75
 M= 2   NC=1  STDERR=       485       485
 M= 5   NC=1  STDERR=       485       485
 M= 5   NC=2  STDERR=       493       493
 M= 5   NC=3  STDERR=       503       503
 VAR   5 ADJ FROM    6.00 TO    9.00
 M= 8   NC=1  STDERR=       457       457
 M= 5   NC=1  STDERR=       457       457
 M= 5   NC=2  STDERR=       464       464
 M= 5   NC=3  STDERR=       472       472
 VAR   5 ADJ FROM    9.00 TO   13.28
 M= 8   NC=1  STDERR=       436       436
 M= 5   NC=1  STDERR=       436       436
 M= 5   NC=2  STDERR=       442       442
 M= 5   NC=3  STDERR=       448       448
 VAR   5 ADJ FROM   13.28 TO   18.88
 M= 8   NC=1  STDERR=       422       422
 M= 5   NC=1  STDERR=       422       422
 M= 5   NC=2  STDERR=       426       426
 M= 5   NC=3  STDERR=       431       431
 VAR   5 ADJ FROM   18.88 TO   25.71
 M= 8   NC=1  STDERR=       413       413
 M= 5   NC=1  STDERR=       413       413
 M= 5   NC=2  STDERR=       416       416
 M= 5   NC=3  STDERR=       419       419
 VAR   5 ADJ FROM   25.71 TO   33.23
 M= 8   NC=1  STDERR=       409       409
 M= 8   NC=1  STDERR=       409       409
 M= 8   NC=2  STDERR=       452       452
 M= 8   NC=3  STDERR=       554       554
 VAR   8 ADJ FROM     .20 TO     .20
 M= 9   NC=1  STDERR=       410       410
 VAR   8 ADJ FROM     .20 TO     .20
 M= 9   NC=1  STDERR=       409       409
 VAR   8 ADJ FROM     .20 TO     .20
 M= 9   NC=1  STDERR=       409       409
 M= 5   NC=1  STDERR=       409       409
 M= 5   NC=2  STDERR=       410       410
 M= 5   NC=3  STDERR=       413       413
 VAR   5 ADJ FROM   33.23 TO   40.78
 M= 8   NC=1  STDERR=       406       406
 M= 1   NC=1  STDERR=       406       406
 M= 1   NC=2  STDERR=       578       578
 M= 1   NC=3  STDERR=       897       897
 VAR   1 ADJ FROM   17.75 TO   18.92
 M= 2   NC=1  STDERR=       433       433
 VAR   1 ADJ FROM   17.75 TO   18.10
 M= 2   NC=1  STDERR=       403       403
 M= 2   NC=2  STDERR=       466       466
 M= 2   NC=3  STDERR=       604       604
 VAR   2 ADJ FROM    1.09 TO    1.13
 M= 5   NC=1  STDERR=       392       392
 M= 5   NC=2  STDERR=       395       395
 M= 5   NC=3  STDERR=       399       399
 VAR   5 ADJ FROM   40.78 TO   55.46
 M= 8   NC=1  STDERR=       384       384
 M= 8   NC=2  STDERR=       413       413
 M= 8   NC=3  STDERR=       509       509
 VAR   8 ADJ FROM     .20 TO     .20
 M= 9   NC=1  STDERR=       384       384
 M= 9   NC=2  STDERR=       405       405
```

EXHIBIT 2

```
M= 9  NC=3 STDERR=       435       435
VAR  9 ADJ FROM     .97 TO    1.17
M= 1  NC=1 STDERR=       383       383
M= 2  NC=1 STDERR=       383       383
M= 2  NC=2 STDERR=       405       405
M= 2  NC=3 STDERR=       516       516
VAR  2 ADJ FROM    1.13 TO    1.10
M= 5  NC=1 STDERR=       382       382
M= 5  NC=1 STDERR=       382       382
M= 5  NC=2 STDERR=       386       386
M= 5  NC=3 STDERR=       392       392
VAR  5 ADJ FROM   55.46 TO   78.26
M= 8  NC=1 STDERR=       371       371
M= 5  NC=1 STDERR=       371       371
M= 5  NC=2 STDERR=       374       374
M= 5  NC=3 STDERR=       378       378
VAR  5 ADJ FROM   78.26 TO  105.51
M= 8  NC=1 STDERR=       365       365
M= 5  NC=1 STDERR=       365       365
M= 5  NC=2 STDERR=       366       366
M= 5  NC=3 STDERR=       369       369
VAR  5 ADJ FROM  105.51 TO  110.87
M= 8  NC=1 STDERR=       364       364

OPTIMIZATION RESULTS

      CA        TR      VAR1      VAR2      VAR3      VAR4      VAR5      VAR6      VAR7    QRECSN
  437.00       180     18.10      1.10      1.50       -0.    110.87       -0.       .70      2000

   FLAG1     FLAG2     FLAG3     FLAG4     FLAG5     FLAG6     FLAG7    FLGNH1    FLGNH2     RTIOR
      -0        -0         1         1        -0         1         1        -0        -0      1.30

 UNIT HGR,NO= 38       LAG=  17.611        C+=   .588
     363      1397      3090      5673      8085      9412      9215      7943      6831      5874
    5051      4344      3736      3213      2763      2376      2043      1757      1511      1299
    1117       961       826       711       611       526       452       389       334       287
     247       213       183       157       135       116       100        86

      NP    VARNH1    VARNH2    STARTQ       NQO       IQA       RQA       IQB       RQB     STRTK
      25       .20      1.17      1100        62        -0       -0.        -0       -0.       .23

  PERIOD      RAIN      LOSS  EXCESS                                          COMP Q     OBS Q
       1       .01       .01    0.                                              1072      1165
       2       .02       .02    0.                                              1044      1165
       3       .04       .04    0.                                              1017      1165
       4       .07       .07    0.                                               990      1165
       5       .06       .06    0.                                               965      1165
       6       .02       .02    0.                                               940      1143
       7       .12       .11     .01                                             918      1099
       8       .11       .09     .02                                             908      1085
       9     0.        0.       0.                                               914      1113
      10       .03       .03    0.                                               938      1136
      11       .20       .12     .08                                            1005      1188
      12       .22       .11     .11                                            1154      1316
      13       .17       .08     .09                                            1430      1527
      14       .01       .01    0.                                              1874      1890
      15       .10       .05     .05                                            2460      2326
      16     0.        0.       0.                                              3058      2777
      17     0.        0.       0.                                              3441      2958
      18     0.        0.       0.                                              3528      2986
      19       .06       .03     .03                                            3381      2986
      20       .08       .04     .04                                            3150      2958
```

21	.45	.13	.32	3049	2958
22	.13	.05	.08	3232	3540
23	.38	.10	.28	3859	4099
24	.21	.06	.15	5073	5608
25	.09	.03	.06	6559	6918
26				8007	8820
27				8981	9244
28				9231	8995
29				8868	8311
30				7999	7512
31				7003	6832
32				6079	6102
33				5282	5376
34				4595	4760
35				4003	4312
36				3493	3868
37				3052	3540
38				2673	3240
39				2345	3000
40				2061	2818
41				2000	2628
42				1948	2482
43				1898	2362
44				1849	2235
45				1801	2158
46				1754	2081
47				1709	2000
48				1664	1930
49				1621	1900
50				1579	1830
51				1538	1780
52				1499	1734
53				1460	1689
54				1422	1644
55				1385	1599
56				1349	1572
57				1314	1554
58				1280	1492
59				1247	1468
60				1215	1396
61				1183	1348
62				1153	1308
TOTAL	2.58	1.26	1.32	173499	184356

EXHIBIT 2

EXHIBIT 3

DEFINITIONS - 23-J2-L211

A - Ratio error allowance **in rainfall excess test**
ACUML - Accumulated loss (minus recovery) in inches
AI - Conversion of I
AJH - Conversion of JH
AKLN - Component of AKLOS
ALAG - Snyder's t_p in hours
ALOSS - Loss in inches
ANQO - Conversion of NQO
AVGQO(N) - Average observed flow
C1 - Interpolation constant and, subsequently, routing coefficient
C2 - 1-C1
CIT - Conversion of IT
CL - Number of time-area intervals per TR unit
CLARK - NCLRK-1
CORMX - Maximum percent adjustment of variable
CORMN - Maximum negative percent adjustment of variable
CORR - Percent adjustment of variable
CP - Snyder's C_p
DA - Drainage area in square miles
DIF2 - Second difference of standard error (DSER2-DSER1)
DLTK - Increment of loss coefficient at start of storm
DQ - Difference between computed and observed flow in cfs
DSER1 - First increment of standard error
DSER2 - Second increment of standard error
EX(N) - Total excess in inches
EXCES(I) - RAIN minus loss in inches
FIN - Indicator, when positive, indicates that optimization is declared and calls for print-out
FLAG(M) - Positive value prevents change of variable having same subscript. Flag 8 applies to VAR(NH1) and 9 to VAR(NH2)
GAIN(N) - Ratio of standard error reduction
GANMX - Maximum GAIN of most recent changes of all variables
I - Index for period number
IMAX - Serial number of maximum observed flow
IPNCH - Indicator, when positive causes punch-out of hydrograph data
IQA(N) - Sequence number of first flow to be temporarily changed
IQB(N) - Sequence number of second flow to be temporarily changed
IREND - Serial number of last period with precipitation exceeding half of maximum precipitation amount for storm
IT - Conversion of T
ITB - Time of concentration in TR units

ITMP - Temporary integer
JH - Temporary index
J1 - Temporary index
K - Temporary index
KCLK - Dimension limit on time-area ordinates
KNHG - Dimension limit on number of hydrographs
KQ - Dimension limit on number of hydrograph ordinates
KUNGQ - Dimension limit on number of unit hydrograph ordinates
M - Subscript of variable currently considered
M1 - Subscript of preceding variable
N - Hydrograph or storm number
NADJ - Number of adjustments made to overcome divergence
NC - Computation number
NC1 - Computation number at start of do-loop
NC2 - Computation number at end of do-loop
NCLRK - Indicator, when positive, calls for reading time-area ordinates numbering NCLRK
NCYCL - Number of cycles completed
NH1 - Subscript of first variable attached to specific hydrograph
NH2 - Subscript of second variable attached to specific hydrograph
NHR - Time unit for plotting
NHT - Total number of hydrographs
NP(N) - Number of observed precipitation periods in storm
NQO(N) - Number of observed flows in hydrograph (also ANQO)
NQO1(N) - First runoff subscript for flood
NQO2(N) - Last runoff subscript for flood
NQO11 - First subscript of hydrograph
NQO22 - Last subscript of hydrograph
NQOP(N) - Last subscript of rain
NQOP1 - Last subscript of rain
NUHGQ - Number of ordinates in unit hydrograph
NVAR - Total number of variables (7+2NHT)
NXINC - Plotting increment
Q(I) - Computed flow in cfs
QCLK(I) - Time-area ordinates in cfs
QMAX - Maximum flow in cfs for Clark unit hydrograph
QO(I) - Observed flow in cfs
QOMAX - Maximum observed flow in cfs
QR - Recession flow in cfs
QRCSN - Flow below which recession rates are maintained as a minimum
QSQ(NC,N) - Sum of squares of DQ values
QUNGR(I) - Unit hydrograph ordinate in cfs
RAIN(I) - Rain plus snowmelt in inches for each period
RMAX - Maximum precipitation in inches for any period
RNQO(N) - Reciprocal of NQO

RQA(N) - Ratio by which flow number IQA is temporarily multiplied
RQB(N) - Ratio by which flow number IQB is temporarily multiplied
RTIOL - Ratio of loss coefficient to that at 10 inches greater ACUML
RTIOR - Ratio of recession flow to that 10 periods later
STDER(NC,N) - Standard error in cfs
STRTK(N) - Loss coefficient on straight line at start of storm (also STRK2)
STRTQ(N) - Flow in cfs at start of storm
SUME - Sum of rainfall excess in inches (also SUME2)
SUML(N) - Sum of rain or observed flows
SUMQO(N) - Sum of observed flows in cfs
SUMR - Sum of rain in inches
T - Time at end of a period in time units of time-area curve
TEMP - Value being tested for preceding variable
TEMP1 - Temporary variable
TEMP2 - Initial value of current variable
TEST - Minimum value of standard error obtained so far
TITLE(K,N) - Title for plotting
TMP - Temporary constant
TR - Rainfall interval in minutes
TRHR - Rainfall interval in hours
VAR(1) - Clark's T_c in hours
VAR(2) - Ratio of Clark's R to T_c
VAR(3) - Exponent of artificial time-area curve
VAR(4) - Ratio of impervious area to total drainage area

VAR(5) - Ratio of K on straight line portion of loss rate curve to K at 10 inches more ACUML
VAR(6) - Recovery loss index in inches, subtracted from ACUML every period
VAR(7) - Exponent of rain in loss computation
VAR(NH1) - Value of K on straight line portion of loss rate curve when ACUML is $\frac{1}{2}$ of storm loss
VAR(NH2) - Accumulated loss increment during initial-loss period. Adds an increment .2 (VAR(NH2)) to K when ACUML is zero, decreasing to zero when ACUML is VAR(NH2).
VAR4 - Recession ratio of succeeding flows
VOL - Volume of unit hydrograph in cfs for time interval used.
XNP - Conversion of NP

SOURCE PROGRAM LISTING

```
C     PROGRAM  23-J2-J211  UNIT HYDROGRAPH AND LOSS RATE OPTIMIZATION
C     SUBROUTINES USED - EXPONENT
C     HYDROLOGIC ENGINEERING CENTER, CORPS OF ENGINEERS, JULY 66
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
C                             READ COMMON DATA
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
      DIMENSION VAR(19),FLAG(9),NP(6),NQO(6),STRTQ(6),NQO1(6),NQO2(6),
     1QO(500),NQOP(6),RAIN(500),QUNGR(100),QSQ(3,7),STRTK(6),QCLK(22),
     2EXCES(500),Q(500),STDER(3,7),RNQO(7),GAIN(19),SUML(6),
     3SUMQO(6),EX(6),TITLE(8,6),AVGQO(6),IQA(6),IQB(6),
     4RQA(6),RQB(6)
      KUNGQ=100
      KNHG=6
      KQ=500
      KCLK=21
   10 PRINT 20
   20 FORMAT (1H1)
C                          THREE TITLE CARDS
   30 READ 40,     (Q(I),I=1,60)
   40 FORMAT (1X,A3,9A4,10A4)
      PRINT 40,      (Q(I),I=1,60)
      READ 1970,    NHT, M, IPNCH, NCLRK
      READ 330,    DA, TR, (VAR(I), I= 1, 7), QRCSN
C        FIVE BLANK CARDS AT END OF INPUT DATA CALL STOP
      IF(DA)50,50,60
   45 PRINT 46
   46 FORMAT(19H DIMENSION EXCEEDED)
   50 STOP
   60 READ 330,      (FLAG(I), I= 1,  9), RTIOR
      PRINT 70
   70 FORMAT (/11H INPUT DATA)
      IF(NHT-KNHG)72,72,45
   72 IF(NCLRK-KCLK)73,73,45
   73 PRINT 80
   80 FORMAT (/32H     NHT         M   IPNCH   NCLRK)
      PRINT 1970,    NHT,M,IPNCH,NCLRK
      PRINT 90
   90 FORMAT (/80H       DA       TR     VAR1     VAR2     VAR3     VAR4     VA
     1R5     VAR6     VAR7  QRECSN)
      PRINT 100,    DA,TR,(VAR(I),I=1,7),QRCSN
  100 FORMAT (F8.2,F8.0,7F8.2,F8.0)
```

EXHIBIT 4

```
      PRINT 110
  110 FORMAT (/80H   FLAG1    FLAG2    FLAG3    FLAG4    FLAG5    FLAG6    FLA
     1G7  FLGNH1  FLGNH2   RTIOR)
      PRINT 111,    (FLAG(I),I=1,9),RTIOR
  111 FORMAT (9F8.0,F8.2)
      QCLK(1)=0.
      TRHR = TR/60.
      VOL = DA*645.0/TRHR
      IF(NCLRK)140,140,120
  120 READ 330,     (Q(I), I= 1, NCLRK )
      FLAG(3)=1.
      CLARK=NCLRK - 1
C     CHANGE TIME-AREA ORDINATES TO CFS FOR 1 INCH
      DO 130 I=1,NCLRK
  130 QCLK(I)  =Q(I)*VOL/Q( NCLRK )
      QCLK( NCLRK + 1 ) = QCLK( NCLRK )
  140  TEMP1= 0.0
       TEMP2 = 0.0
C *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
C                                         COMMON CONSTANTS
C *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
      NVAR = 7 + 2*NHT
      NQ022 = 0
      DO 150 I=1,NVAR
  150 GAIN(I)=0.
      NCYCL = 0
      M1 = 0
      TEST = 999999.
      IF(M)160,160,170
  160 M = 7
  170 NC1 = 1
      NC2 = 3
      CORMX = 5.
      CORMN = 10./1.5-10.
C *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
C                                         INITIATE VARIABLES
C *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
      IF(VAR(3))180,180,210
  180 VAR(3)= 1.5
  210 IF (VAR(5))220,220,230
  220 VAR(5) = 2.
```

EXHIBIT 4
PAGE 2 OF 15

```
  230 IF(FLAG(6))240,240,260
  240 IF (VAR(6))250,250,260
  250 VAR(6) = .0005*TR
  260 IF(FLAG(7))270,270,290
  270 IF(VAR(7))280,280,290
  280 VAR(7) = .3
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
C                              STORM SPECIFICATION
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
  290 DO 580 N=1,NHT
      PRINT 70
      NH1 = N*2+6
      NH2 = NH1+1
      IF (IPNCH) 310,310,300
  300 READ 40,         ( TITLE (I, N), I= 1, 8)
  310 READ 311,  NP(N),VAR(NH1), VAR(NH2), STRTQ(N),NQO(N),IQA(N),RQA(N)
     1,IQB(N),RQB(N)
  311 FORMAT (1X,I7,3F8.0,2I8,F8.0,I8,F8.0)
      PRINT 575
      PRINT 320,  NP(N),VAR(NH1),VAR(NH2),STRTQ(N),NQO(N),IQA(N),RQA(N),
     1IQB(N),RQB(N),N
  320 FORMAT(I8,2F8.2,F8.0,2I8,F8.2,I8,F8.2,I8)
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
C                              STORM DATA
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
      NQO1(N) = NQO22 + 1
      NQO2(N) = NQO1(N) + NQO(N) - 1
      NQO11 = NQO1(N)
      NQO22 = NQO2(N)
      IF(NQO22-KQ)325,325,45
  325 READ 330,     (QO(I), I= NQO11, NQO22 )
  330 FORMAT (1X,F7.0,9F8.0)
      QOMAX=0.
      SUMQO(N) = 0.
      DO 350 I=NQO11,NQO22
      EXCES(I)=0.
      RAIN(I)=0.
      IF(QO(I)-QOMAX)350,340,340
  340 QOMAX=QO(I)
      IMAX=I
  350 SUMQO(N) = SUMQO(N) + QO(I)
```

EXHIBIT 4
PAGE 3 OF 15

```
      NQOP(N) = NQO1(N) + NP(N) - 1
      NQOP1 = NQOP(N)
      READ 330,       (RAIN(J), J= NQO11, NQOP1 )
      ANQO = NQO(N)
      RNQO(N) = 1./ANQO
      AVGQO(N)=SUMQO(N)/ANQO
      SUMR = 0.
      RMAX=0.
      DO 410 I=NQO11,NQOP1
      TMP=RAIN(I)
      IF(TMP-RMAX)390,380,380
  380 RMAX=TMP
  390 IF(TMP-RMAX*.7)410,410,400
  400 IREND=I
  410 SUMR = SUMR + TMP
      EX(N) = SUMQO(N)/VOL
      TMP = SUMR-EX(N)
      IF(TMP)420,420,440
  420 PRINT 430,   N
  430 FORMAT (/34H RUNOFF EXCEEDS RAINFALL FOR FLOODI3)
      TMP = .1
  440  XNP = NP(N)
      SUML(N) = TMP     *.05 - XNP*.05*VAR(6)
      IF(SUML(N))450,450,490
  450 IF(VAR(6))480,480,460
  460 PRINT 470
  470 FORMAT (/30H VAR(6) SET TO ZERO AND FROZEN)
      VAR(6)=0.
      FLAG(6)=1.
  480 SUML( N) = TMP      *0.05
C *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
C                                        INITIATE VARIABLES - 2
C *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
  490 IF(VAR(NH1))500,500,510
  500 VAR(NH1) = 0.5
  510 IF(FLAG(9))520,520,560
  520 IF(VAR(NH2))530,530,560
  530 VAR(NH2) = .5
  560 PRINT 570
  570 FORMAT (/20H MODIFIED INPUT DATA)
      PRINT 575
```

EXHIBIT 4
PAGE 4 OF 15

```
  575 FORMAT (/80H       NP  VARNH1  VARNH2    STRTQ       NQO       IQA       R
     1QA       IQB       RQB        N)
C     CHANGE SELECTED FLOWS TEMPORARILY
      IF(IQB(N))576,576,574
  576 IF(IQA(N))578,578,577
  574 ITMP=NQO11+IQB(N)-1
      QO(ITMP)=QO(ITMP)*RQB(N)
  577 ITMP=NQO11+IQA(N)-1
       QO(ITMP)=QO(ITMP)*RQA(N)
  578 PRINT 320,     NP(N),VAR(NH1),VAR(NH2),STRTQ(N),NQO(N),IQA(N),RQA(N
     1),IQB(N),RQB(N),N
  580 CONTINUE
      ANQO = NQO2(NHT)
      RNQO(7) = 1./ANQO
      IF(VAR(1))590,590,585
  585 IF(VAR(1)-TRHR*1.26)586,620,620
  586 VAR(1)=TRHR*1.26
  590 TMP=IMAX-IREND
      IF(TMP-1.5)600,600,610
  600 VAR(1)=TRHR*2.
      GO TO 620
  610 VAR(1)=(TMP+.5)*TRHR
  620 IF(VAR(2))630,630,640
  630 VAR(2)=1.
  640 PRINT 90
      PRINT 100,     DA,TR,(VAR(I),I=1,7),QRCSN
      PRINT 110
      PRINT 111,   (FLAG(I),I=1,9),RTIOR
      PRINT 650
  650 FORMAT (/7H OUTPUT)
      PRINT 660
  660 FORMAT (/71H M=VAR NO,NC=COMP NO,STDERR GIVEN IN TURN FOR EACH HYD
     1ROGRAPH AND TOTAL)
      FIN=0.
      A=.05
      RTIOR=1./RTIOR**.1
      GO TO 1880
  670 DO 1400 NC = NC1,NC2
      IF(NC-1)680,680,690
  680 TEMP2 = VAR(M)
       IF ( M1 - 3 )  700,700,690
```

EXHIBIT 4

```
  690 IF(M-3)700,700,910
C *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
C                           CLARK UNIT HYDROGRAPH
C *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
C     ITB IS TIME OF CONCENTRATION IN TR UNITS, TRUNCATED
  700 ITB=VAR(1)/TRHR
       IF ( ITB - 100 )730,730,710
  710 PRINT 720
  720  FORMAT ( 24H TC EXCEEDS 100 TR UNITS )
      GO TO 10
  730 IF(NCLRK)740,740,800
  740 TEMP = .5/.5**VAR(3)*VOL
      TMP = VAR(1)/TRHR
      IF(TMP-1.)750,760,760
  750 TMP=1.
  760 ITB = TMP
      DO 790  I=1,ITB
      AI = I
      IF(AI-TMP*.5)770,770,780
  770 QUNGR(I) = TEMP*(AI/TMP)**VAR(3)
      GO TO 790
  780 QUNGR(I) = VOL - TEMP*((TMP-AI)/TMP)**VAR(3)
  790 CONTINUE
      GO TO 820
C                            INTERPOLATION ROUTINE
  800 CL=CLARK/VAR(1)*TRHR
C     CL IS NO OF TIME-AREA INTERVALS PER TR UNIT
      DO 810 I=1,ITB
      AI=I
C     T  IS TIME AT END OF INTERVAL IN TIME UNITS OF TIME-AREA CURVE + 1
C     THE + 1 ACCOUNTS FOR ZERO TIME AT I = 1.
      T=AI*CL+1.
      IT=T
       CIT = IT
       C1 = T - CIT
      C2=1.-C1
  810 QUNGR(I)=QCLK(IT)*C2+QCLK(IT+1)*C1
C                             BASIN ROUTING ROUTINE
  820 ITB=ITB+1
      QUNGR(ITB)=VOL
      DO 830 K=2,ITB
```

```
      I=ITB-K+2
  830 QUNGR(I)=QUNGR(I)-QUNGR(I-1)
      QUNGR(1)=QUNGR(1)-QCLK(1)
      C1=TRHR/(VAR(2)*VAR(1)+.5*TRHR)
      C2=1.-C1
      Q(1)=QUNGR(1)*C1
      QUNGR(1)=Q(1)*.5
      QMAX=QUNGR(1)
       DO 900 I = 2, KUNGQ
      IF(I-ITB)840,840,850
  840 Q(I)=QUNGR(I)*C1+Q(I-1)*C2
      GO TO 860
  850 Q(I)=Q(I-1)*C2
  860 QUNGR(I)=(Q(I)+Q(I-1))*.5
      IF(QUNGR(I)-QMAX)880,880,870
  870 QMAX=QUNGR(I)
      K=I
      GO TO 900
  880 IF(QUNGR(I)-.01*QMAX)890,900,900
  890 NUHGQ=I
      GO TO 901
  900 CONTINUE
      ITB = 0
      NUHGQ=KUNGQ
  901 ALAG=K
      IF (QUNGR(K-1)-QUNGR(K+1)) 902,910,904
  902 ALAG=ALAG+.5-(QUNGR(K)-QUNGR(K+1))/(QUNGR(K)-QUNGR(K-1))
      GO TO 910
  904 ALAG=ALAG-.5+(QUNGR(K)-QUNGR(K-1))/(QUNGR(K)-QUNGR(K+1))
C     *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
C                                             STORM CONSTANTS
C     *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
  910 DO 1370 N=1,NHT
      RAVQO=.5/AVGQO(N)
      NH1 = 2*N+6
      NH2 = NH1 + 1
      NQO11 = NQO1(N)
      NQO22 = NQO2(N)
      NQOP1 = NQOP(N)
  920 STRTK(N)=VAR(NH1) * VAR(5)**SUML(N)
      STRK2=VAR(NH2)*VAR(5)**SUML(N)
```

```
      ACUML = 0.
      QSQ(NC,N) = 0.
      SUME=0.
C *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
C                                    LOSSES
C *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
      DO 1060 J=NQO11,NQOP1
      AKLN = STRTK(N) / VAR(5)**(.1*ACUML)
      IF (ACUML-VAR(NH2))930,960,960
  930 IF(VAR(NH2))960,960,940
  940 DLTK=((1.-ACUML/VAR(NH2))**2)*.2*(VAR(NH2))
      AKLOS=DLTK+AKLN
      GO TO 980
  960 AKLOS=AKLN
      IF (VAR(7)) 970,970,980
  970 IF (RAIN (J)) 990,990,980
  980 ALOSS=AKLOS*TRHR*(RAIN(J)/TRHR)**VAR(7)
      IF (RAIN(J)-ALOSS)990,1000,1000
  990 ALOSS=RAIN(J)
 1000 EXCES(J) = RAIN(J) - ALOSS *(1.-VAR(4))
      SUME=SUME+EXCES(J)
      ACUML=ACUML-VAR(6)+RAIN(J)- EXCES(J)+ALOSS*VAR(4)
      IF(ACUML)1050,1060,1060
 1050 ACUML=0.
 1060 CONTINUE
C     PREVENT ZERO STORM EXCESS
      IF(SUME)1100,1100,1080
 1080 IF(M1)1090,1090,1110
 1090 IF(SUME)1100,1100,1110
 1100 TMP=VAR(NH1)
      VAR(NH1)=VAR(NH1)*.9
      PRINT 1820,  NH1,TMP,VAR(NH1)
      VAR(NH2)=VAR(NH2)*.9
      PRINT 1820, NH2,TMP,VAR(NH2)
      NC1=1
      NC2=3
      VAR(6)=VAR(6)*.9
      GO TO 670
C    ON FIRST RUN, ADJUST LOSS COEFS TO OBTAIN CORRECT VOL APPROX
 1110 IF ( M1 + NC - 1 ) 1160,1160,1190
 1160 TEMP= EX( N)/SUME
```

```
      IF (TEMP -1.-A)1170,1170,1180
 1170 IF (TEMP - 1.+A)1180,1190,1190
 1180 TMP=VAR(NH1)
      VAR (NH1 ) = VAR ( NH1)/TEMP**.5
      PRINT 1820,  NH1,TMP,VAR(NH1)
      TMP=VAR(NH2)
       VAR ( NH2) = VAR(NH2)/TEMP**.5
      PRINT 1820,  NH2,TMP,VAR(NH2)
C         GRADUALLY INCREASE TOLERANCE TO ASSURE CONVERGENCE
      A=A+.05
      TEMP2 = VAR(M)
      GO TO 920
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
C                                HYDROGRAPHS
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
 1190 QA=STRTQ(N)
      DO 1360 J=NQO11,NQO22
      JH = J-NQO11 + 1
      AJH = JH
      QA=QA*RTIOR
      IF (J-NQOP1)1200,1200,1250
 1200 Q(J)=QA+RAIN(J)*QCLK(1)
      IF(JH-NUHGQ)1210,1210,1230
 1210 DO 1220 I=NQO11,J
      K = J + 1 - I
 1220 Q(J) = Q(J) + EXCES(I) * QUNGR(K)
      GO TO 1310
 1230 J1 = J - NUHGQ + 1
      DO 1240 I=J1,J
      K = J + 1 - I
 1240 Q(J) = Q(J) + EXCES(I) * QUNGR(K)
      GO TO 1310
 1250 Q(J)=QA
      IF(JH-NUHGQ)1260,1260,1280
 1260 DO 1270 I=NQO11,NQOP1
      K = J+1-I
 1270 Q(J) = Q(J) + EXCES(I) * QUNGR(K)
      GO TO 1310
 1280 J1 = J - NUHGQ + 1
      IF (J1-NQOP1)1290,1310,1310
 1290 DO 1300 I= J1,NQOP1
```

```
      K = J + 1 - I
 1300 Q(J) = Q(J) + EXCES(I) * QUNGR(K)
 1310 IF (JH-2)1350,1350,1320
C     WHEN Q BELOW QRCSN,CANNOT DROP BELOW RECESSION VALUE,QR
 1320 QR = Q(J-1)* RTIOR
      IF (Q(J)-QR)1330,1350,1350
 1330 IF(Q(J)-QRCSN)1340,1350,1350
 1340 Q(J) = QR
      IF(Q(J)-QRCSN)1350,1350,1345
 1345 Q(J)=QRCSN
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
C                                 STANDARD ERROR
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
 1350 DQ = Q(J) - QO(J)
 1360 QSQ(NC,N) = QSQ(NC,N) + DQ*DQ*(QO(J)+AVGQO(N))*RAVQO
 1370 STDER(NC,N) =       (QSQ(NC,N) * RNQO(N))**.5
      QSQ(NC,7) = 0.
      DO 1380 N= 1,NHT
 1380 QSQ(NC,7) = QSQ (NC,7) + QSQ(NC,N)
      STDER(NC,7) =       (QSQ(NC,7)*RNQO(7))**.5
      PRINT 1390,     M,NC,(STDER(NC,N),N=1,NHT),STDER(NC,7)
 1390 FORMAT(3H M=,I2, 5H  NC=, I1, 8H STDERR=, 7F8.0)
 1400 VAR(M) = VAR(M) - TEMP2 * .1
      IF(ITB)1410,1410,1430
 1410 PRINT 1420
 1420  FORMAT ( 13H UH TRUNCATED)
 1430 IF (NC2-1)1440,1440,1570
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
C                    CHECK FOR DIVERGENCE ON PREVIOUS VARIABLE (M1)
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
 1440 IF (STDER(1,7)-TEST) 1490,1490,1450
 1450 IF(NADJ-2)1460,1480,1480
 1460 VAR(M1)=.3*VAR(M1)+.7*TEMP1
C  TEMP1= INITIAL VALUE OF PRECEDING VARIABLE
C  VAR(M1) = ADJUSTED VALUE OF PRECEDING VARIABLE
      PRINT 1820,      M1,TEMP1, VAR(M1)
      NADJ=NADJ+1
C  TEMP2 = INITIAL VALUE OF PRESENT VARIABLE (M)
 1470 VAR(M) = TEMP2
      GO TO 670
 1480 VAR(M1) = TEMP1
```

EXHIBIT 4
PAGE 10 OF 15

```
      PRINT 1820,       M1, TEMP1,  VAR( M1)
      VAR(M) = TEMP2
      NC2 = 3
      GAIN(M1) = 0.
      IF ( NCYCL -  3) 670,670,1510
 1490 NC1 = 2
      NC2 = 3
      GAIN(M1) = 1. - STDER(1,7) / TEST
 1500 TEST=STDER(1,7)
      IF(NCYCL - 3)670,670,1510
 1510 GANMX = 0.
      DO 1530 I= 1,NVAR
      IF (GAIN(I) - GANMX)1530,1530,1520
 1520 GANMX = GAIN(I)
      J = I
 1530 CONTINUE
      IF (GANMX - .01)1540,1540,1560
 1540 IF(FIN)1550,1550,1930
 1550 FIN = 1.
      NC1=1
      NCYCL = 3
       VAR( M ) =  TEMP2
      M = 1
      GO TO 1880
 1560 VAR(M) = TEMP2
      M = J
      NC1 = 1
      NC2 = 3
      GO TO 670
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
C                                        OPTIMIZATION
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
 1570 DSER1 = STDER(2,7) - STDER(1,7)
      DSER2 = STDER(3,7) - STDER(2,7)
      DIF2 = DSER2 - DSER1
      IF(DIF2)1580,1590,1610
 1580 IF(DSER1)1640,1640,1630
 1590 IF(DSER1)1640,1600,1630
 1600 CORR=0.
      GO TO 1650
 1610 CORR =  DSER1/DIF2 - .5
```

EXHIBIT 4

```
      IF(CORR-CORMN)1640,1650,1620
 1620 IF(CORR-CORMX)1650,1650,1630
 1630 CORR = CORMX
      GO TO 1650
 1640 CORR = CORMN
 1650 TEMP1= TEMP2
      M1 = M
C                                 TEMP = HOLD VALUE FOR VAR( M1 )
      VAR(M) = TEMP2  * (1.+CORR*.1)
      NADJ = 0
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
C                           CHECK FOR REASONABLE MAGNITUDE
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
      IF (M - 2 )1660,1680,1700
 1660 IF(VAR(1) - TRHR*1.26)1670,1810,1810
 1670 VAR(1) =TRHR*1.26
      GO TO 1810
 1680 IF(VAR(2)-.5*TRHR/VAR(1))1690,1810,1810
 1690 VAR(2) = .5*TRHR/VAR(1)
 1700 IF(M-4)1710,1730,1750
 1710 IF(VAR(3)-1.)1720,1810,1810
 1720 VAR(3)=1.
      GO TO 1810
 1730 IF(VAR(4)-1.)1810,1810,1740
 1740 VAR(4) = 1.
      GO TO 1810
 1750 IF(M-6) 1760,1810,1780
 1760 IF(VAR(5)-1.)1770,1810,1810
 1770 VAR(5) = 1.
      GO TO 1810
 1780 IF(M-7)1810,1790,1810
 1790 IF(VAR(7)-1.)1810,1810,1800
 1800 VAR(7) = 1.
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
C                                 CYCLING
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
 1810 PRINT 1820,    M,TEMP1,  VAR( M)
 1820 FORMAT (  4H VARI3, 9H ADJ FROMF7.2,  3H TOF7.2 )
 1830 IF (M-NVAR)1850,1840,1840
 1840 M = 0
      NCYCL = NCYCL + 1
```

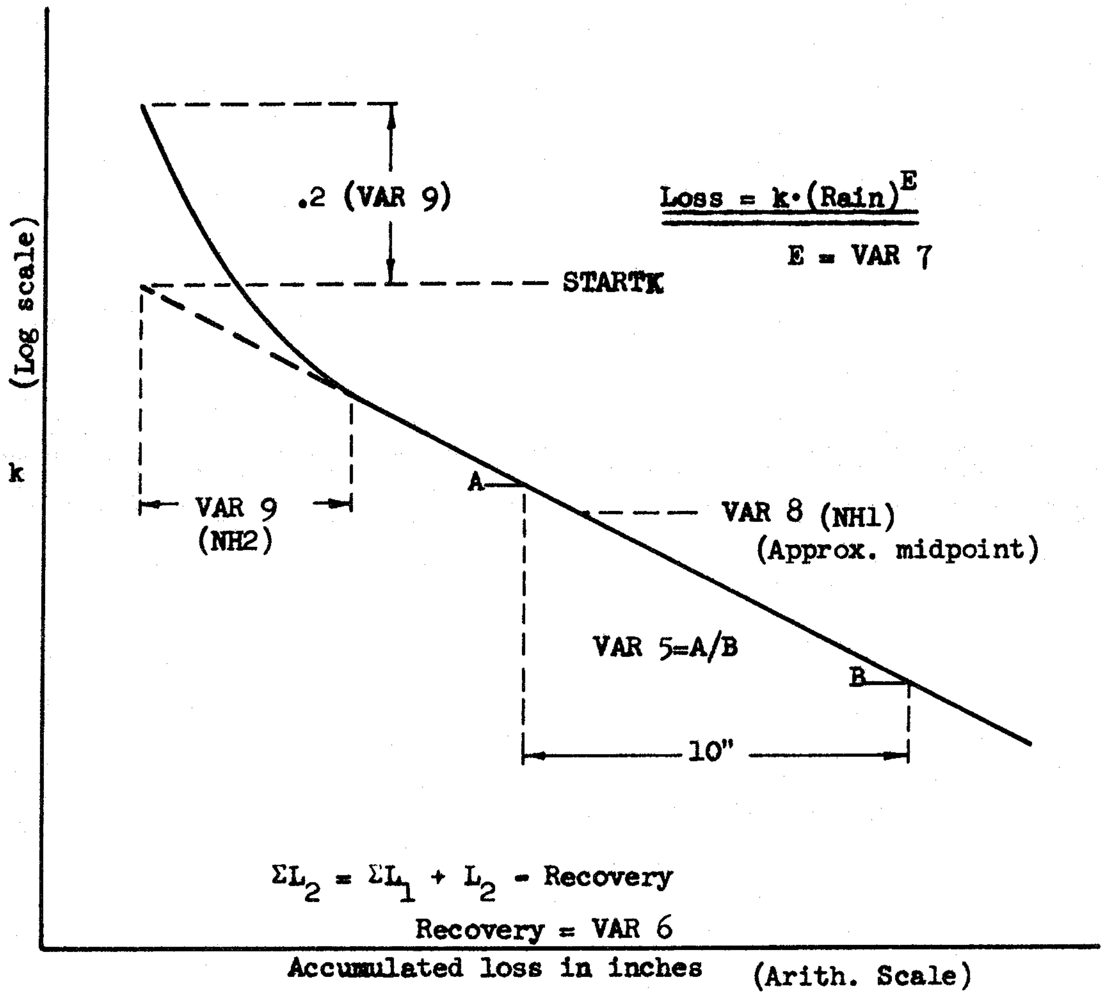
```
C      M1=0 IF NO HYDROGRAPHS YET COMPUTED
 1850 IF(M1)1870,1870,1860
 1860 NC1 = 1
      NC2 = 1
 1870 M = M + 1
 1880 IF(M-7)1890,1890,1900
 1890 IF(FLAG(M))670,670,1850
 1900 IF(M/2*2-M)1910,1920,1920
 1910 IF(FLAG(9))670,670,1830
 1920 IF(FLAG(8))670,670,1850
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
C                                     PUNCH OUT
C  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
 1930 VAR(M) = TEMP2
      PRINT 1940
 1940 FORMAT (/21H OPTIMIZATION RESULTS )
 1950 PRINT 90
      PRINT 100,    DA,TR,(VAR(I),I=1,7),QRCSN
      PRINT 110
      RTIOR=1./RTIOR**10.
      PRINT 111,    (FLAG(I),I=1,9),RTIOR
      ALAG=(ALAG-.75)*1.048*TRHR
      CP    =QMAX*ALAG/(645.0*DA)
      PRINT 1960,     NUHGQ,ALAG,CP
 1960 FORMAT (/14H  UNIT HGR,NO=I3 ,10H       LAG=F8.3,9H       C+=F6.3)
      PRINT 330,     (QUNGR(I),I=1,NUHGQ)
 1970 FORMAT (1X,I7,9I8)
      IF(IPNCH)2000,2000,1980
 1980 PRINT 1990
 1990 FORMAT(/51H DISCHARGE IN THOUSAND CFS, RAIN AND LOSS IN INCHES)
 2000 DO 2170 N=1,NHT
      PRINT 2010
 2010 FORMAT(/80H       NP  VARNH1  VARNH2  STARTQ      NQO       IQA      RQ
     1A      IQB      RQB    STRTK)
      NH1 = N*2+6
      NH2 = NH1+1
      PRINT 2015,    NP(N),VAR(NH1),VAR(NH2),STRTQ(N),NQO(N),IQA(N),RQA(N
     1),IQB(N),RQB(N),STRTK(N)
      NQO11 = NQO1(N)
      NQO22 = NQO2(N)
      NQOP1=NQOP(N)
```

EXHIBIT 4

```
      SUMQ = 0.0
      SUME = 0.0
      SUMR = 0.0
C                REMOVE TEMPORARY CHANGE IN SELECTED FLOWS
      IF(IQB(N))2012,2012,2014
 2012 IF(IQA(N))2018,2018,2016
 2014 ITMP=NQO11+IQB(N)-1
      QO(ITMP)=QO(ITMP)/RQB(N)
 2015 FORMAT(I8,2F8.2,F8.0,2I8,F8.2,I8,2F8.2)
 2016 ITMP=NQO11+IQA(N)-1
      QO(ITMP)=QO(ITMP)/RQA(N)
 2018 PRINT 2020
 2020 FORMAT(/76H  PERIOD    RAIN    LOSS  EXCESS
     1     COMP Q     OBS Q)
      IF(IPNCH)2025,2025,2021
 2021 NHR=TR*.2+.5
      NXINC=10
      K=TR
      WRITE(14,2022)   K, NHR, NXINC
 2022 FORMAT(3I3)
      WRITE(14,40)       (TITLE(I, N), I = 1, 8 )
      WRITE(14,2022)   NQO(N)
 2025 DO 2100 I= NQO11, NQO22
      J = I - NQO11 + 1
      SUMQ = SUMQ + Q(I)
      IF(I - NQOP1)2030,2030,2080
 2030 EXCES(I)=EXCES(I)+RAIN(I)*QCLK(1)
      ITMP=EXCES(I)*100.+.5
      TMP=ITMP
      EXCES(I)=TMP*.01
      ALOSS = RAIN(I) - EXCES(I)
      SUMR = SUMR +RAIN(I)
      SUME = SUME + EXCES(I)
      PRINT 2070,  J, RAIN(I), ALOSS, EXCES(I), Q(I), QO(I)
 2070 FORMAT(I8,3F8.2,F34.0,F10.0)
      GO TO 2095
 2080 PRINT 2090,  J, Q(I),QO(I)
 2090 FORMAT(I8, F58.0, F10.0)
C     PUNCH INPUT TO PLOTTING PROGRAM
      EXCES(I)=RAIN(I)-EXCES(I)
 2095 IF(IPNCH)2100,2100,2097
```

EXHIBIT 4

```
 2097 WRITE(14,2070)      I, RAIN(I), ALOSS, EXCES(I), Q(I), QO(I)
 2100 CONTINUE
      ACUML=SUMR-SUME
      PRINT 2190,  SUMR, ACUML,SUME, SUMQ, SUMQO(N)
 2170 CONTINUE
 2180 FORMAT(/8H TOTAL  6F8.2,2F10.0)
 2190 FORMAT( /8H TOTAL  3F8.2, F34.0, F10.0)
      GO TO 10
      END
```



GENERAL LOSS-RATE FUNCTION

EXHIBIT 5

EXHIBIT 6

INPUT DATA - 23-J2-L211

A. Three output title cards

B. Job data card

1. NHT - Number of hydrographs (storms) for same station, cannot exceed 6
2. M - Variable number with which program starts (will automatically start with M = 7 if not given)
3. IPNCH - Positive value causes punch-out (in addition to print-out) of rain, excess and runoff
4. NCLRK - Number of time-area ordinates to be read, use zero for synthetic time-area curve

C. Job data card

1. DA - Contributing drainage area in square miles
2. TR - Rainfall and runoff interval in minutes
3. VAR(1)* - Clark's T_c in hours
4. VAR(2)* - Ratio of Clark's R to T_c
5. VAR(3)* - Shape factor for synthetic time-area curve (1 or greater)
6. VAR(4)* - Ratio of imperviousness of drainage area (zero to 1)
7. VAR(5)* - Ratio of K on straight line portion of loss rate curve to K at 10 inches more ACUML (1 or greater)
8. VAR(6)* - Recovery loss index in inches, subtracted from ACUML every period
9. VAR(7)* - Exponent of rain in loss computation
10. QRCSN - Flow below which recession rates are maintained as a minimum

D. Job data card

1-9. FLAG - Positive value prevents change of variable having same subscript (VAR(1) is flagged in field 1, VAR(2) is flagged in field 2, etc.). Flag 8 applies to VAR(NH1) and 9 to VAR(NH2) for all hydrographs.

10. RTIOR - Ratio of recession flow to that 10 TR units (C2) later (1 or greater).

*Input values can be omitted, however, it is advantageous to suggest approximate values, especially for VAR(1).

E. Time-area data (omit if NCIRK (B4) is zero or negative)

Q - Cumulative area in any units at equal time increments on basin time-area curve starting with zero time (21 values maximum unless dimension changed)

F#. Title for plotting, Cols. 2-32 only (omit if IPNCH (B3) is zero or negative)

G#. Storm data card

1. NP - Number of precipitation periods starting at beginning of storm and including all zero values up to last positive value
2. VAR(NH1)* - Loss rate index - value of K on straight line portion of loss rate curve when ACUML is $\frac{1}{2}$ of storm loss
3. VAR(NH2)* - Accumulated loss increment during initial-loss period. Adds an increment 0.2 (VAR(NH2)) to K when ACUML is zero, decreasing to zero when ACUML is VAR(NH2).
4. STRTQ - Flow in cfs at <u>start</u> of first TR period of storm
5. NQO - Number of outflow ordinates starting at end of first time interval and including all zero values up to last positive value. Must equal or exceed NP (G1)
6. IQA - Sequence no. of first flow to be temporarily changed if observed flows for each storm are numbered chronologically starting with 1.
7. RQA - Ratio by which flow is temporarily multiplied.
8. IQB - Sequence no. of second flow to be temporarily changed.
9. RQB - Ratio by which flow is temporarily multiplied.

H#. Flow data cards

QO - Consecutive end-of-period flows in cfs NQO values (G5), ten per card. First value occurs TR minutes (C2) after beginning of storm and coincides with end of first rain period.

*Input values can be omitted.

#Cards F through I are repeated in order for NHT (B1) floods.

EXHIBIT 6

I#. Rain data cards

RAIN - Basin-mean rain in inches with decimal point (program will round to nearest hundredth), for each TR period (C2) starting at beginning of storm, consecutive including all zeros, ten per card, NP values (G1).

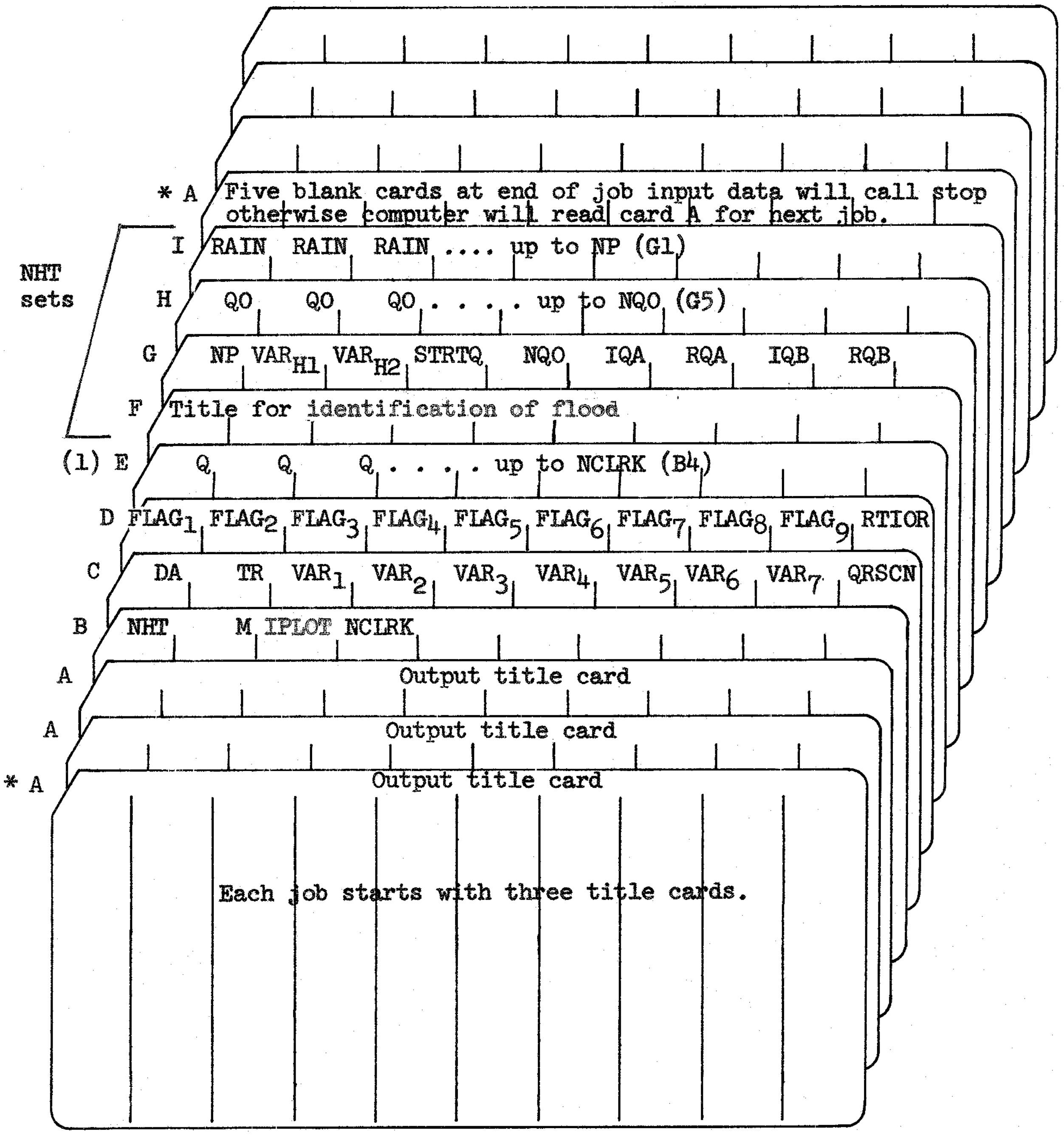
#Cards F through I are repeated in order for NHT (B1) floods.

NOTE: Capital letters identifying input cards can be punched in column 1 of every card for identification. Column 1 is not read by computer and therefore cannot be used for input data.

EXHIBIT 6

EXHIBIT 7

SUMMARY OF REQUIRED CARDS
23-J2-L211



Note:
(1) Omit if NCLRK (B4) is zero or negative.
* The identification "A" must appear on the card in col 1.

Hydrologic Engineering Methods for Water Resources Development

Volume 1	Requirements and General Procedures, 1971
Volume 2	Hydrologic Data Management, 1972
Volume 3	Hydrologic Frequency Analysis, 1975
Volume 4	Hydrograph Analysis, 1973
Volume 5	Hypothetical Floods, 1975
Volume 6	Water Surface Profiles, 1975
Volume 7	Flood Control by Reservoir, 1976
Volume 8	Reservoir Yield, 1975
Volume 9	Reservoir System Analysis for Conservation, 1977
Volume 10	Principles of Groundwater Hydrology, 1972
Volume 11	Water Quality Determinations, 1972
Volume 12	Sediment Transport, 1977