CHAPTER VIII

DETERMINATION OF THE PROBABLE MAXIMUM FLOOD

September 2001

Chapter VIII

Determination of the Probable Maximum Flood

Table of Contents

Figures

Tables

Chapter VIII

Determination of the Probable Maximum Flood

8-1 Background and Purpose

This chapter of the Engineering Guidelines is primarily intended to provide procedures for the development of the Probable Maximum Flood (PMF) for use in the evaluation of proposed and existing dams and other impounding structures. The purpose of these guidelines is to provide consistency in PMF determinations. The guidelines are not a substitute for good engineering judgment and experience when available data clearly call for a departure from recommended procedures. Therefore, the recommended procedures should not be rigidly applied in place of other justifiable solutions.

For about the last 50 years, the PMF has received general acceptance as the design flood for dams in the United States, whose failure would pose a threat to public safety [Myers 1967]. More recently, the PMF has received acceptance as the design flood for large dams in many other countries as well [ICOLD 1991].

The definition of the PMF contained in these Engineering Guidelines is:

> ...the flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in the drainage basin under study.

A PMF is generated by the probable maximum precipitation (PMP), which is defined as:

> ...theoretically, the greatest depth of precipitation for a given duration that is physically possible for a given size storm area at a particular geographic location at a certain time of year.

Developing a PMF hydrograph for a dam safety evaluation generally involves two steps, which are, respectively, hydrologic and hydraulic in nature:

- Modeling of runoff through the project drainage basin to produce an inflow PMF for the project reservoir.

- Routing of the inflow PMF through the project reservoir and dam outlet works to obtain the outflow PMF and the maximum reservoir elevation at the dam.

These steps involve considering several coincident or sequential events, each of which may have a strong effect on the resulting PMF. This chapter attempts to address the use and estimation of those events to avoid compounding of conservatism and to provide a reasonable PMF hydrograph given the limitations of basic hydrologic and meteorological data.

Some important features of a specific project, such as the operation of the reservoir, the outlet works, etc., which are relevant to routing the PMF through the reservoir and dam outlet works, also need to be addressed. The safety of existing or designed dams is the primary concern in adopting the PMF as the criterion for safeguarding the public. This chapter provides guidance on the determination of the PMF. Additional guidance on developing inflow design flood's (IDF's) is included in Chapter 2 of these Guidelines.

8-1.2 Objectives

There is little chance that hydrology will ever become the precise science that designers, owners, and regulators would like to see. So many parameters define the basin characteristics and hydraulics of runoff that the hydrologic engineer will always need to rely on experience and good judgment. This chapter is intended to provide systematic procedures that will consistently produce a reasonable PMF hydrograph and appropriate reservoir flood levels for evaluation of project safety.

While keeping the inherent uncertainty of hydrologic calculations in mind, the objectives of this chapter of the Guidelines are:

- To recommend a preferred method for developing PMF hydrographs.
- To present procedures which, if implemented by two or more qualified and experienced hydrologic engineers, would result in reasonably close or consistent estimates of the PMF.
- To make recommendations regarding the assumptions that must normally be made in developing a PMF hydrograph for gaged and ungaged sites.
- To produce an approach that will minimize the total effort and cost of required studies, while ensuring that the developed hydrograph is reasonable and pertinent for use in the design or safety analysis of civil works.
- To provide guidelines for choosing appropriate hydrologic and hydraulic parameters.

- To provide greater consistency nationally for procedures used in PMF development, while recognizing the wide variety of hydrologic conditions present across the United States.

8-1.3 Overview

It is the responsibility of owners of dams not under FERC jurisdiction to ensure the safety of their projects by using the best available technology. The procedures recommended in this chapter for determining the PMF for FERC jurisdictional projects assume that all dams in the basin upstream of the project will not fail during floods up to the PMF. Therefore, the PMF at the project site will not be a combination of the naturally occurring flood and the flood resulting from a failure of an upstream dam. The PMF at the site is the result of routing the PMF through upstream dams assuming they remain in place. However, this does not preclude owners of FERC jurisdictional dams from considering the failure effect of upstream dams in PMF evaluations.

Previously accepted PMF studies are not required to be reevaluated in accordance with the new Guidelines, unless it is determined that a re-analysis is warranted. Potential reasons to re-analyze an existing PMF include, but are not limited to: significant errors found in the original study or new data becomes available that may significantly alter previous study results; significant changes in the conditions of the drainage basin such as basin development or changes in upstream control structures; changes in the state-of-the-art technology, etc. All new studies should comply with the requirements of these Guidelines.

As PMF determinations are completed using these Guidelines for a project that could affect nearby non-FERC-jurisdictional upstream dams, the FERC will advise the appropriate State Dam Safety Office (State) of the PMF study. The State will be informed that a new PMF study has been done for the FERC-jurisdictional dam, assuming all upstream dams do not fail and that the PMF study is available to the State for its review and information at the FERC Regional Office.

This chapter proposes the use of unit-hydrograph theory as the preferred runoff model for developing an inflow PMF hydrograph. Unit-hydrograph theory was developed by Sherman in 1932 based on five basic assumptions, which are: lumped-parameter model instead of a distributed-parameter model, stationary basin characteristics, uniform rainfall distribution in space and time, constant hydrographic base time based on lag time, and a linear relation between rainfall excess and produced flood discharge. The development of the unit hydrograph is of primary importance in the ultimate development of the PMF hydrograph, because its use will determine both the temporal distribution and peak rate of runoff. The use of the United States Army Corps of Engineers (COE) computer program HEC-1 Flood Hydrograph Package [HEC 1990] is recommended because of the widespread use and experience with that program. A new software package, entitled Hydrologic Modeling System (HEC-HMS), has been developed by the Hydrologic Engineering Center for rainfall-runoff simulation to supersede HEC-1. Since Windows-based HEC-HMS retains most of the capabilities of HEC-1, all references to HEC-1 in this chapter also apply to HEC-HMS. Many United States water-resource agencies have developed models for their own regional use in developing hydrographs for gaged and ungaged basins, including dimensionless unit hydrographs, expressions for lag times, parameters for shaping unit hydrographs, runoff models, etc. This chapter recommends that any special methods be evaluated for applicability before being used.

Development of unit hydrographs for both gaged and ungaged basins is discussed in this chapter. The inherent uncertainties in developing PMF hydrographs are significant, even for locations where quality data are available. Ungaged basins involve even more uncertainties. Final review of a PMF hydrograph should include a sensitivity analysis for parameters having a significant effect on the inflow hydrograph. Section 8-12 contains a glossary that defines technical terms used herein, which are part of the professional language of hydrologic engineering but may have slightly different meanings depending on the user. Cautionary statements have been provided throughout the text where care should be taken in the use of the recommended procedures, or where there are limitations to their application. These statements appear throughout the text in *italics*. The following appendices are included in this chapter:

- **Appendix A** includes a flowchart that summarizes the methodologies in this chapter for determining the PMF for gaged and ungaged drainage basins.

- **Appendix B** includes PMF Study Report Outlines for gaged and ungaged basins.

- **Appendix C** includes a table of HEC-1 data-analysis techniques of the methods for estimating infiltration rates.

- **Appendix D** presents a detailed explanation of the use of the distributed loss rate method, with an example of application of STATSGO (State Soil Geographic Database) data as discussed in Section 8-8.2 for use in assigning loss rates.

8-1.4 Limitations of PMF Simulation

No single method of PMF analysis is without limitations. The information and/or methodologies provided herein are recommended as guidelines that set forth the engineering criteria and procedures rather than standards. The appropriateness of any procedure depends on specific hydrologic and hydraulic characteristics of the watershed and the availability of rainfall, stream flow, and snowmelt records needed to estimate the parameters used in those procedures. Any type of analysis or procedure that is used must be documented and verified. This chapter does not prohibit the use of any method so long as its use is justified for the basin under study. The following are three general limitations in the process of PMF simulation.

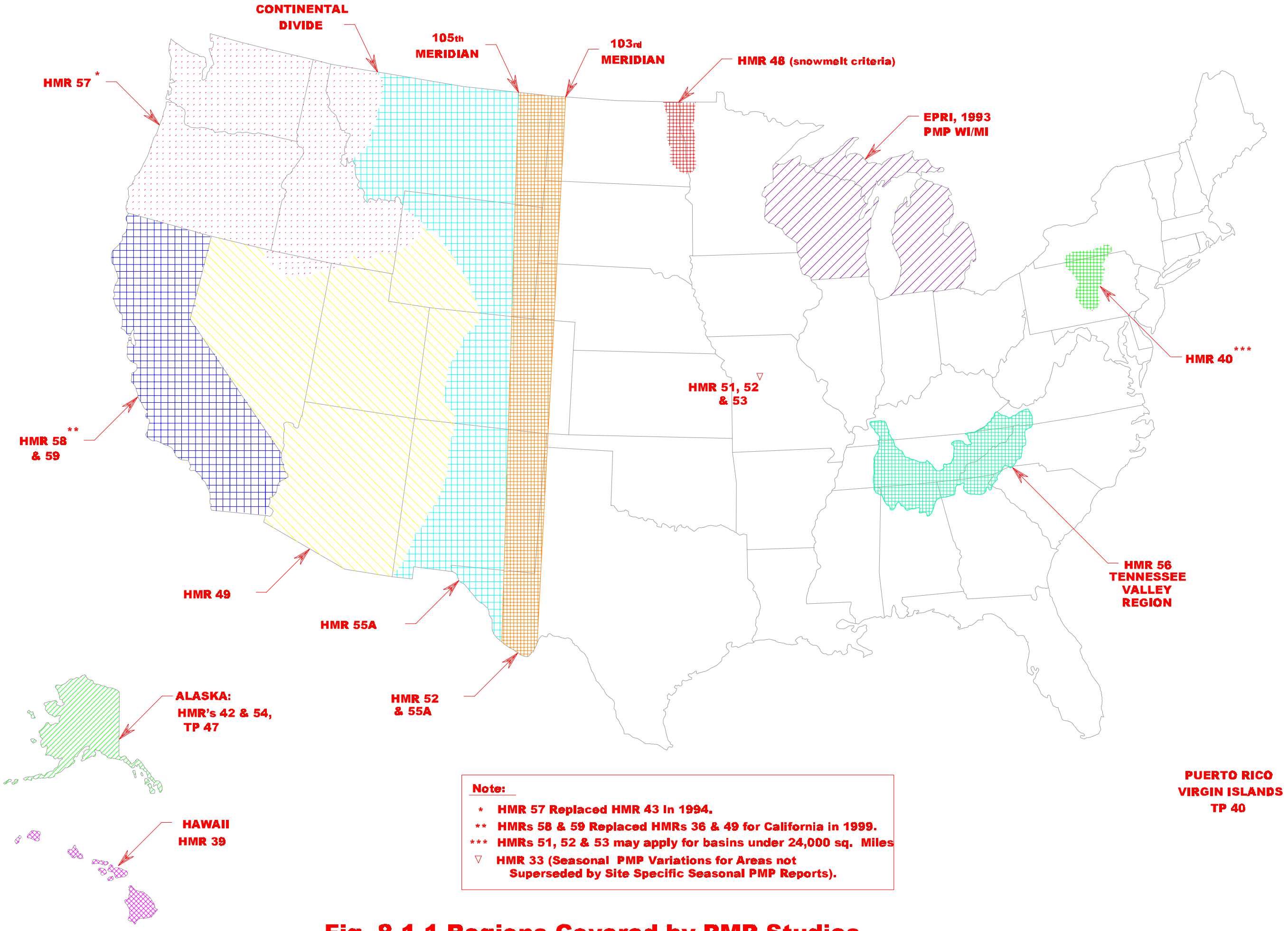
Drainage Basin Size. In general, this chapter covers drainage basins up to about 10,000 square miles, although the size of the drainage area is not necessarily a limiting factor. Consideration has also been given to PMF's produced by local storms that would cover only part of a large basin, or all of a small one, and to general storms that could cover in excess of 10,000-square-miles. The upper limit to the basin size is arbitrary but was made to cover conditions applicable to many dams while still including basins requiring subdivision for analysis. This chapter applies to most basins with multiple FERC-licensed projects; however, procedures for very large drainage basins—such as the lower Missouri or the Columbia Rivers—cannot easily be generalized, since even general storms may not cover the entire basin.

PMP. It is assumed that complete details of the depth-area and duration of the PMP are available and no attention has been given to development of the PMP. However, references are made to developing the isohyetal pattern of the PMP and its use. Often this information can be obtained from the National Weather Service (NWS) Hydrometeorological Reports (HMRs). Because of the storm and flood data they include, the HMR series are important references, but other site-specific PMP studies also may be available. Figure 8-1.1 shows the geographic regions to which each HMR applies. The most recent HMR should be used unless a site-specific PMP study has been approved such as the 1993 EPRI PMP study for the Wisconsin/Michigan area.

Hydrograph Development. Ranges of recommended values of several parameters that must be assumed for developing hydrographs are given throughout the text. The values of these parameters were taken from available material developed by government agencies and other organizations. However, the material cited or quoted does not represent an exhaustive search of the literature, and each section suggests potential sources of additional data. The methods recommended were chosen from those widely recognized and accepted by the hydrologic engineering profession, and for which considerable information is available.

Because the state-of-the-art in hydrology is constantly changing, the procedures suggested herein may require future changes. Therefore, this is a "dynamic" document - one that is subject to review and change as the state of hydrologic engineering is refined or approved.

Where there are limitations to the recommended procedures, or where care should be taken in their use, cautionary statements are provided throughout the text.



Note:

- * HMR 57 Replaced HMR 43 In 1994.
- ** HMRs 58 & 59 Replaced HMRs 36 & 49 for California in 1999.
- *** HMRs 51, 52 & 53 may apply for basins under 24,000 sq. Miles
- ▽ HMR 33 (Seasonal PMP Variations for Areas not Superseded by Site Specific Seasonal PMP Reports).

Fig. 8-1.1 Regions Covered by PMP Studies.

8-2 Preliminary Review of Project and Hydrologic Data

Prior to a site visit, the hydrologic engineer should become familiar with the project and the pertinent hydrologic and topographic information, which will help identify special features that should be observed and the types of data that should be pursued in the field. This section is intended to be an aid in obtaining and reviewing preliminary data.

8-2.1 Identify and Obtain Preliminary Data

General information about the project should be acquired to identify items that should be checked or obtained from the field reconnaissance. Generally, the greater the body of available data, the more confidence in the reliability of the final PMF hydrograph. Each project will dictate the level of required data acquisition. Information should include but not be limited to:

- Topographic or site-specific maps. The maps should show the project location, access roads, layout, and drainage area. Topographic quadrangle maps can be obtained from the United States Geological Survey (USGS) as well as from private vendors and some internet sites. In some areas, topographic maps also are available in digitized form from USGS Earth Science Information Centers (ESIC). Special topographic maps, used during dam design and construction or for other studies, often are available from the dam owner. Satellite imagery, available through the National Aeronautics and Space Administration (NASA), can be useful in addressing conditions within the drainage basin.

- Aerial photographs of the drainage basin. These are sometimes available from the dam owners, the district offices of the United States Forest Service (USFS), and the Farm Service Administration (FSA) (formerly the Agricultural Stabilization and Conservation Service (ASCS)), local or state transportation agencies, or upstream dam owners.

- Drainage basin soil types for estimating infiltration rates. If soil surveys have been developed within the basin, a State Soil Geographic Database (STATSGO), which provides soil association maps and related data, will be available in digital form from state offices of the Natural Resources Conservation Service (NRCS, formerly the Soil Conservation Service (SCS)). These data also are available from the NRCS National

Cartographic and GIS (Geographic Information System) Center in Fort Worth, Texas.

Note: The NRCS established three soil geographic databases representing kinds of soil maps. These include the Soil Survey Geographic (SSURGO) on a county basis at a scale of 1:24,000, the STATSGO mostly at the scale of 1:250,000, and the National Soil Geographic (NATSGO) at a scale of 1:5,000,000.

- <u>Stream gage locations and flow data</u>. These data are available from the USGS Water Supply Papers and Water Resources Data Reports for the state in which the project is located, and from the USGS web site. Unit values (short time interval) data for continuous flood hydrograph can be obtained from the USGS website or district offices of the USGS. Data for many stream gages usually are reported to the USGS even though the gage may be operated and maintained by another federal, state, or local agency; the dam owner; or another private party. If the historical data for the gages are not obtainable from the USGS, the owner of the gage should be contacted. Historical ratings for the gages will be needed and can be obtained from a USGS district office, since they usually are not contained in the annual Water Resources Data Reports. Privately owned firms also may provide digital data containing streamflow information from USGS records. In addition, the dam owner may have streamflow data not available through other sources.

- <u>Precipitation data from gages that are or were operated in or near the basin</u>. Rainfall data and snowpack or snow water equivalent data are generally obtainable from the National Climate Data Center (NCDC) and/or the National Water and Climate Center under NRCS (NWCC). Rainfall data often are available from state water-resource agencies or other federal, state, or local flood-control agencies. Much of the NWS-stored climatological data are available on compact disks from private vendors. In addition, the dam owner may have streamflow and rainfall data that are not reported elsewhere. Upstream dam owners also may have data. Climatological data as required, including temperature, wind speed, and solar radiation also may be available from these organizations.

- <u>Remote sensing data.</u> Remote sensing data can be used as an additional source of information to topographical maps or aerial photographs to provide a source of input data for hydrologic modeling. For instance, these data can be used to determine land use, which affects infiltration rates (Maidment, 1993).

- Hydrologic data for historical storms and associated floods. A search should be made for this information, which will include the rain gage data (particularly from recording gages) within and near the drainage basin and corresponding flood hydrographs. Offices that may have performed special flood studies for severe floods and have such data on file include the COE; USGS; FEMA; NWS district offices; NRCS state offices; TVA; and state or local flood-control agencies. Local newspapers and other media sources can sometimes provide useful information, but any such data must be verified before being used.

- Engineering reports that provide information on dam height and type, reservoir capacity-elevation, spillway type and rating, outlet type and capacity, and power-intake capacity. The dam owner usually is the best source for this information; much of it generally is contained in past safety-analysis reports (in the case of existing projects), which may be available from the dam owner or from state or federal dam-safety agencies.

- Information on project operation during past extreme floods. This information can be obtained from the project owner. Obtaining the information may require reviewing project operation records and interviewing project operators.

- Cross sections for the channels through which the PMF hydrograph may need to be routed. These may be available from FEMA or a local flood-control agency if flood studies have been made for the area. In some cases, cross sections of sufficient accuracy can be taken from 7½-minute USGS maps, but field surveys of critical cross sections may be needed to increase the accuracy of the hydraulic-routing computations.

- Information on land use. Such information may be obtained from USGS topographic maps and local land use maps. Aerial photos also are very helpful for this purpose and are sometimes available from USFS district offices, local and state transportation agencies, or the NRCS state offices. The National Aerial Photography Program (NAPP) is available from the USGS office in Reston, Virginia. Satellite image analysis should be given consideration for cost-effective derivation of these data. Field observations also are desirable. Information on future land use can also be important in rapidly developing urban areas - future runoff conditions may need to be considered in a PMF study.

- Information on geologic conditions within the drainage basin . Geologic maps frequently are available from the USGS district offices, the NRCS state offices, and state departments of natural resources.

8-2.2 Information About Upstream Dams

All existing upstream dams must be identified and information obtained to determine whether or not they create sufficient storage to affect the PMF timing and peak flow. Up-to-date topographic maps of the drainage basin generally will show the locations of all upstream dams with large enough reservoir storage to require consideration. The National Dam Inventory (NATDAM)—available through the FEMA and the COE — lists the height, length, dam type, reservoir volume, date of construction, and ownership for dams in each state. Information desired for each dam includes:

- Type and height of dam, type of outlet works or spillways and rating curves, and a cross section and crest profile of the dam. These data may be necessary for routing of a PMF hydrograph.

- Tables or graphs of surface area and volume versus reservoir elevation.

- Reservoir operation rules that could possibly affect the timing and peak flow of the PMF hydrograph. Operators should be interviewed to obtain historical and proposed information on operation of the reservoir, spillway, outlet works, and power plants during extreme floods to determine how flood operations have been performed in the past. This information also may be of interest in identifying historical floods for development of unit hydrographs.

8-2.3 Field Visit

Once the preliminary information has been obtained and reviewed, an experienced hydrologic engineer should visit the dam, spillway, outlet works, power plant, and the drainage basin to check or confirm information developed in the preliminary review and to obtain firsthand information about the dam, its facilities, and the drainage area.

8-2.3.1 Dam, Spillway, Outlet Works, and Power Plant

The dam, spillway, outlet works, and power plant should be visited to obtain information not available in reports dealing with the site. Such information may include:

- Characteristics of spillways, outlet works, and power intakes.

- Discharge rating curves for each structure. Rating curves should be checked in the field to ensure that they take into account limitations in gate opening, such as orifice flow occurring because a radial gate cannot be opened high enough to provide adequate clearance of the water surface during passage of the PMF.

- Pertinent elevations on the rating curves of spillways and outlet works . Elevations provided should be confirmed.

- Gate operation. It is particularly important to ascertain that the gates are operable to the elevations indicated in the rating curves, and that the gates have been recently operated under full head.

- Flashboards. If an uncontrolled spillway is equipped with flashboards, information should be obtained on their height and the dates on which the flashboards are placed on the spillway and removed. It also is desirable to determine whether or not the flashboards will fail or can be readily released at their design flood elevation.

- Available power and backup systems. Availability of power and the existence of backup systems for operating spillway gates should be ascertained.

- Remote or local operation. It will be necessary to determine if the dam is operated remotely or by local operators, and to obtain details and schedules for operation during extreme floods. Access to the spillway and outlet facilities, and the reliability of remotely located equipment and instrumentation under flooding conditions should be evaluated.

- Physical features of the dam and its appurtenances. Such information will be necessary for routing the inflow PMF through the reservoir and possibly for reverse-reservoir routing of releases to obtain inflow hydrographs from historical floods.

8-2.3.2 Operating Personnel Interviews

Operating personnel should be interviewed. Items of particular interest in addition to operation and maintenance records include:

- Procedures and operation rules for normal and emergency gate operation during extreme floods. An assessment should be made of the reliability inherent in the operation of spillway gates and flashboards, particularly if the project is remotely operated.

- Rule curves for seasonal operation of the reservoir.

- Information on historical floods. Such information includes flood peaks and hydrographs, reservoir levels, maximum rates of reservoir rise, and rainfall depths and timing.

- High-water marks and eyewitness accounts of operations and events occurring during past floods.

- Procedures and results of spillway and outlet-works gate testing.

8-2.3.3 Drainage Basin Assessment

The primary purpose of this assessment is to obtain quantitative information on the drainage basin, with special emphasis on identifying all portions that contribute to runoff. To the extent possible, the drainage basin should be observed by road. Photographs should be taken to establish a record to aid in later recollection. Previously obtained topographic, soil, and geologic maps; aerial photographs; and satellite imagery should be taken to the field for reference. If there are no roads, or if the drainage basin is very large, it may be desirable to fly over the area. Drainage-area observations should include confirming or identifying the following:

- Location of rain gages and stream gages.

- Existing upstream dams.

- Special features within the drainage basin such as marshes, lakes, and closed basins that may delay or reduce runoff.

- Constrictions such as bridge abutments or channel modifications that may influence flood-routing characteristics.

- Manning's "n" and general hydrologic and hydraulic characteristics of stream channels.

- Areas where soil or geologic features or climatological conditions could result in locally different rates of infiltration. These areas include large exposures of rock; areas of high permeability such as karst formations, deep sand, or fractured basalt; cultivated areas; areas of dense forest or managed forest cover; high-altitude meadows; and areas where surface ice conditions are developed by mid-winter thaw and refreeze.

- Large natural constrictions that could act as hydraulic control structures.

- Any significant changes in urbanization, hydrologic use, or land use and cover that may have occurred since surveys for the available topographic maps were conducted, or since the historical floods have occurred.

The following may be necessary if peak flow data from historical floods are incomplete:

- High-water marks along the streams on bridge piers or abutments or along banks. These may be useful for computing a flood peak flow.

- Eyewitness accounts of long-time residents. These will be helpful to obtain information on historical flooding. Verify the accuracy of accounts, if possible.

- Visits to local newspapers and television and radio stations. News reports on historical flooding may be available.

8-3 Data Acquisition

Hydrologic and meteorologic data are necessary to develop unit hydrographs. The primary objectives of data collection are as follows:

- To obtain basic precipitation and streamflow data for use in subsequent analyses.

- To enable the engineer to understand the hydrologic response of the basin for the season when the critical PMF would occur, to increase confidence in simulating the runoff process, and to make appropriate judgments.

In general, data recommended for use in developing a unit hydrograph for a given basin are as follows:

- Streamflow records for major historical floods. It is desirable to have records for at least three major floods and concurrent rainfall data to provide confidence in the representative unit hydrograph.

- Precipitation records for the storms that produced the historical floods and the location and history of all rain gages in the basin.

- Physical characteristics of the watershed including topography, soil types, and land use.

- Snowpack and temperature records in the basin if snowmelt was a factor in historical floods.

In addition, it is necessary to understand the project's physical features, as well as those of upstream dams, to properly route flood hydrographs through the reservoir.

To meet the data acquisition objectives, this section describes the specific data needs and information sources that may be available.

Caution: Delays may be experienced in data collection. These can take place due to time needed to retrieve data from storage and for field data collection. Appropriate time should be allotted (i.e., four to six months) for data collection.

8-3.1 Information from Previous Studies

Since unit hydrographs are commonly developed and used in flood-control studies, local, state, or federal agencies with flood-control responsibilities may have already developed one for the basin of interest. If available and applicable, the use of such unit hydrograph may save considerable time and cost in developing the inflow PMF. If a unit hydrograph is not based on current streamflow or rainfall information, it may be necessary to develop a new unit hydrograph. Previous flood studies performed for nearby dams should also be evaluated for relevant information. All information obtained must be reviewed for quality and applicability; the required review, assessment, and justification procedures are described in Section 8-4. Sources of information for regional flood studies include:

- Local flood control districts
- COE district and division offices
- USBR regional and area offices and the Technical Service Center
- TVA

- NRCS state and district offices
- USGS district offices
- NWS River Forecast Centers
- State water resource agencies
- State dam safety agencies
- State departments of transportation
- Regional planning commissions or agencies
- Dam owners
- FEMA

8-3.2 Streamflow Data

8-3.2.1 Continuous Streamflow Hydrograph

The location of USGS stream gages, along with daily average flows for the water year, are given in the annual Water Resource Data Report issued for each state by the USGS. Historical daily average flows for all streamflow gages ever operated by the USGS also are available on the world wide web at **http://water.usgs.gov/.** The USGS NAWDEX system catalogs sources and types of streamflow data that may not be listed in the Water Resource Data Reports but may be available on its website. A non-recording gage is manually read on a daily basis. Depending upon stream size, a recording gage is read at 5 - 15 minute intervals and is recorded on either a continuous graph or more modern media. The search for streamflow data varies depending on whether the basin is gaged or ungaged. For gaged sites, collection is concentrated on the gages within the basin of interest; for ungaged sites, the collection effort is extended to gaged basins in the region. Daily flow records and maximum flows of record for gages in and near the basin can be obtained from USGS annual Water Resource Data Reports and the previously mentioned web site. Such data are needed to identify historical floods, and should be used when developing a unit hydrograph.

To develop a unit hydrograph, streamflow hydrographs are needed for the identified major historical floods. Continuous streamflow hydrographs can be obtained from USGS district offices, where stage records for the historical floods and rating curves for the pertinent stream gages are also available if questions about the accuracy of the historical flood records arise during the data review. To determine the annual exceedance probability of each flood event, a frequency curve of annual instantaneous peak flows is required. Frequency curves are typically a part of Flood Insurance Studies prepared for FEMA and flood studies prepared by other federal agencies.

Unit hydrographs should be developed from continuous flood inflow hydrographs. It is preferable that stream gages be located on all tributaries entering the reservoir. However, in the absence of flood inflow hydrographs, a continuous flood inflow hydrograph needed for the unit-hydrograph determination can be developed by reverse-reservoir routing. This requires knowledge of project outflow and headwater elevations during major floods. Project outflow can be estimated from downstream stream gage records or project discharges (gate operations and power releases). However, since reverse routing in HEC-1 assumes the use of a level pool, this method may result in a less conservative inflow hydrograph since the "wedge" storage in the reservoir is ignored. For large or long riverine-type reservoirs, the inflow hydrograph may have to be determined using dynamic routing methods. In addition, if the project outflow and headwater level data is not given in hourly or smaller increments of time, then the accuracy of this method may be questionable. However, if reverse-reservoir routing produces a relatively accurate inflow hydrograph, it should also provide an acceptable unit hydrograph. This is because the effect of the reservoir impoundment on flood flows is directly taken into account [Maidment 1993, Newton 1983].

8-3.2.2 Peak Flow and Volume Data

As discussed in Section 8-3.1, the effort in collecting streamflow data will be greatly reduced if a previously developed unit hydrograph is available for the project basin that satisfies the guidelines in this chapter. In that case, the only streamflow data required will be those necessary to identify the occurrence of antecedent floods and to verify the assumed loss rate function. Development of antecedent floods could require data on both annual-flood peak-flow rates and flood-hydrograph volumes. The necessary streamflow data can be obtained from the USGS. In constructing or checking flood-peak frequency curves, flood peaks should be segregated according to cause (e.g., thunderstorm, hurricane, snowmelt, or rain-on-snow). It is particularly important to exclude floods caused by ice jams or dam breaks.

Information about peak rates of flow and the time of peak of past large floods often is helpful when evaluating the reliability of a unit hydrograph. Such information can be obtained from staff gages or crest stage recorders, or from flood marks and other informal flood records often available in special reports about major floods.

8-3.3 Precipitation Data

To develop the unit hydrograph, it is necessary to obtain precipitation data for the storms that caused the identified historical floods. Precipitation data for rain gages within and near the project basin can be obtained from the National Climatic Data Center or from private vendors. Data from continuous recording gages (both within and near the basin) are particularly important in assessing the temporal distribution of rainfall within the basin when developing the unit hydrograph. The altitude and the period of record for all rain gages should be noted. An isohyetal map of annual precipitation should be obtained, if available. NEXRAD precipitation data can complement rain gage records.

Precipitation data for the periods preceding the historical floods will be required if a special study is made to assess antecedent conditions. Special flood and PMP studies—which may have been performed by the COE, USBR, NWS, or other federal or state agencies—usually contain precipitation data that are more detailed and, in general, more thoroughly reviewed and analyzed than that available from other sources (for which supporting documentation are needed). Therefore, it may be beneficial to search for information from such studies.

8-3.4 Applicable Hydrometeorological Reports

Knowledge of the hydrometeorology of the basin and its surrounding areas is necessary to calculate the PMF. Applicable HMR's (Hydrometeorological Reports) providing PMP estimates for the region often include useful information on record storms and the resulting floods. Sources of these data include:

- NWS
- FEMA
- State natural or water-resources related agencies
- Local flood-control districts
- Privately funded regional or site-specific studies that may have been done for some nearby dams. The results of such studies might be obtained from the dam owners.

8-3.5 Physical Characteristics of the Drainage Basin

Some of the parameters commonly used to define a watershed's runoff characteristics include area, elevation, basin slope, land use, basin orientation, and slope and shape of the major watercourse. Most of these parameters can be estimated using topographic maps published by the USGS. Current and past aerial photographs can be very useful in assessing land use or changes in land use. A site visit to the basin should be made to support the parameters chosen for use in the PMF hydrograph development.

Information on soils classification within the basin is desirable for use in estimation of applicable infiltration rates and can be determined from soil survey maps for the areas published by the NRCS. A digital form of the STATSGO data for all 50 states is available from, or is being prepared by, the NRCS National Cartographic and GIS Center in Fort Worth, Texas. Land use data can be obtained from local government agencies, the USFS (Forest Service), or the United States Bureau of Land Management if federal land is involved. Future land use plans should be obtained and considered in the runoff analysis if it is apparent that potential changes could have a significant effect on runoff characteristics. Other resources are available such as Internet downloadable GIS resources, e.g., Digital Elevation Models (DEMs), GIS software programs used to develop basin characteristics from digital files, etc.

8-3.6 Snowpack Water Equivalent and Temperature Data

For sites where snowmelt contribution to extreme floods is possible, snowpack water equivalent, wind speed, and temperature data must be obtained. Locations of snow courses, snow pillows, and weather stations in and near the project basin need to be identified and the altitude and period of record for these stations noted. If snowmelt must be considered in the development of a unit hydrograph, both the snowpack water equivalent and hourly and daily temperature data should be obtained for the periods preceding and concurrent with the major historical floods identified in Sections 8-2.1 and 8-3.3. These data also may be necessary to develop snowpack and temperature sequences for use in computing PMF runoff.

Aerial photographs showing the snow cover pattern throughout the winter and spring are desirable for periods preceding the major historical floods identified in Sections 8-2.1 and 8-3.3, since it will be necessary to define the extent of snow cover for the runoff analysis. The NWS has used aerial photographs to identify the extent of snow-covered areas in some of the north-central states.

Snowpack water equivalent data, as well as NRCS SNOTEL data, may be obtained from NRCS district or state offices or state water resource agencies. Daily temperature data are available from the NWS NCDC. For modeling purposes, the maximum and minimum daily temperatures are used to estimate an hourly temperature distribution.

8-3.7 Data on Existing Reservoirs, Spillways, Outlet Works, and Operation Policy

For an existing project, reservoir water levels, spillway gate operation, turbine releases, and tailwater elevations recorded during passage of the identified historical floods should be obtained—particularly if reverse-reservoir routing will be required to obtain an inflow hydrograph. The operating policies for passage of extreme floods, which were in force when the historic floods occurred, also should be obtained. To route the inflow PMF through the reservoir, reservoir area-capacity data, rating curves for spillways and outlet works, and flood-operation policy must be obtained from the dam's owner.

The rate of sediment deposition in the reservoir should be assessed to determine whether the flood-storage capacity of the reservoir has been reduced. Historical information on sediment deposition may be used to predict future loss of active storage if sediment accumulation has been significant and is anticipated to continue.

Caution: It is important to note the date when this information was developed since changes in active reservoir storage capacity or modifications to spillway and outlet works may have since occurred.

8-4 Review and Assessment of Data

Before using the data obtained as described in Section 8-3 to develop the PMF for the project basin, the data must be reviewed for accuracy and adequacy. This section discusses the review process and acceptance criteria.

8-4.1 Unit Hydrographs

Any unit hydrograph available from a previous study for the project basin or from a regional study must be reviewed and tested for its ability to accurately reproduce major historical flood hydrographs. The best means of proving applicability of the unit hydrograph is to use it to reconstitute the largest of the historical flood hydrographs chosen for review. If the reconstituted flood hydrograph agrees well with the historical flood hydrograph, the unit hydrograph normally can be accepted without adjustment. Acceptance will depend on the historical flood magnitude, as discussed in Section 8-9. If the available unit hydrograph does not reasonably reproduce major floods or is judged not to do so due to changes in basin characteristics or error in the assumed time distribution of rainfall excess, a new unit hydrograph will need to be developed. Unit-hydrograph development is discussed in Sections 8-6 and 8-7.

Caution: It is important to determine the magnitude and importance of the flood hydrographs that were used in producing the unit hydrograph. If the floods used were not of major significance, the unit hydrograph may not accurately predict the peak and timing of major floods. For this reason, small floods should not be used to develop the unit hydrograph.

The predicted peak flow of the inflow PMF may be too low (or too high) as a result of nonlinear effects in the runoff and the channel flow process that violate the unit-hydrograph assumption of linearity between streamflow and excess rainfall. Studies related to these nonlinear effects have been inconclusive [Pilgrim 1988]. If the historical floods used in developing the representative unit hydrographs are large enough to be out-of-bank, the nonlinear effects should not be significant.

8-4.2 Flood Data

The first task in the review of the flood data is to ensure that the historical floods used are the largest for which records are available. They should be the largest floods of record and should preferably have occurred during the season of the critical PMP. However, floods caused by ice jams, debris blockage, or dam break should not be used in unit-hydrograph analysis. It is important to note the cause of the floods (e.g., thunderstorm, general storm, hurricane, snowmelt, or rain-on-snow).

The annual exceedance probability of each of these floods should be determined, as it is preferred that the floods used for unit hydrograph development are significant flow events. To determine the annual exceedance probability of each flood event, a frequency curve of annual instantaneous peak flows is required. Frequency curves are typically a part of Flood Insurance Studies prepared for FEMA and flood studies prepared by other federal agencies. If a previously developed frequency curve cannot be found, one should be developed. Flood flow frequency analyses should be made in accordance with the latest methodology presented in Bulletin No. 17B. The Engineering Manual "Hydrologic Frequency Analysis" EM 1110-2-1415 is a good reference to develop a frequency curve in accordance with Bulletin 17B. The frequency curve(s) should be included in the report.

Flood data must be reviewed for accuracy. The flood hydrograph should be plotted to detect discontinuities and suspicious peaks or lows in the recorded flows. Historical gage ratings, including methods used to extend the range for extreme floods, should be reviewed to make certain that the conversion of recorded stage to discharge was correctly done. Original stage records usually can be obtained from the local USGS district office or the gage owner if questions arise regarding accuracy of recorded flood flows. The following are two situations which need attention during review and assessment of flood data:

- If a slope-area method was originally used to extend the rating curve, a check should be made to ensure that the hydraulic control did not shift to another location during the flood. This may require a computed water-surface profile for the reach.

- If changes in watershed characteristics have occurred since the time of the historical flood, adjustments may be necessary to adequately model the new situation. For example, if the percentage of a watershed's impervious area has changed, the input to the runoff model can be adjusted to reflect the new percentage. Clear cutting of large areas of forests may require changes in both initial abstractions and constant infiltration rates to reflect the changes. Such land use changes will affect the unit hydrograph as well as losses.

Ideally, unit hydrographs should not be developed from storms that produced less than 1 inch of runoff or are not clearly overbank. Unit hydrographs for typical design storms for conventionally engineered projects often are calibrated to flows mostly confined to stream channels or stream channels with some overbank flows. However, PMF-type floods often significantly exceed channel capacity and may become largely conveyed in the overbank areas in which case Manning's roughness coefficients for submerged overbank flows may affect flow travel times, flow depths, etc.

The available flood data should be presented in tabular form and include, but not be limited to, the following: Date of Flood, Peak Flow (cfs), Rainfall associated with the Flood, and Recurrence Interval of the flood event. If no floods have been recorded within the basin of interest, flood records from other basins in the region will need to be evaluated for applicability to unit-hydrograph development. This procedure is covered in Section 8-7.

Caution: If questionable aspects of the flood data cannot be resolved, the data should not be used in unit-hydrograph development.

8-4.3 Precipitation Data

Hyetographs for each storm at each recording rain gage should be plotted and examined for consistency, continuity, accuracy, and completeness. Storm totals and the time distributions for all rain-gage records should be compared to detect obvious inconsistencies. Gaps in records can usually be filled by using regression and correlation analysis with records from nearby gages. If a sufficient number of neighboring gages are available, an average of several gages near the gage with the missing data, double-mass analysis, or other methods may be used to fill the gaps in the record. An isohyetal map of total rainfall for the storms of interest should be prepared using all acceptable rain-gage records. The location of individual isohyets, for zones obviously influenced by orographic effects, can be drawn parallel to elevation contours when the density of rain gages is insufficient to clearly define the rainfall pattern throughout the area. The general pattern should be compared to mean annual or 100-year isohyetal patterns, which can be obtained from Technical Paper 40 or NOAA Atlas 2, published for individual states by the NWS.

Comparisons of the hyetographs and the flood hydrograph should be made to identify suspicious differences in timing between a storm's beginning and end and the rise, recession, and peak of the flood hydrograph. The following are some situations which should be resolved during review and assessment of precipitation data.

- If a major timing difference is noted, additional study of the original data records should be performed.

- The hyetographs from nearby rain gages should be checked to determine if the timing difference is due to a clock problem with the rain gage or the stage recorder.

- Rainfall records at the gage should be analyzed to detect any trends that may coincide with changes in locations of gages or in conditions around them.

- Double-mass analysis or regression methods may be used to adjust rain-gage records to remove spurious trends and produce a homogeneous rainfall record.

- All supporting data and information, including the hyetographs and flood hydrographs, should be included in a graphical format to support their use in the PMF determination.

Caution: Timing adjustments should not be made to the records unless the irregularity is minor or the source of the error can be positively identified.

For this type of study, it is preferable to define the lag time as the elapsed time between the centroid of the hyetograph and the peak of the flood hydrograph. Other definitions of the lag time may be used with appropriate justification. The definition of lag time used in a particular analysis should be consistent with the unit hydrograph method applied.

Because most rain gage records will be available only as daily totals, the records from the most appropriate recording gage(s)—usually the nearest gage with a complete record—should be used in disaggregating daily records to the required temporal distribution. In assembling daily records, it is important to note the time at which each daily gage was read, so that all daily totals can be adjusted to a common daily total.

8-4.4 Snowpack Data

Snowpack data will be required for those basins where snowmelt has been or may be a contributing factor to major floods. The required snowpack-related data include the portion of the basin covered by snow, water equivalent of the snow depth, and hourly or daily minimum and maximum temperatures and wind speed.

8-4.4.1 Water-Equivalent Data

Snowpack water-equivalent data for snowcover that existed during historical storms should be reviewed for completeness, consistency, and adequacy. Adequacy is determined by plotting the recorded snowpack water-equivalent depths against elevation. It is necessary to decide if data are sufficient to define an altitude-depth relationship for the basin, including the lowest elevation of snowcover for mountainous regions. The following are some situations for which additional data are required to estimate snow water-equivalent data.

- If data are available from only one snow course in the basin, which often is the case, data from other basins with a similar orientation and exposure should be obtained.
- If applicable data from other snow courses are not available in sufficient quantity at different altitudes, undefined portions of the altitude-snowpack estimate can be proportioned in accordance with the isohyetal maps for annual basin rainfall.
- It is possible to reconstitute snowpack data for historical floods through the use of runoff models such as the Hydrological Simulation Program-Fortran or the Sacramento Model [Burnash et al. 1973]. If no snowpack data are available, but are required to study the historical floods, such a procedure may be necessary.

8-4.4.2 Temperature Data

Temperature data can directly reflect the resulting snowmelt. Those data should be reviewed for accuracy and for applicability in analyzing historical snowmelt events.

8-4.5 Data on Reservoir Volume, Spillway and Outlet-Works Capacity, and Operation History and Policy

Data on the operating history and performance characteristics of the spillway and outlet works, as well as on the reservoir storage volume, are required. Knowledge of operation policies during extreme floods also will be required for routing the inflow PMF hydrograph. The effect of floating debris on spillway gate operation with the potential of a plugged gate must be considered for all dams that experience a significant amount of debris under normal operating conditions.

8-4.5.1 Reservoir Volume

Data for reservoir area and volume should be reviewed for accuracy and possible changes which may have occurred since the relationship was formulated. The following are appropriate actions for various situations.

- Available data on sediment deposition in the active storage of the reservoir should be reviewed to assess the need for adjustment of the reservoir area and volume characteristics.
- If measured data are not available, visual observations of the reservoir's upper reaches should be made.

8-4.5.2 Spillway and Outlet-Works Capacity

The discharge-capacity relationships of spillways and outlet works should be checked in accordance with available discharge coefficients for tested hydraulic structures, such as those given in the COE Hydraulic Design Criteria [COE 1989]. For unusual spillway crest shapes, the USBR publication "Discharge Coefficients for Irregular Overfall Spillways" [Bradley 1952] and the "Handbook of Hydraulics" [King and Brater 1954] provide additional guidance. Because approach conditions and site-specific geometry can affect the magnitude of the discharge coefficients, precise agreement should not be expected but should be estimated within an acceptable allowance as described below.

- If differences of 10 percent or more are apparent, the source of the original discharge-capacity estimates should be reviewed.
- If adequate physical model studies have been made for the structures, experimentally determined discharge relationships can be accepted.
- If model studies have not been made, values from verified references for discharge coefficients should be used for routing of the PMF inflow. Determine if any structural modifications have been made that could have produced a change.
- Ensure that a common datum has been used for elevations of reservoir and the dam's appurtenances.
- The consideration of powerhouse discharges during a PMF may be reasonable in some cases because of a wide variety of factors such as general unit availability, headwater and tailwater levels, losing the load through transmission outages, and sluicing through the units under no-load conditions.

8-4.5.3 Operation History and Policy

Data on historical operation should be reviewed for correctness, especially if the data will be used to determine inflow floods by reverse-reservoir routing. The location of the reservoir stage recorder should be evaluated to ensure that measured stages are not influenced by drawdown due to spillway or outlet works operation or wind-generated waves. If stage records are available for any other location on the reservoir, the records should be compared to detect any inconsistencies. This will aid in assessing the degree to which the reservoir surface is sloped during passage of extreme floods.

It is necessary to review operation policy and procedures for the passage of extreme floods to develop criteria for routing the inflow PMF hydrograph. The following scenarios describe appropriate actions required for various situations.

- If it is possible for operators to be present at the project and to perform the required operations during the PMF, and if redundant operation systems exist, assume that gates and valves that have been tested under head can be operated as proposed during flood passage.
- If gates and valves that would be operated during passage of an extreme flood have not been tested under head to ensure their operation, it will be necessary to make a detailed evaluation of their condition and reliability. Assumptions on the operation of the gates during passage of a PMF should be made based on the evaluation.
- If the gates are operated remotely, it is necessary to assess the reliability of gate operation that can be expected during an extreme flood. Operations during historical floods should be reviewed to determine whether the operational policies have been consistently applied.

Spillways equipped with flashboards or stoplogs must be reviewed to determine the operation policy relative to their installation and removal. In addition, if the flashboards are designed to fail or collapse, it will be necessary to obtain detailed information on their structural design. The head at which the flashboards will fail or collapse must be checked.

- If the flashboards are designed to be tripped, the tripping operation should be reviewed to ensure that it can be accomplished at the planned time during passage of the design flood or larger floods.

- If the spillway is sometimes blocked with stoplogs that must be removed manually, it will be necessary to determine if there would be sufficient warning time and available equipment to remove the stoplogs.

- It is important to consider the possibility that a spillway or outlet works may be at least partially blocked by debris. The handling of debris during past major floods should be assessed. If a debris-handling plan that has worked successfully in the past is in place and there will not be potential debris production in the areas previously untouched by flood scouring, it is acceptable to assume that blockage will be insignificant during passage of the PMF. If no debris plan exists, the potential loss of spillway capacity must be evaluated with respect to the loss of spillway capacity during the PMF event.

Caution: If deviations from the existing, approved reservoir operating plan are proposed, the changes must be in accordance with the terms and conditions of the project license. The appropriate Regional Office Engineer should be contacted to discuss the proposed changes and obtain guidance concerning the potential for need to amend the project license.

8-5 Approach to Tasks for Probable Maximum Flood Development

The approach and identification of tasks for PMF development depend on whether available hydrologic and meteorologic data records for stations within the basin are sufficient to provide for confidence in developing the PMF hydrograph. If not, the available records must be supplemented with data or unit-hydrograph information from other sources. The basin hydrometeorologic and runoff characteristics also have a role in defining the types of analyses required for the PMF development. The choice of procedures is governed by data availability and an understanding of the hydrologic processes of the project basin developed through review and interpretation of the data collected (Sections 8-3 & 8-4).

Unit-hydrograph theory is recommended for use in developing the PMF hydrograph. It may be desirable to subdivide the basin to adequately treat hydrologic differences within the basin. Some of the required subbasins may not have stream gage records at their outlets which can be used to develop unit hydrographs for the subbasins. For cases where the basin is subdivided, a runoff model must be developed that will incorporate the unit hydrographs constructed for each subbasin, as well as the computations necessary to route and combine flood flows from the subbasins to produce the required PMF hydrograph.

8-5.1 Subdivision of Drainage Basin

Subdivision may be necessary for large basins that are not hydrologically homogeneous or are drained by more than one major tributary. When records for the identified historical floods of interest are available for more than one stream gage in the basin, subdivision usually is advisable. If the reservoir area is relatively large compared to the size of the basin, it should be considered a separate subbasin to allow consideration of direct precipitation on the reservoir surface.

In the process of developing a unit hydrograph, and ultimately a PMF inflow hydrograph, the calculations are made using average lumped conditions for the area. If parts of the drainage basin have hydrologic conditions that differ significantly from the basin average, subdivision should be considered. In such cases, separate analysis of the subbasins can improve the confidence that an appropriate PMF inflow hydrograph has been developed. Subdivision of large basins also is required to properly simulate the effects of spatial distribution of precipitation. Subdivision also may be necessary if the methodology used to simulate the flood event is limited to use on certain size watersheds. Subdivision also should be considered if there are subbasins in the drainage basin that:

- Possess hydrologic characteristics obviously different from the average characteristics of the total basin. Examples include shape; large urban sections in an otherwise undeveloped drainage area; areas of unusually high infiltration rates such as those of fractured basalt; closed subbasins; and large areas of dense or managed forest in an otherwise clear drainage area. Such hydrologic characteristics can be identified from examination of soil maps, geological maps, topographic maps, aerial photos, and land use maps, and from field visits.

- May contribute to delays in flood passage such as marshes, lakes, or high-altitude meadows.

- Experience significantly greater or less rainfall than the basin average due to orographic effects or spatial characteristics of local storms. Such areas are best identified through study of isohyetal maps for individual storms and average-annual rainfall.

- Are controlled by large natural constrictions that can act as hydraulic control structures by restricting cross-sectional area and attenuating water flow.

- Are upstream of dams with sufficient storage to affect the peak flow rate and the timing of floods at the point of interest. Subdivision should definitely be considered if operational and streamflow records exist for the upstream dam for the historical floods of interest.

- Have a total drainage area large enough that it may not be covered by a single storm.

- Do not contribute to runoff from the basin.

- Have significantly steeper or flatter slopes than are typical for the basin.

- Have additional functional stream gages with good historical data.

- Have areas that are covered by snowpack when snowmelt is known to be important for both historical floods and the PMF. The subbasin covered by snow may have different infiltration rates than the rest of the drainage basin.

8-5.2 Gaged and Ungaged (Sub) Basin(s)

It will be necessary to assess the available data and determine whether a basin can be considered as "gaged" or "ungaged" to establish the recommended methodology to be used in computing the inflow PMF hydrograph. For the purposes of this chapter, a gaged basin (or subbasin) is defined as:

One for which available stream flow data (recorded at stations within the basin) and precipitation data are sufficient in quantity and quality to provide for the development of applicable unit hydrographs by enabling accurate calibration and verification with large historical storms. A gaged basin should meet the following requirements:

- If the basin is not subdivided, at least one stream gage with available flood records should be located within the basin, preferably at the inlet to the reservoir. If the gage is located downstream of the dam, sufficient historical operational data must be available to allow reverse-reservoir routing to develop an inflow hydrograph for each recorded historical flood.

- At least one rain gage—preferably a recording gage with complete, correct, and consistent data, should be located within the project basin. In the absence of rain gages within the basin, gages just outside the basin may provide valuable information in regions not affected by orographic precipitation. If records for only one rain gage are available, the catch of that gage should be representative of average basin rainfall.

- Concurrent records of runoff and basin rainfall for at least three severe historical storms is preferred. The historical storms should occur in the same season as the critical PMF, and should have the following characteristics:

  — All runoff-producing parts of the watershed should have contributed runoff.

  — The floods selected for analysis should not be snowmelt dominated, unless it is apparent that the PMF also will be dominated by snowmelt.

  — The historical storms should have generated substantial runoff. Ideally, the flood hydrograph should have at least one inch of runoff from the contributing area and have generated significant overbank flow along most reaches.

For the purposes of this chapter, a basin or subbasin should be treated as "ungaged" if it does not meet this criteria. However, if available data include less than the desired number of storms and corresponding flood hydrographs, all available data from within the basin should still be used to the extent possible in the unit-hydrograph development. Data from other drainage basins in the region that can be justified should also be used to supplement the analysis. If no rain gages are located within the basin but flood data are available, rainfall data from nearby stations can be used if a review indicates that the data—and the results of their use in reconstituting historical flood hydrographs—are acceptable. The general rule is that all site-specific data are potentially valuable and should be evaluated for use.

If a basin is determined to be gaged , Section 8-6 should be used to develop the unit hydrographs. Section 8-7 should be used to develop unit hydrographs for ungaged basins. If a basin does not meet the criteria for gaged basins, it may have individual subbasins that do meet this criteria. For these subbasins, the criteria of Section 8-6 should be applied, and the criteria of Section 8-7 should be applied for the remaining subbasins.

8-5.3 Approach and Identification of Tasks

Once the basin is judged as "gaged" or "ungaged," the approach to developing the PMF inflow hydrograph will be defined accordingly. However, there will be different degrees to which available data within the basin can be used. The following briefly describes the approach, depending on available data:

- Sufficient streamflow and rainfall data of satisfactory quality are available for confidence in developing a unit hydrograph (gaged basin). In this case, the approach will be to subdivide the basin as necessary and to use available data to develop the necessary unit hydrograph and the PMF inflow hydrograph. Details of the approach are given in Section 8-6.

- Stream gage records for major historical floods are available, but available rainfall data are insufficient to develop a unit hydrograph. In this case, rainfall data from gages adjoining the study basin, which recorded the same storm, may be transposed. However, a test for applicability of this transposed rainfall data will be whether or not it allows satisfactory reconstitution of historical flood hydrographs.

- Available streamflow data are insufficient to provide confidence in developing a unit hydrograph. In this case, it will be necessary to follow the guidelines for "ungaged" sites as described in Section 8-7. If any data for major historical floods are available in the basin (e.g., gages, flood marks, informal flood records), they may be valuable in verifying the unit hydrograph's applicability.

- In some cases, where the "ungaged" approach is indicated, it may be possible to use a unit hydrograph developed in other studies or generalized unit-hydrograph parameters developed in regional studies. This possibility is discussed in Section 8-7.

8-6 Unit Hydrograph for Gaged (Sub) Basins

The methods described in the following paragraphs denote the preferred methodology for developing unit hydrographs for gaged basins. Other methods may be applicable, but they must be fully described, justified, and documented.

Section 8-5.2 discusses the criteria for a basin or subbasin to be considered gaged. The COE-developed computer program HEC-1 Flood Hydrograph Package, (or the subsequent COE-developed Hydrologic Modeling System HEC-HMS) is recommended for use in developing unit hydrographs for gaged basins and PMF inflow hydrographs.

Programs with capabilities similar to HEC-1 have been developed by other agencies. Some of these programs have unique capabilities, or incorporate data or relationships applicable to specific regions of the United States. For example, the Tennessee Valley Authority (TVA) has developed computer programs that are specific to the Tennessee River Basin. Similarly, the Los Angeles District of the COE has developed a preprocessor program for HEC-1 that incorporates unit hydrographs for the District's entire region. Other programs may be used but must be fully documented and verified.

If regional studies that have produced accepted results are available, the methods presented in those studies may be used, if justified. Use of the regional unit hydrographs in developing the PMF inflow hydrograph is described in Section 8-7.2.

8-6.1 Historical Floods for Calibration and Verification

Data from severe historical storms and the resulting floods that are available from systematic gaging stations should be considered for use in developing unit hydrographs. Flood hydrographs resulting from single extreme rainfall events with uniform temporal and spatial distributions are the most desirable for use in unit-hydrograph computation. A unit hydrograph developed from a complex storm (i.e., multiple events occurring back-to-back) can be in error and is very difficult to compute, primarily because of problems associated with baseflow separation. However, HEC-1 and HEC-HMS do provide the means to satisfactorily analyze flood hydrographs that are not single-peaked, if required.

It will be difficult to develop a unit hydrograph that generally reproduces all portions of all historical flood hydrographs. The adopted unit hydrograph should be the one judged to best predict the magnitude, shape, and timing of the PMF. Normally, the adopted unit hydrograph should be the one that most faithfully reproduces the largest floods of record without under-prediction of the historical peak flows. If only historical flood peak discharge and time-to-peak data are available, it may be advisable to attempt calibration to that data, assuming a triangular-shaped hydrograph. This may be appropriate if application of historical rainfall with synthetic unit-hydrograph parameters do not provide a good match with the available data.

The greater the number of storms and floods that can be used, the greater the confidence in the developed unit hydrograph. If data from at least three historical floods are available, two should be used for calibration of the unit hydrograph and one for verification. For calibration, unit-hydrograph parameters are computed by analyzing the largest floods with the best (i.e. most reliable) data to develop a representative unit hydrograph; the degree to which the representative unit hydrograph provides for duplication of the verification flood(s) is then assessed. If not, then the unit-hydrograph parameters must be reviewed and modified to improve the fit. When computing the average depth of runoff for unit-hydrograph analysis, care must be taken to exclude those areas that do not drain to the river system. The runoff-contributing areas for each flood should be identified.

Ideally, the floods calibrated for unit-hydrograph development should have occurred during the season when the critical PMP is likely to occur. In choosing the floods to be used for calibration and verification, the distinction between rain-on-snow and rainfall-generated floods should be noted. For the same basin, a rain-on-snow flood will exhibit a longer lag time than an equivalent flood produced by rainfall alone. If the critical PMP will occur during a month when a significant part of the basin will be covered by snow, the calibration floods should include historical floods generated by rain-on-snow. However, if the critical PMP will occur during summer months when snow cover is unlikely, the calibration floods should be selected from rainfall-dominated floods. In analyzing major floods that occurred during a cold season, it will be desirable to judge whether or not the ground was frozen, since frozen ground may have reduced infiltration rates.

8-6.2 Determination of Basin Average Rainfall

Basin average rainfall must be determined for each storm used in developing a unit hydrograph. The method to be used in determining basin average rainfall depends on whether orographic effects are present in the basin.

- If orographic effects are not important, either the Thiessen polygon or the distance-averaging method can be used to calculate the basin average precipitation using recorded rainfall at each gage.

- For basins where orographic effects are important, an isohyetal map provides the best means to determine basin average rainfall. For watersheds having drainage areas in high altitudes, it is important to define the runoff contributing area on the basis of the rain/snow interface line. The basin average rainfall is determined by integrating the areas between isohyets in the subbasin. When orographic effects could be significant, a meteorologist may need to be involved in the development of the basin average rainfall depth.

HEC-1 will compute basin average precipitation from individual gage records, if a weighting factor is entered for each rain gage. When multiplied by the recorded rainfall depth at the gage, the weighting factors yield the portion of the basin average (or subbasin average) rainfall contributed by the gage reading. The weighting factors must be externally computed from the results of either the Thiessen polygon or isohyetal methods. The height-balance polygons method may be needed for a mountainous drainage basin.

Caution: Separate weights may be required to (1) determine total storm volume and (2) develop a temporal distribution of the rainfall depending on the averaging method used.

8-6.3 Cold Season Considerations

It should be determined if at least part of the basin had snowpack or ground subject to frost during historical floods.

8-6.3.1 Snowmelt Considerations

If the basin is one for which at least part of the drainage area is subject to snowpack, and if the historical rainfall-generated floods were influenced by snowmelt, snowmelt calculations must be included in the rainfall-runoff simulation process. The area covered by snow at the time of the flood-producing storm must be determined from the acquired data.

To use the snowmelt function of HEC-1, the temperature at the base elevation of the snowpack is required along with a temperature - lapse rate. For mountainous areas, the elevation usually is taken in increments of 1,000 feet and the lapse rates are given in increments of degree change per 1,000 feet.

- If sufficient temperature information is not available to construct a lapse rate for each storm, a rate of 3°F per 1,000 feet may be used. A 3.5°F lapse rate is used by the COE in the Northwest as a recommended value for the SSARR program. A 3°F lapse rate is typically used in California.

- The energy-budget method of snowmelt computation is recommended for calibration of historical floods. Alternative methods exist and may be used if properly documented and justified. Recommended values for use in snowmelt calculations can be obtained from the U.S. Army Corps of Engineers Snowmelt Manual EM 1110-2-1406 [COE 1960].

- Precipitation should be assumed to fall as snow above the elevation at which it is 34°F. HEC-1 makes this assumption.

Snowmelt from large, relatively flat areas such as the northern Midwest are calculated by HEC-1 in the same manner as for mountainous areas, but temperatures will be more uniform across the area. Areas covered by forests, which will be covered by humus beneath the snow cover, will tend to have higher retention and infiltration rates. HEC-1 provides the capability to consider snowmelt in up to 10 zones of equal increments of elevation.

8-6.3.2 Infiltration Characteristics of Potentially Frozen Soils

In some basins, extreme historical floods result from rain on frozen soils. It may be important to consider these events in unit-hydrograph analysis, especially if the PMF is considered to have a high probability of occurring with frozen-soil conditions. Loss rates for frozen soil conditions can vary considerably depending on the type of soil and the presence of other factors such as forests, wetlands, and high groundwater tables. This is discussed in detail in Section 8-8.4.

8-6.4 Base-Flow Separation

Separation of baseflow from direct runoff in unit-hydrograph analysis has been done in several different ways, none of which are exact. For these guidelines, the procedures specified in HEC-1 should be used. Three parameters must be determined from the recorded flood data and used as input to separate direct runoff and baseflow:

- The flow rate at the beginning of runoff simulation, STRTQ.
- The value of flow at which direct runoff ceases, QRCSN.
- The recession characteristic, RTIOR.

As an aid in calculating these parameters, logarithms of recorded flows during the hydrograph recession should be plotted against the time at one-hour intervals (semilog plot). QRCSN is taken as the flow rate at which the plot of the recession deviates from a straight line and RTIOR is taken as the slope of the straight line portion of the plot.

Caution: Choosing QRCSN can have an important effect on the ordinates of the unit hydrograph and will involve judgment, since the plots are not always smooth and the deviation often is gradual. Figure 8-6.1 shows the way in which baseflow and surface runoff are separated in HEC-1.

8-6.5 Time of Concentration and Clark's Storage Coefficient for Each Subbasin

HEC-1 will calculate values of the time of concentration T_C and storage coefficient R to provide a unit hydrograph which yields, by transformation, an optimized fit to a recorded flood hydrograph [HEC 1990]. R is a coefficient reflecting the effect of storage in the basin and is described in Clark's original paper [Clark 1943]. The time of concentration, T_C, is defined as the time between the cessation of runoff-producing precipitation and the time of the inflection point on the recession limb of the direct runoff hydrograph at which the minimum value of R occurs. As shown in Figure 8-6.2, the value of R may be estimated by dividing the discharge by the rate of change of the discharge at the inflection point on the recession limb of the direct runoff hydrograph.

The ratio $R/(T_C + R)$ tends to be approximately constant for hydrologically similar drainage basins in a region. Values for R and T_C can be computed for input into HEC-1. Using the optimization capability of HEC-1, rainfall and resulting flood flows can be input to the program and values of $R/(T_C + R)$ and T_C are automatically computed so that the unit-hydrograph shape is optimized to produce a best fit between recorded and simulated flood flows. HEC-1 also computes separate values for R and T_C, which should be checked against those estimated from drainage-basin characteristics. If the agreement is good, the value of $R/(T_C + R)$ should be kept constant in the hydrograph analysis. To check HEC-1-derived values for T_C, the time between the end of rainfall excess and the point of inflection (as plotted on the recession hydrograph) should be scaled for each storm and related flood hydrograph. If the value of T_C computed by HEC-1 differs significantly from the scaled value, both should be reviewed and the calculations verified. The scaled value should control, unless a clock-synchronization error is found in either the rainfall or streamflow records.

In addition, a check can be made by calculating T_C using hydraulic theory. This is done by dividing the watercourse from the basin outlet to the top of the basin into segments of approximately uniform slope; USGS quadrangle maps are adequate for this purpose. The time of travel through the various portions of the flow path can be estimated using methods developed by the NRCS [SCS 1986]. Average velocity of flow through each channel reach can be estimated using the Manning equation. Appropriate flow depths can be assumed and Manning's "n" values can be estimated using the USGS publications “Roughness Characteristics of Natural Channels” Barnes [Barnes 1967] and Water Supply Paper No. 2239 “Guide for Selecting Roughness Coefficients for Natural Channels and Flood Plains” [USGS 1988], or the U.S. Department of Transportation’s report entitled “Guide for Selecting Manning’s Roughness Coefficients for Natural Channels and Flood Plains” [FHWA 1984]. Time of travel in each reach is calculated as the length of the reach divided by the average velocity in the reach.

A value for R, the storage coefficient in Clark's unit hydrograph, can be calculated by examination of the observed flood hydrograph as illustrated in Figure 8-6.2. This value of R is not required for the unit-hydrograph determination but should be estimated for comparison with the value calculated by HEC-1 after the unit hydrograph has been optimized using the constant value of $R/(T_C + R)$.

8-6.6 Rainfall Sequence for Recorded Storms

The maximum time increment for the rainfall to be used in the unit-hydrograph analysis is usually calculated as $T_L/5.5$ rounded down to an even number, where T_L is lag time.

This limitation will generally ensure numerical accuracy in the development of the unit hydrograph and the flood hydrograph.

Caution: Sensitivity studies on the effect of the time increment on computational accuracy should be performed if there is any indication that a shorter time increment would result in a higher peak.

Temporal distribution of the basin-average rainfall must be developed for input to HEC-1. This should be done by distributing the calculated basin average rainfall in accordance with records from the nearest recording gage.

Caution: For basins where there may be more than one recording gage, it may be appropriate to subdivide the basin and use the temporal distributions for each gage as input to HEC-1 for the respective subbasin. Averaging recording gage readings usually is not appropriate and must be justified.

8-6.7 Infiltration for Unit-Hydrograph Development

The initial-abstraction and uniform-loss-rate method of simulating infiltration is recommended since it is easy to use, approximates an exponential loss function, and provides sufficient precision. The value of uniform infiltration calculated by HEC-1 for the historical floods should be checked against those expected for the soil types in the basin. This check will provide an indication as to whether the values determined by HEC-1, in the unit-hydrograph optimization process, are consistent with the basin characteristics.

A detailed discussion of the selection of loss rates for the PMF runoff calculations may be found in Section 8-8.

8-6.8 Calibrate Unit Hydrograph

Unit hydrographs must be generated for each historical flood chosen for calibration. The way in which this is accomplished will depend on whether or not the basin is subdivided and the number of stream gages present in the basin.

The flood peak estimate is very sensitive to T_C. Also, the shape of a unit hydrograph can change depending on the magnitude of a flood event. Therefore, for best results, unit hydrographs should be calibrated to floods with overbank flow for most channels in the basin. In general, 2-year floods or less are dominated by mostly channel hydraulics, 10 to 20-year floods will have some overbank hydraulics, and 50 to 100-year floods will have substantial overbank and valley storage hydraulics. The hydraulics of overbank flow is significantly different from channel flow due to increased surface roughness of the flow boundary.

Caution: There are several sources of error that can affect the acceptability of a unit hydrograph. A major potential source of error is the estimate of the temporal distribution of rainfall excess. This estimate depends on the validity of the assumption of basin average rainfall, the estimated temporal distribution of rainfall, and the selection and variability of the infiltration rate. The adopted temporal and/or spatial distribution of rainfall may be erroneous because of clock-synchronization errors, or because of an insufficient number of rain gages to allow for accurate assessment. Given the temporal distribution of rainfall, estimates of the precipitation rainfall excess for a given time depend on the selection of the infiltration rate for that period. All of these assumptions may make it difficult or impossible to develop a unit hydrograph that satisfactorily reconstitutes a major historical flood hydrograph that then may be verified by reproducing another historical flood. The hydrologic engineer needs to be alert to such problems and use engineering judgment as appropriate.

8-6.8.1 Cases Where a Single Basin Unit Hydrograph is Sufficient (No Subdivision)

The rainfall input sequences, as calculated in Section 8-6.6, should be used with the corresponding streamflow sequence and the hydrograph parameters computed in Sections 8-6.3, 8-6.4, and 8-6.5. The value of $R/(T_C + R)$ is calculated from the estimated values of T_C and R or adapted on the basis of available regional values. The parameter can be fixed or allowed to vary when using HEC-1 to develop unit hydrographs. HEC-1 should be programmed to optimize all parameters [HEC 1990a, Section 5] of the hydrographs. For each calculated unit hydrograph, check the HEC-1-calculated values for T_C, R, and the uniform infiltration rate with the values estimated.

Caution: Since HEC-1 makes only a limited number of iterations in this optimization process, more than one trial may be necessary to enable the program to reach an optimum fit. The value of $R/(T_C + R)$ produced by HEC-1 should be input into subsequent runs to ensure that a best fit, in terms of HEC-1 capabilities, has been obtained.

Caution: If the estimated values of T_C or R differ substantially from those calculated (Section 8-6.5), review the calculation of those values. Calculated values for T_C, because of its physical relevance, should be a guide to the final value of $R/(T_C + R)$ chosen as correct for the unit hydrograph.

If the reconstituted historical hydrographs compare well with the recorded hydrographs, no further adjustment of the unit-hydrograph parameters will be necessary. However, if the computed peak is too low, the hydrograph shape is poor, or the calculated values of R or T_C differ greatly from the original estimates, the input parameters should be revised and HEC-1 should be rerun to compute a new hydrograph. This process should be repeated until the fit between the reconstituted and recorded hydrographs can no longer be improved.

A representative unit hydrograph should be prepared using the individual unit hydrographs developed with HEC-1. In general, the representative unit hydrograph should be based on the largest historical flood that occurred during the season of the critical PMP. The representative unit hydrograph can be obtained by adopting appropriate values (T_C and R) from calibrations as opposed to manually adjusting the unit-hydrograph ordinates.

Cautions: If adjustments to the representative unit-hydrograph peak and base are made, the ordinates of the unit hydrograph will need to be adjusted to preserve a runoff volume of 1 inch of rainfall excess.

8-6.8.2 Unit Hydrographs for Subbasins and Channel Routing

If the drainage area basin is to be subdivided, it will be necessary to compute runoff from each subbasin and to route and combine runoff from the subbasins in the downstream direction to develop the hydrograph at the basin outlet.

- If streamflow records are available for each subbasin, the entire process of optimizing the unit hydrograph for each subbasin is the same as described in Section 8-6.8.1.

- If streamflow records are not available at the outlet of some subbasins, it will be necessary to estimate unit hydrographs for these ungaged subbasins. For subbasins smaller than 20 mi^2, this can usually be done with sufficient accuracy by using, for example, SCS dimensionless synthetic unit hydrographs, which requires only an estimate of lag times for the subbasins. For subbasins larger than 20 mi^2 , a unit hydrograph can be developed following the procedures described in Section 8-7.

- If a regional value for $R/(T_C + R)$ is available, it can be used to estimate T_C at the outlet of each subbasin.

The Muskingum-Cunge method of routing, as incorporated in HEC-1, is recommended for channel routing of outflow from each subbasin. Channel cross sections required for the routing can usually be obtained with sufficient accuracy by scaling measurements and elevations from 7½-minute USGS quadrangle maps.

Manning's roughness coefficients, required as input to the routing process, must be estimated on the basis of field observations of the streams. Particular care should be taken to select appropriate "n" values for overbank flow areas. The USGS publications "Roughness Characteristics of Natural Channels" [Barnes 1967] and Water Supply Paper No. 2339 "Guide For Selecting Roughness Coefficients for Natural Channels and Flood Plains", or the U.S. Department of Transportation's report, FHWA-TS-84-204, entitled “Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains” can be used to aid in evaluating roughness coefficients. Also, Ven Te Chow's "Open-Channel Hydraulics" (1959) provides guidance for choosing Manning's "n" values. HEC-1 includes the capability of combining hydrographs in the downstream direction. The combining and routing of the unit hydrographs forms a single-event runoff model for the basin.

Caution: The Muskingum-Cunge routing method uses a single representative cross section defined by eight coordinate points for each routing reach. The method cannot account for backwater effects and should not be used when attenuation of the hydrograph is expected. An example of where this technique might be used is to translate the hydrograph from gages downstream. Where the intention is to properly model the attenuation of the hydrograph, dynamic-wave routing is the preferred method (e.g., when the river is expanding or contracting or where there is natural storage).

Calibration with the historical outflow hydrograph is accomplished differently when routing is involved, because the runoff from each subbasin must be routed and/or combined in the downstream direction to produce the total inflow hydrograph. The agreement between the recorded and reconstituted hydrographs should be examined; if differences are unacceptable, adjustments must be made to the routing parameters and/or the unit hydrograph parameters for each subbasin. The unit hydrograph for each subbasin, if the subbasin is gaged, is also calibrated by checking the accuracy with which its use reproduces the recorded historical floods.

8-6.9 Hydrograph Verification

Once calibration of the unit hydrographs has been completed, the representative unit hydrograph (or the runoff model consisting of the subbasin unit hydrographs and routing calculations) is used with the corresponding basin average rainfall in an attempt to reproduce the historical flood or floods chosen for verification. If the historical hydrographs are duplicated well, the representative unit hydrograph can be accepted. Checking between the historical hydrograph and the generated verification hydrograph can be done automatically with HEC-1 in terms of statistical differences.

- A plot showing a comparison of the hydrographs should be included in the study.

- For the case where a single representative unit hydrograph is involved, only adjustments to the unit-hydrograph parameters will be required. Parameters should only be adjusted within appropriate ranges that can be justified.

- For subdivided basins where the hydrograph generation involves a runoff model, adjustments to both unit-hydrograph parameters and the routing parameters may be needed to achieve better agreement with the historical flood hydrograph.

It is important to be certain that any adjustments to the unit hydrographs or other runoff-model parameters do not significantly decrease the degree of fit achieved in Section 8-6.8 for the historical flood hydrograph. However, the verification process should be continued until an acceptable fit is achieved.

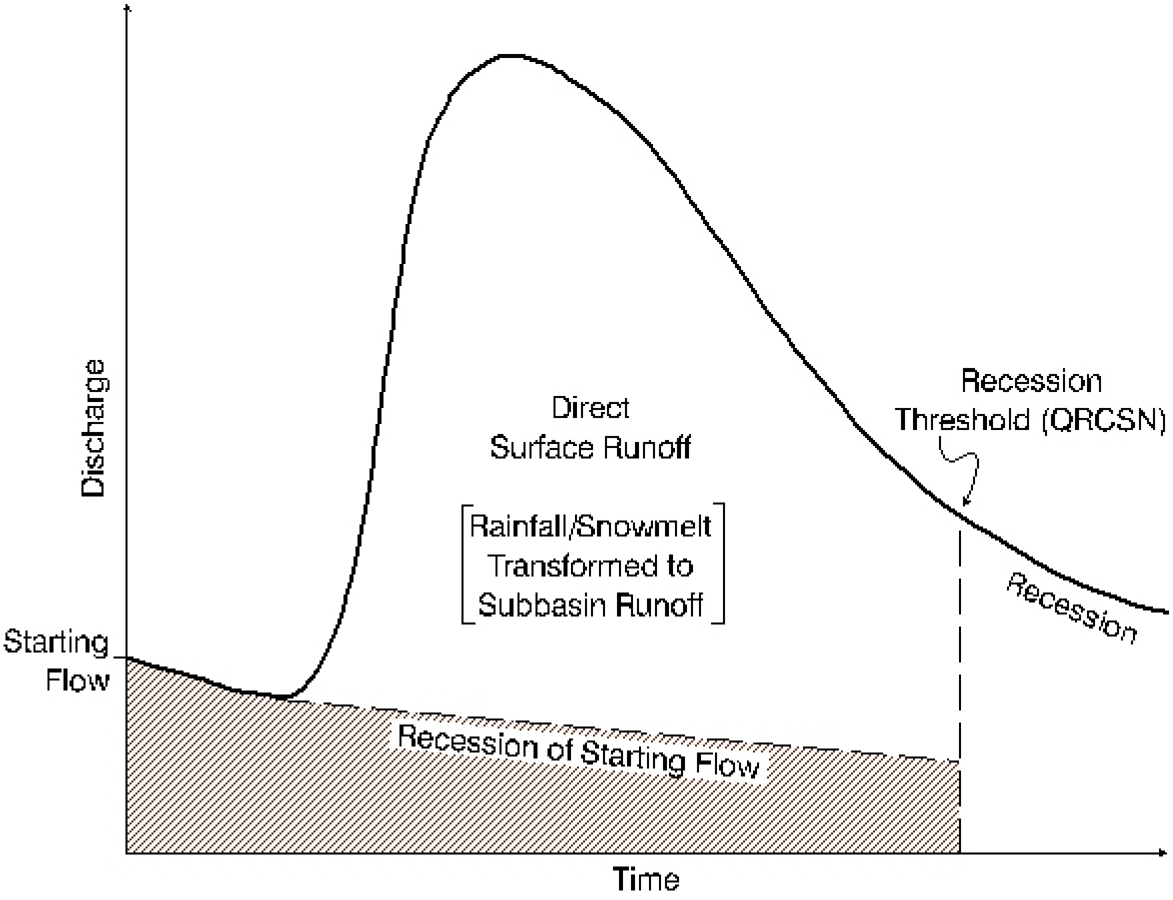


Figure 8-6.1 Baseflow Simulation in HEC-1
[HEC 1990a]

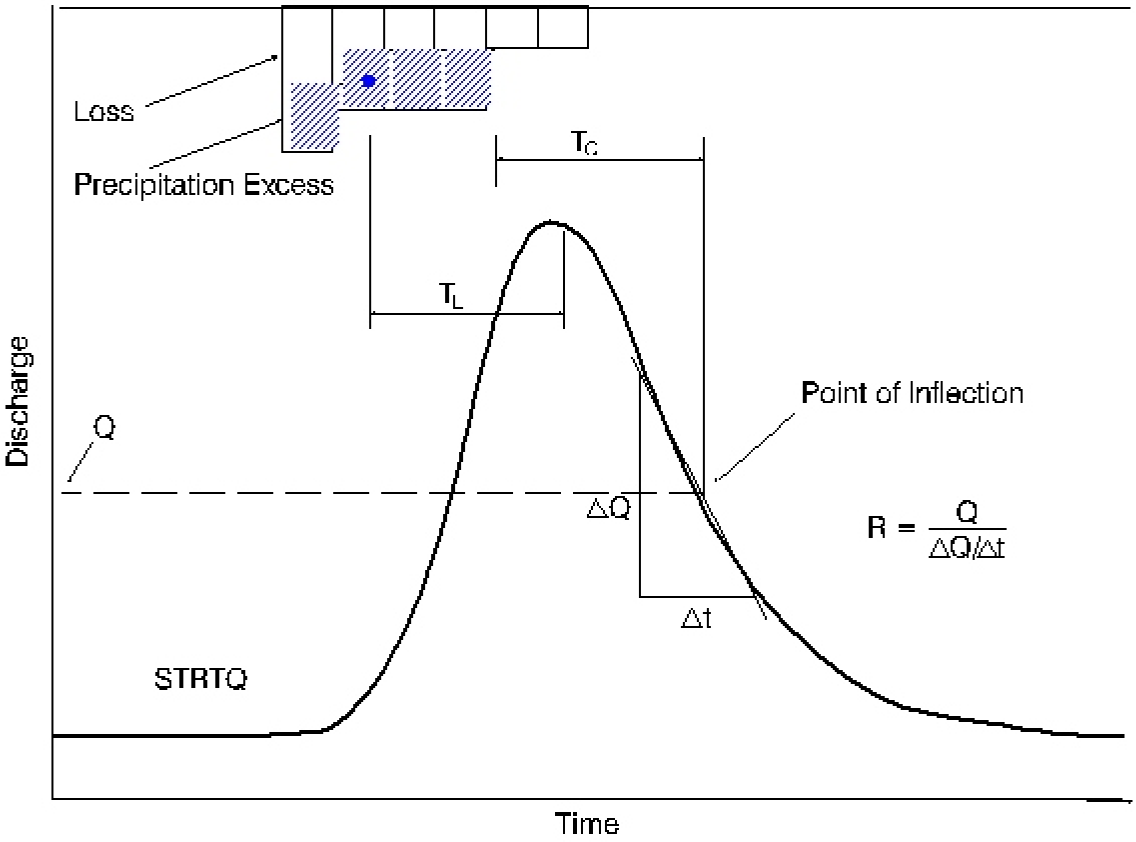


Figure 8-6.2 Estimation of Clark Unit-Hydrograph Parameters
[HEC 1982]

8-7 Unit Hydrographs for Ungaged (Sub)Basin(s)

When a basin does not meet the criteria listed in Section 8-5.2 for gaged basins, it is considered to be an ungaged basin, and a unit hydrograph must be developed synthetically. One of the following approaches should be followed.

- A search should be conducted for regional studies that have developed synthetic unit-hydrographs applicable to the basin.

- A regional study should be performed to develop synthetic unit-hydrograph procedures. The study could develop either a new approach or coefficients for an existing one.

- If no suitable data are available for a regional study, one of the existing approaches should be used, such as those developed by Snyder, Clark, the NRCS , or others. In this situation, the required coefficients must be selected empirically based on coefficients developed for other regions. The applicability of the adopted coefficients must be justified and documented.

- For drainage areas smaller than 20 square miles, it is acceptable to use the SCS (NRCS) dimensionless unit hydrograph; however, adjustments may be necessary depending on basin characteristics (e.g., flat slopes). For basins larger than 20 square miles, an aggregate method can be used if justified and documented.

In a regional analysis, unit hydrographs are developed for gaged drainage basins in the region. A representative unit-hydrograph model is adopted. Relations between the parameters of the unit-hydrograph model and the physical characteristics of the basin are developed. Synthetic unit hydrographs are developed for ungaged basins by means of these established relationships between parameters of the unit-hydrograph model and the physical characteristics of the basin.

Caution: The applicability of any method to an ungaged basin is always subject to question because of the fundamental uncertainty in predicting basin response in terms of defined physical characteristics. In general, any synthetic unit hydrograph should not be used unless the parameters for the unit hydrograph are well defined and correlated with quantifiable basin characteristics, and the unit hydrographs used in developing the relationships have been verified by reproducing the largest historical floods in the records.

Any historical rainfall or peak flow data from within the basin must be used to verify regional synthetic hydrographs and determine their applicability to the basin. Thus, it is always important to use all data available from stations within the basin when developing a PMF hydrograph.

8-7.1 Applicable Unit Hydrograph Procedures for Each Basin (Subbasin)

Many general studies have been performed by local, state, and federal agencies to develop synthetic unit-hydrograph procedures, or coefficients for existing synthetic unit-hydrograph procedures, applicable to a particular region. The following are a few examples of regional studies available from federal, state, and local agencies for developing synthetic unit-hydrograph procedures for ungaged basins.

The COE has developed coefficients for use in computing Snyder and Clark unit hydrographs for many areas in the United States. There is no single source for the COE-developed information, but district offices of the COE can provide information on the results of any studies conducted in their districts.

The USBR has developed a set of lag-time equations, dimensionless unit hydrographs, and S-graphs for different parts of the western states [Cudworth 1989].

The USGS has performed a number of statewide regional studies for the development of unit hydrographs in cooperation with state departments of transportation. These are published as USGS water resources investigation reports. Some of these are referenced in Section 8-11 [USGS 1982, 1986, 1988, 1990].

Caution: Any information obtained must be carefully reviewed to determine if it is applicable to the project basin.

- A first check is to assess whether the basin of interest is hydrologically similar to those used in the regional study. For instance, if the available regional study was developed for basins in a rural setting, the study's applicability to watersheds in an urban environment would be questionable, or vice versa.

  Caution: The reviewer must keep in mind that adjoining basins often are not hydrologically similar even though they may adjoin. Any differences in drainage area, cover, soil type, orientation, or geology should be identified.

- Storm and flood data used in the regional study should meet the same quality requirements as set forth in Section 8-6 for the development of unit hydrographs for "gaged" basins, including the consideration of adjusting unit hydrographs for possible nonlinearity.

- The terminology used to define the various unit hydrographs and basin parameters in the regional study should be clearly understood—particularly the definitions of lag time and channel slope, since a misunderstanding could lead to development of an invalid unit hydrograph.

  Caution: Lag time and channel or basin slope often are defined differently in the various methodologies. The definition of the parameters must be consistent with the methodology used.

- In the Snyder unit hydrograph (Equation 8-7.2), the lag time is defined as the elapsed time from the centroid of the rainfall excess to the unit-hydrograph peak, which is the same definition used by the NRCS.

- The USBR defines the lag time as the time from the center of the unit rainfall excess to the time that 50 percent of the volume of the unit runoff from the basin has passed the concentration point.

- The Los Angeles District of the COE defines the lag time as the time from the beginning of the unit rainfall excess to the instant the resulting hydrograph reaches 50% of the ultimate discharge.

Caution: The hydrologic engineer must have a clear understanding of the definitions of all parameters involved, if using methodologies or studies developed by others. For instance, since many unit hydrographs prepared in the past by federal agencies are based on 6-hour durations, it will be necessary to change the unit duration for the specific duration of the PMP under study.

The capability of a developed unit hydrograph to reconstitute major historical flood hydrographs must be assessed. If reconstitutions were successfully performed in the available study, the unit hydrograph may be acceptable for application to the basin of interest. It also will be desirable to use the unit hydrograph to reconstitute a major historical flood hydrograph on the basin of interest if data are available. If the results of that reconstitution are satisfactory, the unit hydrograph may be acceptable.

Upon obtaining parameters from an acceptable regional study, unit hydrographs for each subbasin should be developed in accordance with the application of the regional study or, in the absence of specific directions, according to common unit-hydrograph theory.

8-7.2 Regional Analysis

If the search for applicable synthetic unit-hydrograph procedures for the basin of interest proves to be fruitless, and the drainage basin is larger than about 100 square miles, a regional analysis will be required.

A regional study could be either relatively easy or require a substantial effort, depending on available data. For regions where systematic records of both rainfall and streamflow have been carefully kept and are readily available, the effort may be as simple as plotting graphs of peak-flow rate and lag time against drainage area; otherwise, the effort can involve significant time and expenditure.

Regional unit-hydrograph studies generally are performed by developing unit hydrographs for historical storms on "gaged" basins within the region. The process of developing unit hydrographs for gaged basins is described in Section 8-6 for basins with adequate data. In the final analysis, the parameters defining the developed unit hydrographs are correlated with measurable basin characteristics to determine if an analytical relationship can be formulated. If the hydrograph parameters correlate well with basin characteristics, the results can then be used to generate unit hydrographs for the ungaged basin of interest.

Caution: Similarity of the study basin to the "gaged" basin is required for a regional analysis to produce reasonable results. The study basin must be similar to the "gaged" basin in topography, slope, soil type, infiltration rates, elevation, and land cover. If the "gaged" basin differs significantly from the study basin in physical properties, it is not an appropriate "gaged" basin to be used in a regional analysis.

To conduct a regional study, "gaged" basins in the region need to be identified. The need for and sources of data for development of unit hydrographs for such basins in the region are the same as given in Section 8-6. Data review should follow the procedures given in Section 8-4. Unit hydrographs used in regional studies should be developed only at gaged sites, and not by some form of transfer or inference from a gaged site to an upstream, downstream, or similar site.

8-7.2.1 Data Required

To evaluate the hydrograph parameters needed for input to HEC-1, an analysis of data for "gaged" basins in the region is required. Rainfall and flood records for all basins in the region should be obtained and examined. Since the objective is to develop a unit hydrograph that can be used to determine the inflow PMF hydrograph, the data obtained should include those indicated in Section 8-3 Data Acquisition. Also, the basins should be visited to obtain information on land use, cover, and the physical characteristics of any dams and reservoirs. If there are dams in any of the basins, information on reservoir area and volume, spillway and outlet works capacity, and operation during historical floods should be obtained.

The following parameters have been found to be useful for correlation of unit-hydrograph parameters in regional analyses:

- Drainage area (A).
- Length of the longest watercourse in miles from the basin outlet to the upper limit of the basin (L).
- Length of the main watercourse in miles from the basin outlet to the point nearest the centroid of the basin area (L_{ca}).
- Channel slope (S).
- Percent impervious area (A_I).
- Percent of area covered by forest.
- Percent of area covered by lakes or marshes.

For each basin analyzed, the following parameters should be computed.

- An estimate of lag time T_L and time of concentration T_C for each basin based on applicable equations obtained from the local flood-control agencies, or calculated as described in Section 8-6.
- The maximum time increment of rainfall to be used in the unit-hydrograph analysis is $T_L/5.5$ rounded to the next lower even number.
- Infiltration rates for each basin/subbasin using methods described in Sections 8-6.3.2 and 8-6.7.

Caution: Because it does not increase the accuracy of the unit hydrograph for the basin, subdivision to areas smaller than that represented by a recording stream gage should not be done.

8-7.2.2 Rainfall Analysis

Basin average rainfall should be computed using the procedures described in Section 8-6.2.
Temporal distribution of rainfall for each storm should be developed for each basin using the procedures described in Section 8-6.6.

8-7.2.3 Development of Generalized Regional Relationships

HEC-1 and the Clark unit-hydrograph method should be used to develop representative unit hydrographs for the selected basins with available data. The selection of the basins should be justified. In general, it is desirable to have gage data for at least four basins in the region. Parameters for use with the Clark unit hydrograph should be developed from the basin data, including Clark's storage coefficient R, and the time of concentration T_C. In addition, it will be necessary to evaluate the HEC-1 baseflow separation parameters STRTQ, RTIOR, and QRCSN. Procedures for determining these parameters are given in Sections 8-6.4 and 8-6.5. Once all input information has been entered, HEC-1 should be used to optimize a unit hydrograph for each selected basin. The HEC-1 runs for each basin should be programmed to optimize the hydrograph parameters while allowing $R/(T_C + R)$ to vary. A representative unit hydrograph must be developed for each basin analyzed.

Once a representative unit hydrograph has been developed for each basin analyzed, the values of $R/(T_C + R)$ for all of the basins should be used in a regression analysis against basin parameters. A very simple regression analysis could be performed by plotting values of peak flow and lag time against drainage area on semi-log or log-log paper. If a well-defined relationship is found, the results can be used to develop a representative unit hydrograph for the project basin.

If a well-defined relationship is not found in the simple regression analysis, it may be that parameters other than drainage area have a strong influence in determining the peak flow rate and lag time for basins in the region. In that case, it will be necessary to perform a multiple linear regression of T_C and $R/(T_C + R)$ against identifiable basin parameters, such as S, L, L_{ca}, and A, or combinations of these parameters. If a portion of the basin is impervious, a measure of that parameter—such as the basin's percentage of impervious drainage area—should be included in the regression analysis. If lakes or marshes exist in the basins, it may also be necessary to include the percent of drainage area occupied and controlled by lakes and marshes as an independent parameter.

A multiple linear regression program will yield values of the coefficient of determination. The coefficient of determination provides a measure of the degree to which the independent variables influence the value of the dependent variable. The regression analysis should be started using all independent parameters and then eliminating those with little influence on the value of the dependent parameter. For basins where impervious areas are small enough to be considered insignificant, the resulting equation for T_C or $(T_C + R)$ may have the form

$$T_c = C_1(\frac{A}{S})^{C_2} \qquad (8\text{-}7.1)$$

where C_1 and C_2 are constants determined in the regression. Ideally, the value of the coefficient of determination will be equal to or greater than 0.9; a perfect correlation would yield a value of 1.0.

Caution: In actuality, the value of the coefficient of determination will often range from 0.6 to 0.8. Different values of the regression constants will be determined for each set of independent variables included in the regression. The hydrologic engineer should review the derived relationships for consistency and use the equation that yields the smallest value of standard error of estimate and the largest value of the coefficient of determination.

Caution: Since $R/(T_C + R)$ tends to be constant for a region, it may not be statistically significant in a regression analysis. In that case, an average value for the region should be computed from the regional results and used for the analysis of the project basin. In either event, the selected values should be justified.

Once the regression analysis has been completed, the values of T_C, R, and $R/(T_C + R)$ can be computed for the project basin in terms of the basin characteristics identified as important in the regression analysis. All parameters then are available for use in the Clark unit-hydrograph option in HEC-1 and can be used to develop the inflow PMF hydrograph.

8-7.3 Empirical Coefficients for Synthetic Unit-Hydrograph Procedures

Failing to find applicable procedures or data to perform a regional analysis, consideration should be given to using empirical coefficients for one of the existing procedures. Empirical coefficients for computing a synthetic unit hydrograph often are presented in technical literature as being applicable to basins described only in general terms, such as rolling hills or coastal plains. These unit hydrographs often are used to design minor civil works projects. However, these unit hydrographs and empirical equations for lag time and time to peak are not acceptable for use in PMF-hydrograph computations, unless there is documented evidence of their applicability, or proof that applicability can be developed. Such justification may exist in the form of special regional studies.

- In this chapter the Clark, Snyder, and SCS unit hydrographs are the only ones recommended, but only because the HEC-1 program includes these methods.

- Other synthetic unit hydrographs may be available from other studies or technical references and may be applicable to the project. If they are used, full documentation must be provided and their use justified.

- Always check and explain regional results by comparison to the time of concentration calculated with the TR 55 program [SCS 1986].

- Most synthetic unit hydrographs have been developed for a given storm duration in keeping with unit-hydrograph theory. It will be necessary to know the duration for any unit-hydrograph considered and to adjust that unit hydrograph to fit the duration required for the basin being considered (required duration must not be more than the lag time divided by 5). Methods for making such adjustments, such as use of the S-Curve, are covered in standard hydrology textbooks. The Snyder parameters employed by HEC-1 are the "standard" lag, t_p, and peaking coefficient, C_p. HEC-1 sets the unit duration of a developed unit hydrograph equal to the computation interval (Δt) using equations based on the Snyder "standard" parameters.

8-7.3.1 Snyder Unit Hydrograph

Many regional studies performed in the United States have concentrated on computing coefficients for the Snyder unit hydrograph in terms of measurable basin parameters. The equations used for the Snyder unit hydrograph are [HEC 1990a]:

$$t_p = C_t(L * L_{ca})^{0.3} \qquad (8\text{-}7.2)$$

$$C_p = \frac{Q_p * t_p}{(640 * A)} \qquad (8\text{-}7.3)$$

where: t_p = Time lag measured from the centroid of precipitation excess to the time of peak flow (hours)

L = Length of the main watercourse (miles)

L_{ca} = Length along the main watercourse measured from the outlet upstream to a point nearest the basin centroid (miles)

Q_p = Peak flow rate of the unit hydrograph (cfs)

A = Drainage area (square miles)

The coefficients C_t and C_p are strictly empirical values often recommended as applicable to specific regions. C_t accounts for storage and slope of the watershed, and C_p is a function of flood-wave velocity and storage.

Snyder unit-hydrograph parameters may be entered in the HEC-1 program if acceptable generalized values are available for the region. The Snyder unit-hydrograph relationships define only the unit-hydrograph peak discharge and the time lag, t_p. Recommended widths of the unit hydrograph at 50 percent and 75 percent of the peak flow can be computed in terms of estimated values of C_t and C_p for the basin [COE 1946]. However, when using HEC-1, this is not required since the program computes a Clark unit hydrograph by estimating T_C and R from the t_p and C_p values of the Snyder unit hydrograph.

Caution:

(1) Unless a regional study has been performed for the selection of appropriate t_p *and* C_p *values as a function of definable basin characteristics, their selection would be entirely judgmental based on the hydrologic engineer's personal impression of basin conditions—a procedure which is not recommended. Selected values for* t_p *and* C_p *should be documented and justified.*

(2) Snyder's original development was performed for large basins in the Appalachian region [Snyder 1938]. If information from detailed regional studies gives values of C_t *and* C_p *in terms of definable parameters for regional drainage basins, use of the Snyder equations may provide satisfactory results. The acceptability of the Snyder method and parameters, or any other method, must be documented and justified.*

8-7.3.2 Clark Unit Hydrograph

The Clark unit hydrograph uses a time-area curve for the basin. Since the unit hydrograph appear to be relatively insensitive to the shape of this time-area curve unless the basin is one with little storage, the automatic generalized curve in HEC-1 can be used. Values for T_C and R should be estimated as described in Section 8-6.

Caution: The means of estimating T_C and R are by no means infallible; it is extremely important that the hydrologic engineer doing this estimation have substantial experience and understand the hydrologic behavior of the basin. Although analytical techniques are indispensable when working on ungaged basins, the judgment of the experienced hydrologic engineer is important. The values selected for T_C and R should be justified.

8-7.3.3 SCS (NRCS) Dimensionless Unit Hydrograph

If applicable data for regional studies are not available, the SCS (NRCS) unit-hydrograph method for ungaged sites—which is described fully in the NRCS National Engineering Handbook [SCS 1985]—may be used for basins with total areas not exceeding 100 square miles. (This upper limit on total area only applies to ungaged sites.) However, subbasins should not exceed 20 square miles if the SCS method is used. The only analytical requirement for application of this method is estimation of the lag time for the basin. In HEC-1, the SCS dimensionless unit hydrograph is fully defined by one parameter—the SCS lag time—and is assumed equal to 0.6 T_C.

Caution: Many empirical equations have been published for estimating T_C, but all are subject to large uncertainties; the hydraulic method of calculating T_C, as recommended in Section 8-6, should be used. The value, method, and equation selected for computation of T_C must be justified and consistent with the respective methodologies.

8-8 Loss Rates for Subbasins

This section pertains to assigning loss rates in the PMF hydrologic model. It will be necessary to assume an infiltration rate representative of saturated conditions in computing the PMF. The infiltration rate should be assumed in accordance with recognizable characteristics of the drainage basin. The HEC-1 model offers five methods for modeling losses, or abstractions. These are the SCS (NRCS) Runoff Curve Number (CN), initial-and-uniform, Green-Ampt equation, Holtan equation, and exponential loss function. Of these, the traditional approach for PMF computations is a basin averaging method using initial and uniform losses, although the SCS method is often used. (Of the remaining three methods, the Holtan method was designed primarily for croplands; the Green-Ampt equation reduces to a uniform loss rate equal to the soil saturated hydraulic conductivity when the soil is saturated; and the exponential equation is based entirely on empirical calibrations.)

When using the initial and uniform loss method to compute the PMF, the peak flow will almost always be insensitive to the initial loss, as will the flood volume in the vicinity of the peak. Therefore, it may be appropriate to set the initial loss to zero, unless a specific hydrologic condition, such as substantial depression storage, justify otherwise. If the SCS loss function is used, Antecedent Moisture Condition (AMC) II is normally assumed when establishing the runoff CN. The CN is determined based on the hydrologic soil-cover characteristics including land use, treatment and hydrologic condition.

Any loss method can be applied in either a *basin-averaged* or *distributed* mode. The HEC-1 model, in which the spatial unit of computation is the basin or subbasin, uses loss functions in a basin-averaged mode. Typically, distributed loss calculations require more effort than basin-averaged calculations. However, they should yield more representative runoff estimates than basin-averaged parameters. A discussion of distributed loss modeling using the STATSGO or SSURGO databases appears in Appendix D.

Infiltration losses can be quite variable depending upon the rainfall intensity and the accuracy with which other inputs to HEC-1 (particularly rainfall distribution) are known. In addition, antecedent conditions for the PMF will be different from the conditions existing prior to historical storms. Regardless of the method used to compute losses, the model must be verified with available historical storm data in accordance with Section 8-8.3. Since some historical events may not be of sufficient size to prevent significant nonlinear effects, the historical floods used for verification should be clearly out-of-bank or it should be shown that saturated soil conditions existed in a significant part of the basin prior to the storm.

For basins where verification is not possible, loss rates at the minimum values from Table 8-8.1 may be used in either the basin-averaged or the distributed loss rate methods. When soil infiltration rates are selected or derived from databases that provide the information as a range, such as the range for hydraulic conductivity presented for each soil layer in the STATSGO or SSURGO databases , the infiltration rate of the least permeable layer of the soil should be assumed to control the soils loss rate. A loss rate that is justified based on site-specific information, such as a review of the geological make-up of the soils, the review of soils information such as county or local soils maps, or actual data obtained from any site investigations within the basin, should be chosen from within this range. The justified infiltration rate may be used in the distributed loss rate method (See Section 8-8.3 and Appendix D). The STATSGO or SSURGO data should not be used to develop a basin-averaged loss rate since the high permeability values for some sandy soil classes in the databases will raise the basin-averaged loss rate to unrealistic values.

8-8.1 Basin-Averaged Methods

This method is recommended because it is relatively simple to use. If other methods are used, they should be justified and, if possible, verified for several large historical floods.

For PMF runoff computations, the soil should be assumed to be saturated with infiltration occurring at the minimum rate applicable to the area-weighted average soil type covering each subbasin. Soil data for the drainage basin should be examined and the major soil classifications delineated. An area-weighted average soil classification should be established for each subbasin that can be identified with a NRCS Hydrologic Soil Classification (A, B, C, or D). The minimum infiltration rate for the average hydrologic soil classification should be selected from the information provided in the 1955 Yearbook of Agriculture [USDA 1955] unless a larger infiltration rate can be justified based upon a review of available soil and geologic maps of the watershed or other technical reports or field investigations. The percentage of the area of each subbasin that is impervious should include areas of open water, wetlands, frozen soils with high silt content, etc. Table 8-8.1 provides the general soil characteristics and minimum infiltration rates taken from the USDA reference.

Table 8-8.1 Minimum Infiltration Rates for Hydrologic Soil Groups [USDA 1955]

Hydrologic Group	**Minimum[*] Infiltration Rates (in./hr)**	**Soil Description**
A	0.30 to 0.45	Deep sand, deep loess, aggregated silts
B	0.15 to 0.30	Shallow loess, sandy loam
C	0.05 to 0.15	Clay loams, shallow loam, soils low in organic content, soils usually high in clay
D	0 to 0.05	Soils that swell significantly when wet, heavy plastic clays, certain saline soils
[*] For each hydrologic group, use lowest value unless a higher value can be justified.		

8-8.2 Distributed Loss Rate Method

The use of basin-averaged loss parameters, especially for large watersheds, can give inconsistent results for basins with spatially diverse characteristics. As the availability of terrain and spatial data becomes common place, the use of geographic grids for hydrologic analyses may become more practical. The use of a grid system will permit a more detailed modeling of hydrologic processes than is possible with lumped parameter methods. Currently, the HEC-GeoHMS computer program utilizes GIS terrain and spatial information for input into hydrological models such as HEC-HMS. Future advancements in hydrologic modeling software is expected and the use of new modeling software is acceptable provided adequate information concerning the modeling process is presented.

The distributed loss rate method described below gives the advantages of simulating losses in a distributed fashion in a fairly simple, economical model structure such as the HEC-1 model. Although it has been developed for use with the uniform loss rate method, the principle of separating basins or subbasins into sections with homogeneous runoff characteristics could be applied to any loss rate method.

Within a watershed, factors affecting the generation of runoff from rainfall include type and depth of soils, land cover, and the presence of saturated soils. “Partial area” theory, which is now generally accepted as a model for runoff generation on natural watersheds, holds that only a portion of a watershed contributes direct runoff during a storm. The size and location of the runoff-producing portion or “contributing area” can vary as a result of the progressive saturation of the watershed soils.

The physical complexity of the watershed response leads to difficulties in using a single, time-invariant, basin-averaged loss rate to represent conditions during all storms. Suppose a watershed contains soils with a wide range of permeabilities , and a few areas that are essentially impervious due to clays and high water tables. Any precipitation event will generate some runoff, because of the impervious areas. If uniform basin loss rates are calculated by subtracting the runoff rate from the rainfall rate during an observed storm, the calculated loss rate during any event must always be less than the rainfall intensity because some runoff will occur from the impervious areas. For example, a 1-inch-per-hour storm must always yield a calculated loss rate less than one inch per hour - even if 90 percent of the basin has soils with 10-inch-per-hour permeability. Another way to view this is to consider that there is no way to measure a 10-inch-per-hour permeability, unless the rainfall rate is at least 10 inches per hour. This means that for a watershed with spatially diverse loss rates, *the calibrated loss rates of the contributing areas depend on the intensity of the storm.*

As a simple example, consider a watershed with 70 percent of its area having a loss rate of 4 inches per hour and 30 percent of the area having a loss rate of 0.5 inches per hour. For a 1-hour, 1-inch rainfall event, the area-averaged rainfall excess will be 0.15 inches ((1.0 - 0.5)*0.30), and the effective basin-averaged loss rate will be 0.85 inch per hour (1.0 - 0.15). For a 1-hour, 2-inch rainfall event, the area-averaged rainfall excess will be 0.45 inches and the effective basin-averaged loss rate will be 1.55 inches per hour. For a 1-hour, 4-inch rainfall, the area-averaged rainfall excess will be 1.05 inches and the effective basin averaged loss rate will be 2.95 inches per hour, which is equal to the actual area-averaged basin loss rate. For all three cases, 30 percent of the basin is contributing all of the runoff and the remaining 70 percent is contributing no runoff. If the storm intensity exceeds 4 inches per hour, then 100 percent of the basin will be contributing runoff.

It's important to note that the effective basin-averaged loss rate will be equal to the actual basin-averaged loss rate if the storm intensity is at least as large as the highest distributed loss rate. However, for storm intensities less than the highest distributed loss rate, the effective basin-averaged loss rate will always be greater than the actual basin-averaged loss rate.

It follows that using a basin-averaged loss rate calibrated on one storm to calculate the rainfall excess during a storm of a different intensity will not correctly predict the excess. Neither will using a spatial average of the actual basin loss rates. In our example, if the watershed model is given a 2.95-inch-per-hour basin averaged loss rate, any modeled storm with an intensity less than 2.95 inches per hour will yield no runoff at all. The effective basin average loss rate for a moderate-sized storm (for example, a 5-year or 10-year storm) is unlikely to be the same as that for a 100-year storm or, especially, a Probable Maximum Storm (PMS). It is important to recall that standard references on inferring loss rates from soil characteristics (such as Table 8-8.1 of the *Guidelines*) were developed and tested with more common design storms in mind - not the PMS. Therefore, depending on the antecedent soil moisture conditions and the intensity of the storm chosen for use in selecting the loss rates, the hydrologic model will likely yield reasonable results for storms of similar size and antecedent conditions, but may not correctly predict runoff from larger storms such as the PMS.

8-8.2.1 Application of Distributed Loss Rate Method

Using distributed loss rates avoids the particular problems associated with spatial averaging. Certain assumptions are still necessary. The two main assumptions are that (1) any unit of soil has a representative loss rate that does not vary over time, and (2) appropriate loss rates for a soil/land cover combination can be inferred from maps or other published data. One drawback of the method is that, if a distributed loss rate model is verified with an observed event and found not to predict the rainfall excess well, there is no single parameter that can be adjusted to provide a “fit.” Instead, it is necessary to re-evaluate all of the assumptions and data sources that were used in developing the distributed model.

A detailed, step-by-step description of the application of the distributed loss rate method using STATSGO or SSURGO soils data is provided in Appendix D. The method generally relies on digital soils and land cover databases that can be converted to a GIS format and analyzed to identify areas of intersection between land cover and soil types. From the spatial data and other information within the GIS (such as layer-by-layer soil permeability contained in the NRCS’s STATSGO soils database), loss rates are assigned to each combination of soil type and land cover occurring in the basin. A table or database is then constructed listing the area percent of each subbasin having each loss rate. Finally, for the storm being modeled, hourly rainfall rates are applied to each loss rate category separately to compute rainfall excess; and the rainfall excess amounts are weighted by area and summed over the basin or subbasin to give an hourly sequence of rainfall excess generation. Note that in this procedure, the rainfall *excess* is area-averaged, which is necessary to apply it in a conventional lumped-basin model. This excess amount is storm-specific. This is a very different procedure, arithmetically, from area-averaging the *loss potential* of the basin soils, which may or may not be fully utilized during a given storm.

8-8.3 Verification and Model Adjustment

Regardless of the method used to compute losses, the model should be verified with available historical storm data. Since some historical events may not be of sufficient size to prevent nonlinear effects, the historical events used for adjusting loss rates should be clearly out-of-bank floods or saturated soil conditions must have existed in a significant part of the basin prior to the storm. The model should be run at a location with historical time sequence data for several historical storms, and the results compared. A plot of these results should be included with the study. If the modeled peak flow and runoff volume underestimates the observed peak flow and volume of the historical storms, then adjustments to the loss rates should be done. The emphasis should primarily be placed on achieving a good fit of the runoff volume since it is determined primarily by the loss rates, whereas the peak flow is effected by the loss rates and the unitgraph parameters. Adjustments should consider the amount and reliability of the information available on the physical characteristics of the soil in the study basin. Other sources of hydrologic information should be explored, such as:

(a) depth-to-bedrock or depth-to-water-table maps: are subsurface characteristics shown in the soils or land cover maps affecting infiltration and resulting runoff?

(b) more detailed soil maps: for instance, do county soil maps support the distribution of soil types indicated by the initial analysis or is actual field data available?

(c) does rapid subsurface flow (interflow) to rivers and streams occur?

(d) other site- and storm-specific conditions: did land use, land cover, groundwater, soil behavior, etc. affect the runoff?

(e) lack of detail (either spatial or temporal) in the rainfall data. Hourly rainfall is essential to accomplish the verification, and if the rain gage locations do not accurately represent the full range of storm intensities over the basin, it is very difficult to verify that the model is performing correctly.

(f) are unit hydrographs obtained from other sources still valid?

If the minimum values from the SCS Minimum Infiltration Rates for Hydrologic Soil Groups found in Table 8-8.1, or the minimums of the saturated hydraulic conductivity range of the least permeable layer (as provided in the STATSGO or SSURGO databases) are used to model the losses in the PMF model (with the appropriate adjustments for impervious areas), and if there are no historical floods that can be used to verify the model, then no further adjustments are necessary to verify the model. This would apply to all ungaged basins and the portions of the gaged basins that were non-contributing during the historical events.

If however, a loss rate other than the minimum is selected based on adequate justification, a sensitivity analyses should be performed. Supporting data for justification purposes may include a review of the geological make-up of the soils, the review of soils information such as county or local soils maps, or actual data obtained from any site investigations within the basin. Sound engineering judgment must be used to select and justify the loss rates if they are significantly larger than the intensity of the historical rain event used for verification. The sensitivity analysis should compare the runoff hydrograph developed by using the justified loss rates versus a runoff hydrograph developed by using the minimum value of the range of the least permeable layer of the soil column. The results of this sensitivity analysis should be plotted on a single graph for ease of review.

Loss rates may be adjusted as necessary if the model can be verified using historical events. However, loss rates unaffected by the verification process should not be adjusted from the minimum values unless additional physically based information is available to support selecting a loss rate higher than the minimum values.

As additional information becomes available, such as flood events larger than historical events, the model should be re-run to see if it adequately predicts the new flood event. If the model does not adequately predict the new flood event, adjustments should be made to the loss rates, unitgraph parameters, or other parameters. When drainage basins do not contain adequate rainfall/runoff data, the installation of rain gages and flow gages should be considered.

Caution: In the HEC-1 computer program, the Snowmelt Loss Rate (LM) overrides the Uniform Loss Rate (LU) in a rain-on-snow analysis when the ground is covered with snow. When the snowpack is depleted, the HEC-1 program then uses the LU variable for the overall loss rate. Although it is possible for the snow-covered ground loss rate to be less than the snow free loss rate, no literature on this subject quantifies this relationship. Care must be used to ensure that the verification of the model adequately considers the effect of changes in the snowpack during storm events. If possible, the LU and LM variables should verified independently of each other.

8-8.4 Infiltration Characteristics of Soils Under Frozen Conditions

Many researchers have identified the effects of soil freezing on the infiltration capacity of soils. Types of frost, soil structure, and antecedent soil moisture content have all been noted as factors influencing frozen soil infiltration capacity. The structure type of soil frost has a strong influence on the rate of infiltration of a soil [Trimble et al. 1987]. Because of different vegetation cover and surface soil characteristics, soils will respond differently to freezing, producing different types of soil frost structures. These structures are most commonly classified as either concrete or granular frost. Soils with concrete frost, which allow very little infiltration, are identified by dense thin ice lenses and ice crystals.

Granular frost, typically found in woodland soils, consists of small frost particles intermingled with soil particles. Frost structures are related to the moisture content of the frozen soil [Post and Dreibelbis 1942]. Soils frozen at low moisture content may become granulated and provide little impediment to infiltration. Conversely, soils frozen at high moisture contents often freeze into massive, dense, concrete-like structures that are nearly impermeable to water [Zuzel and Pikul 1987]. Reduced levels of moisture content are found in forested areas because of interception and evapotranspiration [Kane and Stein 1983]. These low moisture contents result in granular frost structures in the winter.

Frozen sandy soils typically do not develop a concrete, or impermeable, frost. For example, in Engelmark's [1987] set of laboratory experiments, infiltration rates were measured in a fine sand. The grain-size curve of the fine sand indicated 84 percent passing a #40 sieve and 5 percent passing a #200 sieve. Infiltration rates obtained for this soil in the frozen state were between 1-2 mm/min. (2.4-4.7 in./hr). Another experiment executed by Blackburn and Wood [1990] in a sandy soil provided a range of infiltration rates of 0.42-1.08 mm/min (1-2.4 in./hr), depending on the type of frost.

When coarse soil types are combined with the vegetation, a low soil moisture content can be predicted. Even heavy rainfall rates may not exceed the rate of infiltration in soils and they will not become saturated. With these conditions, a granular soil frost will predominate in the winter. Granular soil frost is far from impervious; it typically has infiltration rates the same as, or even higher than, the soil in an unfrozen condition [Blackburn and Wood 1990].

Based on these observations, the following guidelines should be followed in estimating cool-season loss rates:

- Wetlands should be modeled as impervious elements. These soils, even if they are sandy, may intersect the seasonal high water table and thus have a higher potential to produce a concrete type of frost.
- Soils with high silt content associated with high groundwater tables should be assumed to be impervious.
- Clays should also be assumed to be impervious.
- Forested soils or soils with a minimum 4-inch humus depth should have unfrozen condition infiltration rates applied [Kane and Stein 1983].
- Nonforested soils, other than sands or sandy loams, should be considered impervious when they occur within the historical maximum frost depth.
- Infiltration rates for normal granular soils, such as sand and sandy loam, should be assumed equal to the unfrozen condition. If, however, the granular soil exhibits a high moisture content, this assumption may not be appropriate.

Caution: Situations may exist where an ice layer can form on the soil surface as a result of a mid winter thaw and refreeze. This condition may significantly reduce the infiltration rate obtainable by granular soils.

8-9 Probable Maximum Flood Development

Sections 8-5, 8-6, and 8-7 described the process of developing the necessary runoff model for use in computing the inflow PMF hydrograph. Section 8-8 provides guidance for selecting loss rate parameters and verifying the model. For simple basins, this runoff model will consist of a single representative unit hydrograph. For more complex basins, the runoff model will consist of a combination of unit hydrographs for subbasins and a streamflow-routing process. The runoff model is used to calculate the inflow PMF hydrograph. This section provides guidelines for calculating the PMF including parameters related to the PMP, antecedent hydrologic conditions, snowmelt, base flow, and channel routing. In addition, guidelines for a sensitivity analysis of the calculated inflow PMF are provided in Section 8-9.6.

8-9.1 Spatial Distribution and Disaggregation of the Probable Maximum Precipitation

To compute the inflow PMF, it is necessary to determine both a temporal and spatial distribution of the PMP on the project basin.

8-9.1.1 Storm Duration

A primary assumption on which this chapter is based is that complete depth-duration information is available for the PMP for both general and local storms, so that the necessary design storms can be constructed. A local storm is one with a relatively small area of influence such as a thunderstorm. Local storms of short duration and high intensity can produce a critical PMF for dams located on very small drainage basins (up to about 1,000 mi^2), or where the antecedent operating level of the reservoir can be higher (such as due to flashboard installations or closure of spillway gates) during the late spring and summer months. In addition, the local season PMP may govern for larger basins with unusual shapes. However, for other small basins, the inflow PMF produced by a long-duration general storm, when routed through the reservoir, will result in higher reservoir levels and may produce the largest rate of outflow. Thus, it is usually necessary to develop inflow hydrographs for both general and local seasonal PMPs to establish the PMF.

8-9.1.2 Storm Spatial Distribution

Basin-average or subbasin-average rainfall must be developed for the PMF model. This will require establishment of a spatial distribution for the PMP within the basin. Rainfall data are seldom available from a large enough number of rain gages to allow construction of an accurate isohyetal map for each historical storm. If a historical storm has been studied by the COE, USBR, USGS, or NWS, isohyetal maps may have been developed from rainfall depth information obtained during "bucket surveys." If isohyetal maps are available for any of the historical extreme storms that have occurred in the area, or if they can be constructed from data available, they could be used in defining the spatial distribution of storm rainfall for the PMP.

Individual storm distribution may be biased because of a singular feature of the storm. For this reason, this chapter recommends that the elliptical isohyetal map produced by the NWS in Hydrometeorological Report No. 52 [NWS 1982] be used in the region east of the 105th meridian. For other areas, refer to the appropriate HMR or site specific study (Figure 8-1.1).

The storm pattern on the basin should be adjusted so that the maximum rainfall volume falls on the drainage basin. In general, this will require that the area of greatest rainfall depth be approximately centered on the basin, and that the storm pattern be rotated so that the basin is covered to the greatest extent possible by the isohyets of greatest rainfall depth. If the basin is subdivided, the peak runoff rate might result from a different centering. A sensitivity analysis is required to determine the critical centering of the PMS to optimize the storm's spatial distribution. Generally, a storm centered over the middle of the basin will produce the PMF with the largest volume. A storm centered closer to the dam may produce a higher peak discharge and may result in a higher maximum water surface elevation. Other basin characteristics reflected in the model, such as loss rates, unit hydrograph parameters, basin subdivision, and subbasin or basin shape, may have an impact on the optimal storm centering and orientation.

The computer program HMR52, which was developed by the Hydrologic Engineering Center of the COE, can be used to apply the procedures contained in HMR 52 [COE 1984]. In Wisconsin and Michigan, the computer program WMPMS (which is a modified version of HMR52) is available through the Electric Power Research Institute (EPRI). These programs automatically produce a 72-hour storm. However, the storm totals are balanced so that lesser durations are also PMP values for the storm size.

For other locations such as the western states, the areal distribution of the storm cannot be generalized as readily due to orographic influences or unique storm patterns. Dependence must be placed on the patterns produced by the historical storm, mean annual precipitation patterns, or 50-year or longer return period precipitation patterns such as those found in NOAA Atlas 2 (Miller et. al., 1973). If insufficient data exist to provide for development of an isohyetal pattern, a uniform distribution over the basin may be assumed. The method used by the USBR, known as successive subtraction, can be used to advantage [Cudworth 1989]. The successive subtraction technique allows for centering a storm over a subbasin when an isohyetal pattern is not available. This situation is common in the mountainous areas of the western U.S.

8-9.1.3 Temporal Distribution of the Probable Maximum Precipitation

The depth-duration relationship for the PMP should be taken from the envelope curve included in the PMP data. In general, if the peak period of rainfall is placed at the beginning of the storm, the peak rate of runoff will be minimized because the largest rates of infiltration and initial abstraction will act to reduce the peak rate of runoff. For this chapter, it is recommended that the peak 6–hour period of rainfall be placed between the half and two-thirds point of the storm and that the remaining 6–hour increments be arranged in alternating descending order on each side of the peak, beginning with the time period that precedes the peak 6–hour period. Hourly increments of rainfall should be taken from the PMP envelope curve and distributed so as to provide a smooth temporal curve. Reference should be made to the appropriate HMR or site specific study.

8-9.2 Antecedent and Coincident Conditions

The inflow PMF hydrograph that produces the critical conditions within the reservoir and at the dam may depend on either the peak inflow rate or the timing and volume of PMF inflow, depending on the spillway capacity and reservoir storage available at the beginning of the flood. Thus, the inflow PMF hydrograph could result from a high-intensity local storm, or a general storm with a long duration.

Caution: Although it may be possible to assess in advance whether the peak outflow and/or the maximum reservoir water-surface elevation will be produced by a local or a general storm, an inflow hydrograph should be generated and routed through the reservoir for each storm.

8-9.2.1 Antecedent Conditions

<u>What reservoir level is reasonable as the starting elevation when routing the inflow PMF through the reservoir, considering the possibility of antecedent storms</u>? It is advisable to determine if a water resources agency has conducted special regional studies related to antecedent storms. If so, the results should be considered for application. In the absence of antecedent storm information, the following four approaches are recommended as acceptable alternatives:

(1) <u>Consider that the reservoir surface is at a predefined annual maximum level at the start of PMF inflow</u>. It will be necessary to determine the annual maximum reservoir level for each dam, depending on the characteristics of the dam, its spillway and outlet works, and the historical and specified operation plans. For most hydroelectric projects, the annual maximum reservoir level should be defined as the annual maximum normal operating level. If flashboards are normally used on the dam during the time of the PMF, they should be assumed to be in place for the determination of the annual maximum reservoir level. Routing of the PMF through the reservoir should assume that flashboards fail or collapse at their design level.

(2) <u>Use an operating rule curve, when available, to identify the reservoir surface corresponding to the maximum storage level for the season of the controlling PMP</u>. A 100-year, 24-hour storm—using the percentages of the 24-hour maximum temporal distribution developed for the PMP—should be assumed to

end three days prior to the PMP. The runoff hydrograph from this 100-year storm should be routed through the reservoir using established project operating rules, with the beginning reservoir level at the normal maximum storage level for the season. The reservoir level at the beginning of inflow from PMP runoff should be taken as the level produced by the routed inflow from the 100-year storm, but it need not be greater than the annual maximum reservoir level.

(3) Use or develop a wet-year rule curve to establish the reservoir level that would exist at the start of the inflow PMF. To develop this rule curve, assume that the reservoir level at the beginning of the inflow PMF is at the average of the five consecutive, highest wet-year reservoir levels occurring during the season of the critical PMP. The assumed starting level need not be higher than the annual maximum reservoir level.

(4) Analyze historical extreme floods and antecedent storms for the region. A possible procedure can be found in HMR 56 [NWS 1986]. If the analysis shows it is probable that antecedent storms do occur in the region and could significantly influence the maximum reservoir level and the magnitude of the routed PMF outflow, develop a storm that could reasonably be expected to occur antecedent to the PMP as follows:

    (a) Prepare an arithmetic plot of the antecedent storm rainfall expressed as a percentage of the principal storm versus the principal storm rainfall in inches. Draw an envelope line of the maximum values and extrapolate to the estimated PMP depth.

    (b) Plot the number of dry or zero-precipitation days preceding the principal storm rainfall versus the principal storm rainfall amount (in.). Draw a line enveloping these numbers (of days), extending it to the range of the estimated PMP.

    (c) Read a total rainfall depth for the antecedent storm from the plot obtained in step (a) by multiplying the value of the total PMP depth.

    (d) Set the time between the antecedent storm rainfall and the PMP equal to the extended value found in step (b).

    (e) Use both the antecedent storm and the PMP to develop an inflow PMF hydrograph.

Average monthly flow should be obtained for the months during the season when the critical PMP would occur. Tabulated monthly average data are available in USGS water data reports and its web site. The average monthly flow for the month of the critical PMP should be added to the inflow PMF hydrograph before routing through the reservoir. When using HEC-1 this initial flow is the parameter STRTQ. For the case when the basin has been subdivided, the initial flow will already have been added as described in Section 8-9.4. For "ungaged" basins, the average monthly flow per square mile of drainage area, obtained from records for nearby "gaged" basins, should be used to compute the initial flow.

In summary, the hydrologist should make sure that antecedent conditions represent reasonable meteorologic conditions. The report should include meteorological justification for assumed antecedent conditions. The antecedent assumptions should be compatible with the initial reservoir elevation used for routing the PMF. For example, selecting a starting reservoir level based on the annual maximum or a wet-year rule curve assumes that a large storm or snowmelt has occurred prior to the PMF. This may preclude using an initial abstraction to determine excess precipitation during the PMP event since the antecedent condition would have left the soil saturated.

Caution: A reservoir cannot be assumed to be drawn down at the beginning of the PMF unless a drawdown is documented as the normal operating procedure prior to an impending storm for that season. In this case, a lower inflow PMF during a different season may produce a higher reservoir elevation. This should be checked.

8-9.2.2 Coincident Hydrometeorological Conditions

Assume the pertinent physical conditions of soil-moisture content, frozen ground (see Section 8-8), and snowpack water equivalent that could reasonably be expected to occur antecedent to the PMP. If snowpack is apt to exist in at least part of the drainage basin in the season when the critical PMP would occur, an antecedent 100-year snowpack (covering the area that could be subject to snowpack) should be assumed to exist at the time when the PMP occurs (see Section 8-9.2.3).

For basins and seasons where the PMF will have a snowmelt contribution, it is necessary to adopt temperature and snowpack criteria for use in developing the PMF. The following steps should be followed:

- Identify the area that may be covered by snowpack at the time the PMP begins by considering the data on historical snowpack coverage obtained in Section 8-3.
- Assume a 100–year snowpack water equivalent and snowpack areal distribution.

- Develop the coincident temperature sequence and temperature–elevation distribution from data analyzed in Section 8-4. In California and the Northwestern states, the temperature sequence coincident with the PMP can be found in NWS HMR Nos. 58 and 57, respectively. For other areas, the maximum temperature sequence observed in the area for the season of the critical PMP is recommended.

- In areas east of the 103rd Meridian, seasonal PMP values can be obtained from HMR Nos. 33 and 53 where an updated site-specific study of seasonal PMP values is not available.

8-9.2.3 Snowmelt Estimates

Snowmelt during the PMF should be computed using the energy-budget method available in the HEC-1 Flood Hydrograph Package. The energy-budget method is preferable to the degree-day (temperature index) method because the degree-day method was developed specifically for rain-free periods. The energy budget method, on the other hand, was developed for either rain-on-snow or rain-free periods. In the case of a PMS, the heat added to the snowpack by the rain is an important (and sometimes even dominant) melt factor.

The HEC-1 model input calls for several variables, such as shortwave radiation and dewpoint temperature, which may be difficult to estimate. However, the rain-on-snow equation makes several simplifications, leaving only a few input variables that are important to estimate. These are:

- snowmelt temperature
- temperature sequence
- wind speed
- snowpack water equivalent
- rainfall sequence

The snowmelt temperature may be taken to be 32° F. The temperature sequence is selected from historical temperature sequence data, with the qualification that the sequence was associated with the simultaneous occurrence of rainfall and snow on the ground. The maximum historical daily temperature sequence meeting these requirements is assumed to coincide optimally with the PMS. Depending on the depth of the snowpack, the maximum historical temperature sequence data may need to begin as much as 72 hours prior to the start of the PMS, or it may need to begin sometime during the PMS, in order to determine the highest reservoir level. Sensitivity studies of the start of the maximum historical temperature sequence data should normally be done.

In some cases snowpack records will not be available. Water equivalence data are rarely recorded. If total snowpack depth is available, assume a 100-year snowpack for the month of the cool-season probable maximum storm and a starting water equivalence of 30 percent (Gray and Prowse, 1992). If no historical information on snowpack is available, an unlimited water equivalent may be assumed.

Seasonal 100-year, 3-day flood discharges may be used in lieu of the snowmelt component in non-mountainous regions, if temperature sequence data and snowpack depths are absent. This flood is the annual maximum three day consecutive average discharge exceeded with a probability of 0.01. This flow should be added to the normal base flow covering the entire time base of the hydrograph and be combined with seasonal rain on frost-conditioned soils.

Note: The evaluation of two PMF scenario are required in the area west of the Continental Divide. This includes (a) PMP on 100-yr snowpack, and (b) 100-yr precipitation on Probable Maximum Snowpack.

8-9.3 Reservoir and Channel-Routing Approach

Routing of the inflow flood hydrographs from subbasins to the dam site will generally be through natural channels and upstream reservoirs. The following procedures should be used:

- Since level pool routing is less data intensive and simpler to use to route through an upstream reservoir, it is recommended for use in the HEC-1 program. Although dynamic routing is more precise, it is more data intensive to use and must be done outside of HEC-1. Either routing technique is considered appropriate.

- The Muskingum-Cunge method, as incorporated in HEC–1, should be used to perform any channel routing from subbasins to the basin outlet. Cross sections of the channels, along with Manning's roughness coefficients, will be required to use the Muskingum-Cunge routing method. For most cases, cross sections for routing the PMF can be obtained from 7½-minute USGS quadrangle maps. HEC–1 has the capability to compute and combine hydrographs from side areas with the routed channel hydrograph.

Caution: Muskingum-Cunge uses a single (representative) cross section defined by eight coordinate points for each routing reach. The method cannot account for backwater effects and should not be used when attenuation of the hydrograph is expected. An example of where this technique might be used is when translating a hydrograph from an upstream location to a downstream point where off-channel storage is insignificant. Where the intention is to properly model the attenuation of the hydrograph, dynamic-wave routing is the preferred method (e.g., when the river is expanding or contracting or where there is natural storage).

- If evidence is available with regard to channel loss rates occurring during passage of floods, those rates may be used in the routing process. However, their effect is usually small compared to PMF flow and often can be neglected.

- Large natural constrictions should be used as control points for channel routing.

8-9.4 Base Flow Coincident with Probable Maximum Flood

The flow rate in the river for basins or subbasins at the time the PMP begins should be consistent with the antecedent approach selected from Section 8-9.2.1. Average monthly flow should be obtained for the months during the season when the critical PMP would occur. Tabulated monthly average flow data are available in USGS water data reports or from the USGS web site. The average monthly flow for the month of the critical PMP should be used and added to the inflow PMF hydrograph before routing through the reservoir, or combining or routing subbasin hydrographs. When using HEC-1, the initial flow is the parameter STRTQ. For "ungaged" basins, the average monthly flow per square mile of drainage area, obtained from records for nearby "gaged" basins, should be used to compute the required initial base flow. If the 100-year, 3-day snowmelt option, as delineated in Section 8-9.2.3, is used, there is no need for an additional base flow component as that component is already included in the data record used for the statistical analysis.

8-9.5 Inflow PMF Hydrograph

Use the input developed in Sections 8-8 and 8-9.1 through 8-9.4, and run HEC-1 to compute the inflow PMF hydrograph. Whole model verification should be done using historical data as discussed in Section 8-8.3. The procedures of the inflow PMF hydrograph development outlined in this chapter rely on model calibration and verification using historical data. The flood data used for calibration will usually have return periods of less than 100 years. Lag times should be adjusted to account for PMF conditions. A PMP event will produce rainfall intensities much greater than anything previously experienced in the study area. This will shorten lag times so that appropriate adjustments to them are needed for the severe conditions which could be expected in generating the PMF.

8-9.6 Review and Sensitivity Analysis of Representative PMF Hydrograph

The first computed inflow PMF hydrograph should be considered as preliminary. A review of the assumptions considered to have a significant effect on the PMF should be made to assess the sensitivity of the individual parameters on the magnitude of the PMF. The following steps should be performed for each study.

- A sensitivity analysis should be made to determine the degree the PMF is effected by key parameters, such as the time of concentration, loss rates, etc., even if conservative values for those parameters were assumed.

- If the PMF is particularly sensitive to the magnitude of a parameter, the source of the parameter determination should be reviewed to ensure that the chosen value is reasonable.

- The results of the sensitivity analysis and the selection of the sensitive parameters should be documented and justified.

8-10 Reservoir Routing to Obtain the Outflow PMF Hydrograph

The preceding sections led to the development of the inflow PMF hydrograph, which must be routed through the reservoir to determine the maximum reservoir elevation and peak discharge at the dam. Assumptions of reservoir starting elevation and initial outflow must be made.

8-10.1 Initial Assumptions

The following assumptions should be made to route the inflow PMF through the reservoir:

- Use the reservoir area-volume-elevation information as obtained and reviewed in Sections 8-3 and 8-4, respectively.

- Use spillway and outlet-works capacities established in Section 8-4.5.2.

- Use the existing gate operating policy as established in Section 8-4.5.3. Any deviations from the accepted reservoir operations must be reviewed to assure the deviations are within the terms and conditions of the project license. Proposed changes to the operating plan should be discussed with the appropriate Regional Office prior to incorporating the changes into the routing of the PMF. Some of the available computer models are not set up to deal with a gated control spillways. Sensitivity analyses of the simulated gated spillway releases should be developed to determine the outflow discharges due to gate operating changes.

- Considerations regarding reservoir starting elevations were given in Section 8-9.2.1 and should be considered simultaneously with the gate and flashboard operations discussed in Section 8-4.5.3 to determine the critical reservoir starting elevation. If the considerations regarding operation of the gates or failure or removal of flashboards indicate a higher reservoir starting elevation than would be given by the considerations in Section 8-9.2.1, the higher elevation should be used.

8-10.2 Routing Procedures

Level-pool-routing procedures can generally be used. Whether or not level-pool-routing procedures are satisfactory will depend on the unit hydrograph used to develop the inflow PMF hydrograph and the dynamic effect of the reservoir on flood flows. The dynamic effects of the reservoir could be pronounced for large or long and narrow reservoirs, and is usually negligible for small reservoirs. Some adjustment for so-called "wedge storage" during rapidly rising pool levels may be necessary.

Caution: If reverse-reservoir routing was used to develop the inflow hydrograph to the reservoir during passage of the historical floods used in the unit-hydrograph analysis, some of the dynamic effects will have already been implicitly included in the developed inflow PMF hydrograph. Although dynamic effects during passage of a PMF may be more dramatic than during the analyzed historical floods, they are satisfactorily approximated in the reverse-reservoir routing process. Level-pool-routing procedures can be used in these situations.

An alternative is to use a distributed inflow procedure where all inflows to the reservoir rim are estimated. This requires developing inflow PMF hydrograph at all major tributaries and the direct rainfall on the reservoir. The inflows are then routed through the reservoir using dynamic routing procedures or simple translation with timing based on wave celerity calculations. Dynamic reservoir flood routing procedures—although mathematically complex and sometimes difficult because of numerical instability—can be accomplished using the NWS unsteady routing program DAMBRK (Fread 1989) or FLDWAV (Fread 1997).

The flood-passage operations should be reviewed after the initial routing of the inflow PMF to assess the sensitivity of the resulting maximum outflow rate and reservoir elevation to the assumed reservoir starting elevation.

8-10.3 Reporting Requirements

As a general rule for preparing reports, sufficient documentation should be provided to allow the FERC staff to verify the reasoning and check the analyses of the PMF estimate. Using the recommended report format (Appendix B) will help provide the necessary level of information on each component of the study. Input and output files for computer analysis should be provided as printout in submittals and also on 3.5-inch diskettes or CD-ROM. If programs are used that are not readily available or not in common use, the FERC staff might request code documentation, users manuals, and an executable version.

8-11 References

American Meteorological Society (1959), Glossary of Meteorology, Boston, Massachusetts.

American Public Health Association, etc. (1981), Glossary Water and Wastewater Control Engineering, Washington, D. C. 20037

American Society of Civil Engineers (ASCE) (1996), Hydrology Handbook, New York, New York

Bailey, S.M. and G.R. Schneider (1939), "The Probable Maximum Flood and its Relation to Spillway Capacity," Civil Engineering, Vol. 9, No. 1, American Society of Civil Engineers, New York, New York.

Barnes, H.H. (1967), Roughness Characteristics of Natural Channels, Geological Survey Water Supply Paper 1849, United States Department of Interior, Geological Survey, Branch of Distribution, Arlington, Virginia.

Blackburn, W.H. and M.K. Wood (1990), "Influence of Soil Frost on Infiltration of Shrub Coppice Dune and Dune Interspace Soils in Southeastern Nevada," Great Basin Naturalist 50(1):41-46.

Bradley, J.N. (1952), "Discharge Coefficients for Irregular Overflow Spillways," United States Bureau of Reclamation Engineering Monograph No. 9, Denver Federal Center, Denver Colorado.

Burnash, J.C., R.L. Ferral, and R.A. McGuire (March 1973), "A Generalized Streamflow Simulation System; Conceptual Modeling for Digital Computers," Joint Federal-State River Forecaster Center, United States Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, and State of California, Department of Water Resources.

Chow, V.T. (1959), "Open-Channel Hydraulics," McGraw Hill, Inc.

Clark, C.O. (1943), "Storage and the Unit Hydrograph," Transactions of American Society of Civil Engineers, Vol. 108.

Crawford, N.H. and R.K. Linsley (July 1966), "Digital Simulation in Hydrology: Stanford Watershed Model IV," Technical Report No. 39, Stanford University, Department of Civil Engineering.

Cudworth, A.G. (1989), Flood Hydrology Manual, United States Department of the Interior, Bureau of Reclamation, Denver Federal Center, Denver, Colorado.

Electric Power Research Institute (EPRI), (1993). Probable Maximum Precipitation Study for Wisconsin and Michigan (Research Project 2917-29). Volume 1–Prepared by North American Weather Consultants. Volume 2–Prepared by Mead & Hunt, Inc.

Ely, P.B. and J.C. Peters (1984), "Probable Maximum Flood Estimation - Eastern United States," Paper No. 84017, Water Resources Bulletin, Vol. 20, No. 3.

Engelmark, H. (1987), "Rate of Infiltration into Frozen and Unfrozen Fine Sand," Canadian Journal of Earth Sciences, 25:343-347.

Federal Emergency Management Agency (1991), Probable Maximum Precipitation and Probable Maximum Flood Workshop, Proceedings of the Workshop, May 1-4, Washington, D.C.

Fetter, C. W. (1988), Applied Hydrogeology, Macmillan Publishing Company, New York, New York

Fread, D. (1989), The NWS DAMBRK MODEL: Theoretical Background/User Documentation, Hydrologic Research Laboratory, Office of Hydrology, United States National Weather Service, National Oceanic and Atmospheric Administration, Silver Spring, Maryland.

Gray, Don M. and Terry D. Prowse (1992), "Snow and Floating Ice," Chapter 7 in Handbook of Hydrology, David Maidment, Ed. McGraw-Hill Publishers, 1982.

Hathaway, G. (1939), "The Importance of Meteorological Studies in the Design of Flood Control Structures," Bulletin of the American Meteorological Society, Vol. 20, pp. 248-253.

Hathaway, G. (1944), "Discussion of the Primary Role of Meteorology in Flood Flow Estimating," Transactions of American Society of Civil Engineers, Vol. 109.

Henderson, F. M. (1966), Open Channel Flow, University of Canterbury, Christchurch, New Zealand

Hershfield, David M. (1961), Technical Paper No. 40 - Rainfall Frequency Atlas of the United States, Engineering Division, Soil Conservation Service, United States Department of Agriculture.

Hoggan, D.H. (1989), Computer Assisted Flood Plain Hydraulics, McGraw-Hill Publishing Company, New York, New York.

Hydrologic Engineering Center (1990), HEC-1, Flood Hydrograph Package, User's Manual, U.S. Army Corps of Engineers, Davis, California.

Hydrologic Engineering Center (1990), HEC-2, Water Surface Profiles, User's Manual, U.S. Army Corps of Engineers, Davis, California.

Hydrologic Engineering Center (1984), HMR-52, Probable Maximum Storm (Eastern United States), U.S. Army Corps of Engineers, Davis, California.

Hydrologic Engineering Center (1982), Training Document No. 15, Hydrologic Analysis of Ungaged Watersheds Using HEC-1, U.S. Army Corps of Engineers, Davis, California.

International Commission on Large Dams (1991), "Selection of Design Flood," Bulletin 82, Paris, France.
Kane, D.L. and J. Stein (1983), "Water Movement into Seasonally Frozen Soils," Water Resources Research, 19(6):1547-1557.

King, H.W. and E.F. Brater (1954), Handbook of Hydraulics, McGraw Hill, Inc., New York, New York.

Linsley, Ray K., Jr. and Joseph B. Franzini (1979), Water Resources Engineering, 3rd edition, McGraw-Hill Inc., New York, New York

Linsley, Ray K., Jr., Max A. Kohler and Joseph L. H. Paulhus (1975), Hydrology for Engineers, 2nd edition, McGraw-Hill Inc., New York, New York

Maidment, David R., Editor in Chief (1993), Handbook of Hydrology, McGraw Hill Inc., ISBN 0-07-039732-5. See page 10.3, Routing Model Selection, by D.L. Fread.

McCuen, Richard H. (1998), Hydrologic Analysis and Design, Prentice-Hall, Inc., Upper Saddle River, New Jersey

Mead, D.W. (1908), Water Power Engineering, McGraw Hill Book Company, New York, New York.

Miller, J.F., Frederick, R.H. and Tracey, R.S. (1973), NOAA ATLAS 2, Precipitation–Frequency Atlas of the Western United States, Volume IX–Washington, United States Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Washington, D.C.

Myers, V.A. (1967), "The Estimation of Extreme Precipitation as the Basis for Design Floods, Resume of Practice in the United States," Proceedings of the Leningrad Symposium, Floods and Their Computation, International Association of Scientific Hydrology, August.

Morgan, A.E. (1914), "Discussion on Flood Flows," Transactions of American Society of Civil Engineers, Vol. 77, American Society of Civil Engineers, New York, New York.

National Cartography and GIS Center (1994), State Soil Geographic (STATSGO) Data Base - Data use information, United States Department of Agriculture, Natural Resources Conservation Service, Fort Worth, Texas

National Weather Service (1956), Seasonal Variation of the Probable Maximum Precipitation East of the 105th Meridian for Areas from 10 to 1,000 Square Miles and Durations of 6, 12, 24, and 48 Hours, Hydrometeorological Report No. 33, United States Department of Commerce, National Oceanic and Atmospheric Administration, United States Weather Bureau, Washington, D.C.

National Weather Service (1963), Hydrometeorological Report No. 39, Probable Maximum Precipitation in the Hawaiian Islands, United States Department of Commerce, National Oceanic and Atmospheric Administration, United States Weather Bureau, Washington, D.C.

National Weather Service (1964), Hydrometeorological Report No. 40, Probable Maximum Precipitation over the Susquehanna River Basin above Harrisburg, Pennsylvania, United States Department of Commerce, National Oceanic and Atmospheric Administration, United States Weather Bureau, Washington, D.C.

National Weather Service (1965), Hydrometeorological Report No. 41, Probable Maximum Precipitation Over the Tennessee River Basin Above Chattanooga, United States Department of Commerce, National Oceanic and Atmospheric Administration, United States Weather Bureau, Washington, D.C.

National Weather Service (1973), Hydrometeorological Report No. 47, Meteorological Criteria for Extreme floods for Four Basins in the Tennessee and Cumberland River Watershed, United States Department of Commerce, National Oceanic and Atmospheric Administration, United States Weather Bureau, Washington, D.C.

National Weather Service (1973), Hydrometeorological Report No. 48, Probable Maximum Precipitation and Snowmelt Criteria for Red River of the North above Pembina, and Souris River above Minot, North Dakota, United States Department of

Commerce, National Oceanic and Atmospheric Administration, United States Weather Bureau, Washington, D.C.

National Weather Service (1977), Hydrometeorological Report No. 49, Probable Maximum Precipitation Estimates, Colorado River and Great Basin Drainages, United States Department of Commerce, National Oceanic and Atmospheric Administration, United States Weather Bureau, Washington, D.C.

National Weather Service (1978), Hydrometeorological Report No. 51, Probable Maximum Precipitation Estimates–United States East of the 105th Meridian, United States Department of Commerce, National Oceanic and Atmospheric Administration, United States Weather Bureau, Washington, D.C.

National Weather Service (1982), Hydrometeorological Report No. 52, Probable Maximum Application of Precipitation Estimates–United States East of the 105th Meridian, United States Department of Commerce, National Oceanic and Atmospheric Administration, United States Weather Bureau, Washington, D.C.

National Weather Service (1980), Hydrometeorological Report No. 53, 1980 Seasonal Variation of 10-Square-Mile Probable Maximum Precipitation Estimates, United States East of the 105th Meridian, United States Department of Commerce, National Oceanic and Atmospheric Administration, United States Weather Bureau, Washington, D.C.

National Weather Service (1983), Hydrometeorological Report No. 54, Probable Maximum Precipitation and Snowmelt Criteria for Southeast Alaska, United States Department of Commerce, National Oceanic and Atmospheric Administration, United States Weather Bureau, Washington, D.C.

National Weather Service (1988), Hydrometeorological Report No. 55A, Probable Maximum Precipitation Estimates–United States Between the Continental Divide and the 103rd Meridian, United States Department of Commerce, National Oceanic and Atmospheric Administration, United States Weather Bureau, Washington, D.C.

National Weather Service (1986), Hydrometeorological Report No. 56, Probable Maximum Precipitation Estimates with Areal Distribution for Tennessee River Drainages Less Than 3,000 Square Miles in Area, United States Department of Commerce, National Oceanic and Atmospheric Administration, United States Weather Bureau, Washington, D.C.

National Weather Service (1994), Hydrometeorological Report No. 57, Probable Maximum Precipitation for the Pacific Northwest, United States Department of Commerce, National Oceanic and Atmospheric Administration, United States Weather

Bureau, Washington, D.C., October 1994.

National Weather Service (1998), Hydrometeorological Report No. 58, Probable Maximum Precipitation for California, United States Department of Commerce, National Oceanic and Atmospheric Administration, United States Department of the Army, Corps of Engineers, Silver Spring, MD, October 1998.

National Weather Service (1999), Hydrometeorological Report No. 59, Probable Maximum Precipitation for California, United States Department of Commerce, National Oceanic and Atmospheric Administration, U.S. Department of the Army, Corps of Engineers, Silver Spring, MD., February 1999.

National Weather Service (1961), Technical Paper 42, Generalized Estimate of Probable Maximum Precipitation and Rainfall Frequency Data for Puerto Rico and Virgin Islands, United States Department of Commerce, National Oceanic and Atmospheric Administration, United States Weather Bureau, Washington, D.C.

National Weather Service (1963), Technical Paper 47, Probable Maximum Precipitation and Rainfall–Frequency Data for Alaska, United States Department of Commerce, National Oceanic and Atmospheric Administration, United States Weather Bureau, Washington, D.C.

Newton, Donald W. (1983), "Realistic Assessment of Maximum Flood Potentials," Journal of the Hydraulics Division, American Society of Civil Engineers, Volume 109, No. 6, June 1983, figures 4 and 5, page 911.

Pilgrim, D.H., I.A. Rowbottom, and G.L. Wright (1988), "Estimation of Spillway Design Floods for Australian Dams," Transactions, 16th Congress of the International Commission on Large Dams, San Francisco, California.

Post, F.A. and F.R. Dreibelbis (1942), "Some Influences of Frost Penetration and Microclimate on the Water Relationships of Woodland, Pasture and Cultivated Soils," Soil Science Proceedings, 7:95-104.

Snitter, N.J. (1979), Transactions of the 13th Congress, New Delhi, India, International Commission on Large Dams, Paris, France.

Snyder, F.F. (May 1964), "Hydrology of Spillway Design: Large Structures - Adequate Data," Proceedings of the American Society of Civil Engineers, Journal of the Hydraulics Division, New York, N.Y.

Snyder, F.M. (1938), "Synthetic Unit Graphs," Transactions of the American Geophysical Union, Vol. 19.

Soil Conservation Service (1985), National Engineering Handbook, "Section 4, Hydrology," United States Department of Agriculture, Washington, D.C.

Soil Conservation Service (1986), "Urban Hydrology for Small Watersheds," Technical Release No. 55, (TR-55), Washington, D.C.

Trimble, G.R., T.S. Sartz, and R.S. Pierce (1987), "How Type of Soil Frost Affects Infiltration," Journal of Soil and Water Conservation, 13(1):81-82.

U.S. Army Corps of Engineers (1946), Engineering Manual for Civil Works, Part 2, Chapter 5, Washington, D.C.

U.S. Army Corps of Engineers (1960), Runoff from Snowmelt, Superintendent of Documents, Washington, D.C.

U.S. Army Corps of Engineers (1987), Hydraulic Design Criteria, Waterways Experiment Station, Vicksburg, Mississippi.

United States Department of Agriculture (1955), Yearbook of Agriculture, Washington, D.C.

United States Department of the Interior, Bureau of Reclamation (1987), Design of Small Dams, Denver, Colorado

United States Geological Survey (1982), Water-Resource Investigations 82-13, "Time of Concentration and Storage Coefficient Values for Illinois Streams," (J.B. Graf, G. Garklavs, and K.A. Oberg), Water Resources Division, Urbana, Illinois.

United States Geological Survey (1988), Water Supply Paper 2339, "Guide for Selecting Roughness Coefficients for Natural Channels and Flood Plains," Washington, D.C.

United States Geological Survey (1986), Water Resources Investigations Report 86-4192. "Techniques for Simulating Flood Hydrograph and Estimating Flood Volumes for Ungaged Basins in Central Tennessee," (C.H. Robbins), Water Resources Division, Nashville, Tennessee.

United States Geological Survey (1986), Water Resources Investigations Report 86-4004. "Simulation of Flood Hydrograph for Georgia Streams," (E.J. Inman), Water Resources Division, Doraville, Georgia.

United States Geological Survey (1988), Water Resources Investigations Report 88-404. "Estimating Flood Hydrograph and Volumes for Alabama Streams," (D.A. Olin and J.B. Atkins), Water Resources Division, Tuscaloosa, Alabama.

United States Geological Survey (1990), Water Resources Investigations Report 89-4087. "Determination of Flood Hydrograph for Streams in South Carolina," (L.R. Bohman), Water Resources Division, Columbia, South Carolina.

World Meteorological Organization (1986), "Manual for Estimation of Probable Maximum Precipitation," Operational Hydrology Report No. 1, Secretariat of the World Meteorological Organization, Geneva, Switzerland.

Zuzel, J.F. and J.L. Pikul, Jr. (1987), "Infiltration into a Seasonally Frozen Agricultural Soil," Journal of Soil and Water Conservation, 42:447-450.

8-12 Glossary

Some hydrologic terms have slightly different definitions depending upon the agency using them. These terms have been defined on the basis of the meaning used in these Guidelines.

Accuracy - The state of being free from errors, i.e. the absolute nearness to the truth. In physical measurements, it is the degree of agreement between the quantity measured and the actual quantity. For example, clock records of rainfall and streamflow can be out of synchronization, implying that measured time is not accurate. The prediction accuracy of a rainfall-runoff model should not be confused with "precision," which denotes the reproducibility of the measurement or computation and its refinement, e.g. 0.001, 0.01, 0.1, or 0.

Active Storage - That portion of reservoir storage which is filled and emptied from year to year as the reservoir is operated normally.

Altitude-Depth Relationship - A relationship between snowpack water equivalent and elevation for a given drainage basin.

Antecedent Moisture Condition (AMC) - The degree of wetness of a watershed at the beginning of a storm. Three levels of AMC are designated as AMC-I, AMC-II, and AMC-III. AMC-I is the lower limit of moisture; AMC-II is the average moisture; and AMC-III is the upper limit of moisture with relatively small, medium, and large curve numbers (CNs), respectively.

Antecedent Storm - A storm that occurred prior to the storm of interest.

Baseflow - The streamflow rate occurring during recession of a hydrograph. Baseflow is separate from direct runoff.

Basin - The surface area within a given drainage system.

Basin-Averaged (Uniform Infiltration Loss Rate) Method (or Basin-Approximate Method) -
The method is the most practical approach to estimate the area-weighted constant loss rate of soils for a (sub)basin. Particularly for PMF runoff computations, the soil should be assumed to be saturated with infiltration occurring at the minimum rate that has been empirically determined in relation to the hydrologic soil group from USDA [1955] literature. The spatially average soil classification should be established for the drainage area that can be identified with a SCS Hydrologic Soil Classification (A, B, C, or D).

Basin Average Rainfall - The spatially averaged rainfall depth within a drainage basin for a particular given total storm or time increment of that storm.

Basin (or Watershed) Characteristics - The physical characteristics of a drainage basin that control its average hydrologic response in terms of runoff. These characteristics include watershed relief (the most common parameters are channel slope, watershed slope, and hypsometric curve; the greater the relief, the shorter the time of concentration, Tc), watershed shape, direction, altitude, drainage pattern, land use and soil type, time of flow parameters (commonly including Tc, time lag, reach travel times, etc.), storage and vegetation within channels, etc.

Bucket Surveys - Supplemental "unofficial observations" (e.g., observations made by individuals, radio and TV stations, and city and county public works departments) surveys of precipitation data conducted immediately after the occurrence of severe storm and flood events. The bucket surveys are beneficial as the network of precipitation stations is still far from sufficient to provide the necessary temporal and spatial data for detailed analyses of observed storm precipitation.

Calibration - A process of adjusting input parameters of a rainfall-runoff model within physical limits using a 'trial-and-error" procedure to compare the output of the computed hydrograph with the observed hydrograph or measured values until the model satisfactorily or most closely simulates a hydrologic system it represents.

Channel Slope - The gradient measured by drop in elevation over channel distance, in foot per foot. The application should be consistent with the methodology.

Channel Storage - The total volume of flowing water in the stream channel under consideration during a period of time, or the in-channel stored water volume depending on the stage of the water surface in the channel under consideration at any time.

Clark Unit Hydrograph - A synthetic unit-hydrograph developed by C.O. Clark for which two parameters Tc and storage coefficient (R), and a time area curve are estimated to account for storage in the basin as well as movement of runoff by translation of the flood wave. This method uses the concept of the instantaneous unit hydrograph to define a unique unit hydrograph for a gaged or ungaged basin.

Coefficient of Determination (r^2) - A measure of the degree to which a regression line explains the variance in the dependent variable.

Composite Unit Hydrograph - The unit hydrograph developed from the unit hydrograph generated from historical storms and flood data. It is the unit hydrograph judged to be representative of the hydrologic response of the drainage-basin system.

Consistency - The status of agreement or compatibility among hydrologic data if no unusual changes or are present in the data.

Continuity - An uninterrupted succession of a record if the record contains no periods for which data are missing. If data collection is based on a certain frequency, this process may result in missed observations of significant events; such as daily flow measurements at set times may miss peak values.

Continuous Streamflow Hydrograph - A hydrograph formed from continuous stage recording at a streamgage.

Contributing Area - The total area from which surface water commonly is removed by gravity to the outlet in a drainage basin.

Cross Section - A vertical section taken across a stream channel or a reservoir, usually used to determine flow area and hydraulic radius for flow routing.

Daily Flow Records - A record of average daily flows at a streamgage.

Degree-Day Method - A method to calculate snowmelt in terms of a degree-day factor [HEC 1990] determined from measured snowpack, runoff, and temperature for a historical storm. Degree-day is defined as a day with an average temperature on degree above 32 degrees F. The average is usually obtained by averaging the maximum and minimum for the day.

Design Flood - The flood hydrograph for which a given project and its appurtenances are designed.

Dimensionless Unit Hydrograph - A unit hydrograph whose vertical and horizontal coordinates have been made dimensionless by dividing by the hydrograph peak flow and the time to peak, respectively.

Disaggregation - The process of converting rainfall depths for one increment of time to the incremental depths for smaller increments of time.

Distributed (Uniform Infiltration Loss Rate) Method (or Detailed Method) - The method is an approach to estimate loss rates for the (sub)basin based on physical soil properties using spatially detailed soils and land cover maps of the basin. Theoretically, any measure of loss estimation may be applied in a distributed fashion. For instance, the STATSGO's hydrologic soil groups or soil series or digital data of similar (or finer if available) spatial resolution can be used to apply the distributed loss method. This method allows the hydrologist to calibrate loss rates (if the (sub)basin gaged) on the basis of permeability of each soil type, modified as necessary for other factors, such as bedrock, groundwater conditions, AMC, land cover, land features, etc., that may affect runoff.

Distributed-Parameter Models - Rainfall-runoff simulation models that account for spatial variations in hydrologic parameters from point to point throughout a drainage basin. These models can also minimize the effect of lumpimg watershed characteristics such as soil types, soil profiles, impervious areas, and land uses into single parameters representing the entire catchment.

Double-Mass Analysis - A plot of accumulated rainfall depth for one raingage against average accumulated depth at another gage (or group of gages) in the same climatic area used to detect trends or inconsistencies within the data.

Drainage Area - The area of a drainage basin.

Drainage Basin - The area contributing direct runoff to a stream. Specifically, the delineated land bounded by a hydrologic surface drainage divide (or topographic divide, i.e., the line that follows the ridges or summits forming the exterior boundary of a drainage basin), from which surface runoff is drained to a point of interest (i.e., the outlet) on a watercourse. Also called a drainage area or a catchment (i.e., the land tributary to a stream) for some cases or, on a large scale, a watershed.

Drainage Pattern - An indicator of the drainage flow characteristics of storm runoff in a basin, which can be represented by a number of parameters such as drainage density, Horton's laws, etc.

Duration - The length of an actual or assumed period of time over which rainfall or rainfall excess occurs.

Dynamic Effects - The effects on a channel or reservoir inflow hydrograph caused by several factors which generally are considered in an unsteady flow's continuity and momentum equations, including flood-wave wedge storage, water surface rate-of-rise, lateral local inflow per unit distance, local acceleration, convective acceleration, etc.

Dynamic Wave - The wave resulting from a change in flow rate in an open channel with the movement properties principally following the continuity and momentum (i.e., inertial influences also considered) equations. It is a wave whose behavior is dependent not only on depth, but on effects of local and convective acceleration.

Dynamic (i.e. unsteady) Reservoir Flood Routing - The flood routing procedures through a reservoir using momentum and continuity equations by considering dynamic effects as a large inflowing flood wave passes through the reservoir pool.

Emergency Gate Operation - The operation of gates on a controlled spillway when there is danger of the dam being overtopped if the gates are not opened sufficiently or for an emergency situation.

Energy-Budget Method - A method to calculate snowmelt due to heat transferred from rain and the environment to the snowpack. Energy inputs to the snowmelt process are longwave and shortwave (solar) radiation, convection, release of heat due to condensation, ground heat, and heat introduced by rain (U.S. Army Corps of Engineers, 1956).

Envelope Curve - A smooth curve covering all peak values of rainfall plotted against other factors, such as area or time.

Extreme (or Major) Flood - A flood whose peak flow is significantly larger than most historical floods.

Flashboards - Structures which temporarily raise the crest of an overflow spillway. Usually the flashboards are made from wooden planks supported by structural members.

Flood - A runoff event that causes a river or reservoir to rise above normal nondamaging limits

Flood Hydrograph - A record of continuous streamflow versus time for a given flood at a selected location on a stream.

Flood Peak - The highest flow discharge attained during the passage of a flood wave

Flood Routing - The process of progressively determining the timing and shape of a flood wave at successive points along a river to estimate the outflow flood at a downstream point from the inflow flood at an upstream point. Flood routing methods may be classified as either hydrologic routing (i.e., lumped flow routing) or hydraulic routing (i.e., distributed flow routing). Basically, in hydrologic routing, the flow is computed as a function of time at one location along the watercourse. However, in hydraulic routing, the flow is computed as a function of time simultaneously at several cross sections. Some typical, well accepted hydrologic routing methods include Muskingum River and level-pool reservoir routing methods and hydraulic routing methods include Muskingum-Cunge and dynamic-wave routing methods.

Flood Storage - That portion of reservoir storage which is expressly reserved for storage of flood water.

Flood Wave - A large moving swell of water on the surface of a water body. Specifically, it is a distinct rise in streamflow to a crest in response to runoff generated by precipitation or melting snow and its subsequent recession after the precipitation or melting snow ends.

Front - The interface between two air masses of different density. When a front is moving in the direction from cold air to warm, a cold front results, and vice versa.

Gaged Basin - A watershed where available hydrologic data, recorded at stations within the basin, are sufficient in quantity and quality to provide confidence in development of a hydrograph at the drainage-basin outlet.

General Storm - A storm caused by a frontal movement which generally covers a large area (ranging from over 500 up to 60,000 mi^2) and has a duration longer than 6 hours.

Geographic Information System (GIS) - An electronic system of maps (points, lines, and polygons) connected to tables of data that describe the features on the maps with the ability of managing (capture and storage), manipulating (retrieval and analysis), and displaying spatial data. For instance, the integration of GIS with the curve number model is an example of a GIS application to determine curve numbers for runoff analysis through processing spatial data such as land use, land cover, hydrologic soil group, slope, and other factors varying across a drainage basin by applying GIS overlay with the NRCS' STATSGO.

High-Water Mark - A mark which identifies the maximum stage which occurred at a particular location during an historical flood.

Homogeneous Data - Hydrologic data that all comes from the same phenomena during the same time period.

Hydraulics - The physical science and technology of the static and dynamic behavior of water or other fluids; about dealing with fluid properties, or the mechanism (i.e., a system of governing physical laws) of fluid flows or forces and its applications in engineering.

Hydrograph - Rate of flow in a stream plotted against time for a particular section.

Hydrology - The scientific study of water on and within the earth and related applications; about dealing with water's occurrence, quantification, spatial and temporal distributions, circulation, interactions with its environments such as ground surface, underground media, atmosphere, etc.

Hydrologic Characteristics - The physical characteristics of precipitation (e.g. mean or isohyetal, intensity, duration, frequency, etc.), evapotranspiration, and streamflow (e.g. monthly and annual volumes, low-flow rates, floods, etc.) in a given drainage basin. The primary controlling features of these characteristics are the basin's physiographic regions and climatic patterns.

Hydrologic Condition - The feature (or factor) of land cover that can influence infiltration based on the status of treatment or practice of the surface vegetation when the SCS CN method is used to estimate runoff. The hydrologic condition usually is classified as good, fair, or poor to reflect a relatively low, average or high CN or runoff, respectively.

Hydrologic Soil Groups - The classified four groups of soils (A, B, C, D) that are designated by SCS to indicate the degree of runoff potential, very low, low, moderate, and high as their infiltration rate are high, moderate, slow and very slow infiltration rates under similar storm and cover conditions, respectively.

Hydrologic Units (HU) - Subbasins or subwatersheds. Each HU is the drainage area of a minor tributary flowing into the main stream or a major tributary.

Hydrometeorology - The interdisciplinary science of meteorology and hydrology related to the occurrence of extreme rainfall and extreme floods.

Hydrometeorological Report - Name given to a set of National Weather Service publications. These publications contain generalized studies of extreme rainfall for a given region. Such reports provide generalized information for estimating probable maximum precipitation of a particular duration for given locations within the region.

Hyetograph - A graph of incremental rainfall depth, rainfall excess, or both versus time at a sampling point or for a drainage basin.

Infiltration Capacity - The maximum rate at which the soil, when in a given condition, can absorb falling rain or melting snow. The infiltration capacity depends on (a) basin characteristics such as soil type, land use, and vegetation cover; (b) climate characteristics such as rainfall intensity, temperature; and (c) underlying geological conditions.

Infiltration Rate - The rate at which rainfall is absorbed through the soil surface and into the subsoil. It must equal the infiltration capacity or the rainfall rate, whichever is lesser. It is expressed in depth of water per unit time (usually inches per hour). The infiltration rate is determined by the smaller of either the entry (or penetration) rate at which water enters the surface of the soil or the transmission rate at which the water percolates the soil in either the vertical or horizontal direction in a given drainage area. The infiltration rate is varied until it reaches the given soil's ultimate minimum infiltration capacity (an approximate constant rate) under a fully saturated condition.

Inflow PMF Hydrograph - The hydrograph which represents PMF runoff entering a reservoir.

Initial Abstraction (or Loss) - The portion of rainfall on a basin that is intercepted by vegetation, held in derpressions, or evaporated.

Initial (or starting) Flow - The streamflow equal to the subsurface flow (i.e. without direct runoff) at the time when a hydrograph simulation begins. In HEC-1, the initial flow is the variate (i.e. random variable) designated as the STRTQ that does not necessarily start from the streamflow without direct runoff.

Interflow - Water that infiltrates the soil and reappears as seepage or spring flow during the period of runoff. Interflow is also called a rapid subsurface flow or subsurface runoff.

Isohyet - A line on a map, connecting points of equal rainfall amounts. Isohyets are used to develop an isohyetal map of single storm or annual rainfall depths for given time intervals.

Isohyetal Pattern - Spatial distribution of rainfall represented by lines of equal rainfall depth (isohyets).

Kinematic Wave - The wave resulting from a change in flow rate in an open channel with the movement property principally following from the equation of continuity. The velocity of the wave is proportional to the change in depth.

Lag Time (T_L) - The time which locates the runoff hydrograph relative to the occurrence of a storm. Lag time generally is determined as the difference in time between the centroid of rainfall excess and the peak of the runoff hydrograph, for instance, T_L applied in the Snyder or the NRCS dimensionless unit hydrograph methodologies. However, definitions of T_L differ depending on the methodology used. In the SCS dimensionless unit hydrograph method for example, the average relation of lag time to time of concentration is $T_L = 0.6\ T_c$.

Land Cover - The extent and type of vegetation covering the drainage basin.

Lapse Rate - The rate at which air temperature decreases with increasing altitude within a given drainage basin.

Level-Pool (Reservoir) Routing - The reservoir flood routing technique which assumes the reservoir always has a horizontal water surface throughout its length. That is, the reservoir is sufficiently large that the inflow has a negligible effect on the outflow.

Local Storms - Thunderstorms resulting from local convection which covers a limited area, generally not more than 500 mi^2.

Loss Rate - The rates of infiltration for a given soil type.

Lumped-Parameter Models - Rainfall-runoff simulation models that ignore spatial variations in hydrologic parameters throughout a drainage basin. A typical example of a lumped parameter is the time of concentration which is held constant for all storms to compute a unit hydrograph.

Manning Equation - The following equation for calculation of the average uniform velocity in an open channel $V = 1.486/n * R_H{}^{2/3} * S^{1/2}$ where V is the average velocity, R_H is the hydraulic radius for the section, S is the average slope of the channel, and "n" is a coefficient reflecting the roughness of the channel. The equation should be applied to segments of the channel that have constant slopes and gradually varying geometric characteristics.

Manning's "n" - The coefficient used in the denominator of the Manning equation to represent the effect of channel roughness.

Maximum Normal Operating Level - The maximum reservoir water-surface elevation which a hydroelectric project is normally operated during the year.

Maximum Possible Flood - An earlier term used to describe the Probable Maximum Flood.

Maximum Probable Precipitation - An earlier term used to describe the Probable Maximum Precipitation.

Minimum Infiltration Rate - The minimum rate at which infiltration occurs after the soil is saturated. This minimum rate is governed by the rate at which precipitation can enter the soil surface and percolate to the subsurface.

Model - A physical process-simulation system that accounts for all of its known properties by relating known inputs with outputs. In mathematical (or digital) models (or formulations), the behavior of the system is represented with a set of equations that numerically simulate the system behavior to predict hydrologic events resulting from representative future hydrologic inputs. Alternative mathematical models of hydrologic processes from various approaches have been produced to reproduce the historical record in a statistical sense.

Nonlinear Effects - The tendency for a drainage basin to yield peak flows for greater depths of storm runoff which are larger than a linear proportion would indicate.

NEXRAD (Next Generation Weather Radar) Precipitation Data - The precipitation measurement obtained by using a radar system with hydrometeorological capabilities of collecting information for gage-adjusted radar-rainfall estimate. The most important advantage of using radar measurement of rainfall is the coverage that the radar system provides of a large area for precipitation estimation with high spatial and temporal resolution as small as 6 minute time interval and 4 km^2 area, respectively.

Operation Rules - The rules by which controlled spillways and outlet works are operated.

Optimization Process - The process of determining a set of parameters that best replicates an observed runoff hydrograph for a drainage basin. The HEC-1 program has an automatic process built into the program which performs such an optimization.

Orographic Effects - The effects of topographic variations on precipitation.

Overland Flow - Runoff flowing over the surface of a drainage basin prior to reaching a channel.

Peak Flow - The maximum flow rate on a runoff hydrograph.

Permeability (or Permeability Coefficient) (k) - The capacity (or ability) of a geologic material (e.g., soil) to transmit water through it or the quality of the soil that enables water to move through it while overcoming surface tension and any other capillary actions under given water and soil properties. It is expressed in water transmission distance per unit time (usually inches per hour). Historically SCS' soil survey has used "vertical" permeability as a term for saturated hydraulic conductivity that is an estimate of vertical water movement in the given soil column under a saturated condition at a temperature of 60 degrees F. The degree of permeability depends upon the size and shape of the opening and the extent of the interconnections of permeable substance. For example, a high permeability occurs for soils having a large porosity, such as sands and gravels.

Preliminary Data - Physical and hydrologic data collected for a given project and its drainage basin prior to making a visit to the site.

Probable Maximum Flood (PMF) - The flood that may be expected theoretically from the most severe combination of critical meteorologic conditions that usually produce the PMP and critical hydrologic conditions that are reasonably possible in the drainage basin under study.

Probable Maximum Precipitation (PMP) - The greatest depth of precipitation theoretically for a given duration that is physically possible over a given size storm area at a particular geographical location during a certain time of year.

Probable Maximum Storm (PMS) - A total design storm that has been adjusted, realistically patterned (spatially-temporally) on the basis of recorded storms, to a single PMP area size and duration deemed critical.

Rainfall Excess - The part of the rainfall appearing as direct runoff which is not lost to infiltration, depression storage, and interception. (In comparison, effective rainfall includes rainfall excess and interflow)

Rainfall Sequence - The sequence of incremental rainfall depth used to develop a runoff hydrograph resulting from the storm.

Rating Curve - A relationship between stage and flow rate developed for a particular streamgage location.

Recession - The portion of the hydrograph showing a decline in the rate of runoff.

Reconstitution - The analytical process of using a developed unit hydrograph and historical storm rainfall to reproduce a historical flood hydrograph.

Redundant Operating System - An additional system for operating spillway and outlet works gates which is independent of all other systems.

Regional Studies (Analyses) - Studies of hydrologic data from drainage basins in a hydrologically homogeneous or representative region to develop generalized information for calculation of a unit hydrograph for an ungaged area.

Regression - The mathematical analysis performed to assess the statistical correlation and linear relation between a hydrologic parameter and physical or other hydrologic parameters for the drainage basin. Through logarithmic transformations some forms of nonlinear relations can be evaluated.

Remote Sensing Data - The measurement of the electromagnetic spectrum to characterize the landscape by using aerial photos, airborne sensors, or other like data collected by satellite.

Representative Unit Hydrograph - The unit hydrograph which represents the hydrologic response of the drainage basin. It is the same as the composite unit hydrograph.

Reservoir Starting Level - The reservoir water-surface elevation assumed to be present at the beginning of the inflow PMF.

Reverse-Reservoir Routing - The reservoir routing technique that assumes the use of a level pool to develop an inflow unit hydrograph based on the recorded reservoir outflow and headwater elevations during one or more major floods. This assumption will be more accurate only if the size of the reservoir is relatively large and/or wedge storage during the passage of the flood wave is relatively small.

River Basin - The drainage basin for a river upstream from a selected point.

Routed Outflow - The downstream hydrograph that results from routing of a flood hydrograph through a reservoir using the relevant capacities of the spillway and outlet works.

Routing - The analytical process of computing the movement of a flood wave as it passes through a reservoir or a channel.

Runoff Curve Number (CN) - The number (up to 100) assigned by SCS to hydrologic soil-cover complexes (i.e., a combination of a hydrologic soil group and a land use and treatment class) to indicate the runoff potential, i.e., the larger the CN, the greater the runoff potential.

Runoff Modeling - The analytical process of computing the portion of rainfall from a given storm, and/or snow melt that runs off the land into surface waters. In these Guidelines, the unit hydrograph is used as an essential component of the runoff model.

Safety Evaluation (As applied to a dam.) - The process of determining the ability of dam and its appurtenances to pass a given flood.

Sediment - The produced materials of wearing away of the land surface by erosive agents such as water, wind, ice, and gravity in a process of natural geologic erosion or accelerated erosion resulting from land-use alterations.

Sensitivity Analysis - The process to find the rate of change of one hydrologic factor with respect to change in another factor to either measure the effect of one factor on another or explore the importance or influence of one element with respect to some criterion. Mathematically, sensitivity is simply defined as the derivative of model results with respect to the model's input parameter of interest. Sensitivity of input parameters of numerous variables in the categories of runoff and reservoir operations can be analyzed with respect to the peak flow discharge.

<u>Slope-Area Method</u> - A process of determination, by indirect measurement, of the flood peak discharge by field survey of a reach of channel and high-water marks, usually after a flood has passed (the formulas referring to Chow, 1959, p147). Usually, discharge is computed by the Manning formula with modified "n" values (relatively, small "n" values for high discharge but large for low discharge) to account for nonuniform flow through regular valley channels free from bends.

<u>Snow Course</u> - A defined line on a drainage basin, laid out and permanently marked, along which depths of snowpack and water content are determined from the sampled snow at definite distances or stations at appropriate times during a snow survey and recorded on a regular basis.

<u>Snow Cover</u> -. The accumulated snow and ice on the surface of the ground in a drainage basin at any time.

<u>Snowfall</u> - Precipitation assumed to fall as snow if the zone temperature is less than the base temperature (i.e. freezing temperature varied from 32^0 F) plus two degrees.

<u>Snowmelt</u> - Melt of snow occurring when the temperature is equal to or greater than the base temperature that varies with the zone atmospheric pressure.

<u>Snowmelt Calculation</u> - Estimation of the snowmelt occurring for a given snowpack and a given set of meteorologic conditions.

<u>Snowpack</u> - The depth of existing snow in a drainage basin expressed in equivalent water content.

<u>Snow Pillow</u> - A device for the measurement of snow pack water equivalent through a process of weighing the overlying snow.

<u>Snyder Unit Hydrograph</u> - A synthetic unit hydrograph for an ungaged basin developed by F.M. Snyder for which the peak flow and lag time are estimated in terms of regional parameters (standard lag, t_p and storage coefficient, C_p).

<u>Soil Map</u> - A map identifying and showing the areal distribution of soil types.

<u>Soil Moisture Content</u> - The quantity of water present in the soil, usually expressed in percentage of wet weight. The quantity at the beginning of a historical storm is of

primary interest.

Soil Water Storage - The amount of water the soils of a watershed which is stored at a given time. The amount for a given watershed is continually varying as rainfall or evapotranspiration takes place.

Spatial Rainfall Distribution - The variation of rainfall with location in a drainage basin.

Spillway - The structure provided to pass flows which are not passed through the outlet works or the power plant. The spillway may be an overflow type or an orifice type.

Spurious Trend - A trend in hydrologic data with time that appears in the data but ~~is~~ actually is the result of data errors or other anomalies rather than a real climatic effect.

Standard Error of Estimate - The square root of the variance between values of a given hydrologic data set and values estimated with a statistical, mathematical, or other model of the process of interest.

STATSGO - The State Soil Geographic Database at a scale of 1:250,000 that provides soil association maps and related data, including soil hydraulic conductivity, available in digital format from the NRCS.

Storage Coefficient (R) - A coefficient used with the Clark unit hydrograph which is related to storage effects of the basin. For estimation of this parameter see Figure 8-6.2.

Storage of Watershed - The total water volume stored in a watershed of interest; the difference between inputs (e.g., rainfall, base flow) and outputs (e.g., runoff, infiltration and other losses) of the hydrologic cycle during a period of time. Watershed storage directly affects the shape and the time distribution of the runoff hydrograph.

Storm Transposition - The analytical process of moving historical storm data from the location where it occurred to the location of interest.

Streamflow - The record of flow rate at a given point in a stream.

Streamgage - A gage which measures and records the water-surface elevation (stage) in a stream. The recorded stage is converted to streamflow by use of a rating curve.

Subbasin - A subdivision of a drainage basin.

Subdivision - The process of dividing a drainage basin into subbasins.

Synthetic Unit Hydrograph - A unit hydrograph for an ungaged basin that has been developed based on unit hydrograph developed at gage sites within a hydrologically homogeneous or representative region. Synthetic unit hydrograph are estimated for ungaged basins by means of relations between parameters of the unit-hydrograph model and the physical characteristics of the basin.

Temporal rainfall distribution - The variation of rainfall depth with time in order for a given storm.

Time of Concentration (T_c) - There are two commonly accepted definitions depending upon the method used: (1) the rational method defines T_c as the time required for runoff or water to travel from the most hydraulically distant point in the watershed to the outlet or point of interest, or (2) the Clark unit hydrograph method defines T_c as the time between the end of rainfall excess from a rainfall hyetograph and the inflection point on the recession of the direct runoff hydrograph.

Thiessen Polygon Method - The method of dividing a drainage basin into individual polygons each raingage represents within these subdivisions the basin-average rainfall for a given storm is estimated by calculating a mean rainfall amount at each gage station based on each subdivision area's weight in proportion to the basin area. The subdivision is made by developing polygons whose boundaries are defined by lines bisecting the lines connecting adjacent gage locations.

Uncontrolled Spillway - A spillway where overflow is not controlled.

Ungaged Basin - A basin for which available hydrologic data, recorded at stations within the basin, are insufficient in quantity and quality to provide confidence in development of an inflow hydrograph, or a basin for which input and output measurements necessary for calibration are not available.

Uniform Loss Rate - The constant rate of infiltration, or called the minimum infiltration rate, assumed to occur after initial losses and soil saturation have been satisfied. It ~~is~~ can be estimated from average soil characteristics or calibrated from significant historical flood events.

Unit Duration - The time increment of rainfall to be used in the unit-hydrograph analysis which is usually calculated as T_L /5.5, where T_L is a lag time, rounded down to an even number.

Unit Hydrograph - The direct runoff hydrograph from a given drainage basin representing one unit (inch or mm) of rainfall excess for a specified duration and areal distribution. Typically the rainfall excess should be spatially and temporally uniform.

Urban Area - An area which has been developed for urban use.

Validation - The process of demonstrating that estimated model parameters or basic theory behind a model is correct or valid. This can only be done by carefully controlled experiments with new detailed and accurate input and output data.

Verification Hydrograph - A computed hydrograph of a historical flood which is generated using the corresponding rainfall data and the developed unit hydrograph as a means of checking the suitability of the unit hydrograph and/or the runoff model by comparing with the observed hydrograph or measured values.

Variability - The randomness with respect to the mean in the indicated physical process.

Watercourse - The path which runoff follows during passage from a drainage area.

Water Equivalent - The depth of water (in inches), that results from melting a given depth of snow.

Watershed - Another term meaning drainage basin.

Water Table - The upper surface of ground water.

Wave Celerity - The velocity of the waveshape in relation to the body of fluid through which the waves are propagated.

8-13 Appendices

Appendix A - Determining the PMF for Civil Works Flow Chart

Appendix B - Probable Maximum Flood Study Report Outline

Appendix C -Hec-1 Data-Analysis Techniques of Infiltration Rate Estimate Methods

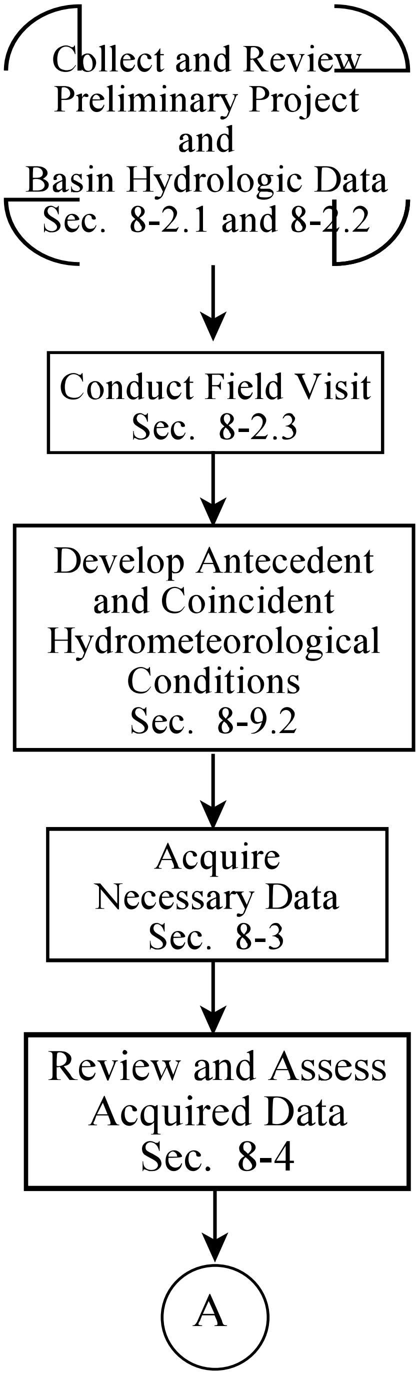
Appendix D - Distributed Loss Rate Methods Using STATSGO or SSURGO Databases

Appendix A

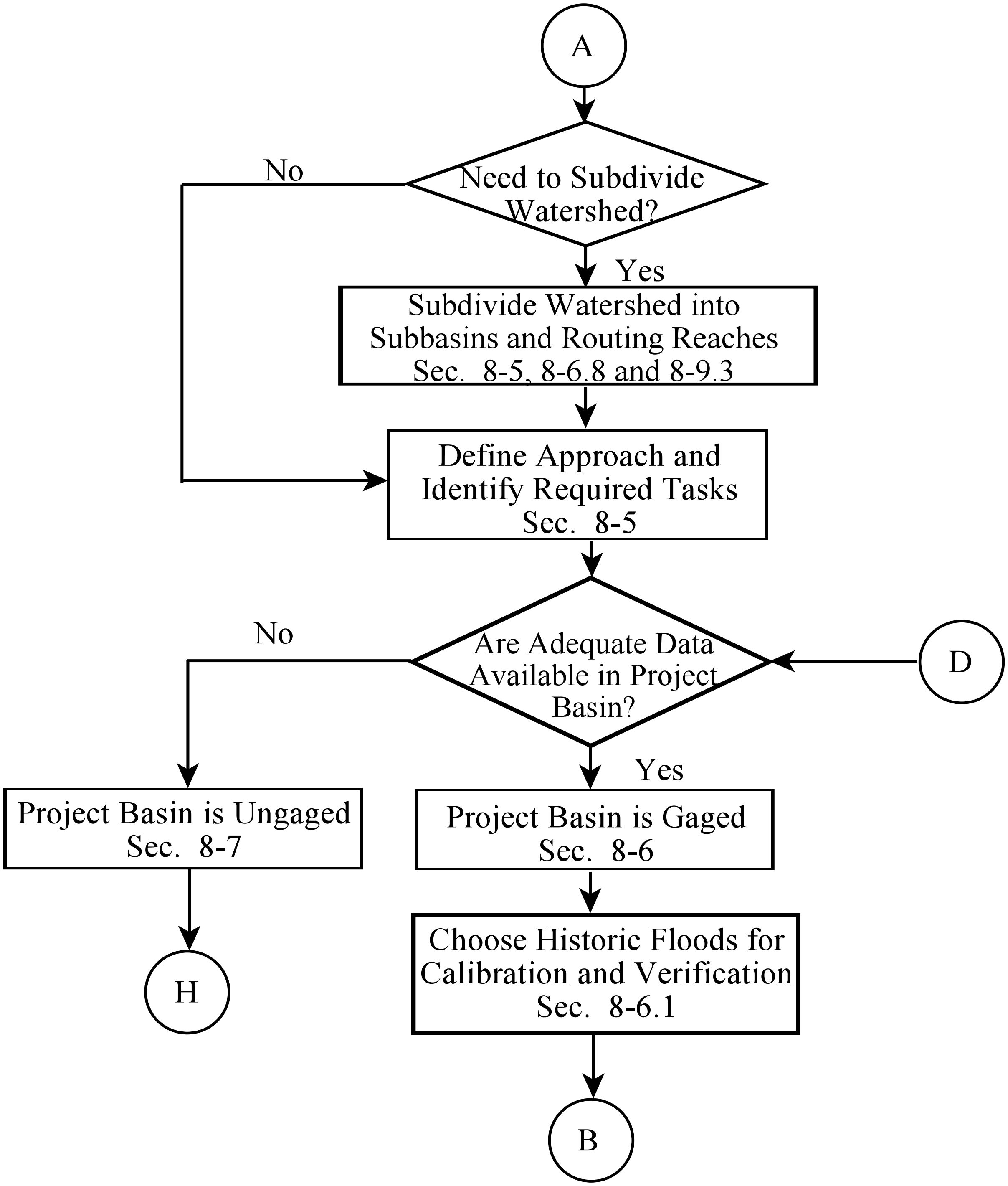
Determining the PMF for Civil Works Flow Charts

As an aid for determining the PMF for gaged and ungaged basins, these flow charts show the sequence of required decisions and analyses. Chapter and section references are shown for each flow chart element.

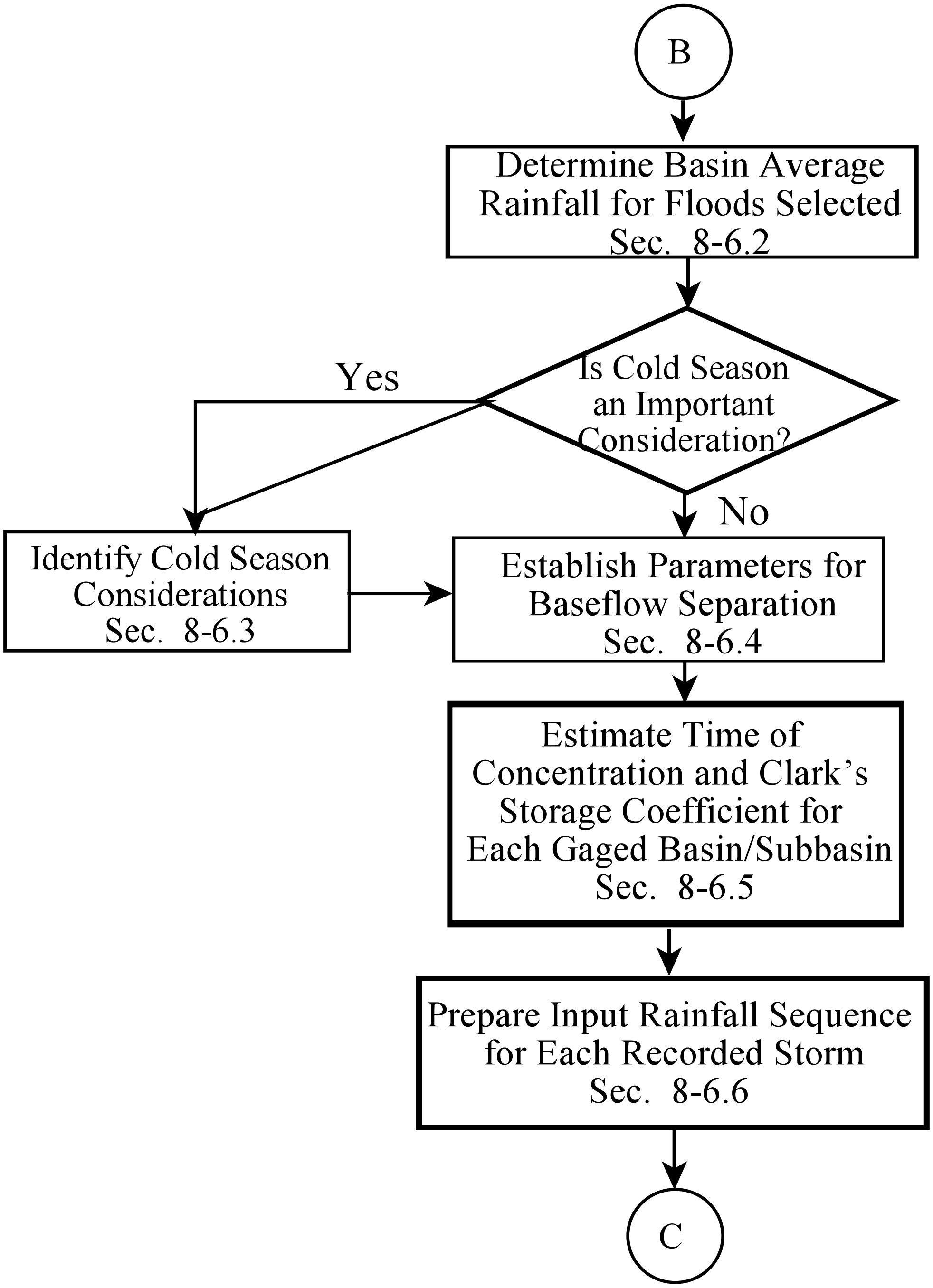
DETERMINING THE PROBABLE MAXIMUM FLOOD FOR CIVIL WORKS
FLOW CHART



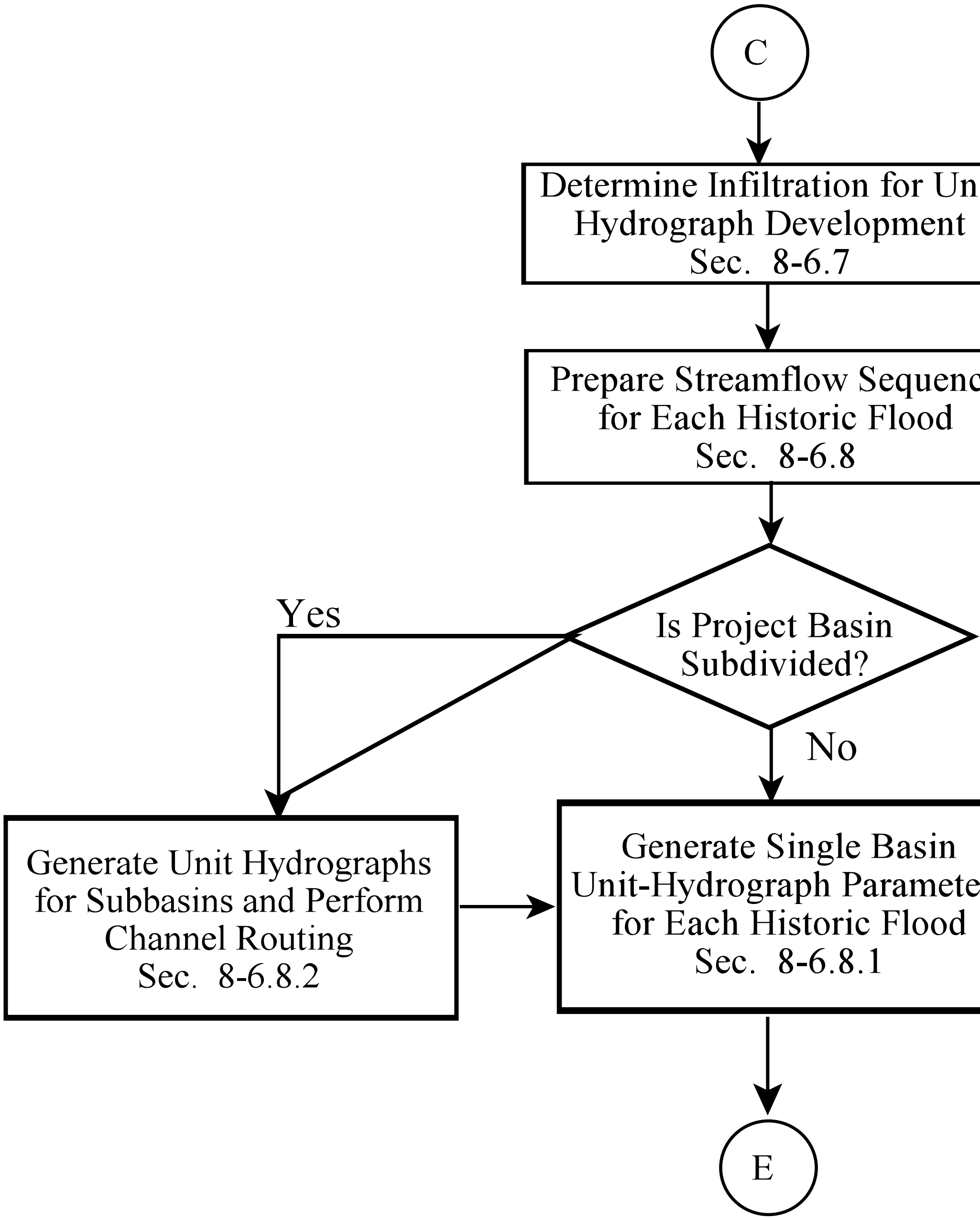
PMF DEVELOPMENT



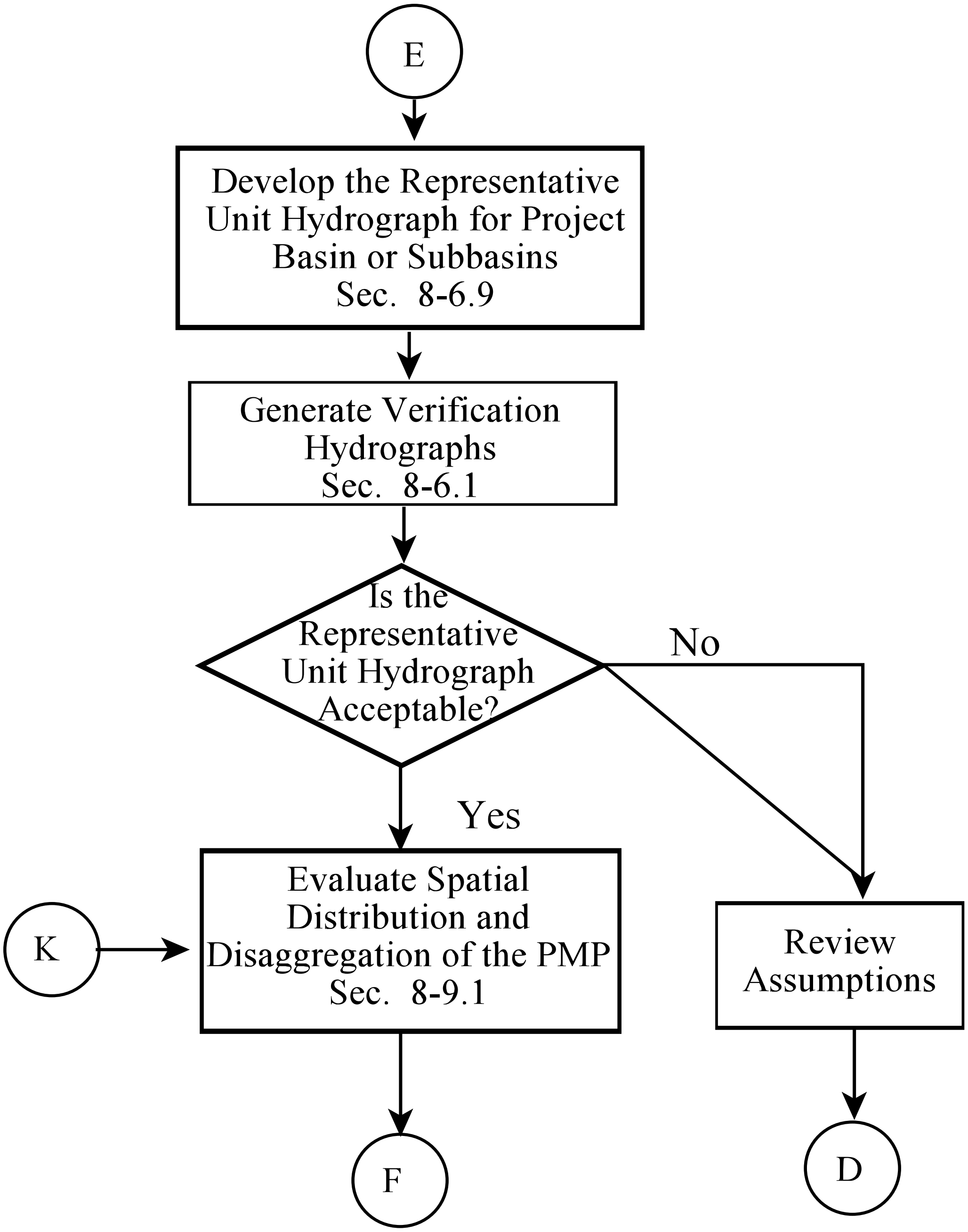
PMF DEVELOPMENT
(Gaged Basins)



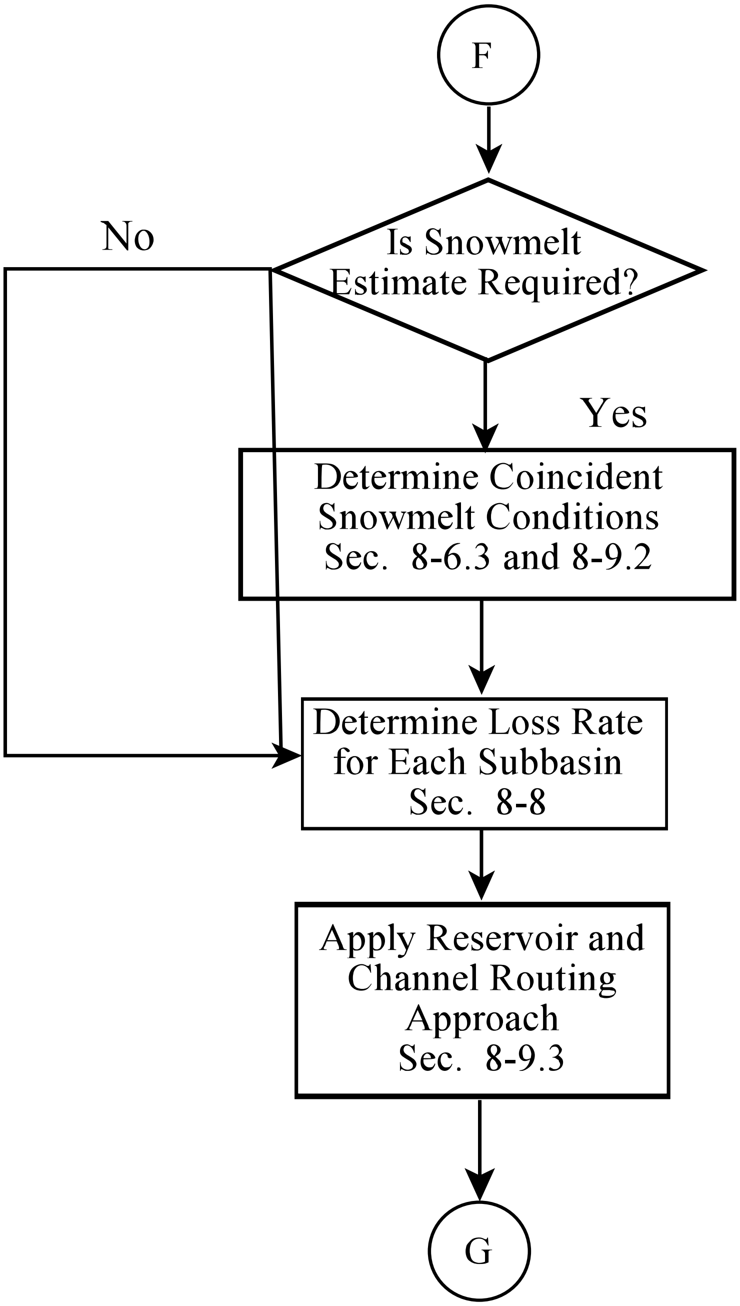
PMF DEVELOPMENT
(Gaged Basins)



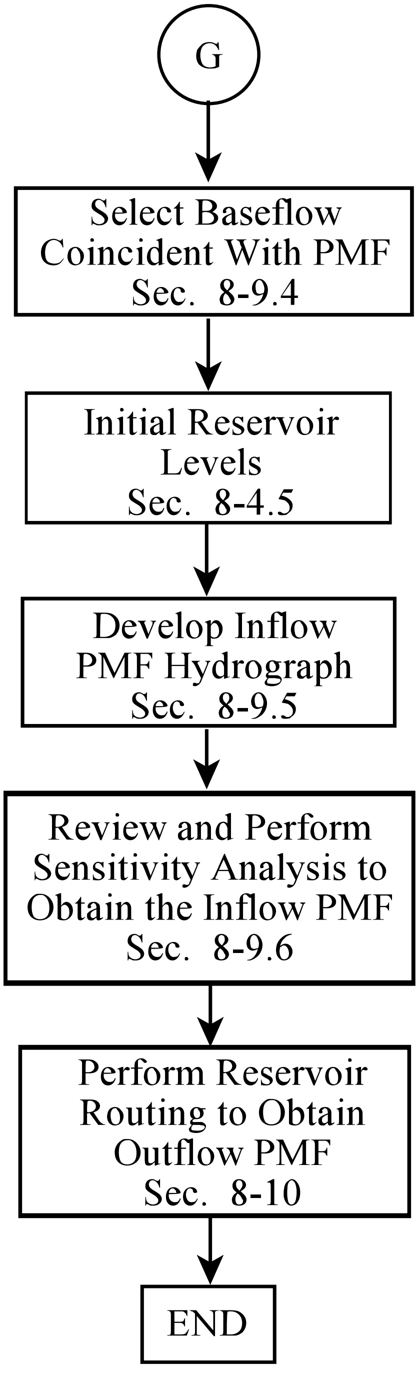
PMF DEVELOPMENT
(Gaged Basins)



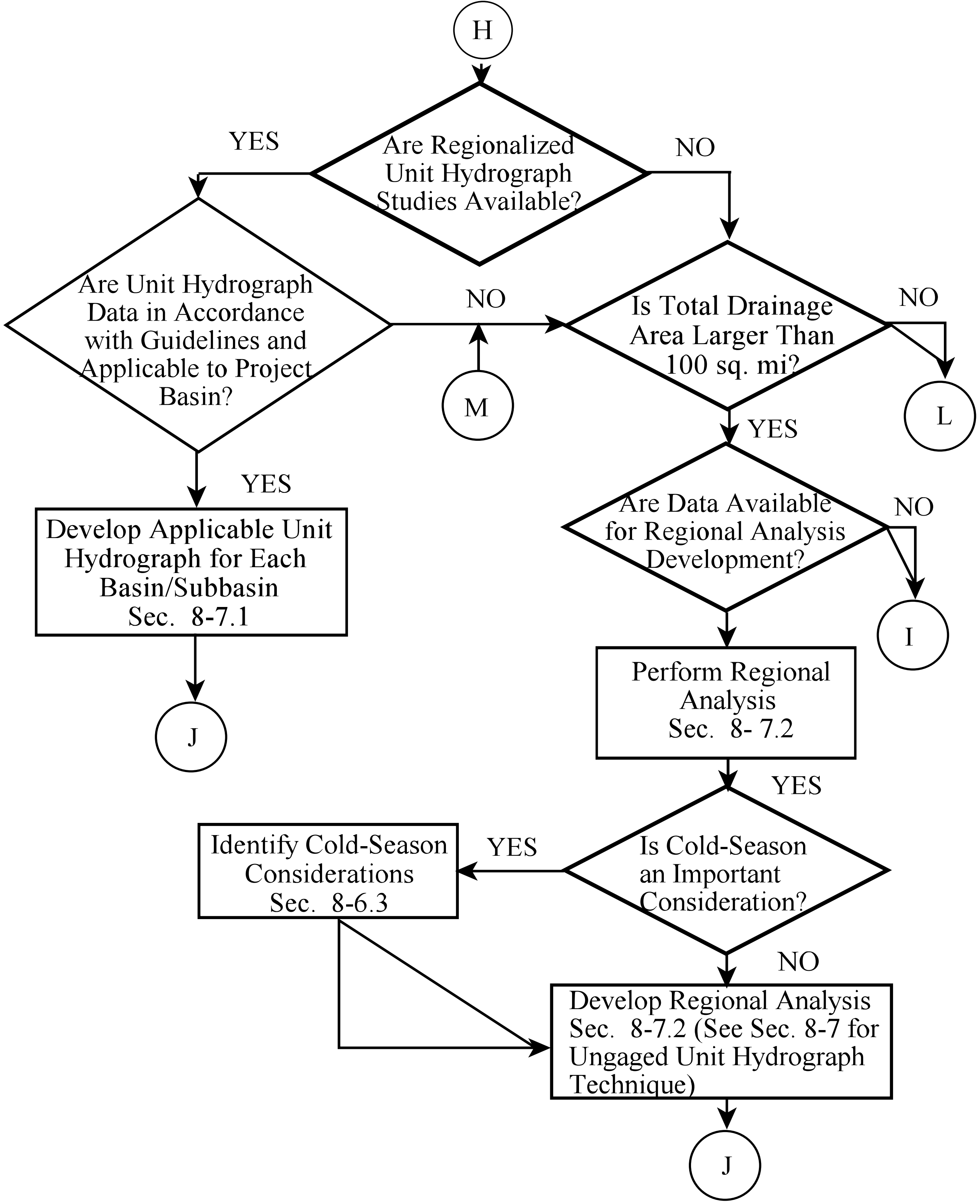
PMF DEVELOPMENT
(Gaged Basins)



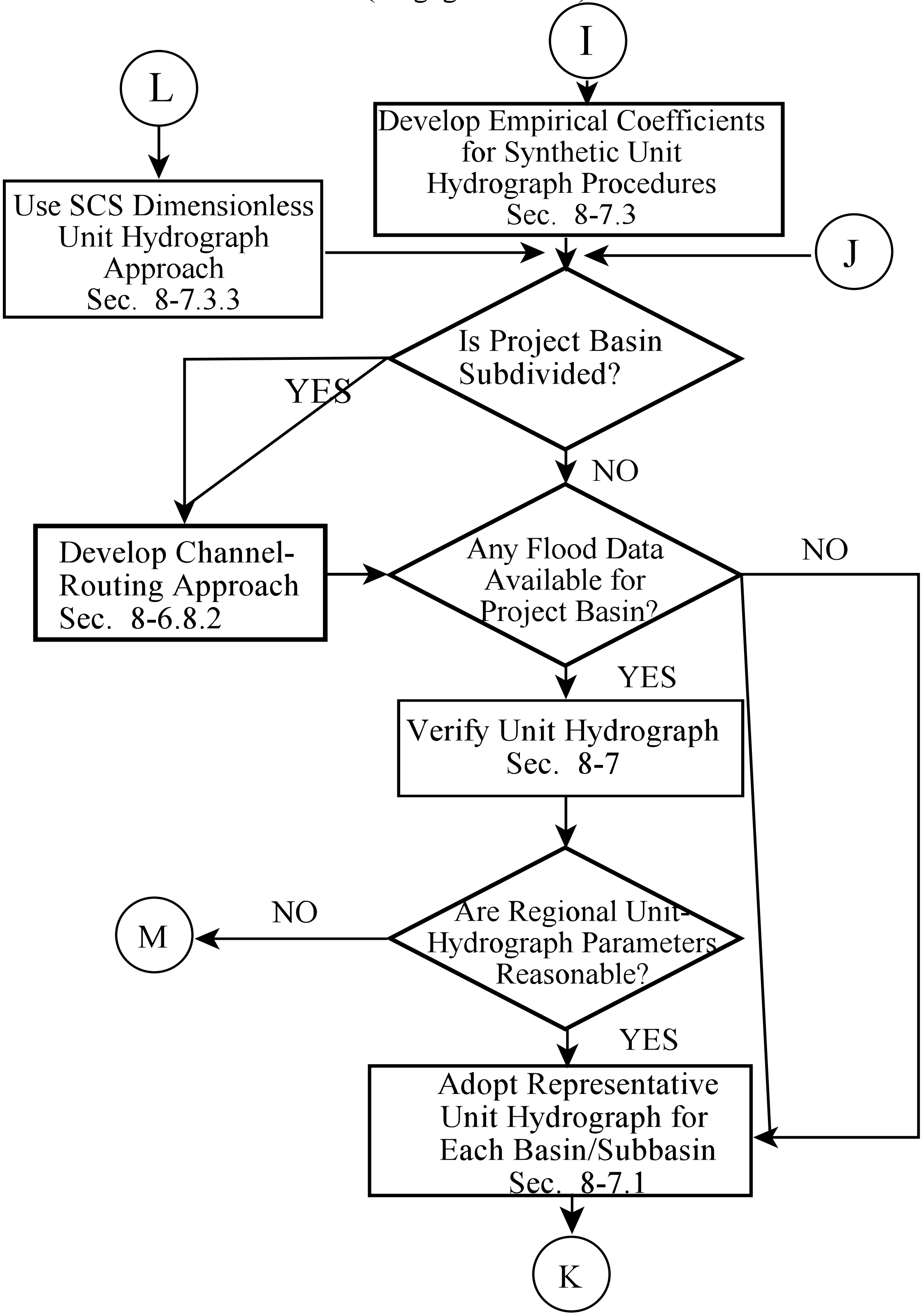
PMF DEVELOPMENT
(Gaged Basins)



PMF DEVELOPMENT
(Ungaged Basins)



PMF DEVELOPMENT
(Ungaged Basins)



Appendix B

Probable Maximum Flood Study Report Outline

The following study report outline should assist the analyst in documenting PMF studies. The outline parallels the reasoning in Chapter VII and the flow chart, except that some subject areas are consolidated to avoid repeating information in the written report. When subject headings are not applicable to the study, an explanation should be provided.

PMF STUDY REPORT OUTLINE

GAGED BASINS

I. PROJECT DESCRIPTION

- A. Project Data . . . . 8-2.1 - 8-2.3, 8-4.5
- B. Basin Hydrologic Data . . . . 8-2.1 - 8-2.3, 8-3.5
- C. Upstream Dams 8-2.2, 8-3.7
- D. Field Visit 8-2.3
- E. Previous Studies . . . . 8-2.1 - 8-2.2, 8-3.1

II. WATERSHED MODEL AND SUBDIVISION

- A. Watershed Model Methodology 8-1.2
- B. Subbasin Definition 8-5.1
- C. Channel Routing Method 8-6.8.2, 8-9.3

III. HISTORIC FLOOD RECORDS

- A. Stream Gages 8-3.2
- B. Historic Floods . . . . 8-3.2, 8-4.1 - 8-4.2, 8-6.1
- C. Precipitation Associated with Historic Floods 8-3.3, 8-3.4, 8-4.3, 8-6.2, 8-6.6
- D. Snowpack and Snowmelt During Historic Floods 8-3.6, 8-6.3

IV. UNIT HYDROGRAPH DEVELOPMENT

- A. Approach and Tasks 8-5.3, 8-6.5
- B. Baseflow Separation 8-6.4
- C. Preliminary Estimates of Clark Parameters 8-6.5
- D. Estimate of Infiltration During Historic Floods 8-6.7
- E. Subbasin Unit Hydrograph Parameters 8-6.8

V. UNIT HYDROGRAPH VERIFICATION 8-6.9

VI. PROBABLE MAXIMUM PRECIPITATION

- A. Probable Maximum Precipitation Data 8-3.4, 8-9.1
- B. Candidate Storms for PMF 8-9.1

VIII. COINCIDENT HYDROMETEOROLOGICAL AND HYDROLOGICAL CONDITIONS FOR THE PROBABLE MAXIMUM FLOOD

IX. PMF HYDROGRAPHS

PMF STUDY REPORT OUTLINE
UNGAGED BASINS

I. PROJECT DESCRIPTION

- A. Project Data . . . . 8-2.1 - 8-2.3, 8-4.5
- B. Basin Hydrologic Data . . . . 8-2.1 - 8-2.3, 8-3.5
- C. Upstream Dams 8-2.2, 8-3.7
- D. Field Visit 8-2.3
- E. Previous Studies . . . . 8-2.1 - 8-2.2, 8-3.1

II. WATERSHED MODEL AND SUBDIVISION

- A Watershed Model Methodology 8-1.2
- B. Subbasin Definition 8-5.1
- C. Channel Routing Method 8-9.3

III. HISTORIC FLOOD RECORDS

- A. Stream Gages 8-3.2
- B. Historic Floods . . . . 8-3.2, 8-4.1 - 8-4.2

IV. UNIT HYDROGRAPH DEVELOPMENT

- A. Approach and Tasks 8-5.3, 8-7
- B. Existing Studies 8-7.1
- C. Regional Analysis *(include details as Appendix)* 8-7.2
  - (1) Gaged Basins Used in Analysis
  - (2) Cold-Season Considerations
  - (3) Regional Relationship for Unit Hydrograph Parameters

OR

- C. Synthetic Unit Hydrographs 8-7.3

OR

- C. SCS Dimensionless Unit Hydrograph 8-7.3.3

V. UNIT HYDROGRAPH VERIFICATION 8-6.9

VI. PROBABLE MAXIMUM STORM

- A. Probable Maximum Precipitation Data 8-3.4, 8-9.1
- B. Candidate Storms for PMF 8-9.1

Appendix C

HEC-1 Data-Analysis Techniques of Infiltration Rate Estimate Methods

Infiltration can vary temporally and spatially in a drainage basin as a very complex physical process. Selection of data-analysis techniques or measurement techniques should consider these effects. Two approaches are used to estimate loss rates of subbasins including basin-averaged methods and distributed methods. Each approach basically should be based on physical soil properties and land covers. The most practical (i.e. simplest) application is to use a constant loss rate rather than an unsteady rate. The constant rate associated initial loss might be considered to represent the total loss due to surface factors and volume infiltrated prior to attaining the soils relatively long-term infiltration rate.

Table VIII-C lists five models applied in the HEC-1 computer program. The use of relatively small, homogeneous watersheds is recommended to minimize spatial variations of infiltration rates over larger areas. In general, an upper limit of 25 mi^2 for study-watershed drainage areas was suggested to minimize the effects of lumping infiltration rates.

Parameters of simple empirical infiltration models or models with physically based or measurable parameters need to be estimated. Parameter estimation techniques are categorized by application to gaged or ungaged analysis below.

(A) Ungaged Parameter Estimation

Physical characteristics of the watershed may be the only information available for estimating parameters on a theoretical basis.

(B) Gaged Parameter Estimation

Rainfall-runoff records are used to estimate infiltration model parameters. The basic element of a gaged estimation is to utilize an optimization algorithm to choose model parameters so that some measure of the difference between observed and predicted hydrographs is minimized. This approach to parameter estimation is essentially a regression analysis based on recorded data of a number of events.

Table VIII.C Comparisons of Infiltration Models

INFILTRATION MODELS	**SOIL BASIS**	**DOMINANT FACTORS**	**DISAD-VANTAGE**	**APPLICA-BILITY**
Rainfall Excess Models (*const. or unif. loss rates)*	--		--	--
A. Index Models Data source for loss rates: (1) Hydrologic soil groups (USDA 1955) (2) NRCS' SSURGO data base (3) NRCS' STATSGO data base (4) Calibration/regional studies	(1) Four hydrologic soil groups (2) & (3) Physical soil properties using spatially detailed soils and land cover (4) None	(1) hydrologic soil types; (2) & (3) soil series and its permeability which is affected by ground cover conditions; (4) rainfall excess	(1), (2) & (3) Independent from rainfall intensity and volume, and (1) Inaccurate basin-avaerage rate; (2) Data from 1:250,000 maps and too crude soils associations; (3) Incomplete database; (4) calibrated parameters are related to the intensity of the calibration storm	(1)) Hydrologically similar watersheds (2) & (3) mainly for cultivation of crops, for engineering design applications if justified*,* (4) when design storm is of similar magnitude to calibration storm
B. NRCS Runoff Curve Number (RCN) Model: RCN decays as the total volume of accumulated infiltration increases and is reflected as AMC I, II, or III)	Four hydrologic soil groups, land cover & nd treatment, AMC	hydrologic soil-cover com-plexes (cover includes land use, treatment, hydrologic con-dition), AMC	Minimal physical theory (conditions not considered such as near-surface bedrock)	Small, agricultural frost-free watersheds
Empirical Models *(unsteady loss rates)*	--		--	--
A. Cumulative Loss-Dependent Loss Rate: Exponential Loss Model	2 parameters related to basin character., one to antec. moisture deficiency, one to both	rainfall intensity, accumulated losses (or soil moisture storage), impervious area	(a) At least three sets of storm and flow data required; (b) less accuracy for extrapolating rates	Engineering design applications
B. Time-Dependent Loss Rate: Holtan Model- exponential rate	Parameters for cultivated soils	soil moisture storage, ground cover, surface pore space and volume, ultimate infiltration capacity	Param.. fitting to vegetative data rather than measurable soil characteristics	Agricultural lands
Approximate Theory-Based Models (unsteady or *constant loss rates)*	--		--	--
Green-Ampt Model (using Darcy's law) (The loss rate is constant after the soil reaches saturation - most of the Green-Ampt equation deals with what happens before that time.)	Physical properties of the soil column	well-defined wetting front, constant volumetric water contents, constant soil-water suction	No adjustments for watershed non-homogeneity, surface storage, or vegetation effects	Small-scale crop or range lands

Appendix D
Distributed Loss Rate Methods Using STATSGO or SSURGO Databases

Sections 8-8.2 and 8-8.3 discuss using the distributed loss rate method for developing PMF studies. This appendix discusses in more detail the use of STATSGO or SSURGO soil databases with the distributed loss rate method.

Digital soil maps are now available from the NRCS in the NATSGO, STATSGO, and SSURGO series. The NATSGO series, which is designed to provide a regional overview of soils on a national scale, is the least detailed of the three databases and does not provide adequate detail for watershed studies. The STATSGO series was designed for regional planning and river basin studies. STATSGO maps soils to the association level and provides data on individual soil series within each association. SSURGO, which is not complete as of 2000, is the most detailed of the three databases and will be a digital form of county soil survey maps. In the distributed loss method, the STATSGO series or digital data of similar (or finer) spatial resolution should be used.

Unlike the basin-averaged loss rate method - which uses spatially averaged minimum loss rates that have been empirically determined in relation to the hydrologic soil groups - the distributed loss rate method allows the hydrologist to assign loss rates on the basis of physical properties of each soil unit, modified as necessary for other factors, such as bedrock, groundwater levels, vegetation, etc., that may affect runoff.

Loss rates for a given soil unit can be derived from a soils database that contains sufficient information to determine how much area within the subbasin each soil unit occupies, and approximate areas of overlap between soil units and hydrologically significant land cover types (such as wetlands and forests). For all but the smallest basins, the application of the method will only be practical when the database is available digitally and can be read into a GIS format that is easily superimposed on a digital subbasin boundary map and land cover map. The discussion that follows will reference the STATSGO database, but it is also applicable to basins where the SSURGO database has been completed and digitized.

STATSGO classifies each layer of each soil unit within one of several standard logarithmic ranges of permeability (saturated hydraulic conductivity). The least permeable layer should be assumed to control losses for the area occupied by that soil unit. For application purposes, it is necessary to represent the range of each layer as a single value. The procedures for ungaged and gaged basins are as follows.

<u>Ungaged (sub) basins</u>. Since no historical data is available to verify the model, the

minimum value from either the Minimum Infiltration Rates for the Hydrologic Soil Groups found in Table 8-8.1 or the minimum value of the given range of the permeability (saturated hydraulic conductivity) of the least permeable layer, as provided in the STATSGO database, should be used as the loss rate for each soil class. Deviations from the minimum value are acceptable with adequate, physically based, justification. Potential sources of information include a review of the geological make-up of the soils, review of soils information such as county or local soils maps, or actual data obtained from field investigations. However, the STATSGO or SSURGO data should not be used to develop a basin-averaged loss rate since the high permeability values for some sandy soil classes in the databases will raise the basin-averaged loss rate to unrealistic values. Regional analyses are allowable with adequate support for the transfer of data from gaged basins with similar hydrological properties. Factors to consider for transferring data include the following:

- Basin size, slope, soil types (and distribution), soil column depth to bedrock, land cover, etc., are similar to a gaged basin in the study area (study basin);

- Adequate stream flow data are available from gages located downstream of, but in close proximity to the study basin;

- Several large, single peaked storms are available that are centered in the study basin close to the stream flow gages that provide for adequate basin coverage. Since some historical events may not be of sufficient size to prevent nonlinear effects, the historical events used for adjusting loss rates should be clearly out-of-bank floods or saturated soil conditions must have existed in a significant part of the basin prior to the storm.

Gaged (sub) basins. A value within the range of the saturated hydraulic conductivity of the least permeable layer can be selected as the preliminary loss rate if appropriately justified. Physically based information, such as a review of the geological make-up of the soils, review of soils information such as county or local soils maps, or actual data obtained from field investigations, is necessary to support the selected rate. After considering all hydrologic influences such as wetlands, open water, etc., the model and selected loss rate should be verified with rainfall-runoff records for several large flood events. Since some historical events may not be of sufficient size to prevent nonlinear effects, the historical events used for adjusting loss rates should be clearly out-of-bank floods or saturated soil conditions must have existed in a significant part of the basin prior to the storm. If this verification does not support the selected loss rates, further investigations and adjustments are required. The procedures for verifying the model and adjusting the loss rates are discussed in Section 8-8.3.

The method presented here is designed for use with HEC-1 or a similar basin model. Because assigned parameters other than USDA recommendations for basin-average uniform loss rate (Section 8-8.1), are usually less conservative, it is important to verify the results of a distributed model using large historical events. The assumptions for assigning initial distributed loss parameters should be considered base line assumptions. Deviation from the base line assumption is not justified when there is an inadequate rain gage distribution within the study basin, or the proportion and/or location of the gaged subarea relative to the entire basin size is small. The loss rate may require adjustment based on model verification with historical storm hydrographs, geologic considerations, groundwater elevation, land cover, or other parameters found to affect runoff. Testing of the initial runoff model with historical events and careful evaluation of hydrologic factors other than the baseline assumptions are necessary to ensure that the model adequately represents runoff processes for extreme storms.

As additional information becomes available, such as flood events larger than historical events, the model should be re-run to determine if it adequately predicts the new flood event. If the model does not adequately predict the new flood event, adjustments should be made to the loss rates and/or the unitgraph parameters. When drainage basins do not contain adequate rainfall/runoff data, the installation of rain gages and flow gages should be considered.

When using HEC-1 or a similar "lumped" basin model, the following steps should be taken to develop the distributed runoff model:

A. Assigning Loss Rates

1. Digitally overlay the basin or subbasin boundary map, the soil unit/association map (such as STATSGO), and the land cover map.

2. For each subbasin, determine the percentage of area covered by each soil unit. STATSGO maps soils at the association level (not the unit level) and gives the percentage of area represented by each soil unit. When using STATSGO, it is necessary to assume that this typical distribution applies to the soil association as it occurs in the subbasin.

3. For each subbasin, determine what percentage of each soil unit is occupied by (a) open water and wetlands; (b) forests (if frozen soils are a consideration); and (c) other land uses such as urban, agricultural, and rangeland/grassland areas.

4. From the information gathered in steps 1-3, classify all of the basin or subbasin area into loss rate groups, using the following assumptions:

> a. As a baseline assumption, the infiltration capacity of the least permeable layer in the soil profile should be assumed to control the soil's loss rate. Each soil unit is assigned a uniform loss rate based upon the review of the available soils data. Sources of data include soils and geologic maps of the watershed, other technical reports, or field investigations. These sources should be reviewed to support the selection of the loss rate if it is larger than the minimum value of the range.
>
> b. For any area occupied by open water or wetlands, the uniform rate should be changed to zero, regardless of underlying soil type. In basins with high water tables or shallow impermeable layers, the loss rate may also need to be set to zero - deviations from a zero loss rate must be justified.
>
> c. If a cool season analysis is performed, the loss rates should be further adjusted in accordance with Section 8-8.3.

5. For each subbasin, tabulate the percent of area with each warm-season and cool-season (if applicable) loss rate.

6. A STATSGO soil series map with the soil association designations should be included in the study.

B. Determination of Rainfall Excess and Model Verification

1. Calculate precipitation to be modeled (historical rainfall for model verification, or the PMP for PMF simulation) in hourly increments for each subbasin.

2. For each hour of the storm being modeled, calculate the difference between the rainfall increment and the hourly loss rate for each of the loss classes defined in (A)(4), above. If positive, the difference is the hourly rate of rainfall excess from that loss class. If negative, there is no rainfall excess for that loss class and time increment.

3. For each hour, multiply the rainfall excess from each loss class in each subbasin by the area of the portion of the subbasin area occupied by that loss class. Sum the rainfall excess over all loss classes in the subbasin for each subbasin. This will produce the total rainfall excess for each subbasin. A spreadsheet

program can be set up to perform this function, but care must be taken to ensure the timing is correct.

4. Use the resulting subbasin total rainfall excess hyetographs as rainfall input in the HEC-1 or other watershed model, setting losses in the watershed model equal to zero. Run the model to produce the runoff hydrograph from each subbasin.

5. Verify the model and adjust loss rates as appropriate in accordance with Section 8-8.3.

6. Provide a table showing the precipitation, losses, excess, and snowmelt for each time increment for each subbasin, similar to the HEC-1 program output.

7. For each loss rate category within each subbasin, provide a summary table showing the percent area of the subbasin, the baseline loss rate values, and the loss rate values after adjustments have been made.

8. A sensitivity analysis should be performed to compare the selected loss rates and loss rates that are more conservative. At a minimum, an inflow hydrograph developed by using justifiable loss rates and a hydrograph developed using a loss rate equal to the minimum value of the least permeable layer of the STATSGO database should be plotted. Intermediate values between the selected loss rate and the minimum value may also be plotted for comparison purposes.

Note: Steps B2 through B4 can be directly modeled in HEC-1 or HEC-HMS by taking advantage of the linear assumption of unit hydrograph theory. In the above steps, the rainfall excess for each soil loss rate class are combined for each time step to form the input rainfall excess hyetograph, which is then used in HEC-1 with the loss rate set to zero to compute the runoff hydrograph. This hydrograph can also be developed by first computing the rainfall excess hyetographs for each loss rate class, and then combining them. All of this can be done using HEC-1 by subdividing a subbasin into pseudo-subbasins corresponding to each loss rate class. For each pseudo-subbasin, the basin area is set equal to the area of the portion of the subbasin area occupied by that loss rate class similar to Step B3 above, and the uniform loss rate parameter (LU) is set equal to the loss rate for that loss rate class. The subbasin areas for the pseudo-subbasins should add up to the actual subbasin area in order to ensure that the proper volume of runoff is computed. The unitgraph parameters and the precipitation values for the pseudo-subbasins are equivalent to the values developed for that subbasin in order to preserve the proper timing, shape, and volume of the subbasin hydrograph. The baseflow can be accounted for by including it in one of the pseudo-subbasins. The outflow hydrographs from the pseudo-subbasins can then be combined using HEC-1 to produce the outflow hydrograph for that subbasin. The advantage of this method is that everything can be done within

HEC-1, and it is much easier to observe how each loss rate class contributes to the total runoff for each subbasin. Consequently, sensitivity analyses and verification/model adjustments required by Step B5 above are also easier to perform, and documentation of the analysis required by Step B6 above can be done within HEC-1.

Major Terms of STATSGO Data Base

Several terms commonly used to describe soil types or components are defined as follows and shown in Fig. 1:

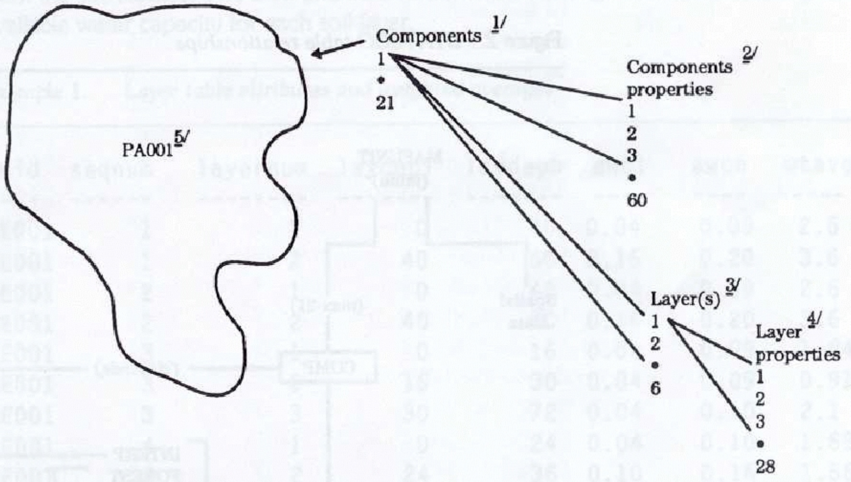
1. Soil Profile

Soil Series - A specific soil type, for example: Massena, Sun, Mosherville.
Component - A specific soil series phase (i.e. soil properties).
Soil Association - A collection of soil series in a soil column. Each soil association in STATSGO can contain up to 21 different soil series (i.e., components).
Soil Layer - A layer (essentially horizontal) of a soil series which defines the soil column. Up to six different layers may be identified for a series. Each layer within a soil column is identified with a layer number ("LAYERNUM"), starting from the top of the soil and counting downward. Both the maximum and minimum k values for a soil layer are provided.
Limiting Layer - The layer with the smallest minimum permeabilty of all layers of a soil association.

2. Map Units

Soil Unit - The unit is usually represented by a single soil series. A soil map shows the soil units over a drainage basin.
MUID - The mapping unit identifier which represents a particular soil association. The soil associations are identified by "MUID" numbers, for examples, NY013, NY033, and NYW (water body) in New York State.
MUID Sequence Number - The sequence number which is associated with a MUID for different components and their percentages of the soil association.

Figure 1. *STATSGO map unit*



[1] STATSGO map units consist of 1 to 21 components.

[2] For each component, there are 60 soil properties and interpretations in 84 different data elements (component tables), for example, flooding.

[3] For each component, there are 1 to 6 soil layers.

[4] For each layer, there are 28 soil properties; for example, percent clay.

[5] A map unit identifier created by concatenation of the two-character State FIPS code and a three-digit Arabic number. It uniquely identifies a map unit within a State.