RESEARCH DATA ASSEMBLY FOR SMALL WATERSHED FLOODS

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CER63EML-EFS-VMY37

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PREFACE

The concept of collecting and storing a large amount of existing data on floods from small watersheds as part of a wider research program in this field was originated by V. M. Yevdjevich; Professor, Civil Engineering Department, Colorado State University.

The plan of this report and the general procedures described herein were developed jointly by the three authors. The report was prepared by E. M. Laurenson of the Civil Engineering Section, Colorado State University (on sabbatical leave from the University of New South Wales, Australia) in consultation with the other two authors.

The research planning and activity leading to this report has been sponsored by the Colorado Agricultural Experiment Station.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

LIST OF FIGURES

LIST OF TABLES

SUMMARY

As part of a long-term research project in flood estimation for small watersheds, it is proposed to collect, process, and store rainfall, streamflow and catchment data for several hundred recorded floods on small watersheds. Basic data will be obtained from many sources both within and without the United States, and will be processed to provide, for each flood event, a hydrograph, an average hyetograph and measures of catchment characteristics and catchment conditions. Processed data will be stored on punched cards and magnetic tape for easy use and distribution, and the unprocessed and partially processed data will be systematically filed for future reference.

This report describes in detail the criteria for acceptance of data, the processing and analysis to be applied to the data, procedures for storing and filing of data, and the methods of indexing the data for easy retrieval.

It is envisaged that the establishment of this large collection of high quality data on floods from small watersheds will facilitate and promote research in this field, eventually leading to improved methods of flood estimation for small watersheds.

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1. INTRODUCTION

1.1 Objectives

It is well known that the magnitude and shape of the flood hydrograph produced by a storm on a watershed[1] are determined by a large number of factors, which describe the intensity and distribution (in both time and area) of rainfall, the physical nature of the watershed and the condition of the watershed at the time of the flood event. The number of variables involved makes the problem of determining hydrographs from rainfall and other data extremely complex. Furthermore, in hydrologic design, the necessity of estimating the flood of a given probability introduces great difficulties as the relationship between storm probability and flood probability is not, at present, well understood, and the available data are often insufficient to determine reliably the probability of extreme values of rainfall and streamflow. As the problem of flood estimation for small, ungaged catchments is a common one, much effort has been expended in the development of solutions of it. These solutions normally provide empirical relationships for the derivation of unitgraphs or the estimation of the flood peak of any given probability for catchments within a given region. Generally, the number of factors used in estimating the flood is so limited that the empirical relationships cannot be used outside of a limited region, and even within the region, the accuracy of prediction is not high.

There is a clear need for improvement in the accuracy and the generality of methods of flood estimation for small watersheds, and this can only be achieved through a greater understanding of the relationships between the hydrograph and the rainfall and catchment factors that affect it. As a first step toward this understanding, it is intended at Colorado State University, to collect, process and store in a form suitable for ready analysis, a large volume of data on floods from small watersheds. These data will comprise records of rainfall and streamflow, and information on catchment characteristics and catchment conditions for several hundred or thousand floods that have been recorded on experimental and other small watersheds.

[1] The terms "watershed," "catchment," and "river basin" are used synonymously in this report, with "catchment" being most used.

This report describes in detail the proposed system for the collection, processing, filing, storage, and retrieval of these flood data. The collected and processed data will constitute a hydrologic data unit for floods from small watersheds; and, while established primarily for research projects in Colorado State University, this unit would provide data in a generally useful and readily usable form to other organizations desiring it. Thus the data will be used for graduate thesis projects, research projects in the Colorado Experiment Station, projects sponsored by government agencies, and for research in both government and private institutions elsewhere. These data are a fundamental requisite for any modern and sophisticated research into the relationship between rainfall and flood runoff for small watersheds.

Research in the field of flood estimation for small watersheds will be greatly facilitated by having most of the available high quality data collected in one place and organized in a form suitable for ready distribution and use, since the normally burdensome task of collecting and processing basic data will be largely eliminated. Furthermore, the proposed hydrologic data unit for this particular hydrologic problem should make for greater use of the large amount of small watershed flood data that is now widely scattered and not realizing its full potential.

Dozens of experimental watersheds exist in the world, and very valuable data are available. This study of floods on small watersheds represents only one of the many hydrologic problems that could be studied using the large amount of small watershed data available.

Development of this hydrologic data unit forms one part of a three-pronged attack on the problem of reproducing flood hydrographs from the rainfall and catchment factors that cause them. The other two phases will be theoretical studies and physical studies on a rainfall-runoff simulation platform aimed at developing mathematical and mathematical-physical models of the processes involved in formation of a flood hydrograph. All three phases will be very closely related, and the data collected and organized in the first phase will be used in the development and testing of theories in the second phase.

The development and widespread use of high speed digital computers has opened up new fields and new methods of inquiry in hydrology as in other sciences. Hydrologic studies need no longer be restricted to small regions because of the great volume of data that would have to be handled in a more general investigation. Thus, the collection in one place of small watershed flood data from the whole of the United States and from many other parts of the world is now a practicable and useful procedure. As a natural consequence of this approach, the data will be stored on punched cards and magnetic tape to facilitate both reproduction and input to computers.

1.2 Types of Data

The basic data available for the study of floods from small watersheds consist of the charts from water stage recorders, discharge measurements, and the records from individual rain gages. The physiographic, geologic and other properties of the watershed are often represented on maps. To be of use in hydrologic investigations, these basic data must be processed, but the processed data must be general enough to be of use in a wide range of investigations, thus, it has been decided here to process the data to the stage of having, for each flood event, --

(i) a hydrograph,
(ii) an average or representative hyetograph for the catchment,
(iii) measures of a wide range of catchment characteristics,
(iv) measures of the condition of the catchment at the time of the flood event, and
(v) identification data for the flood event.

These items will be stored on punched cards and magnetic tape, but all basic data, source documents, and partially processed data will be systematically filed for further study, which will be required in some investigations.

1.3 Sources of Data

Data for inclusion in the project will be obtained from a wide variety of sources, of which the major ones will be U.S. federal government agencies. However, some state government agencies, universities, and private organizations in the U.S.A., and many agencies in other countries also collect data of the type desired, and the cooperation of these organizations will also be sought. Use will also be made of publications such as: "Selected Runoff Events for Small Agricultural Watersheds in the United States," issued by the Agricultural Research Service, (U.S. Dept. of Agriculture, 1961), and similar published data.

In some instances, all of the basic data (on streamflow, rainfall, and catchment characteristics) will be available from a single source, but in many cases it will be necessary to go to different sources for the three different types of information. The list of data sources is therefore divided into:

(i) Sources of streamflow data,
(ii) Sources of rainfall and climatic data, and
(iii) Sources of data on catchment characteristics.

Listings of the potential data sources in U.S.A. under these three headings are given in Appendix A. Although United States organizations only are listed in this appendix, it is intended to expand the system to include data from other countries. Appendix A indicates many sources in general terms only, but it will be supplemented later by a complete card file giving specific names (or titles) and addresses of the people or administrative units from whom data has been or can be obtained (see Section 5.2).

1.4 Outline of Report

The remaining parts of this report present details of the collection, processing, and storage of the data on floods from small watersheds. Section 2 presents criteria that have been set up to ensure that the data collected will be of high quality and of use in solving the particular problems of flood estimation on small, predominantly rural watersheds. In Section 3, the methods that will be used to process, store, and file the rainfall and streamflow data area described in detail, while Section 4 discusses the problems of identifying and measuring the pertinent catchment characteristics. Indexing of the data to provide for easy retrieval is discussed in Section 5, and potential uses of the stored data are indicated in Section 6.

Throughout the report, specific details of proposed procedures are given, with examples where necessary, in order that the report can serve as a manual as well as a general exposition of the data project.

2. CRITERIA FOR SELECTION OF BASIC DATA

2.1 General

To be of value in this study, the data selected, and the watersheds to which they apply must satisfy certain criteria determined by the specific purpose of the study. The purpose is to examine the relationships between characteristics of flood hydrographs of small watersheds and the storm and catchment factors that affect these characteristics. The criteria for selection of data that have been established in accordance with this aim are discussed in Sections 2.2 to 2.6 below.

2.2 Completeness of Available Data

It is necessary that adequate information on streamflow, rainfall, and catchment characteristics be available. For streamflow, this implies the need for a complete and continuous record of stage throughout the flood event, and a reliable rating curve or rating table to convert this stage record to a discharge hydrograph. For rainfall, it implies the existence of at least one complete recording rain gage record that is representative of the storm pattern on the catchment, and a sufficient number (which will depend upon catchment area) of recording or non-recording rain gages to measure the average storm rainfall on the catchment. In the case of very small watersheds, one recording gage may, of course, serve both purposes. Rainfall records must also be available for 30 days before the storm as an indication of antecedent conditions.

The minimum requirement for information about the watershed is the existence of a contour map with sufficient detail to permit determination of catchment area, overland slope, stream slope, watershed shape, shape of drainage net, and drainage density. Preferably, recorded information should also be available on the soil, geology, and vegetation types on the watershed, but absence of these data will not disqualify a watershed, as they can readily be determined by field inspection.

2.3 Size and Type of Watershed

A rather arbitrary decision has been made to limit the maximum size of watershed used to about 40 square miles (about 100 square kilometers). The purpose of this was primarily to limit the amount of data collected to manageable proportions, and secondarily to restrict the data to catchments of a size that is usually ungaged, and for which the need for rainfall-streamflow type flood estimation procedures is greatest.

At the lower end of the size range, no specific areal limit has been set, but data will be collected only for areas with a natural stream channel, not for runoff plots nor for areas in which the runoff is concentrated into artificial channels such as graded banks. The reasons for this limitation are the same as those for the upper limit on area.

It is intended that the great majority of catchments used will be between 0.1 and 40 square miles in area, but a few catchments outside these limits will also be selected to assist in generalizing results obtained from the data. Between the limits of 0.1 and 40 square miles, care will be taken not to introduce bias into generalizations by having a disproportionate number of catchments within any narrow size range.

A further criterion is that data will be collected only for predominately rural, and not for urban watersheds. This is in order to keep the data homogeneous, and to limit the amount of data collected but also, more importantly, because the problems of flood estimation in storm water drainage systems are different in many ways from those of rural catchment flood estimation.

2.4 Type of Input

Usually, flood flows occur as a result of:

(i) rainfall,
(ii) snowmelt,
(iii) rainfall combined with snowmelt,
(iv) accidents in nature (e.g. landslides, snow avalanches, with sudden release of stored water).

In order to restrict the scope of the study to something that is reasonably attainable, no consideration will be given to snowmelt or accidental events, and, accordingly, data will be collected only for floods resulting from rainfall with no or negligible snowmelt. Since the existence of snow on the watershed will not normally be recorded, (except on large areas for water runoff forecasts) exclusion of events resulting from rain on snow will frequently have to be made on the basis of location of watershed and time of year.

2.5 Magnitude of Flood

Many previous investigations have demonstrated that difficulties arise in reproducing the hydrographs of small floods. The reasons for this are not understood, but they probably have something to do with uneven areal and time distributions of rainfall and runoff, and channel losses. In any case, since small rises are not of great practical importance, it is intended to avoid the worst of these difficulties by collecting data for significant rises only. Two alternative criteria have been established for this purpose. When the data necessary for a probability study are available, only floods with an average frequency less than once in one year will be accepted. When the data necessary for a probability study are not available, floods will be accepted only if their peak discharge exceeds 15-25 c.f.s./sq. mi. depending on the average water yield of the particular catchment. These are rather low limits, but they should exclude those minor rises that are often difficult to reproduce, while including all those that would be of value in determining the relationships between floods and their causes.

2.6 Areal Uniformity of Rainfall

Extreme areal non-uniformity of rainfall coupled with changing patterns of areal distribution from storm to storm also leads to difficulties in relating streamflow to rainfall. While it is intended to study the effects of areal non-uniformity of rainfall at a later date, it is nevertheless considered desirable, at least in the initial stage of data collection, to exclude those storms that are very non-uniform with respect to area. This will tend to avoid difficulties for which there are, at present, no simple solutions.

Since convenient and satisfactory measures of areal non-uniformity of rainfall have not yet been developed, the exclusion of extremely non-uniform storms will have to be done in a subjective way, but objective criteria will be developed and used as part of the research program using the data collected. As a general guide, however, it is suggested that storms be excluded if it appears likely that surface runoff did not occur over the whole of the catchment.

2.7 Summary of Criteria

The requirements of data and catchments for inclusion in this project as discussed in Sections 2.2 to 2.6 above, can now be summarized as follows:

(i) Complete and continuous stage record.
(ii) Adequate rating curve or table.
(iii) At least one complete and representative recording rain gage record.
(iv) Sufficient rain gages to give average catchment rainfall accurately.
(v) Thirty days of antecedent rainfall records.
(vi) Contour map with suitable scale and contour interval.
(vii) Preferably, but not necessarily, descriptions of soil, geology, and vegetal cover.
(viii) Catchment area not greater than about 40 square miles.
(ix) Catchment must have a natural stream channel.
(x) Catchment must be predominantly rural, not highly urbanized.
(xi) Streamflow due to rainfall only (not snowmelt).
(xii) Average frequency of peak discharge less than once in one year, or peak discharge not less than 15-25 c.f.s./sq. mi. (for use when frequency study is not possible).
(xiii) Runoff occurred from whole of catchment.

3. PROCESSING AND STORAGE OF RAINFALL AND STREAMFLOW DATA

3.1 General Considerations

3.1.1 Processing of Recorded Data. Raw streamflow and recording rain gage data usually consist of ink traces of stage and accumulated rainfall respectively against time on charts, while raw daily rainfall data consist of tabulated figures. Flood estimation investigations usually require processing of these data to give, for each rise in the stream, a hydrograph, isohyetal map, and hyetographs at the various recording rain gages. Frequently, a single hyetograph representative of the whole catchment is required.

Preparation of hyetographs for individual stations, and of hydrographs, from the basic data can usually be done with little subjectivity, and with negligible loss of the detail contained in the original records. Derivation of an average hyetograph for a catchment from more than one individual hyetograph involves more subjective judgment, and loses much of the information presented by the individual hyetographs, but on the other hand, it puts the data into a suitable form for some hydrologic investigations. The form of study envisaged in this project will involve the use of average or of representative hyetographs, and, consequently, it is intended to process the rainfall data to this stage. However, derivation of the average or representative hyetograph will involve the preparation of hyetographs (and mass curves) for individual stations, and these will be retained in an easily available form.

Determination of the areal average or equivalent uniform depth of rainfall can often best be done by drawing and processing an isohyetal map. Further, the isohyetal map is a desirable tool in any study involving consideration of areal variations of rainfall, and even if used only qualitatively, is of great value in illustrating the characteristics of a storm. It is therefore intended to prepare isohyetal maps for all storms on catchments having four or more rain gages. It is known that many of the catchments to be studied have only one rain gage so that an isohyetal map cannot be prepared, and for catchments with only two or three rain gages, an isohyetal map is of little significance, and will not be drawn.

Streamflow data will simply be processed to the stage of a discharge hydrograph expressed in terms of discrete ordinates of instantaneous discharge.

Multiple peak hydrographs resulting from more than one distinct burst of rain provide problems in analysis. If the peaks are quite distinct, it is usual to separate the hydrograph into individual parts, each resulting from a single burst of rain. As this separation is quite a subjective process, however, it is considered better for the present purposes to store the actual hydrograph ordinates in a single series, and merely to give some indication in the stored data that the hydrograph is multi-peaked. Similarly, the hyetograph will be stored as a single series, but, if possible, separate isohyetal maps will be prepared for each burst of rain.

The criteria for deciding that two adjacent streamflow peaks should be treated as two rather than one peak are--(i) the bursts of rain causing the two peaks are clearly distinguishable, and (ii) it will be possible to separate the streamflows from the two bursts with confidence. More objective criteria than these will be developed in due course. For convenience in recognizing multi-peaked hydrographs in the stored data, the number of peaks (counted on the basis of the above criteria) will be indicated by a number (1, 2, 3 etc.) stored with the data for each event.

Since probability of occurrence of both storms and floods is of interest in flood estimation, it is intended to make estimates of these probabilities for each event. This will involve, in most cases, considerable sampling errors, and selection of the method of estimating probability is itself a subjective procedure if the sample is very small, so it is not expected that these estimates will have a high degree of reliability in many cases. Nevertheless, probability of occurrence is such an important aspect of a storm or flood, that it is considered desirable to provide an estimate of it.

It is intended, then, to obtain raw data of rainfall and streamflow, and to process this in such a way as to provide, for each storm-flood event:

(i) hyetographs for individual recording rain gages,
(ii) an isohyetal map,
(iii) an average or representative hyetograph for the catchment,
(iv) a hydrograph, and
(v) probability estimates of both storm and flood.

Details of the derivation of items (i), (ii), and (iii) are discussed in Section 3.2 below, of item (iv) in Section 3.3, and of item (v) in Section 3.4

3.1.2 Storage of Raw and Processed Data. It is expected that data will be collected, processed, and stored for something of the order of 1000-2500 storm-flood events. Further processing or analysis of the data in hydrologic investigations would be facilitated by the use of an electronic computer, and, accordingly, it is intended to store the processed data on punched cards and magnetic tape, the cards to be used for work on smaller, lower speed computers, and for some regional or river basin studies, and the tape for large computing jobs on high-speed computers, and flood events for catchments from large areas. It may also prove desirable to convert the punched data to storage on some other medium such as magnetic disc, and this can easily be effected in future if necessary.

In addition to the hydrographs and average hyetographs for all events, there will be isohyetal maps, hyetographs for individual stations, daily rainfall records, recording rain gage charts, stream stage recorder charts, and rating tables. Not all of these data will be stored on cards and tape; some of it will simply be filed away for future reference. Copies of original recorder charts, daily rainfall records, and isohyetal maps when available will naturally be filed in this way, and the plotted hyetographs of individual stations will also be filed. Subsequent use of the words "stored" and "filed" in this report will respectively refer to (i) storage on punched cards, magnetic tape, or some similar medium for ready input to a computer or duplication for dissemination; and (ii) filing of written or graphical material in some systematic way for individual reference purposes.

Details of the disposition of data between storage and filing, and the layout of data on the punched cards and magnetic tape are given in Section 3. 5 below.

3. 2 Processing of Rainfall Data

3. 2. 1 General. As explained in Section 3. 1, raw rainfall data usually consist of recorder charts showing cumulative rainfall plotted against time, and tabulated values of daily rainfall, and it is intended to process such data to produce hyetographs for individual stations, an isohyetal map, and an average or representative hyetograph for each storm. Details of this processing are given below in Sections 3. 2. 2 to 3. 2. 7.

3. 2. 2 Correction of Rainfall Records. Correction of recording rain gage charts for errors in both time and cumulative depth should be made at the time the rainfall amounts are read from the charts. Time errors usually result from gain or loss of the clock, and occasionally from chart slippage or from incorrect setting of the pen when the chart is put on. A linear variation of the error between commencement and finish of the trace can be assumed for the purpose of computing corrections, but the rate of change of error is usually sufficiently low that a constant correction can be applied over a period of several hours. Some of the research areas may be equipped with a combination recorder where rainfall and stream stage are both recorded on the one chart. In such cases, the hyetograph and hydrograph will always be in correct time relation to each other, but it may still be necessary to correct for a gaining or losing clock.

Errors in the indicated total cumulative rainfall can arise from various causes. In the case of tipping bucket rain gages, the total volume of rainfall is collected in the gage as well as being indicated on the chart. If the measured volume does not agree with the indicated volume, the error is usually prorated over the period of time receiving the highest intensity, because at high intensities there is a tendency for the gage to "under-register" the rainfall. It is expected that, in many cases, any necessary corrections will already have been made by the agency collecting the data.

Errors in daily rainfall figures can arise from a variety of causes. Large errors in these figures (e. g. entering a fall on the wrong day, or entering two days' fall on one day) can often be detected and sometimes corrected by comparison with the records of surrounding stations. Such errors will be corrected where this can be done with confidence, but sometimes it may be necessary simply to ignore a figure that is clearly in error. As it is not always possible to make definite corrections, these matters are best dealt with by making notes on the tabulations of daily rainfall rather than by changing the tabulated figures. These notes can then be taken into account when preparing the isohyetal maps.

3. 2. 3 Hyetographs for Individual Stations. Hyetographs will be plotted for all recording rain gage stations on or near the catchment under consideration. The decision as to whether any particular station off the catchment should be considered is a predominantly subjective one, and will depend on the distance from the catchment, differences in the physical meteorological factors between the gage and the catchment, and the availability of other recording gages on or near the catchment. If, in the light of these considerations, it appears that a particular gage will represent a significant portion of the catchment better than any other gage, its hyetograph will be plotted.

All hyetographs for a particular storm on a given catchment will be plotted on the same sheet and with the same scales and time origin, but separated vertically from each other for clarity. A constant time interval will be used throughout all hyetographs for a given catchment to facilitate both comparison of hyetographs for different stations and the conversion of rainfall amounts to intensities. The time interval used will vary from catchment to catchment, its value depending basically upon the response time of the catchment to changes in rainfall intensity. This criterion implies a tendency to shorter time intervals for smaller catchments. This vague, general criterion, however, must be applied in conjunction with another criterion, which is that the time interval chosen should be short enough to show the more obvious changes in rainfall intensity or, in other words, it should not be so long as to lose much of the detail contained in the original chart. It may also happen, that the shortness of the time interval is limited by a cramped time scale on the recording rain gage chart. A further requirement is that the time interval used will always be a multiple of five minutes to facilitate comparison of hyetographs.

It is now clear that selection of an appropriate time interval for a particular catchment is a subjective process with no very clear guides to assist in making the decision. Practice in the assembly of data may furnish more objective criteria for selection of time interval. In view of this, the tendency should be to err on the side of too short rather than too long an interval, as this ensures that needed detail will not be lost. On the other hand, it results in an unnecessarily large amount of numerical computation, so the tendency must not be taken too far. As a rough indication, experience shows that an interval of the order of 5 minutes is often appropriate for an area of several acres, a one-hour interval for areas about 20 to 40 square miles, while two hours might be suitable for some of the catchments of about 40 to 50 square miles. These figures are give only to illustrate order of magnitude, and will be applied in conjunction with the criteria given above, that all significant changes in intensity should be shown, the significance of these changes being affected by the response time of the catchment.

3. 2. 4 Isohyetal Map. As explained in Section 3. 1 an isohyetal map is necessary in the determination of equivalent uniform depth of rainfall, and is also desirable simply for the purpose of illustrating the areal distribution of rainfall. In preparing the isohyetal map, it is first necessary to determine the period of time to which the map is to apply. This time period is best determined by inspection of the hyetographs and hydrograph, which usually reveals just what period of rainfall is associated with a particular rise in the stream. It is thus necessary to plot the hydrograph on the same sheet as the hyetographs and to the same time scale so that an appropriate portion of the total stream hydrograph and the corresponding period of rainfall can be selected.

When the storm period has been selected, it is possible to determine storm period rainfalls at the daily-read stations as well as at the recording stations. Frequently, this will merely involve taking the total fall for one or two or possibly three days of the record, but sometimes it will be necessary to compute a proportion of a daily total at a non-recording gage, based on the proportion of storm period rainfall to daily fall at the nearest recording gage.

Storm period rainfalls for all stations on or near the catchment are next plotted on a map, and the isohyets drawn. On small catchments, differences in orographic effects over the catchment on rainfall are usually small, but in cases where this is not so, the isohyetal map will be drawn over a contour map of the catchment so that orographic effects can be allowed for in drawing the isohyets between rainfall stations.

3.2.5 Average or Representative Hyetograph. As stated in Section 3.1.1, considerable subjectivity enters into the determination of an average hyetograph; several variations in procedure are possible, and different procedures are applicable under different circumstances. The difficulties that arise, and the procedures that are to be used in this project are discussed below.

In the first place, it is necessary to estimate the equivalent uniform depth of storm rainfall on the catchment. Many catchments will have only one rain gage, which will be assumed representative of the whole catchment. In the case of catchments having two or three rain gages, no isohyetal map will have been prepared, and average rainfall will be computed as either an arithmetic mean or Thiessen mean of the station rainfalls. The arithmetic mean will be used if there is little variation in the station rainfalls or if the stations are uniformly distributed, and the Thiessen mean otherwise. For those storms for which an isohyetal map has been prepared (catchments with four or more rain gages), areal average rainfall will be determined by measuring areas between isohyets and computing a weighted average depth.

In computing arithmetic mean rainfalls, judgment must be used in deciding which stations off but near the catchment should be included in the computation. Inclusion of any particular station will depend upon whether it is representative of a significant portion of the catchment that is not covered by some other gage.

When the equivalent uniform depth (or total volume of the average or representative hyetograph) has been determined, it is necessary to fix the temporal pattern of this graph. In this aspect of the problem, there are three common situations, with a different solution appropriate to each. They are:

(i) only one recording rain gage is significant for the catchment;
(ii) more than one gage is significant, but all have similar patterns;
(iii) more than one gage is significant, and their patterns are dissimilar.

In the first case, where only one recording gage need be considered, the average hyetograph is obtained simply by multiplying all ordinates of the station hyetograph by the ratio of equivalent uniform depth of rainfall to station rainfall.

When more than one recording rain gage record is available, it is, in general, desirable to plot mass curves for all gages on the one sheet and to sketch in an "average" mass curve conforming as closely as possible to the average shape of the station mass curves, and having the correct total rainfall. If, however, the time patterns at the several gages are very similar to each other (case (ii) above), this time-consuming procedure will yield a result little different from any of the individual mass curves. Accordingly, in such cases, it is adequate and desirable simply to adopt the pattern of the most representative individual gage and adjust its ordinates proportionately to give the correct total rainfall.

In case (iii), where the individual station hyetographs are markedly different from each other, an "average" mass curve as representative as possible of the catchment rainfall must be drawn subjectively on a plot of the individual station mass curves. No completely objective arithmetic averaging procedure is appropriate since such procedures tend to damp out fluctuations in the individual curves, and this damping can make the average curve quite unrepresentative of the actual storm. However, the times of start and finish of rainfall at the several stations can be averaged as also can the times and magnitudes of peaks in rainfall intensity, but in doing this, weight should be given to the areas represented by the individual gages.

Procedures for preparation of the average or representative hyetograph can now be summarized as follows:

A. Determination of equivalent uniform depth, or total volume of the average hyetograph.
   (i) Where only one rainfall station is significant, this is used to give the total depth.
   (ii) Where two or three rain gages are significant, use an arithmetic mean if this will give an accurate estimate, or a Thessen weighted mean otherwise.
   (iii) Where four or more rain gages are significant, an isohyetal map will have been prepared, and equivalent uniform depth will be estimated by planimetering areas between isohyets, and computing a weighted average depth.

B. Determination of Shape of Average Hyetograph.
   (i) If only one recording rain gage is significant, adjust the ordinates of its hyetograph proportionately to give the correct total rainfall as computed in A above.
   (ii) If more than one recording gage is significant, but all gages have similar patterns, adopt the hyetograph of the most representative gage, and adjust its ordinates proportionately to give the correct total rainfall.
   (iii) If a number of gages with different patterns is available, draw mass curves of storm rainfall for all stations on the one graph, and sketch in an average curve by eye in such a way as to retain all significant features of the individual curves, to have the correct total rainfall, and to have the average times of start and finish of rainfall and the average time and magnitude of peak rainfall intensity.

Prepare the average hyetograph by taking increments of the average mass curve.

3.2.6 Measures of Temporal and Areal Variation of Rainfall. Existing methods of describing the temporal and areal distributions of rainfall might have disadvantages for some approaches to research in flood estimation for small watersheds, and new methods of description might be necessary. Consequently, in the theoretical phase of this three-phase attack on the problem of floods from small watersheds, it is intended to develop parameters representing the temporal and areal variations in storm rainfall. These parameters will be used to study the effect of these characteristics on flood hydrographs.

While parameters representing temporal variations in rainfall can be computed readily from stored hyetograph ordinates, this is not possible for areal variations, which will be depicted only on the isohyetal maps. It will be necessary to develop and test numerical measures of the degree of variability and the location of the greatest intensities, since suitable measures of these characteristics are not at present available. This emphasizes the importance of filing the isohyetal maps, daily rainfall records, and other types of partially processed data for future reference and use.

3.2.7 Storm Duration. This is inversely correlated to some extent with loss rate, short storms tending to be associated with high loss rates. Definition of the storm duration must be arbitrary, and it is considered that the most significant period from the point of view of effect on average loss rate is the net supply period (T_S), i.e., the total period for which rainfall intensity exceeds loss rate excluding the period of initial loss. Determination of this period requires the determination of loss rate and initial loss, but it is considered desirable to derive these factors in any case as they represent alternative characteristics that could be used in relating hyetographs to hydrographs in place of a number of other characteristics, as can be seen from Fig. 1.

As a second, easily determined, index of storm duration, the total duration of the storm (T) including the initial and residual periods will be determined and recorded. It is not expected that this time period will prove to have as much significance as T_S, and its determination almost invariably involves subjective decisions as to exactly when "the storm period" begins and ends, but it is easily determined and may prove useful.

3.3 Processing of Streamflow Data

The main object here is to obtain, for each rise, a set of discharge ordinates that adequately represents the stream hydrograph. However, since a general assessment of the hydrograph characteristics requires a graphical representation, and since much of the manipulation of hydrographs in flood investigations is performed graphically, it is desirable to have the hydrograph plotted as well as recorded as discrete ordinates on cards and tape. The stage hydrograph on the recorder chart is not adequate for these purposes, and accordingly it is proposed to plot hydrographs of all rises.

Correction of recorder traces for both time and stage will, if necessary, be made (as with the recording rain gage charts) at the time the stage heights are transcribed from the chart to a tabulation of stage vs time. The corrected stage heights at corrected times can then be converted to discharge by means of a rating table for the station, and the discharges entered in a third column of the tabulation. The discharge hydrograph will then be plotted to suitable scales, which may vary from catchment and from flood to flood on the one catchment.

In plotting the hydrographs, discharges will be determined at irregular time intervals so that none of the detail contained on the recorder charts is lost. However, since most arithmetic operations on hydrographs are facilitated by having ordinates at equal intervals of time, the discharge values to be stored on cards and tape will be taken off the plotted hydrographs with a constant time increment. This time increment will be chosen such that the major features of the hydrograph will be reflected, but minor fluctuations may have to be ignored. It is frequently found that a period of about one quarter the time of rise is appropriate, and the period should seldom be greater than one-third the period of rise. It should always be either the same as, or a multiple of, the time increment used for the hyetographs of the catchment, and must, of course, be in phase with the hyetograph periods. Further, the same time increment will be used for all hydrographs of a given catchment.

3.4 Probability Estimates

3.4.1 Rainfall. Probability of occurrence will be estimated for all the storms studied. Since the probability of any actual storm intensity varies with the duration considered, it will be necessary in most cases to compute probabilities for two or three different durations. Exceptions to this rule will occur only in the case of very short, intense storms with durations of only one or two time periods. In the more usual case, when two or three different durations must be considered, no general rule can be given for selecting the durations to be used. These will be selected arbitrarily by inspection of the hyetographs, in such a way as to include that portion of the storm most significant in formation of the hydrograph peak.

Storm intensities for the selected durations will be taken from the average hyetograph, which means that they will apply to an area rather than a point. On the other hand, rainfall intensity-duration-frequency relations are almost invariably prepared for point rainfall. This apparent inconsistency, however, does not lead to any error as the point rainfalls used in intensity-duration-frequency studies are not, in general, focal intensities, and the probability determined from such a study is the probability of receiving a given intensity at any point in an area rather than at one specific point. While the relationship between the probabilities of areal and point rainfalls is not clearly understood, it would appear that the probability of receiving a certain average intensity over a small area would be close to, if not equal to, the probability of receiving the same intensity at any point on the area. This is because, for storms of a given average intensity on an area, any particular point will experience various intensities, some greater and some less than the average intensity over the area. However, over a long period of time, the experience of the sample point will be representative of the experience of the area.

It has now been indicated that probabilities will be determined for areal average rainfalls for two or three arbitrarily selected durations within each storm period. In the case of catchments for which an intensity-duration-frequency study has already been carried out, determination of the probabilities will be a simple matter. In other cases, it will be necessary to either carry out an intensity-duration-frequency-study, or use a generalized intensity-duration-frequency study such as that of the U. S. Weather Bureau (U. S.W. B., 1961).

It is proposed to adopt the former procedure of carrying out a probability study in those cases where a long-term recording rain gage record of the order of 15 years or more is available. In performing these intensity-duration-frequency studies, the partial duration series will be used rather than the annual series in order to give a correct picture of the frequency of occurrence of the more common intensities. This means that, for any given duration, all intensities greater than some arbitrary minimum will be included in the series for probability analysis, regardless of how many or how few of these occur in any one year. The annual series, on the other hand, uses only the highest intensity in each year regardless of how low it might be. Probability will be computed from the formula $p = m/(n + 1)$ where p = probability, m = rank in order of magnitude, and n = length of record in years. Intensity-probability relations will be determined for a wide range of durations, and the results plotted in the usual form of a family of intensity-duration curves with recurrence interval as a parameter.

Where a long term recording rain gage record is not available, it will be necessary to estimate the probabilities of actual storms from the generalized relations of U. S. Weather Bureau Technical Paper No. 40 (U. S. W. B. 1961) for U.S.A., or similar data for other countries. This publication by U. S. Weather Bureau contains a series of maps of the United States showing isopluvial lines of rainfall depth for various durations and recurrence intervals. To use these maps for the purposes of this project, it will be necessary to take values from several of the maps for the particular location concerned, and plot an intensity-duration-frequency graph to facilitate interpolation of the actual values of duration and intensity.

Use of the generalized maps is an awkward procedure and does not result in highly accurate probability estimates; but, on the other hand, the sampling errors involved in the use of a short record of a station on or near the catchment concerned are also great. There must be a certain minimum length of record where the sampling error from a single record becomes greater than the error from using generalized curves based on long-term records from stations removed from the catchment. It is assumed here that this lower limit is about 10-15 years.

3.4.2 Streamflow. The same principles will be applied in estimating the probabilities of the flood peaks as for the rainfall intensities. Thus, three general approaches are possible, as follows:

(i) If a probability study has already been carried out for the station concerned, this can be used.
(ii) If a record of 15 years or more is available, but no probability study has been made, such an analysis will be carried out as part of this project.
(iii) If neither (i) nor (ii) applies, it is possible that a regional frequency study has been made for the region concerned, and this could be used.

Exceptions to this general plan, however, will almost certainly be necessary in some cases. For instance, if the record is shorter than 15 years and no regional frequency study is available, it may be necessary to analyze the short record by itself, but it should be recognized that the sampling errors for even the more frequent floods can be great in such cases.

Where a probability study is carried out, the partial duration series will be used, probability will be computed from the formula $p = m/(n + 1)$, and a curve will be fitted graphically to the plotted points. It is intended to estimate the probabilities of peak discharges, and possibly, in some cases, of flood volumes for various time intervals.

3.5 Storage and Filing of Rainfall and Streamflow Data.

3.5.1 General. All types of raw, processed, or partially processed data that have been discussed above will be either stored on punched cards and magnetic tape, or will be filed in graphical or tabular form. The dispostion of the various items between these two forms of storage is indicated in Table I.

In tabulating and storing the hydrograph, the first ordinate will invariably be taken at the time of commencement of the average or representative hyetograph, even if this implies several hydrograph ordinates equal to zero. This procedure relates the time scale of the stored hydrograph to that of the stored hyetograph. These time scales will be related to absolute time by noting the date and time of the commencement of the average or representative hyetograph, and storing this information, along with a number indicating the watershed concerned, as identification data for the event.

Along with the information listed in Table I will be stored information about the catchment on which the flood occurred. This catchment information is discussed fully in Section 4 of this report, and consists partly of data that is different for different floods and partly of data that is the same for different floods. The latter type will be repeated in the stored data for all floods on a given catchment so that the stored data for each event is complete in itself as a given separate flood event. This will facilitate analysis of the data and also the incorporation into the system of data for additional floods. This last facility is very important, as it is intended to expand the system from time to time with additional data both from catchments included in the initial scheme and from new catchments both in U. S. A. and in other countries.

3.5.2 Punching of Data. The detailed layout of data on the punched cards is described in Appendix B.

3.5.3 Preparation of Data for Punching. A detailed example of the analysis of raw data necessary to obtain all items of information required is given in Appendix C. This example covers both the rainfall and streamflow data that has been discussed above in Section 3, and the catchment data to be discussed in the following pages in Section 4.

TABLE I

DISPOSITION OF STORED AND FILED DATA

	STORED	FILED
Rainfall Data	-Ordinates of average or representative hyetograph -Time increment of hyetograph -Equiv. uniform depth of rainfall -Overall storm duration -Net duration of supply period -For one, two, or three periods of each storm, the duration, mean rainfall intensity, and their joint probability	-Daily rainfall records -Recording rain gage data (either copies of original charts or tabulated figures) -Isohyetal maps -Hyetographs of individual stations (plotted) -Individual station and average mass curves (if plotted) -Average hyetograph (tabulated) -Intensity-duration-frequency data (if obtained) -Intensity-duration-frequency curves (if plotted)
Streamflow Data	-Ordinates of hydrograph -Time increment of hydrograph -Peak discharge -Probability of peak discharge -Probability of flood volume (for various time intervals)	-Stage hydrograph (copy of original chart, if obtained) -Stage and discharge hydrographs (tab.) -Discharge hydrograph (plotted) -Rating table or curve -Partial duration series of flood peaks (if obtained) -Flood frequency curve (if plotted)

4. CATCHMENT CHARACTERISTICS DURING FLOODS

4.1 Factors to be Evaluated

4.1.1 Levels of Influence on Hydrograph. Literally dozens of catchment characteristics have an influence on the shape and magnitude of flood hydrographs. It is not, however, necessary to develop measures of, nor to evaluate, all of these because:

(a) It is sometimes possible to express the effect of several factors by means of a single index (e.g., the loss rate or ϕ-index expresses the effects of infiltration losses, depression storage losses, interception losses and evaporative losses during a storm);

(b) Most of the factors operate on the hydrograph through their effect on other factors. In other words, there exist various levels of influence, and each factor at each level is influenced by a number of other factors at a level further removed from the hydrograph. If all the factors at a given level are evaluated, then all influences on the hydrograph are covered, and it is not necessary to evaluate other factors at higher or lower levels.

Figure 1 illustrates diagrammatically the levels of influence, and the way in which each factor is affected by a number of others. The particular selection and arrangement of factors affecting the hydrograph in this diagram are not, of course, the only ones possible; the diagram could be varied in many details, since it contains a number of arbitrary features, as listed below:

(i) the hydrograph is viewed as the sum of surface runoff (including channel precipitation) and sub-surface runoff (including groundwater flow and interflow). This division is arbitrary, but is convenient;

(ii) three indices (the ϕ-index or loss rate, an antecedent precipitation index, and season) are used, each representing in a single factor the effects of several other factors. Use of these indices is, of course, an arbitrary convenience;

(iii) the branches of influence could be extended upwards almost indefinitely, but a situation would very soon be reached where hundreds of factors, all far removed from a streamflow hydrograph are involved. (For instance, the factors influencing catchment shape such as rock types, geological structure and age of structure could be listed, and then the factors that determined the particular geological structure could be listed, and so on, but there is no point in listing so many factors, whose influence on the hydrograph is so far removed.) Thus the point at which each branch of the diagram terminates has been arbitrarily selected;

(iv) the branches of influence are not completely independent of each other, as many factors influence more than one other factor. For instance, the types and distribution of vegetal cover influence both the ϕ-index and the surface roughness.

Figure 1 systematizes the factors that can be said to affect the hydrograph, and thus enables a selection of such factors to be made, that covers all lines of influence. For this purpose, those factors shown in Figure 1 as influencing others but not being influenced themselves (that is, the topmost factors in the diagram, such as stream slope and catchment shape) can be called "primary" factors. They are not "primary" in any absolute sense, of course, as explained in (iii) above, but insofar as Figure 1 is concerned, they are the primary or causal factors.

In order to embrace all the factors affecting the hydrograph, it is merely necessary to select a series of factors that includes the influences of all the primary factors. To take an extreme example, if both the sub-surface runoff hydrograph and the surface runoff hydrograph were defined and evaluated, all primary influences would be covered. At the other extreme, all of the primary factors could be evaluated. Numerous other groups of factors between these two extremes could be selected, that would still include all effects of all primary factors.

4.1.2 Selection of Factors to be Evaluated. In selecting a set of factors for evaluation and recording in connection with the study of the relationship between rainfall and streamflow for small watersheds, three criteria were used. These were:

(i) the set selected must be complete in the sense that it includes all effects of all primary factors (as explained in Section 4.1.1 above);

(ii) suitable measures of the characteristics must be available, in the form of numerical measures that can be related to the basic dimensional quantities of length, mass and time; rather than graphical measures, or numerical measures related merely to some arbitrary, dimensionless, numerical scale;

(iii) the measures of the characteristics can be evaluated from readily available data, and without use of the hydrograph. This requirement is necessary as it is intended to use the data to develop methods of hydrograph synthesis for ungaged catchments.

In fact, it did not prove possible to satisfy completely all three criteria, and some compromise was necessary. The factors selected as providing a reasonable compromise are listed in Table II along with the measures of these characteristics that it is proposed to evaluate and store. Considerations that led to this particular selection are given in detail in Section 4.2

4.1.3 Classification of Factors. Various schemes of classification of the factors affecting flood hydrographs are possible, but for the purpose of storing, retrieving, and using flood data for several floods on each of many watersheds, the most convenient classification lists separately:

(i) factors that are constant from storm to storm on a given catchment;

(ii) factors that change from storm to storm on a given catchment.

Characteristics of the storm itself come under category (ii), but the evaluation and storage of these are dealt with in Section 3.2, this section dealing only with catchment characteristics during storms. Measures of the factors that are constant from storm to storm are discussed in Section 4.2 on the following pages, while those that vary from storm to storm are dealt with in Section 4.3

TABLE II

CATCHMENT CHARACTERISTICS DURING FLOODS

A. Characteristics Constant from Flood to Flood

Characteristic	Measure		
	Symbol	Units[1]	For Definition, see section
Catchment Area	A	sq. m.	4.2.1
Channel Storage	K	------	4.2.2
Drainage Density	D_d	m./sq.m.	4.2.3
Shape	L	miles	4.2.4
	W	miles	4.2.4
	F	------	4.2.4
	C	------	4.2.4
	L_c[2]	miles	4.2.4
	L_m	------	4.2.4
	s_d	------	4.2.4
Stream Slope	S_1	ft/mile	4.2.5
	S_2	ft/mile	4.2.5
	S_3	ft/mile	4.2.5
	S_4	ft/mile	4.2.5
Overland Slope	R_1	ft/mile	4.2.6
	R_2	ft/mile	4.2.6
	R_3	ft/mile	4.2.6
	R_4	ft/mile	4.2.6
	R_5	ft/mile	4.2.6
	R_6	ft/mile	4.2.6

[1] 1 mile = 1.609 km.
1 sq. m. = 2.59 sq. km.
1 m./sq. m. = 0.621 km./sq. km.
1 ft./mile = 0.189 m./km.

[2] Usually called L_{ca}

B. Characteristics that Vary from Flood to Flood

Characteristic	Measure		
	Symbol	Units[1]	For Definition, see Section
Antecedent Wetness	P_a[2]	in.	4.3.1
	Q_i	c.f.s.	4.3.1
Season	I_s	------	4.3.2
Standard Infiltration Capacity	f_s	in./hr.	4.3.3
Interception Capacity	I	in.	4.3.4
Initial Loss	L_i	in.	4.3.5
Loss Rate	ϕ	in./hr.	4.3.5

[1] 1 in. = 25.4 mm.
1 c.f.s. = 0.0283 cu.m./sec.
1 in./hr. = 25.4 mm./hr.

[2] Usually called API

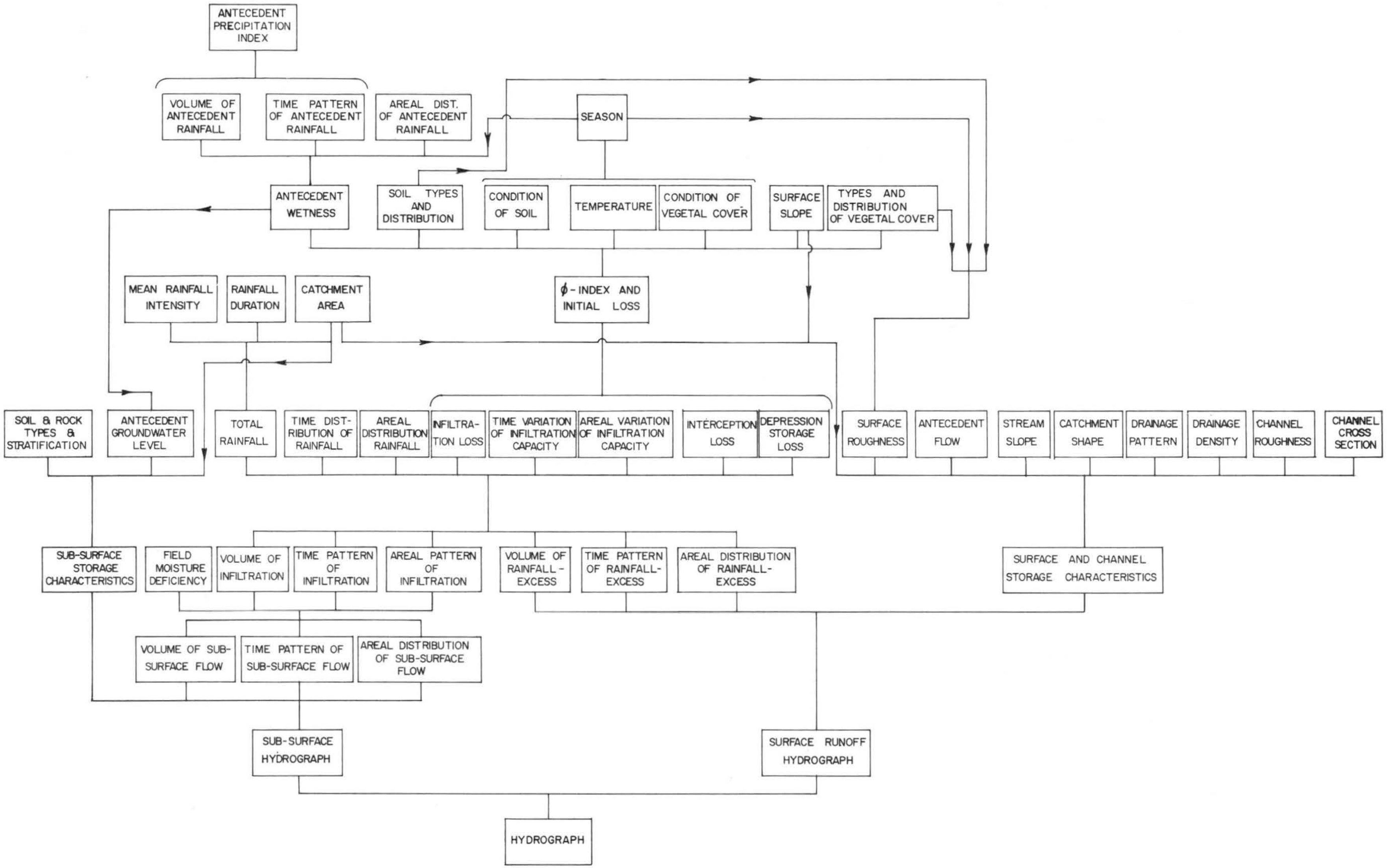

Figure 1. Factors influencing hydrograph

The constant catchment factors may be easily changed or added to later during a research program, by recomputing or redefining them, and by writing a program to add them to the cards or magnetic tapes.

4.2 Measures of Constant Catchment Characteristics

4.2.1 Catchment Area. This factor clearly has an important effect on the hydrograph. It will be expressed in square miles.

4.2.2 Channel Cross Section and Roughness. These factors affect the storage delay time of channel storage. Storage delay time ($K = dS/dQ$) is a measure of how much the storage (S) in the channel system increases for a unit increase in discharge (Q). It thus depends on velocity of flow since, with a high velocity, water entering the channels is quickly removed, rather than remaining in temporary storage, and vice versa. Thus a high velocity implies a low storage delay time and a low velocity a high delay time. Flow velocity in turn depends upon roughness, slope and hydraulic radius. Measures of channel slope are dealt with in Section 4.2.5, while here we are concerned with the effects of roughness and hydraulic radius.

It is, of course, possible to define measures of roughness and hydraulic radius at a particular cross section of a stream, but these factors are so extremely variable from point to point along a stream that it is extremely difficult to obtain measures of them that are representative of the whole stream system. Consideration has been given to using the Manning roughness coefficient and the hydraulic radius at bankfull stage at the outlets as indices of these characteristics for the whole stream system, but it is extremely doubtful whether the accuracy and reliability of these measures for their intended purpose justifies their determination.

Consequently, it has been decided not to use these measures, but to use a more direct indication of channel storage characteristics determined from the hydrograph, in the hope that it might be correlated later with directly measureable characteristics. The measure to be used is the average hourly depletion ratio of the upper parts of the hydrograph recession curves. This will be determined by graphically fitting an equation of the form --

$$Q_t = Q_o K^t$$

where Q_t and Q_o are discharges at time t and an arbitrary zero time respectively, t is time in hours, and K is the hourly depletion ratio, to the upper part of each available recession curve. Fitting will be done by plotting the recessions on semi-logarthmic paper (discharge to log. scale and time to linear scale), and fitting a straight line by eye to the points representing the upper part of the recession. The hourly depletion ratios so determined from all available hydrographs will then be averaged. The upper part of the recession is specified since this is more representative of the channel storage as distinct from the sub-surface storage, and the value of depletion ratio normally increases toward the lower part of the recession.

4.2.3 Drainage Density. In computing the drainage density (D_d), it is proposed to measure all streams either marked on the map or clearly defined by the contours. Further, all streams will be measured to the boundary of the catchment, not merely to the end of the line drawn on the map, since this point is determined quite arbitrarily by the cartographer.

4.2.4 Effective Shape. This term is used to imply the combined effect of the shape of the catchment and the configuration of the drainage net. The only available measures of effective shape are graphical measures (such as the area-shape curve), but since numerical measures are required, it is intended to use two measurable characteristics of a graphical measure to indicate effective shape. These measures are discussed below.

In addition to measures of effective shape, a number of factors indicative of catchment shape alone (and independent or nearly independent of drainage net configuration) are available. Since one of the purposes of this and future projects is to assess the usefulness of various measures of catchment characteristics, these other factors will also be determined and stored in the system. All of the measures of shape and effective shape to be determined are listed below.

(i) Average Width of Catchment (W). This is obtained by dividing catchment area (A) by the length of the main stream measured from the outlet to the catchment boundary (L), and will be expressed in miles. Considered in conjunction with L or A, it is a measure of catchment shape. The length of the main stream (L) will, therefore, be stored. The "main stream" at any confluence is defined as that draining the greatest area.

(ii) Form Factor (F). Ratio of average width to length of main stream (measured to the catchment boundary), $F = W/L = A/L^2$.

(iii) Compactness Coefficient (C). This is the ratio of the perimeter of the catchment (P) to the circumference of a circle having the same area (A). Thus, $C = 0.28\ P/A^{1/2}$.

(iv) Length to Center of Area (L_c). The original definition will be used here, namely, the length along the main stream from the outlet to a point adjacent to the center of area of the catchment. Considered in conjunction with L or A, this also is a measure of catchment shape, which, however, depends slightly upon drainage net configuration.

(v) Characteristics of the Area-Shape Curve. The area-shape curve (a plot of width of catchment against distance from outlet) and its integral, the area-distance curve (plot of area within a given flow distance of outlet against that distance) do reflect the drainage net configuration as well as the shape of the catchment boundary. Since both of these diagrams present the same information, further consideration can be restricted to one of them only, the area-shape curve.

While this curve does include the effects of drainage net configuration, it does not include the effects of slope variations from point to point of the drainage net. These variations affect the travel time from any point to the outlet (defined as the time between the occurrence of an element of rainfall-excess at the point and the center of mass of the resulting surface runoff at the outlet), since travel time through any reach is inversely proportional to the square root of stream slope in that reach. Thus, by dividing all reach lengths by the square root of the slope, a "modified area-shape curve" can be obtained, that includes the effects of catchment shape, drainage net configuration, and stream slope variations.

It should be noted, however, that the modified area-shape curve does not include the effects of variations in hydraulic radius on velocity of flow and travel time. In the majority of cases these effects would tend to compensate for those of slope variations, but no information is available as to the strength of this tendency or as to how often it exists. Until information of this kind becomes available, or a convenient method of allowing for hydraulic radius variations is developed, it is not possible to express a preference for either the modified or the unmodified area-shape curve, and it is probably as well to use the more easily derived unmodified curve.

Various methods have been proposed for determination of the area-shape curve. One is to mark on a map of the catchment isopleths of travel distance from the outlet in the form of a bar chart, whose ordinates could, if desired, be converted to width, and smoothed. A second procedure is to divide the catchment into sub-areas bounded by watershed lines, determine the length, average width, and distance from outlet of each sub-area, and then to sum the sub-area widths at various distances from the outlet and plot these data. A third possible method is an extension of the grid method recommended by Busby and Benson (1960) for determination of Σal and L_c (redefined by them as the mean travel distance for the catchment). If travel distance was sampled at the intersection points of a square grid placed on a map of the catchment, and the frequency distribution of the sample plotted with ordinates of the distribution multiplied by the area of one square of the grid, an area-shape curve would result.

If it is desired to avoid the use of graphical measures of catchment characteristics, it would be necessary to express the area-shape curve by means of numerical parameters. This could be done conveniently and adequately by use of the mean and coefficient of variation of the distribution of travel distance determined from a grid sample. Finally, as it is desirable to have a measure of effective shape that is independent of other factors, it is considered that the mean travel distance should be expressed dimensionlessly as a ratio of the mean travel distance to the square root of catchment area A .

Thus it is proposed to use two measures of effective shape, L_m , the mean travel distance divided by square root of catchment area, and s_d, the standard deviation of the dimensionless area-shape curve, both determined from a sample obtained by measuring travel distance to the outlet from each intersection of a square grid placed on a map of the catchment.

4.2.5 Stream Slope. It seems appropriate, as is usual, to consider the main stream only, not giving any specific consideration to tributary streams. In general, the slope of the main stream varies throughout its length, and it is desirable to develop a single measure of slope that is representative of the whole stream. Several such measures have been proposed in the literature. Some will be used here.

Firstly, a slope equal to the total fall over the total length of the main stream (S_1) has been used, but this has little to commend it, as short lengths of stream with high slopes have an effect on the average slope value out of all proportion to their effect on travel times. In an effort to overcome this defect, a second method uses a longitudinal profile of the main stream and gives a slope (S_2) such that a straight line drawn from the outlet on the longitudinal profile of the main stream at a slope S_2 has the same average elevation as the actual stream profile. This procedure is effective if the steep slopes occur at the upstream end of the stream, but not if they occur at the lower end, in the middle reaches, or at both ends.

Since the main significance of slope variations is the effect they have on travel time, the most useful slope measure is the uniform slope that would result in the same overall travel time as the actual stream, all other channel characteristics such as length, roughness, and hydraulic radius being unchanged. If it is assumed that the combined effects of roughness and hydraulic radius are constant over the whole length of the main stream, such an equivalent uniform slope can be obtained by dividing the main stream into a number of reaches, and computing

$$S_3 = \left[\frac{\Sigma\, l_i}{\Sigma(l_i / s_i^{1/2})}\right]^2$$

where l_i and s_i are the length and slope respectively, of any reach i .

A final slope measure that has been proposed by Benson (1959) is the overall slope of the central portion of the main stream (S_4) excluding the upper 15% and the lower 10% of its length. It would appear that the effectiveness of this measure, depending as it does on the particular stream profile, would vary largely from stream to stream.

It is considered that the equivalent uniform slope of the main stream (S_3) described above is a logical and useful single measure of stream slope, but in accordance with the principle of determining and storing a variety of measures of a single catchment characteristic in order to determine the most useful measure, it is intended to compute S_1, S_2, S_3, and S_4 as defined above for each of the catchments used in the study.

4.2.6 Overland Slope. As with stream slope, it is desirable to obtain a single overland slope value that is representative of the effects of the overland slopes on the hydrograph. This problem is more difficult though, as surface slope varies in two dimensions whereas stream slope varies in only one. As a consequence, the several methods that have been proposed for determining a representative overland or surface slope are concerned with an areal averaging procedure and ignore the question of slope variations on travel time. The various overland slope measures that have been proposed in the literature are discussed below.

$$\text{(i)}\, R_1 = \frac{hL_t}{A}$$

where R_1 = average overland slope, h = contour interval, L_t = total length of contours on a map of the catchment, and A = catchment area, all in appropriate units. While this formula undoubtedly gives a good measure of average overland slope, considerable labor is involved in measuring the lengths of many contours, and equally good measures involving less work are available.

$$\text{(ii) } R_2 = \frac{1.57\ h.N}{L}$$

where a square grid is placed on a contour map of the catchment, and N = the number of intersections of contour lines with grid lines, h = contour interval, and L_g = total length of grid lines within the catchment. This measure should approximate very closely to the true average overland slope and is more easily determined than any other measure that provides equivalent accuracy. It is proposed to use this measure in the data storage project.

(iii) Mean overland slope can be determined by measuring areas between adjacent contours and dividing this by the average length of the two adjacent contours to determine the average width of the strip. The contour interval divided by this average width gives the mean slope of the strip. Slopes determined for all such strips on the catchment can then be weighted according to area to give the average overland slope (R_3) for the catchment. A great amount of work is involved in this procedure, and it is not justified merely to obtain an estimate of average overland slope.

(iv) Mean (R_4) or median (R_5) slope can be determined by point sampling of slope at the intersections of a square grid placed on a map of the catchment or at points having coordinates drawn from a table of random numbers. The grid sampling method is attractive, but involves more work than the method described in (ii) above.

(v) The relief ratio (R_6) due to Schumm is defined as the ratio of total basin relief to basin length measured as the longest dimension of the basin. This is an index of overland slope, but it is considered that it would not satisfactorily reflect the true average slope.

(vi) The hypsometric curve also gives an indication of overland slopes, but some of the measures described above give a more direct indication than the curve or any parameters of the curve. Consideration of all the above measures of overland slope leads to the conclusion that method (ii) is probably the most satisfactory as it gives a good estimate of mean slope with a not unreasonable amount of work. Nevertheless, as with other catchment characteristics, all available measures R_1, R_2, --- R_6, will be determined and stored.

4.2.7 Surface Roughness. This factor affects the delay time of detention storage, but there is not, at the present time, any suitable measure of its effect, either directly or as measures of the factors that influence surface roughness. The nearest approach to a suitable measure would be Izzard's retardance coefficient C (See Linsley, Kohler, and Paulhus, 1949, p, 277), but values of this coefficient have been determined for only two types of grassed surface and these were on artificially plane surfaces. Consequently, there is barely sufficient information available to evaluate a surface roughness measure, and it is necessary and not justified to ignore the effect of this factor.

4.3 Measures of Variable Catchment Characteristics.

4.3.1 Antecedent Wetness. The two commonly used indices of antecedent wetness are the antecedent precipitation index (P_a) and the low flow discharge in the stream at the commencement of the rise (Q_i). The former index would be expected to reflect well the effects of rainfall that occurred only a short time before the storm, while the latter would be better reflect occurrences a considerable time before the storm, being little affected by recent events. Furthermore, it is expected that, with the small catchments being dealt with in this project, the low flow preceding the rise will frequently be zero, and thus be insensitive to the actual state of antecedent wetness. Nevertheless, both indices have obvious advantages over the other, and it is intended to determine both for all flood events. The antecedent precipitation index will be computed from the formula

$$P_a = \sum_{i=1}^{30} P_i\, 0.85^{t_i}$$

where P_a is the antecedent precipitation index, and P_i is the precipitation in inches recorded t_i days before the storm. Because of the disadvantages of the above indices of antecedent wetness, attempts have been made to develop indices based on the water balance. In particular, Chapman (1963), estimated the field moisture deficiency (which he referred to also as a catchment dryness index), and found this to be a more efficient index of catchment wetness or dryness than antecedent precipitation index for determining storm rainfall. Indices such as this will probably prove to be the most useful in the long run as they are directly related to the amount of moisture on the catchment at the time of interest, not at some time previously as are the other indices discussed. For the present project, however, the water balance method has a disadvantage in that considerable work is involved in developing an empirical relationship between soil moisture deficiency and potential evapotranspiration. Since a very large number of catchments will be involved in this project, it is not at present proposed to determine a water balance-type index of antecedent wetness, but this may prove desirable at a later date.

4.3.2 Season. Season or time of year is an index of the condition of soil and vegetal cover and of temperature. It has an influence on loss rate, antecedent wetness, field moisture deficiency, antecedent flow, and surface roughness of the catchment. All of these seasonal influences tend to result in lower discharges in summer than in winter, other things being equal. It thus seems likely that a suitable index of season would have low values for midsummer and high values for midwinter, possibly with a kind of sine curve variation in between. For instance, the index could be given a value of zero in July and unity in January (in the northern hemisphere), and calculated from the formula

$$I_s = \frac{\sin\frac{(M-10)\pi}{6} + 1}{2}$$

where M is the number of the month in which the storm occurs. The scale of this index could be more finely divided by using the week or the day instead of the month of the year. However, it is considered that the precision of the index as a measure of the effects of season is not sufficiently great to justify this. For this reason, and since use of the month number is simpler, it is proposed to use the formula on the previous page for computation of the seasonal index.

For catchments in the southern hemisphere, the constant 10 in the equation must be replaced by 4 to give an index of zero in midsummer and unity in midwinter.

It is realized that this formula will give only a very approximate index of the many indirect effects of season, and it will be used with caution until its value can be assessed. However, the effects of season are so varied, and the data on many of these effects is so scarce, that it is desirable to have some simple numerical index of these effects such as is given by the above formula.

4.3.3 Standard Infiltration Capacity. This factor is introduced as an index of the effects of soil types and vegetal cover on infiltration capacity. The other factors that affect initial loss and infiltration capacity, namely antecedent wetness, surface slope, interception, and the factors of which season is an index, are dealt with elsewhere. Standard infiltration capacity is the infiltration capacity of a given soil and cover combination under certain specified or standardized conditions. A suitable means of determining such an index is provided in the Hydrology Handbook of the American Society of Civil Engineers (1949). This gives values of f_1, the infiltration capacity of bare soil after one hour of continuous rainfall with specified antecedent conditions for various types of soil. Also, cover factors applicable to different classes of vegetal cover are given. Multiplication of f_1 by the cover factor gives a standard infiltration capacity that reflects the influences of soil and cover types only. It should be noted, however, that a wide range of values for this index can be determined by different persons from the same data, so the index must be regarded as very approximate, and used with caution. However, no better and readily determined index of the effects of soil types and vegetal cover on infiltration capacity is known to the authors.

4.3.4 Interception Loss. The loss of water by interception during a storm can be regarded as consisting of two parts, the initial interception capacity of the vegetation, and the continuous evaporative loss from the vegetation throughout the storm. The former component depends on the nature and condition of the vegetation, and the latter on these factors together with storm duration and the climatic factors that determine evaporation. Little data is available to assist in the estimation of interception loss for a storm, but if the nature and condition of the vegetation, and the amount of rainfall is known, the data given by Linsley, Kohler, and Paulhus (1949, p. 268) can be used to give a rough estimate. In estimating interception loss, it should be remembered that both primary and secondary interception must be considered. It should be remembered also that antecedent wetness affects the availability of initial interception capacity, and this capacity should not be counted as loss if it has been filled by recent antecedent precipitation.

As with the seasonal index and standard infiltration capacity, the interception loss estimate is very approximate, and must be used with caution.

4.3.5 Initial Loss and Loss Rate. The set of catchment characteristics discussed above satisfies the requirements outlined in Section 4.1 that all effects of all primary characteristics should be covered. Consequently, initial loss and loss rate are not essential to the study of the relationship between hydrographs and their causative factors. Nevertheless they are included here for the following reasons:

(i) they have to be derived to determine the net supply period, one of the factors included in the above set. (Note that in a design problem, net supply period would have to be estimated from the initial storm duration as loss rate would not be known).

(ii) the factors included in the above set that determine losses may not provide an adequate explanation of the effect of losses on the hydrograph. If this proves to be the case, the initial loss and loss rate could be used in place of those factors with more likelihood of success since the relationship between losses and the hydrograph is much less complex than that between the factors influencing losses and the hydrograph.

4.4 Neglected Characteristics

Careful comparison of the factors listed in Table I and discussed in Sections 4.2 and 4.3 above with Figure 1 will reveal that some of the primary factors of Figure 1 have been neglected. These factors are:

(i) Surface roughness. Neglected because there is no adequate measure of it as explained in Section 4.2.

(ii) Areal distribution of antecedent rainfall. Neglected because it has, in all probability, a very small effect, and computing a suitable measure of it would involve a disproportionate amount of work.

(iii) Temporal and areal variations of infiltration capacity. Neglected because there is no practicable way of evaluating measures of these characteristics. Their effect is probably small in any case.

(iv) Depression storage loss has not been mentioned specifically, but it is intended that surface slope and antecedent precipitation index be used as indicators of this factor.

(v) Storm factors, although not dealt with in this section, have been considered in Section 3.2.

In view of the above explanations of neglected or apparently neglected characteristics, it is considered that the set of catchment characteristics selected satisfies the three criteria stated in Section 4.1 as well as possible, though not perfectly. Those criteria were, briefly, that all effects of all primary factors should be covered, that suitable measures of the characteristics should be available, and that the measures could be evaluated without use of the flood hydrograph.

In any case, it is not intended that the list of measures of catchment characteristics developed above should be inflexible and exhaustive. Provision has been made in the allocation of storage space for the inclusion of a large number of additional factors that may be determined in the future.

5. INDEXING AND RETRIEVAL OF DATA

5.1 Purpose of Index

As an unusually large volume of data is to be collected, processed, and stored in this project, it is necessary that a systematic index of the data available be maintained. This index must serve the triple purpose of:

(i) providing a convenient and accessible listing of the pertinent characteristics of the watersheds and flood events in the system.
(ii) providing a convenient means of identifying all events having certain specified characteristics, and
(iii) providing references to the location of particular information in the set of punched cards, the magnetic tape or tapes, and the folders of filed graphical and tabular material.

A listing of pertinent characteristics of the flood events is necessary, as these data cannot conveniently be read from punched cards or magnetic tape, and they will be surrounded by a mass of detail in the filed data. A concise outline of each event is therefore necessary to facilitate decisions about the suitability of any particular event for any given purpose.

Furthermore, it is desirable in the preliminary stages of many investigations to be able to select all events having certain characteristics and to reject all others. For instance, all events within a certain geographical region might be required, or all events on catchments within a certain size range, and so on.

It will often be desired to perform this discrimination without the use of electronic equipment, which may not be immediately available. This purpose can conveniently be served by the use of a "Keysort" card which is a simple index card, available in standard sizes, but which has a series of small holes punched around the margin of the card. By the use of a code and by punching out the edges of selected holes (converting them from holes to slots), cards can be prepared for discrimination on the basis of several different characteristics.

Finally, of course, the index of data in the system must serve the main purpose of any index, by providing a reference to the location of the detailed information that is indexed. This is necessary to facilitate retrieval of the data required for any particular purpose. As explained earlier, the detailed information on any flood event will be in three locations, the set of punched cards, the magnetic tapes, and the set of folders containing unprocessed and partially processed data.

5.2 Form of Index

5.2.1 General As explained above, the uses of the index make it desirable to use a "Keysort"-type card filing system in which information can be not only written on the card, but also coded and punched around the edges of the card. Only data that will frequently be the basis of selection (such as catchment area) will be punched, however, the major part of the information being simply written on the cards.

Three separate indexes will be formed as follows:

(i) Index of sources of data
(ii) Index of watersheds for which data are available
(iii) Index of flood events for which data are available.

Details of these are given in Sections 5.2.2 to 5.2.4 below.

It was pointed out in Section 3.5, that flood data stored on the punched cards and magnetic tape would not be segregated on the basis of watershed, but that each event would be complete in itself, containing all necessary watershed characteristics. This was to facilitate machine analysis and also expansion of the system of data. However, in the case of filed data and the "Keysort" card index, there are advantages in a watershed index separate from the flood event index. This arrangement will eliminate much repetition in entering data on the index cards, simplify the actual process of discrimination on the basis of watershed characteristics, and cause no problem in the incorporation of additional floods into the system.

Consistent with this arrangement of the index, individual flood events will be identified by assigning one two-digit number to each major river basin, a second to each watershed within the basin, and a third to each flood on the watershed. Thus, a combined serial number such as 012706 indicates Flood No. 6 from Watershed No. 27 in River Basin No. 1.

5.2.2 Data Source Index. This will consist of a set of 3 inch by 5 inch "Keysort" cards on which will be typed the names and addresses of all federal, state, and private agencies, and their various divisions, districts, experiment stations, etc., that have furnished or might be able to furnish hydrologic data of the types required for the project. It is not expected that this index will be very large, at least in the early stages of the project, and, consequently, these cards will initially be filed alphabetically by name of agency. If and when this index grows to a size where this system is inconvenient, use will be made of the "Keysort" holes to indicate (in some code to be developed):

(i) geographical location,
(ii) type of data available,
(iii) type of private or public agency,
(iv) initial letter of the name of the agency.

5.2.3 Watershed Index. Five inch by eight inch "Keysort" cards will be used for this index, with one card for each watershed.

Punched Data. Two items of data will be punched on the edges of the card; namely, geographical location and order of magnitude of watershed area.

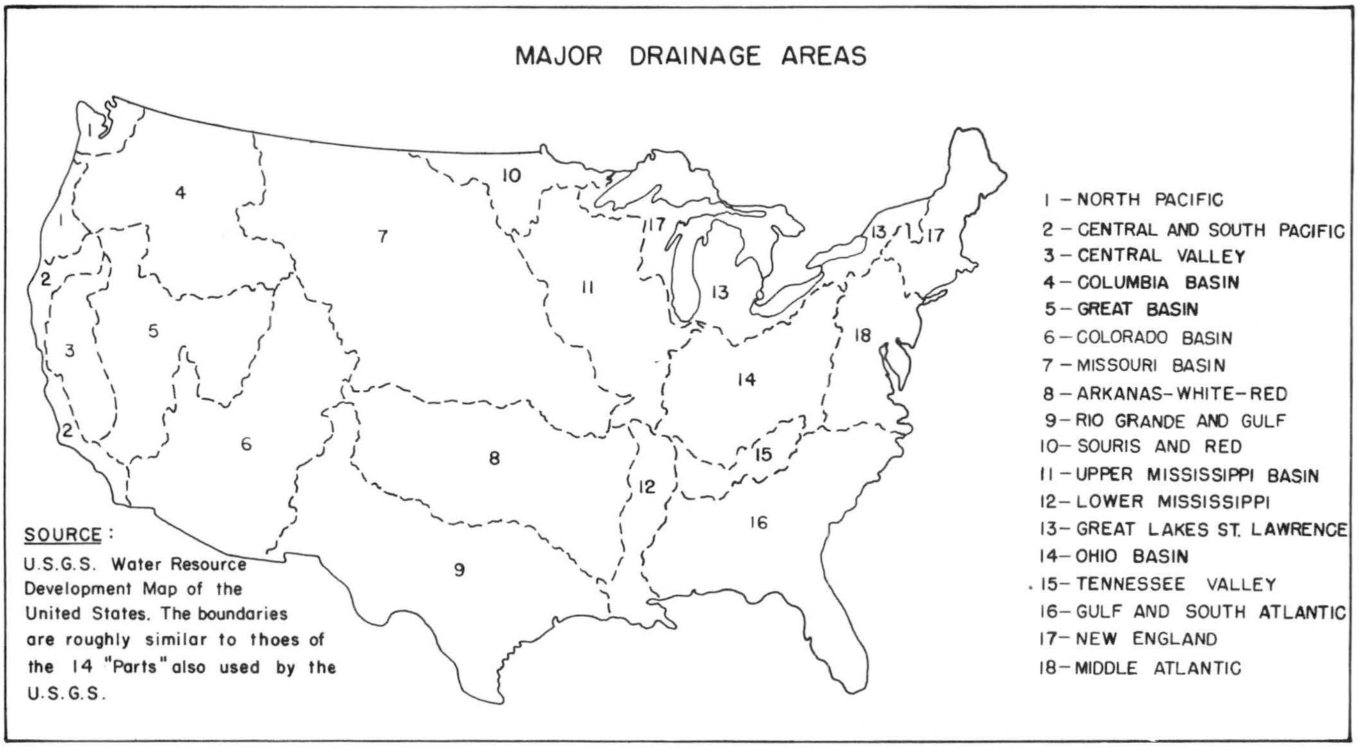

Fig. 2. Major Drainage Areas of the Contiguous United States.

(i) Geographical location will be indicated by the main river basin in which the catchment is situated. Division of the United States into main river basins, and the code numbers that have been assigned to these basins is indicated in Figure 2. (Further code numbers will be added later for areas outside the contiguous United States). The units digit of the code number will be punched in holes 1 to 4 of the "Keysort" card, and the tens digit in holes 5 to 8.

(ii) Order of size will be indicated in holes 9 to 12 of the card as follows; where A = catchment area in square miles.

For $A < 0.1$, punch hole 9,
For $0.1 < A \le 1$, punch hole 10,
For $1 < A \le 10$, punch hole 11,
For $10 < A$, punch hole 12.

Listed Data. The following information will be listed on the card:

(i) Name of watershed.
(ii) Serial number of watershed.
(iii) Reference to filed data on watershed.
(iv) Catchment area in square miles.
(v) Name of main river basin in which watershed is situated.
(v) Name and index number of U.S.G.S quadrangle map on which outlet of catchment is located, and map reference to the catchment outlet.
(viii) Number of flood events for which data are stored (subject to change).
(ix) Source(s) of rainfall data for watershed.
(x) Source(s) of streamflow data for watershed.
(xi) All factors listed in Part A of Table II (See Section 4).

A facsimile of a typical watershed index card is shown as Figure 3.

5.2.4 Flood Event Index. Again, five inch by eight inch "Keysort" cards will be used, with one card for each flood event.

Punched Data. Information to be coded and punched around the edges of the card is as follows:

(i) Serial No. of watershed and river basin. The two digits of the watershed No. in holes 1-4 and 5-8, and the two digits of the River Basin No. in holes 9-12 and 13-16.

(ii) Order of magnitude of peak discharge, Q in c.f.s.
For $Q < 10$, punch hole 17,
For $10 < Q \le 100$, punch hole 18,
For $100 < Q < 1000$, punch hole 19,
For $1000 < Q$, punch hole 20.

(iii) Order of magnitude of peak discharge $q = Q/A$ in c.f.s./sq. mile.
For $q < 50$, punch hole 21,
For $50 < q \le 150$, punch hole 22,
For $150 < q \le 500$, punch hole 23,
For $500 < q$, punch hole 24,

(iv) Order of magnitude of total storm rainfall averaged over the watershed, P_a in inches inches.
For $P_a \le 1$, punch hole 25,

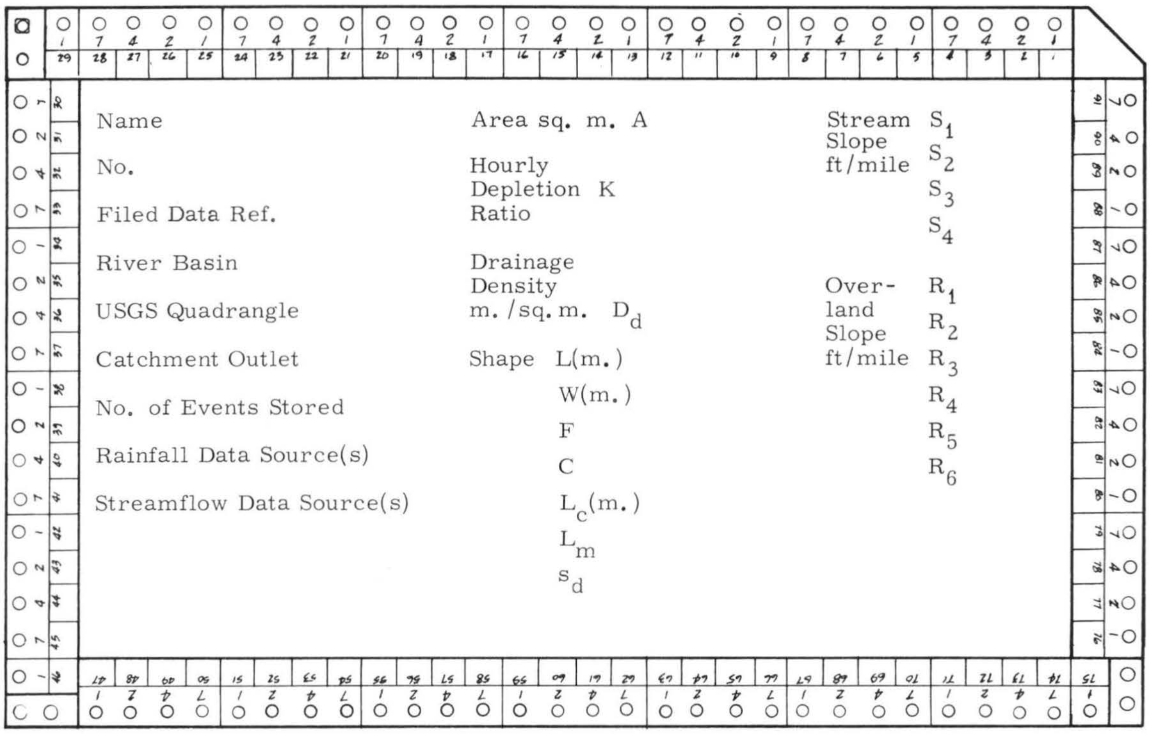

Fig. 3. Facsimile of Watershed Index Card

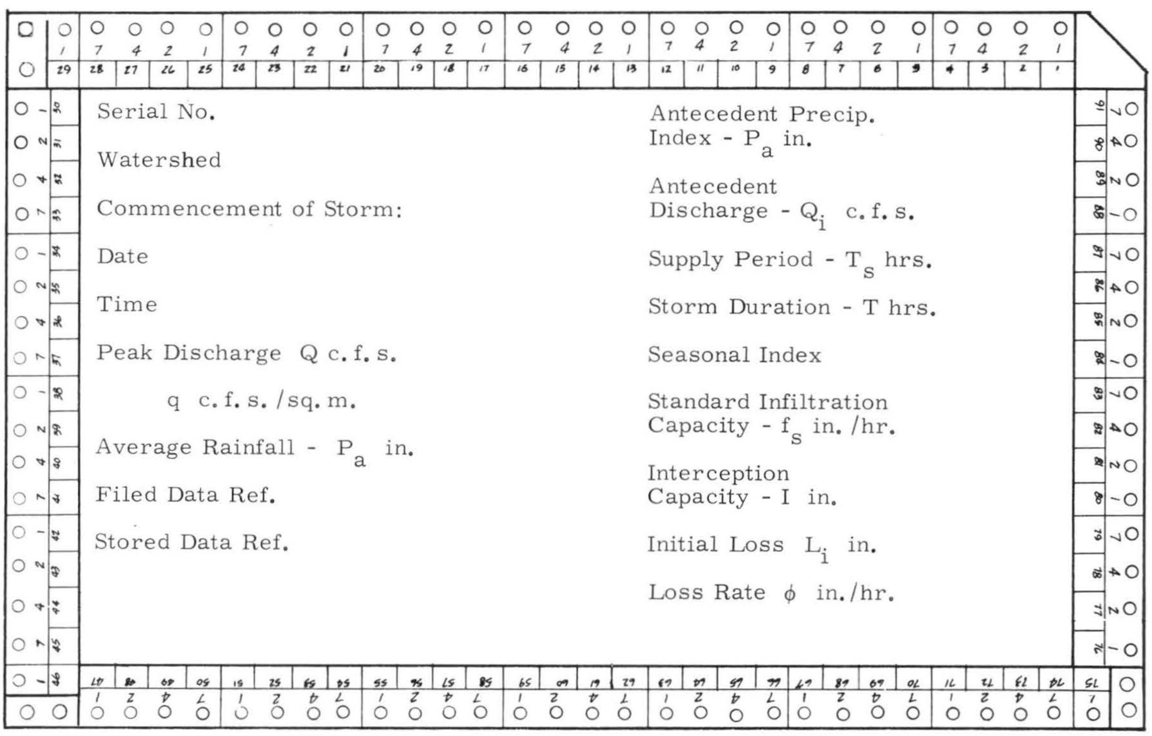

Fig. 4. Facsimile of Flood Event Index Card

For $1 < P_a \leq 2$, punch hole 26,
For $2 < P_a \leq 4$, punch hole 27,
For $4 < P_a$, punch hole 28.

(v) Storm duration, measured as the overall duration of rainfall directly associated with the hydrograph stored, including the period of initial loss and the period of residual rain, if any. This will be the period chosen for preparation of the isohyetal map, when such a map is drawn. If storm duration is given the symbol T, in hours,
For $T \leq 2$, punch hole 29,
For $2 < T \leq 6$, punch hole 30,
For $6 < T \leq 24$, punch hole 31,
For $24 < T$, punch hole 32.

Listed Data. The following information will be listed on the card:

(i) Serial number of flood event (including watershed number, e.g. 012706
(ii) Name of watershed,
(iii) Date and time of commencement of storm,
(iv) Peak discharge in c.f.s. (Q),
(v) Peak discharge in c.f.s./sq. mile (q),
(vi) Total storm rainfall averaged over the watershed in inches (P_a),
(vii) Storm duration as defined above, in hours (T),
(viii) Reference to filed data on storm and flood,
(ix) Reference to stored data in punched cards and on magnetic tape,
(x) All factors listed in Part B of Table II. (See Section 4).

A facsimile of a typical flood event index card is shown as Figure 4.

6. POTENTIAL USES OF DATA

The stored data will provide material for a very wide range of research projects within the field of flood estimation for small watersheds. However, the data unit is not designed for investigations of monthly or annual rainfall-runoff relations. As an indication of the potential uses of the data, several specific research topics are discussed below.

(i) Parametric representation of storm rainfall on a catchment. Present methods of indicating storm rainfall on a catchment by a series of hyetographs for different points are clumsy. Considerable advantage would be gained if the storm could be represented by a few simple parameters or coefficients defining some mathematical function that fits the actual rainfall distribution in time and space.

(ii) Parametric representation of hydrographs. This would similarly facilitate the handling of flood hydrographs, by eliminating the need for listing a large number of ordinates. It would be necessary to fit some mathematical expression or expressions that are completely defined by relatively few parameters to actual hydrographs.

(iii) Relation between storm probability and flood probability. This is one of the important but unsolved problems in flood hydrology today.

(iv) Determination of the best and most useful measures of various catchment characteristics. Many different methods have been proposed for expressing such factors as catchment shape and stream slope. Investigations using the data of this project could indicate which measures best describe the characteristics they purport to measure, insofar as their effects on floods are concerned.

(v) Determination of the way in which various factors affect the hydrograph. In an investigation such as this, the way in which peak discharge and other parameters of the hydrograph vary with changes in such things as average overland slope, average rainfall intensity etc. would be determined.

(vi) Study of catchment storage characteristics. The delay time of catchment storage and its dependence on discharge and other factors, and the different effects on floods of surface and subsurface storage could be studied.

(vii) Development of hydrographs from rainfall and catchment data. This is an all-embracing aim, and the end to which all the other projects is directed. When this end is satisfactorily achieved, practical methods of flood estimation for ungaged catchments will be available, if data on rainfall and the catchment are available or can be obtained.

The above list of potential uses of the stored data is not by any means exhaustive; it merely indicates the lines along which the overall research program into flood estimation for small watersheds is proceeding at Colorado State University. Many other research projects in this field that would be facilitated by the availability of the data unit described in this report exist, and will suggest themselves to the reader.

7. CONCLUSION

7.1 Review

Lack of adequate data in a readily usable form has frequently been a limiting factor in the development and testing of theories of hydrologic processes. The collection, partial analysis, and storage on punched cards and magnetic tape of an unusually large amount of data as described in this report will greatly eliminate this difficulty insofar as flood estimation for small watersheds is concerned. Indeed, it is hoped that this advance, coupled with theoretical analysis supported by studies on physical research facilities, will lead to the development of new and reliable procedures for obtaining flood hydrographs from a knowledge of the rainfall and catchment factors that cause them.

As a very large amount of data will be involved in this project (about 1500 storm-flood events), it is essential that the procedures for selection, processing, storage, and retrieval of data be clearly specified and efficiently implemented. Specification of these procedures has been the major aim of this report, data selection being dealt with in Section 2, processing and storage in Section 3 and 4, and provision for data retrieval in Section 5. To facilitate the use of these specifications in carrying out the project, the main features of all procedures are summarized in Section 7.2, together with references to earlier sections of this report, which must be referred to for greater detail.

Although the proposed data collection and storage system is primarily designed for a research project being carried out at Colorado State University, the data will nevertheless be in a generally useful form, and will be available to other organizations and for other research projects. An indication of the potential uses of the data for projects other than the one being conducted at Colorado State University is given in Section 6 above.

7.2 Summary of Data-Handling Procedures

The following tabulations outline the whole of the procedures proposed in connection with the collection, processing, storage, and retrieval of rainfall, streamflow, and catchment data.

A. Criteria for Selection of Data

Criterion	Ref. Section
Complete information on rainfall, streamflow, catchment	2.2
Watershed area not greater than about 40 sq. m. (about 100 sq. km.)	2.3
Watershed must have natural channel	2.3
Watershed must be predominantly rural, not urban	2.3
Streamflow results from rainfall only	2.4
Average frequency of peak discharge less than once in one year, or	
Peak discharge not less than 15-25 c.f.s./sq. m.	2.5
Runoff occurred from whole of catchment	2.6

B. Processing of Rainfall and Streamflow Data

Process	Ref. Section
Correct both recording and non-recording precipitation gage data if necessary	3.2.2
Plot hyetographs for all recording gages	3.2.3
Prepare isohyetal map	3.2.4
Prepare average or representative hyetograph for catchment	3.2.5
Correct stream stage record if necessary	3.3
Tabulate stage and discharge	3.3
Plot hydrograph	3.3
Determine discharges at regular time intervals from hydrograph	3.3
Estimate rainfall intensity probabilities for 2 or 3 durations	3.4.1
Estimate probability of peak discharge	3.4.2

C. Storage of Rainfall and Streamflow Data

Refer to Section 3.5 for details.
Store on punched cards and magnetic tape--
(i) Average hyetograph, time increment of hyetograph, total average rainfall, probability, mean intensity and duration for one, two, or three periods during storm, duration of supply period, and overall storm duration.
(ii) Ordinates, time increment, and peak discharge of hydrograph. Probability of peak discharge.

File for convenient future reference:--
(i) Copies of recording and non-recording rain gage data, isohyetal maps, individual station hyetographs and mass curves (if plotted), average hyetograph, intensity-duration-frequency data and curves (if obtained).
(ii) Copy of original stage record, tabulated stage and discharge hydrographs, plotted discharge hydrograph, rating table, partial duration series of flood peaks and flood frequency curve (if obtained).

D. Catchment Characteristics during Floods

Determine and store on punched cards and magnetic tape the following measures of catchment factors:--

1. Characteristics Constant from Flood to Flood

Characteristic	Ref. Section
Catchment Area	4.2.1
Channel Storage (Hourly Depletion Ratio)	4.2.2
Drainage Density	4.2.3
Shape: Length of main stream	4.2.4
Average width of catchment	4.2.4
Form factor	4.2.4
Compactness coefficient	4.2.4
Length to center of area	4.2.4
Mean travel distance/$(\text{area})^{1/2}$	4.2.4
Standard deviation of dimensionless area-shape curve	4.2.4
Stream Slope: S_1	4.2.5
S_2	4.2.5
S_3	4.2.5
S_4	4.2.5
Overland Slope: R_1	4.2.6
R_2	4.2.6
R_3	4.2.6
R_4	4.2.6
R_5	4.2.6
R_6	4.2.6

2. Characteristics that Vary from Flood to Flood

Characteristic	Ref. Section
Antecedent Wetness: Antecedent precipitation index	4.3.1
Antecedent discharge	4.3.1
Season	4.3.2
Standard Infiltration Capacity	4.3.3
Interception Capacity	4.3.4
Initial Loss	4.3.5
Loss Rate	4.3.5

E. Indexing of Data

Provide for easy retrieval of wanted data by preparing three "Keysort" card indexes as follows--

Index	Information Punched on each card	Information Listed on each card	Ref. Section
Data Source	Nil (initially)	Name and address of person or agency that can provide hydrologic data.	5.2.2
Watershed	Location Size	Name and serial number of watershed, reference to filed data, number of flood events stored, sources of data, constant catchment characteristics	5.2.3
Flood Event	Serial No. of watershed	Serial No. of flood, name of watershed, date and time of flood event, peak discharge, average rainfall, storm duration, references to filed and stored data, variable catchment characteristics	5.2.4

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APPENDIX A

SOURCES OF HYDROLOGIC DATA IN USA

1. Sources of Streamflow Data

    1. U. S. Geological Survey district offices in most states of the country.
    2. State Engineer or hydrographer in each state for those records which may not be available from the U. S. Geological Survey for that state.
    3. State Department of Natural or Water Resources where available.
    4. Local municipal or industrial water supply, flood control or irrigation districts.
    5. Bureau of Reclamation.
    6. Corps of Engineers.
    7. Agricultural Research Service, local research areas.
    8. U. S. Forest Service, Forest and Range Experiment Stations.
    9. Tennessee Valley Authority.
    10. State Agricultural Experiment Stations in each state,
    11. Local electric power companies using water power.

2. Sources of Rainfall and Climatic Data

    1. U. S. Weather Bureau, State Climatologist in each state.
    2. U. S. Weather Bureau, Weather Records Center, Asheville, N. C.
    3. Bureau of Reclamation.
    4. Corps of Engineers.
    5. Agricultural Research Service, local research areas.
    6. U. S. Forest Service, Forest and Range Experiment Stations.
    7. Tennessee Valley Authority.
    8. State Department of Natural or Water Resources.
    9. Local newspapers, radio stations.

3. Sources of Data on Catchment Characteristics

    1. U. S. Geological Survey, Map distribution offices. An index map is available showing the topographic and planimetric maps available. Some geologic maps are also available from these offices.
    2. U. S. Geological Survey, Map production units. Preliminary prints of new maps and aerial photos may be viewed or obtained here.
    3. U. S. Forest Service, planimetric and topographic maps of national forests also some aerial photos may be obtained.
    4. Agricultural Research Service, local research areas.
    5. U. S. Department of Agriculture, Soil Conservation Service for soil and land use maps, in farmed areas.
    6. U. S. Department of Agriculture, Agricultural Commodity Stabilization for aerial photos of farmed areas.
    7. Tennessee Valley Authority for topographic, soils, vegetation and land use maps.
    8. State Experiment Stations for soils and land use maps of each state.
    9. Bureau of Reclamation for land classification maps of existing or potential project areas.

APPENDIX B

PUNCHING OF DATA

As the data is collected, it will be punched into IBM cards. After all the data has been punched, corrected, and ordered, it will be transferred to a magnetic tape. An IBM 1401 data processing system which will be installed at the Colorado State University in June, 1964, will be used for this purpose. With the data on magnetic tape, calculations can be made using the IBM 7094 computer at Western Data Processing, Los Angeles, California (Colorado State University has a cooperative arrangement with this installation), or several high-speed computers in Boulder, Colorado. It is planned to have a telephone connection between Western Data Processing and Colorado State University, with input and output function to be handled at Colorado State University, and computing to be done at Western Data Processing.

The data will be punched as follows--

First Card: Identification, Rainfall, and Streamflow Data

Item	Unit	Decimal Digits	Decimal Places	Columns
Serial Number (eg 012706)	----	----	----	1-6
Date (month, date, year)	----	6	----	7-12
Time of commencement (hrs, min)	----	4	----	13-16
Time increment of hyetograph	min.	3	0	17-19
Equiv. uniform depth of rainfall	in.	4	2	20-23
Overall storm duration	hrs.	3	1	24-26
Number of hyetograph ordinates	----	2	0	27-28
Number of sets of data of next three items	----	1	0	29
Duration (arbitrary)	min.	4	0	30-33
Mean rainfall intensity (for above dur.)	in/hr	4	2	34-37
Probability (of above intensity)	----	3	3	38-40
Second set of data as in 30-40	----	----	----	41-51
Third set of data as in 30-40	----	----	----	52-62
Number of hydrograph ordinates	----	2	0	63-64
Time increment of hydrograph	min.	3	0	65-67
Peak discharge (a x 10^b), a	c.f.s.	3	2	68-70
Peak discharge exponent, b	----	1	0	71-72
(sign in Col. 71)	----	----	----	----
Probability of peak discharge	----	3	3	73-75
Number of hydrograph peaks	----	1	0	76
Blank	----	----	----	77-78
01 (Number of card)	----	2	0	79-80

Second card: Catchment data (constant)

Item	Unit	Decimal Digits	Decimal Places	Columns
Serial number	----	----	----	1-6
Catchment area ($A=cx10^d$), c	sq. mi.	3	2	7-9
Exponent for catchment area, d	----	1	0	10-11
(sign in col. 10)	----	----	----	----
Hourly depletion ratio, K	----	3	3	12-14
Drainage density, D_d	mi./sq. mi.	3	1	15-17
Length of main stream, L	miles	4	2	18-21
Average width of catchment A/L	miles	3	2	22-24
Form factor, F	----	3	2	25-27
Compactness coefficient	----	3	2	28-30
Length to center of area, L_c	miles	4	2	31-34
Mean travel dist. $/(\text{area})^{1/2}$, L_m	----	3	2	35-37
Std. dev. of dimensionless time-area diag., s_d	----	3	2	38-40
Stream slope, S_1	ft/mile	3	0	41-43
S_2	"	3	0	44-46
S_3	"	3	0	47-49
S_4	"	3	0	50-52
Overland slope, R_1	"	4	0	53-56
R_2	"	4	0	57-60
R_3	"	4	0	61-64
R_4	"	4	0	65-68
R_5	"	4	0	69-72
R_6	----	4	4	73-76
Blank	----	----	----	77-78
02 (Number of card)	----	2	0	79-80

Third card: Catchment data (variable)

Item	Unit	Decimal Digits	Decimal Places	Columns
Serial Number	----	----	----	1-6
Antecedent precipitation index, P_a	in.	4	2	7-10
Antecedent discharge, q_i	c.f.s.	4	1	11-14
Seasonal index	----	3	2	15-17
Standard infiltration capacity, f_s	in. /hr.	3	2	18-20
Interception capacity, I	in.	2	2	21-22
Initial loss, L_i	in.	3	2	23-25
Loss rate, ϕ	in./hr	3	2	26-28
Duration of supply period, T_s	hrs.	3	1	29-31
Space for additional data	----	----	----	32-78
03 (Number of card)	----	2	0	79-80

Additional Cards: Hyetograph ordinates

Item	Unit	Decimal Digits	Decimal Places	Columns
Serial Number	----	----	----	1-6
Ordinates	in./hr.	3	2	7-9
of				10-12
hyetograph				----
				76-78
Number of card. Start this series with 10, 11, ----	----	2	0	79-80

Additional cards: Hydrograph ordinates

Item	Unit	Decimal Digits	Decimal Places	Columns
Serial Number	----	----	----	1-6
Exponent for hydrograph ordinates	----	----	----	----
(Sign in Col. 7)($a \times 10^b$), b	----	1	0	7-8
Ordinates	c. f. s.	3	2	9-11
of				12-14
hydrograph				----
				75-77
Blank				78
Number of card. Start this series with 20, 21, ----	----	2	0	79-80

APPENDIX C

EXAMPLE OF DATA PREPARATION

As an example of the analysis necessary in preparing data for storage and filing, the flood of July 10, 1951 on Watershed W-3, Hastings, Nebraska, will be used. Rainfall and streamflow data for this event have been published by the Agricultural Research Service ("Selected Runoff Events for Small Agricultural Watersheds in the United States," pp. 44.1-2, 44.1-3). (U.S. Dept. of Agriculture 1960). A contour map of the catchment is available on p. 44.1-8 of the same publication, and a description of the catchment is given on p. 44.1-1 of "Monthly Precipitation and Runoff for Small Agricultural Watersheds in the United States," also published by the Agricultural Research Service (U.S. Dept. of Agriculture, undated).

The rainfall and streamflow data to be obtained for storage are listed in Table I, Section 2.5, and the catchment data in Table II, Section 4.1.2.

IDENTIFICATION DATA

Serial Number

Not yet determined but will be expressed in a form such as 012706 indicating Flood No. 6 of Watershed No. 27 in River Basin No. 1.

Date of Commencement of Storm

July 10, 1951, punched as 071051.

Time of Commencement of Storm

0450

RAINFALL DATA

Isohyetal Map and Equivalent Uniform Depth of Rainfall

Total storm rainfalls are provided for nine stations on or near the catchment. Figure C-1 shows the isohyetal map prepared from these data, and the computation of the equivalent uniform depth of rainfall (P_a)

$$P_a = 2.70 \text{ in.}$$

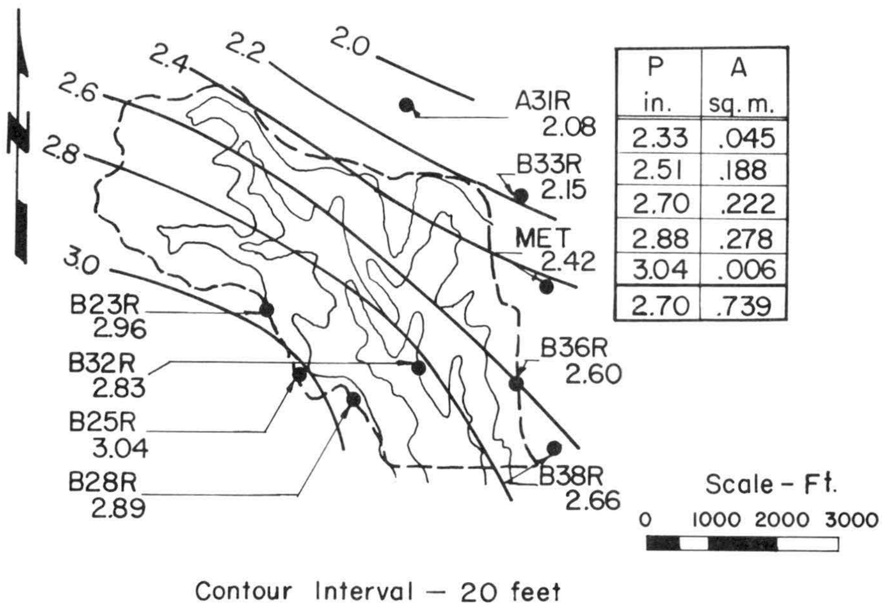

Fig. C-1. Watershed W-3, Hastings, Nebraska. Isohyetal Map for Period 4:50 A. M. to 12:40 P. M., July 10, 1951.

Average Hyetograph

Mass curves of rainfall are available for three of the nine stations. These mass curves are plotted on Fig. C-2, which also shows the average mass curve sketched in by eye to conform as closely as possible to the three actual mass curves and have the calculated total rainfall of 2.70 in.

A time increment of 10 minutes is selected for the hyetograph so as to define all significant changes in rainfall intensity. The average hyetograph is determined from the average mass curve, and is plotted (together with the hydrograph) on Fig. C-3. The number of hyetograph ordinates is 18, including 5 zeroes.

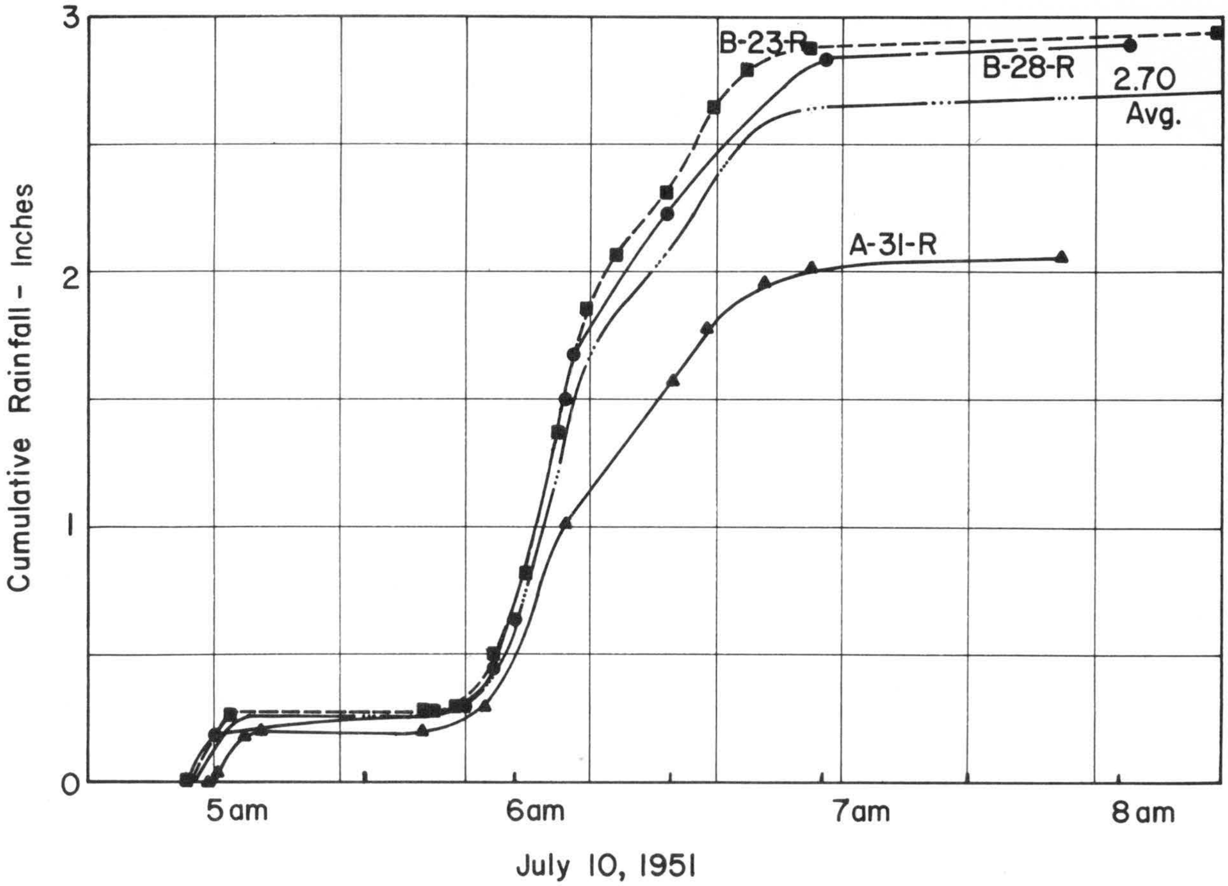

Fig. C-2. Mass Curves of Rainfall, Storm of July 10, 1951, Watershed W-3, Hastings, Nebraska.

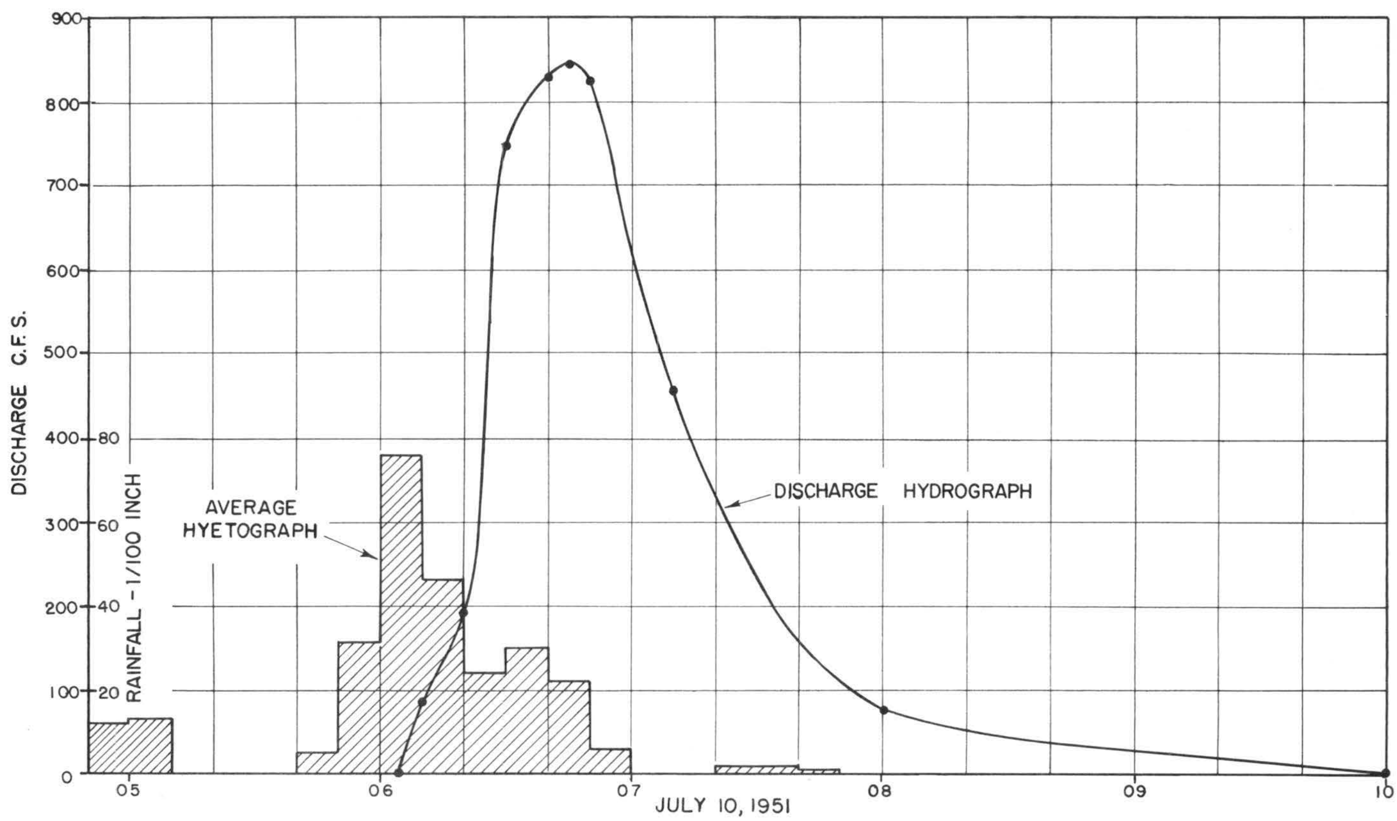

Fig. C-3. Hydrograph and Average Hyetograph, July 10, 1951, Watershed W-3, Hastings, Nebraska.

From the average hyetograph, the overall storm duration, T = 3.0 hours.

The net duration of the supply period (T_s) cannot be determined until the loss rate has been calculated. This will be done by means of a computer at a later date, and the value of T_s will be computed at the same time.

Probability Data

Since an intensity-duration-frequency study has not yet been carried out for this catchment, the probability data will be obtained from U.S.W.B. Technical Paper No. 40. Selected data for the Hastings, Nebraska area taken from this paper are plotted on Fig. C-4. The same data were also plotted in the form of depth-duration curves with recurrence interval as a parameter, but these curves are not shown. Recurrence intervals and probabilities were determined from these two sets of curves for the most intense 20 minute period of the storm, the most intense 60 minutes, and for the entire storm duration of 180 minutes. The results are as follows:

Duration min.	Rainfall in.	Recurrence Int. years	Probability
20	1.22	4	0.250
60	2.29	7	0.140
180	2.70	8	0.130

(Note that although storage space is provided for three digits in the probability figures, only two signicant figures are used in any one case.)

STREAMFLOW DATA

Hydrograph

The available data comprise discharge values at irregular time intervals. The hydrograph is plotted from these values on Fig. C-3, and ordinates for storage can be taken off the plotted hydrograph at constant increments of time in phase with the hyetograph ordinates. In this case a time increment of 10 minutes is desirable to define the hydrograph adequately. This time increment was also used for the hyetograph.

As the maximum hydrograph ordinate is between 10^2 and 10^3, the ordinates will be expressed in the form $a \times 10^2$ (i.e. the exponent $b = +2$). It should also be noted that the first eight hydrograph ordinates will be zero. Total number of hydrograph ordinates is 32.

Peak Discharge

This is read from the hydrograph as 845 c.f.s., and stored as 8.45×10^2.

Probability of Peak Discharge

A complete record of maximum annual floods for the period 1939-1956 is available in "Annual Maximum Flows from Small Watersheds in the United States" published by the Agricultural Research Service (U.S. Dept. of Agriculture, 1958). Since the flood under consideration is the largest recorded in that 18 year period, the annual series could be used in place of the partial duration series for probability analysis, but it is considered desirable to bring the record up to date before carrying out the probability study. Accordingly, the probability of the peak discharge has not been calculated.

CATCHMENT DATA

Catchment Area

Planimetered from map, Fig. C-1.

A = 0.74 sq. mi.

stored as 7.40×10^{-1}

i.e. c = 7.40, d = - 1

Hourly Depletion Ratio

Recession curves of three floods for which data are given in "Selected Runoff Events for Small Agricultural Watersheds in the United States" are plotted semi-logarithmically on Fig. C-5. Although four floods are available, one is omitted because its recession is clearly affected by rainfall after the peak. The average hourly depletion ratio determined from these three curves is 0.086.

Drainage Density

A contour map of the catchment showing the stream system is shown on Fig. C-6. All marked stream systems are extended up to the watershed line in accordance with the contours. Total length of extended streams was measured as 8.36 miles, and catchment area is 0.74 sq. mi., so drainage density is 11.3 miles/sq. m.

Shape

Length of main stream (extended to catchment boundary) L = 1.64 miles

Average width $W = A/L = 0.74/1.64 = 0.45$ miles

Form factor $F = W/L = 0.45/1.64 = 0.28$

Compactness coefficient (C)

Perimeter P of catchment measured as 3.91 miles

$$C = 0.28\ P/A^{1/2} = 0.28 \times 3.91/0.74^{1/2} = 1.18$$

Length to Center of Area (L_c)

The centroid of the catchment is determined and is shown on the map, Fig. C-6. Distance along the main stream to a point adjacent to the center of area is measured as 0.48 miles.

Area-Shape Curve

Parameters of the area-shape curve are determined without actually drawing the curve. A square grid is placed over a map of the catchment as shown in Fig. C-6, and the travel distance from each grid intersection to the outlet is measured. The mean of these travel distances is then determined as 1.84 miles. In order to express this dimensionlessly, it is divided by the square root of catchment area giving $L_m = 0.86$

A dimensionless measure of the dispersion of the area-shape curve is obtained by computing

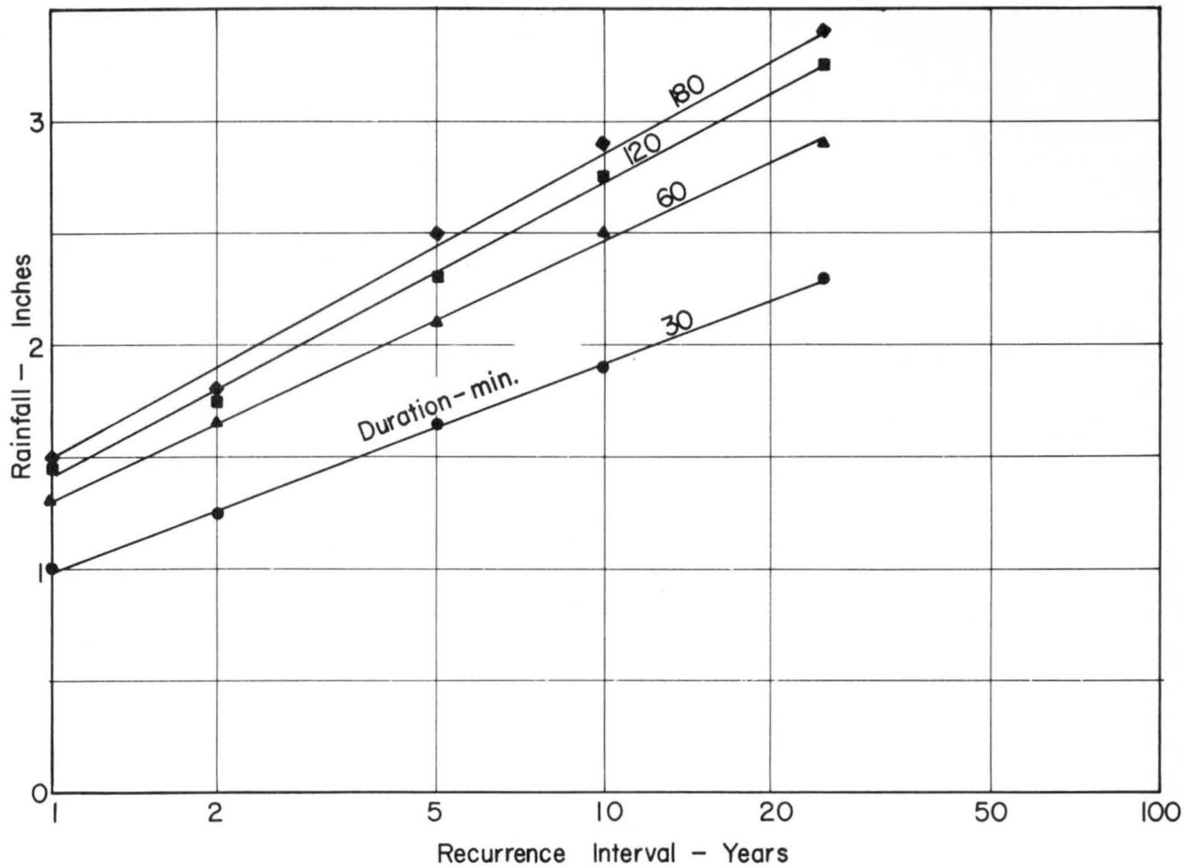

Fig. C-4. Depth-Duration-Recurrence Interval Curves for Hastings, Nebraska.

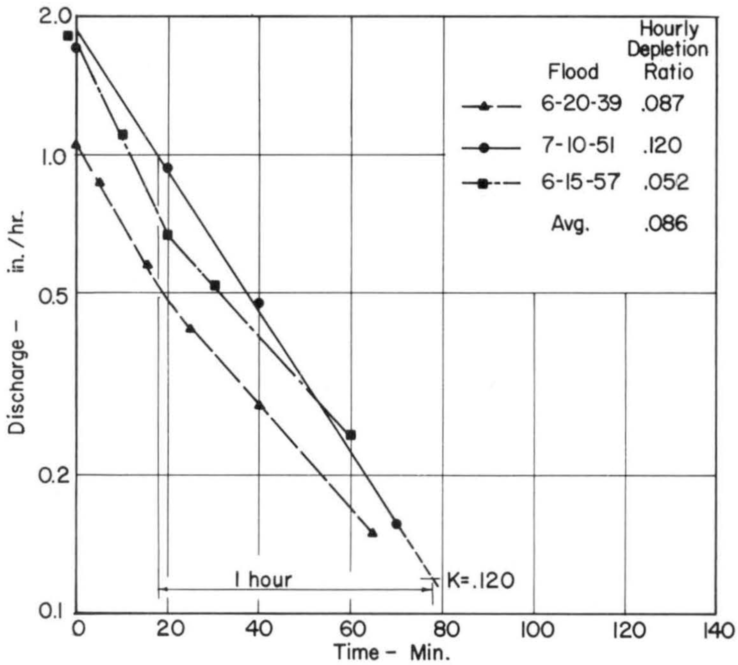

Fig. C-5. Hydrograph Recession Curves, Watershed W-3, Hastings, Nebraska.

the standard deviation of the travel distance determined above (0. 283 miles) and dividing it by the square root of catchment area giving

$$s_d = 0.33$$

Stream Slope

S_1 = total fall/length of main stream

$$= \frac{2000-1925}{1.64}$$

$$= 46 \text{ ft/mile}$$

S_2 and S_3

The main stream is divided into reaches between contour lines.

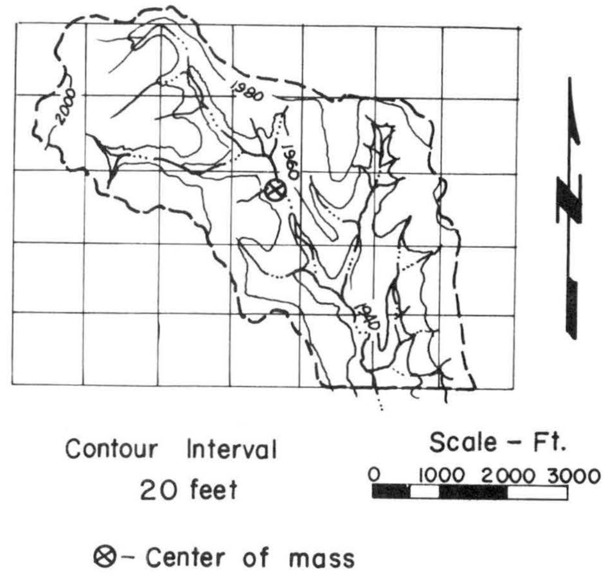

Fig. C-6. Contour Map of Watershed W-3, Hastings, Nebraska.

Point	Elev. ft.	Elev. above outlet-h ft.	Length l-mi.	$\frac{l(h_1+h_2)}{2}$	$l/s^{1/2}$
1	1925	0			
			0.65	4.9	0.135
2	1940	15			
			0.53	13.3	0.086
3	1960	35			
			0.24	10.8	0.026
4	1980	55			
			0.20	13.0	0.020
5	2000	75			
			1.62	52.0	0.267

Average elevation of stream above outlet

$$= 52.0/1.62$$
$$= 32.1 \text{ ft}$$

$$S_2 = \frac{32.1 \times 2}{1.62}$$
$$= 40 \text{ ft/mile}$$

$$S_3 = \left[\frac{\Sigma l}{\Sigma\, l/s^{1/2}}\right]^2$$
$$= \left[\frac{1.62}{0.267}\right]^2$$
$$= 37 \text{ ft/mile}$$

S_4

Elevation 10% of length of main stream from outlet = 1934 ft

Elevation 85% of length of main stream from outlet = 1974. 7 ft

75% of length of main stream = 1. 23 miles

$$S_4 = \frac{1974.7-1934}{1.23}$$
$$= 33 \text{ ft/mile}$$

Overland Slope

(i) Total length of contours measured from Fig. C-6. L_t = 9. 18 miles.

Contour interval h = 20 ft

Catchment area A = 0. 74 sq. mi.

$$R_1 = h\, L_t/A$$
$$= \frac{20 \times 9.18}{0.74}$$
$$= 248 \text{ ft/mi.}$$

(ii) Using the square grid of Fig. C-6, No. of intersections of contour lines and grid lines = 58. Total length of grid lines L_g = 7. 5 miles.

$$R_2 = \frac{1.57\, h\, N}{L_g}$$
$$= \frac{1.57 \times 20 \times 58}{7.5}$$
$$= 243 \text{ ft/mile}$$

(iii)

Contour (H) ft.	Length (L) miles	Av Length $\bar{L}$ - mi.	Area (A) sq. mi.	$W = \frac{A}{\bar{L}}$ mi.	$S = \frac{\Delta H}{W}$	S x A
1925	0					
		1.01	0.046	0.0455	329	15.2
1940	2.02					
		3.18	0.196	0.0616	324	63.4
1960	4.35					
		3.59	0.248	0.0691	289	71.6
1980	2.83					
		1.51	0.250	0.1658	121	30.3
2000	0.20					
			0.740			180.5

$$R_3 = \frac{\Sigma(S \times A)}{\Sigma A} = \frac{180.5}{0.74} = 244 \text{ ft/mile}$$

(iv) Surface slope is determined at each grid intersection of Fig. C-6, and the mean (R_4) and median (R_5) of these slopes are then determined.

R_4 = 180 ft/mile
R_5 = 187 ft/mile

(v) Relief ratio $= \frac{\text{total basin relief}}{\text{longest dimension of basin}}$

$$= \frac{2000-1925}{1.32 \times 5280}$$
$$= 0.0108$$

Antecedent Precipitation Index

Daily rainfalls for one month prior to the storm are given on p. 44.1-2 of "Selected Runoff Events for Small Agricultural Watersheds in the United States." Using these data P_a is calculated as follows.

Days before storm t_i - days	Rainfall P_i-in.	0.85^{t_i}	$P_i \times 0.85^{t_i}$
13	0.20	0.1209	0.024
15	1.75	0.0874	0.153
18	0.88	0.0536	0.047
20	0.48	0.0388	0.019
26	0.10	0.0146	0.001
27	0.78	0.0124	0.010
			0.254

P_a = 0.25 in.

Antecedent Discharge

From hydrograph $Q_i = 0$.

Seasonal Index

Since the storm occurred in July, M = 7 and

$$I_s = \frac{\sin\left\{\frac{7-10}{7}\pi\right\} + 1}{2}$$

$= 0.00$

Standard Infiltration Capacity

From Table 9, p. 48 of "Hydrology Handbook" (ASCE, 1949), the value of f_1 (for bare soil) is taken as 0.30 in/hr since the soil of the catchment falls in the "Intermediate" group (catchment soils are described on p. 44.1-1 of "Monthly Precipitation and Runoff for Small Agricultural Watersheds in the United States."

Vegetal cover is described on p. 44.1-2 of "Selected Runoff Events for Small Agricultural Watersheds in the United States, and a cover factor of 2.0 is selected from Table 10, p. 49 of "Hydrology Handbook."

Thus, standard infiltration capacity,

f_s = 2.0 x 0.30
= 0.60 in/hr

Interception Capacity

Estimated from Table 11-2, p. 268 of "Applied Hydrology" by Linsley, Kohler and Paulhus as 0.01 inch.

Initial Loss and Loss Rate

These items are to be determined and entered at a later date, the loss rate being determined with the use of a computer.