PART 2

HYDROLOGIC ANALYSIS

Chapter 5
Hydrologic Engineering Data

5-1. Meteorological Data

The extent of meteorological observations is determined by the data needs and use and the availability of personnel and equipment. Data usually recorded at weather stations include air (sometimes water) temperature, precipitation, wind, and evaporation. As indicated below, more extensive recording of various types of data is often made for special purposes. The primary source of meteorological data for the United States is the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center in Asheville, North Carolina. Data are available from NOAA in computer-readable form as well as published reports. NOAA publication "Selective Guide to Climatic Data Sources" is an excellent reference for data availability. Private vendor sources employing compact disc (CD) technology using NOAA records are also available.

a. Storm meteorology. The determination of runoff potential, particularly flood potential, in areas where hydrologic data are scarce can be based on a knowledge of storm meteorology. This includes sources of moisture in the paths over which the storm has traveled, as well as a knowledge of the mechanics of storm activity. Derivation of hydrologic quantities associated with various storms must take into consideration the type of storm, its path, potential moisture capacity and stability of the atmosphere, isobar, wind and isotherm patterns, and the nature and intensity of fronts separating air masses. These are usually described adequately in the synoptic charts that are prepared at regular (usually 6-hr) intervals for weather forecasting purposes and associated upper-air soundings. Where such charts are available, it is important that they be retained as a permanent record of meteorological activity for use in supplementing information contained in the regularly prepared hemispheric charts. These latter charts summarize the daily synoptic situation throughout the hemisphere but do not contain all of the data that are of interest or that would have direct bearing on the derivation of design criteria.

(1) NOAA monthly publication "Storm Data" (1959-present) documents the time, location, and the meteorologic characteristics of all reported severe storms or unusual weather phenomena. Synoptic maps are published by NOAA on a weekly basis in "Daily Weather Maps, Weekly Series" and on a monthly basis, "Synoptic Weather Maps, Daily Series, Northern Hemisphere Sea-Level and 500-Millibar Charts and Data Tabulations."

(2) Storm data including synoptic charts for selected historic storms are included in the "Hydrometeorological Reports" and "Technical Memorandum" prepared by the National Weather Service (NWS) Office of Hydrology in Silver Spring, MD. Other sources of meteorological data include the National Hurricane Center in Coral Gables, FL, and state climatologists as well as U.S. Geological Survey and Corps flood reports.

b. Precipitation. Monthly summaries of observed hourly and daily precipitation data are published by NOAA in "Climatical Data" and "Hourly Precipitation Data." Precipitation data are also available from NOAA in computer-readable media. Precipitation data for significant historic storms (1870's-1960's) are tabulated in "Storm Rainfall in the United States, Depth, Area, Duration Data."

(1) There are usually local, or state agencies, collecting precipitation data for their own use. These data could provide additional storm information. However, precipitation measurements at remote unattended locations may not be consistently and accurately recorded, particularly where snow and hail frequently occur. For this reason, records obtained at unattended locations must be interpreted with care. When an observer is regularly on-site, the times of occurrence of snowfall and hail should be noted to make accurate use of the data. The exact location and elevation of the gauge are important considerations in precipitation measurement and evaluation. For uniform use, this is best expressed in terms of latitude and longitude and in meters or feet of elevation above sea level. Of primary importance in processing the data is tabulating precipitation at regular intervals. This should be done daily for non-recording gauges with the time of observation stated. Continuously recording gauges should be tabulated hourly. The original recording charts should be preserved in order to permit study of high-intensity precipitation during short intervals for certain applications.

(2) Procedures to develop standard project and probable maximum precipitation estimates are presented in NWS hydrometeorological reports and technical memorandum. Chapter 7 of this manual provides an overview of hypothetical storms and their application to flood-runoff analysis.

c. Snowpack. Where snowmelt contributes significantly to runoff, observations of the snowpack characteristics can be of considerable value in the development of hydrologic design criteria. The observation of water equivalent (weight) of a vertical column sampled from the snowpack at specified locations and observation times is of primary importance. As the observations will ordinarily be used as an index for surrounding regions, the elevation and exposure of the location must be known. The depth of snowpack is of secondary importance, but some observations of the areal extent of the snowpack are often useful.

(1) An important element in processing snowpack observation data is the adjustment of observations at all locations to a common date, such as the first of each month during the snowpack accumulation season. Since these observations are often made by traveling survey teams, they are not made simultaneously. Also, they cannot always be made at a specified time because it is impossible to obtain accurate or representative measurements during snowstorms.

(2) Where continuous recordings of snowpack water equivalent by means of radioactive gauges or snow pillows are available, these can be used on a basis for adjusting manual observations at nearby locations. Otherwise, some judgment or correlation technique based on precipitation measurements is required to adjust the observations data to a uniform date at all locations. It is important to preserve the original records whenever such adjustments are made. However, data that are disseminated for use in design should be the adjusted systematic quantities.

(3) The primary agency for the collection and distribution of snowpack data is the Soil Conservation Service (SCS) (Department of Agriculture, Washington, D.C.). From January through May each year, the SCS publishes a monthly report titled, "Water Supply Outlook." These reports provide snowpack and streamflow forecast data for each state and region. The SCS also issues "Basin Outlook Reports," a monthly regional summary of snow depth and water content. Additionally, NOAA distributes an annual tabulation of snowpack data in their "Snow Cover Surveys." Climatoligcal precipitation data published monthly by NOAA also include information on snowfall and snow on the ground.

d. Temperatures. In most hydrologic applications of temperature data, maximum and minimum temperatures for each day at ground level are very useful. Continuous records of diurnal temperature variations at selected locations can be used to determine the daily temperature pattern fairly accurately at nearby locations where only the maximum and minimum temperatures are known. In applying temperature data to large areas, it must be recognized that temperatures normally decrease with increasing elevation and latitude. It is also important to preserve all of the original temperature records. Summaries of daily maximum and minimum temperatures should be maintained and, where feasible, published. The NOAA report series on "Climatography of the United States" by city, state, or region also provides information on daily and monthly normal temperatures.

e. Moisture. Atmospheric moisture is a major factor influencing the occurrence of precipitation. This moisture can be measured by atmospheric soundings which record temperature, pressure, relative humidity, and other items. Total moisture in the atmosphere can be integrated and expressed as a depth of water. During storms, the vertical distribution of moisture in the atmosphere ordinarily follows a rather definite pattern. Total moisture can therefore be related to the moisture at the surface, which is a function of the dew point at the surface. Accordingly, a record of daily dew points is of considerable value. Here, again, the elevation, latitude and longitude of the measuring station must be known. NOAA publication "Local Climatological Data" is a primary source for observed dew point, pressure, and temperature data.

f. Winds. Probably the most difficult meteorological element to evaluate is wind speed and direction. Quite commonly, the direction of surface winds reverses diurnally, and wind speeds fluctuate greatly from hour to hour and minute to minute. There is also a radical change of wind speed and direction with altitude. The speed and direction at lower levels is greatly influenced by obstructions such as mountains, and locally by small obstructions such as buildings and trees. Accordingly, it is important that great care is exercised in selecting a location and altitude for wind measurement. For most hydrologic applications, wind measurements at elevations of 5 to 15 m above the ground surface are satisfactory. It is important to preserve all basic records of winds, including data on the location, ground elevation, and the height of the anemometer above the ground. An anemometer is an instrument for measuring and indicating the force or speed of the wind. Where continuous records are available, hourly tabulations of speed and direction are highly desirable. Total wind movement and the prevailing direction for each day are also useful data. Daily wind data for each state are published in NOAA publications "Local Climatological Data" and "Climatological Data."

g. Evaporation. Evaporation data is usually required for reservoir studies, particularly for low-flow analysis. Reservoir evaporation is typically estimated by measuring pan evaporation or computing potential evaporation. There are several methods of estimating potential evaporation, based on meteorological information. Pruitt (1990) reviewed various approaches in an evaluation of the methodology and results published in "A Preliminary

Assessment of Corps of Engineer Reservoirs, Their Purposes and Susceptibility to Drought," (HEC 1990e).

(1) Evaporation is usually measured by using a pan about 4 ft (1.2 m) in diameter filled with water to a depth of about 8 in. (0.2 m). Daily evaporation can be calculated by subtracting the previous day's reading from today's reading and adding the precipitation for the intervening period. The pan should be occasionally refilled and this fact noted in the record. This volume of added water, divided by the area of the pan, is equal to the daily evaporation amount expressed in inches or millimeters. A tabulation of daily evaporation amounts should be maintained and, if possible, published. It is essential that a rain gauge be maintained at the evaporation pan site, and it is usually desirable that temperature, dew point (or wet-bulb temperature) and low-level wind measurements also be made at the site for future study purposes.

(2) NOAA Technical Report "NWS 33, Evaporation Atlas for the Contiguous United States" (Farnsworth, Thompson, and Peck 1982) provides maps showing annual and May-October evaporation in addition to pan coefficients for the contiguous United States. Companion report "NWS 34, Mean Monthly, Seasonal, and Annual Pan Evaporation for the United States" documents monthly evaporation data which was used in the development of the evaporation atlas. Daily observed evaporation data are published for each state in NOAA publications "Local Climatological Data" and in "Climatological Data."

h. Upper air soundings. Upper air soundings are available from NOAA National Climatic Data Center in Asheville, NC. The soundings provide atmospheric pressure, temperature, dew point temperature, wind speed, and direction data from which lapse rate, atmospheric stability, and jet stream strength can be determined. These meteorological parameters are necessary to a comprehensive storm study.

5-2. Topographic Data

a. Mapping. For most hydrologic studies, it is essential that good topographic maps be used. It is important that the maps contain contours of ground-surface elevation, so that drainage basins can be delineated and important features such as slopes, exposure, and stream patterns can be measured. United States Operational Navigation Charts, with a scale of 1:1,000,000 and contour intervals of 1,000 ft, are available for most parts of the world. However, mapping to a much larger scale (1:25,000) and smaller contour intervals in the range of 5-20 ft (1.5 to 6 m) are usually necessary for satisfactory hydrologic studies. The USGS 7.5 Minute Series (Scale 1:24,000), with a typical contour interval of 5 or 10 ft (1.5 or 3.0 m), provides a good basic map for watershed studies. The USGS publications "Catalog of Published Maps" and "Index to Maps" are excellent guides to readily available topographic data for each state. Reports by the USGS are available through Books and Open File Reports Section, USGS, Federal Center, Box 25425, Denver, CO, or by contacting the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161.

b. Digital mapping. Increasingly, topographic data are available in digital form. One form of computer description of topography is a digital elevation model (DEM). Geographic information systems (GIS) can link land attributes to topographic data and other information concerning processes and properties related to geographic locations. DEM and GIS representations of topologic data are part of a general group of digital terrain models (DTM). Some of the earliest applications in hydrologic modeling used grid cell (raster) storage of information. An example of raster-based GIS is the Corps' Geographic Resource Analysis Support System (GRASS). An alternate approach utilizes a collection of irregularly spaced points connected by lines to produce triangles, known as triangular irregular network (TIN). The use of DEM and TIN data and processing software is rapidly changing and may soon become the standard operation for developing terrain and related hydrologic models. A review of GIS applications in hydrology is provided by DeVantier et al. (HEC 1993).

c. Stream patterns and profiles. Where detailed studies of floodplains are required, computation of water-surface profiles is necessary. Basic data needed for this computation include detailed cross sections of the river and overbank areas at frequent intervals. These are usually obtained by special field surveys and/or aerial photography. When these surveys are made, it is important to document and date the data and resulting models, then permanently preserve the information so it is readily available for future reference. Observations of actual water-surface elevations during maximum flood stages (high-water marks) are invaluable for calibrating and validating models for profile computations.

d. Lakes and swamps. The rate of runoff from any watershed is greatly influenced by the existence of lakes, swamps, and similar storage areas. It is therefore important to indicate these areas on available maps. Data on the outlet characteristics of lakes are important because, in the absence of outflow measurements, the outflow can often be computed using the relationship between the amount of water stored in the lake and its outlet characteristics.

e. Soil and geology. Certain maps of soils and geology can be very useful in surface-water studies if they show characteristics that relate to perviousness of the basin. These can be used for estimating loss rates during storms. Of particular interest are areas of extensive sandy soils that do not contribute to runoff and areas of limestone and volcanic formations that are highly pervious and can store large amounts of water beneath the surface in a short time. Additionally, watershed sediment yield estimates will depend on similar information. The SCS soil survey reports are the primary source of soil and permeability data. State geologic survey or mineral resource agencies are also a useful source of geologic data.

f. Vegetal cover. Often the type of vegetation more accurately reflects variation in hydrologic phenomena than does the type of soil or the geology. In transposing information to areas of little or no hydrologic data, generalized maps of vegetal cover are very helpful. As with soil and geology, vegetation has a significant impact on sediment yield. In the arid southwest, time since the watershed last burned is a significant parameter in estimating total sediment yield for a storm event. The U.S. Forest Service, the Agricultural Stabilization and Conservation Service (ASCS) and, in western states, the Bureau of Land Management are sources of vegetal cover maps. State forest, agricultural agencies, or USGS topographic maps also provide information on vegetal cover.

g. Existing improvements. Streamflow at any particular location can be greatly affected by hydraulic structures located upstream. It is important, therefore, that essential data be obtained on all significant hydraulic structures located in and upstream from a study area. For diversion structures, detailed data are required on the size of the diversion dam, capacity of the diversion canal, and the probable size of flood required to wash out the diversion dam. In the case of storage reservoirs, detailed data on the relation of storage capacity to elevation, location, and size of outlets and spillways, types, sizes, and operation of control gates, and sizes of power plant and penstocks should be known. Bridges can produce backwater effects which will cause upstream flooding. This flooding may be produced by the approach roads, constriction of the channel and floodplain, pier shapes, the angle between the piers and the streamflow, or the pier length-width ratios.

5-3. Streamflow Data

The availability of streamflow data is a significant factor in the selection of an appropriate technical method for reservoir studies. It is important to be cognizant of the nature, source, reliability, and adequacy of available data. If estimates are needed, the assumptions used should be documented, and the effect of errors in the estimates on the technical procedure and results should be considered.

a. Measurement. Streamflow data are usually best obtained by means of a continuous record of river stage, supplemented by frequent meter measurements of flows that can be related to corresponding river stages. It is important that stage measurements be made at a good control section, even if a weir or other control structures must be constructed. Each meter measurement should consist of velocity measurements within each of several (6-20, where practical) subdivisions within the channel cross section. Velocity for a subdivision is usually taken as the velocity at a depth of 60 percent (0.6) of the distance from the surface to the streambed or as the average of velocities taken at 20 and 80 percent (0.2 and 0.8) of the depth at the middle of the subdivision. River stage readings should be made immediately before and after the cross section is metered. The average of these two stages is the stage associated with the measurement. The measurement is computed by integrating the rates of flow (m^3/s) in all subdivisions of the cross section.

(1) Measurements of stream velocity and computed streamflow are usually recorded on standard forms. When measurements have been made for a sufficient range of flows, the rating curve of flow versus stage can be developed. The rating curve can be used to convert the continuous record of stage into a continuous record of flow. The flows should be averaged for each day in order to construct a tabulation of mean daily flows. This constitutes the most commonly published record of runoff.

(2) For flood studies, it is particularly important to obtain accurate records of short-period variations during high river stages and to obtain meter measurements at or near the maximum stage during as many floods as possible. Where the river profile is very flat, as in estuaries and major rivers, it is advisable to obtain measurements frequently on the rising and on the falling stage to determine if a looped, or hysteresis, effect exists in the rating. The reason for this is that the hydraulic slope can change greatly, resulting in different rating curves for rising and falling stages.

b. Streamflow data sources. The USGS is the primary agency for documenting and publishing flow data in the United States. Daily flow data for each state are published in the USGS annual "Water Data Report." The USGS National Water Data Exchange (NAWDEX) computerized database identifies sources of water data. The National Water Data Storage and Retrieval System (WATSTORE) provides processing, storage, and retrieval of surface water, groundwater, and water quality data.

NAWDEX is only an index of the contents of WATSTORE. These programs will eventually be integrated into a National Water Information System, which will also combine the National Water-Use Information Program and Water Resources Scientific Information Center (Mosley and McKerchar 1993). Commercial data services have also provided convenient access to USGS daily and peak flow files on CD.

c. Flow conditions. Reservoirs substantially alter the distribution of flow in time. Many other developments, such as urbanization, diversions, or cultivation and irrigation of large areas can also have a significant effect on watershed yield and the distribution of flow in time. The degree that flows are modified depends on the scale and manner of the development, as well as the magnitude, time, and areal distribution of rainfall (and snowmelt, if pertinent). Most reservoir evaluations require an assessment based on a consistent flow data set. Various terms are used to define what condition the data represent:

(1) Natural conditions in the drainage basin are defined as the hydrologic conditions that would prevail if no regulatory works or other development affecting basin runoff and streamflow were constructed. The effects of natural lakes and swamp areas are included.

(2) Present conditions are defined as the conditions that exist at, or near, the time of study. If there are upstream reservoirs in the basin, the observed flow record would represent "regulated flow." Flow records, preceding current reservoir projects, would be adjusted to reflect those project operations in order to have consistent "present conditions" flow.

(3) Unregulated conditions reflect the present (or recent) basin development, but without the effect of reservoir regulation. Unlike natural conditions which are difficult to determine, only the effect of reservoir operation and major diversions are removed from the historic data.

(4) Without-project conditions are defined as the conditions that would prevail if the project under consideration were not constructed but with all existing and future projects under construction assumed to exist.

(5) With-project conditions are defined as the conditions that will exist after the project is completed and after completion of all projects having an equal or higher priority of construction.

5-4. Adjustment of Streamflow Data

The adjustment of recorded streamflows is often required before the data can be used in water resources development studies. This is because flow information usually is required at locations other than gauging stations and for conditions of upstream development other than those under which flows occurred historically. In correlating flows between locations, it is important to use "natural" flows (unaffected by artificial storage and diversion) in order that correlation procedures will apply logically and efficiently. In generating flows, natural flows should be used because general frequency functions, characteristic of natural flows, are employed in this process.

a. Natural conditions. When feasible, flow data should be converted to natural conditions. The conversion is made by adding historical storage changes (plus net evaporation) and upstream diversions (less return flows) to historical flows at the gauging stations for each time interval in turn. Under some conditions, it may be necessary to account for differences in channel and overbank infiltration losses, distributary flow diversions, travel times, and other factors.

b. Unregulated conditions. It is not always feasible to convert flows to natural conditions. Often, required data are not available. Also, the hydrologic effects and timing of some basin developments are not known to sufficiently define the required adjustments. An alternative is to adjust the data to a uniform basin condition, usually near current time. The primary adjustments should remove special influences, such as major reservoirs and diversions, that would cause unnatural variations of flow.

c. Reservoir holdouts. The primary effect of reservoir operation is the storage of excess river flow during high-flow periods, and the release of stored water during low-flow periods. The flow adjustment process requires the addition of the change in water stored (hold-outs) in each time step to the observed regulated flow. Holdouts, both positive and negative, are routed down the channel to each gauge and algebraically added to the observed flow. Hydrologic routing methods, typically used for these adjustments, are described in Chapter 9 of EM 1110-2-1417. The HEC Data Storage System (HEC-DSS) software (HEC 1995) provides a convenient data management system and utilities to route flows and add, subtract, or adjust long time-series flow data.

d. Reservoir losses. The nonproject inflow represents the flow at the project site without the reservoir and includes runoff from the entire effective drainage area above the dam, including the reservoir area. Under nonproject conditions, runoff from the area to be inundated by the reservoir is ordinarily only a fraction of the total precipitation which falls on that area. However, under project conditions infiltration losses over the reservoir area are usually minimal during a rainfall event. Thus, practically all the precipitation falling on the reservoir area will appear as runoff. Therefore, the inflow will be greater under project conditions than under nonproject conditions, if inflow is defined as total contribution to the reservoir before evaporation losses are considered. In order to determine the amount of water available for use at the reservoir, evaporation must be subtracted from project inflow. In operation studies, nonproject inflow is ordinarily converted to available water in one operation without computing project inflow as defined above. This is done in one of two ways: by means of a constant annual loss each year with seasonal variation or with a different loss each period, expressed as a function of observed precipitation and evaporation. These two methods are described in the following paragraphs.

(1) Constant annual loss procedure consists of estimating the evapotranspiration and infiltration losses over the reservoir area for conditions without the project, and the evaporation and infiltration losses over the reservoir area with the project. Nonproject losses are usually estimated as the difference between average annual precipitation and average annual runoff at the location, distributed seasonally in accordance with precipitation and temperature variations. These are expressed in millimeters of depth. Under project conditions, infiltration losses are usually ignored, and losses are considered to consist of only direct evaporation from the lake area, expressed in millimeters for each period. The difference between these losses is the net loss due to the project. Figure 5-1 illustrates the differences between nonproject and project losses.

(2) The variable loss approach uses historical records of long-term average monthly precipitation and evaporation data to account for the change in losses due to a reservoir project. This is accomplished by estimating the average runoff coefficient, the ratio of runoff to rainfall, for the reservoir area under preproject conditions and subtracting this from the runoff coefficient for the reservoir area under project conditions. The runoff coefficient for project conditions is usually 1.0, but a lower coefficient may be used if substantial infiltration or leakage from the reservoir is anticipated. The difference between preproject and project runoff coefficients is the net gain expressed as a ratio of precipitation falling on the reservoir. This is often estimated to be 0.7 for semi-arid regions. This increase in runoff is subtracted from gross reservoir evaporation, often estimated as 0.7 of pan evaporation, to obtain a net loss.

e. Other losses. In final project studies it is often necessary to consider other types of project losses which may be of minor importance in preliminary studies. Often, these losses cannot be estimated until a project design has been adopted. The importance of these losses is dependent upon their relative magnitude. That is, losses of 5 m^3/s might be considered unimportant for a stream which has a minimum average annual flow of 1,500 m^3/s. Such losses, though, would be significant from a stream with a minimum average annual flow of 25 m^3/s. Various types of losses are discussed in the following paragraphs.

(1) The term "losses" may not actually denote a physical loss of water from the system as a whole. Usually, water unavailable for a specific project purpose is called a "loss" for that purpose although it may be used at some other point or for some other purpose. For example, water which leaves the reservoir through a pipeline for municipal water supply or fish hatchery requirements might be called a loss to power. Likewise, leakages through turbines, dams, conduits, and spillway gates are considered losses to hydropower generation, but they are ordinarily not losses to flow requirements at a downstream station. Furthermore, such losses that become available for use below the dam should be added to inflow at points downstream from the project.

(2) Leakage at a dam or in a reservoir area is considered a loss for purposes which are dependent upon availability of water at the dam or in the reservoir itself. These purposes include power generation, pipelines from the reservoir, and any purpose which utilizes pump intakes which are located at or above the dam. As a rule, leakage through, around, or under a dam is relatively small and is difficult to quantify before a project is actually constructed. In some cases, the measured leakage at a similar dam or geologic area may be used as a basis for estimating losses at a proposed project. The amount of leakage is a function of the type and size of dam, the geologic conditions, and the hydrostatic pressure against the dam.

(3) Leakage from conduits and spillway gates is a function of gate perimeter, type of seal, and head on the gate, and it varies with the square root of the head. The amount of leakage may again be measured at existing projects with various types of seals, and a leakage rate computed per meter of perimeter for a given head. This rate may then be used to compute estimated leakage for a

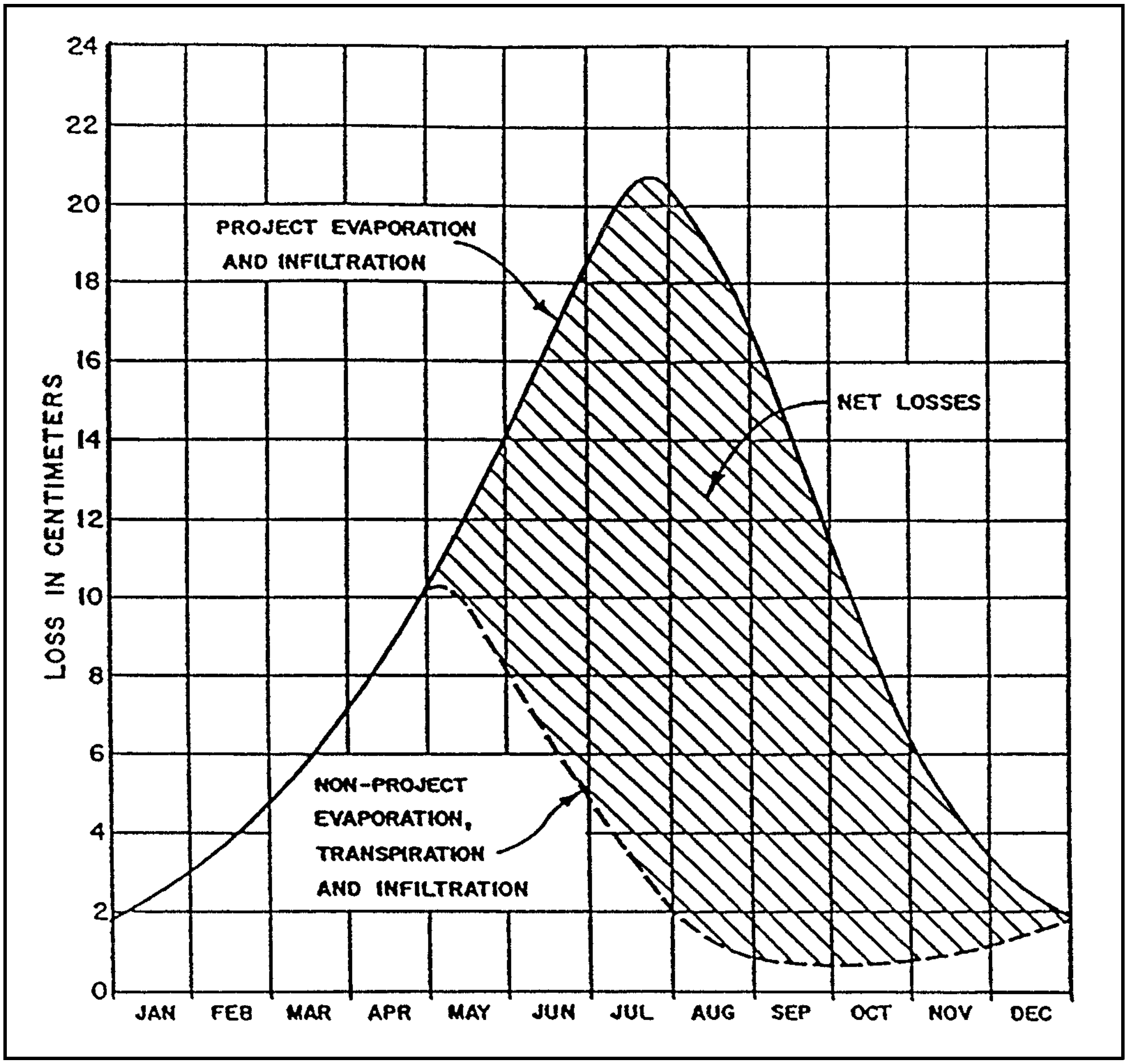

Figure 5-1. Project and nonproject reservoir losses

proposed project by using the proposed size and number of gates and the proposed head on the gates.

(4) If a proposed project will include power, and if the area demand is such that the turbines will sometimes be idle, it is advisable to estimate leakage through the turbines when closed. This leakage is a function of the type of penstock gate, type of turbine wicket gate, number of turbines, and head on the turbine. The actual leakage through a turbine may be measured at the time of acceptance and during annual maintenance inspections, or the measurements of similar existing projects may be used to estimate leakage for a proposed project. An estimate of the percent of time that a unit will be closed may be obtained from actual operational records for existing units in the same demand area. The measured or estimated leakage rate is then reduced by multiplying by the proportion of time the unit will be closed. For example, suppose that leakage through a turbine has been measured at 0.1 m^3/s, and the operation records indicate that the unit is closed 60 percent of the time. The average leakage rate would be estimated at 0.1×0.6 or 0.06 m^3/s.

(5) The inclusion of a navigation lock at a dam requires that locking operations and leakages through the lock be considered. The leakage is dependent upon the lift or head, the type and size of lock, and the type of gates and seals. Again, estimates can be made from observed leakage at similar structures. Water required for locking operations should also be deducted from water available at the dam site. These demands can be computed by multiplying the volume of water required for a single locking operation

times the number of operations anticipated in a given time period and converting the product to a flow rate over the given period.

(6) Water use for purposes related to project operations is often treated as a loss. Station use for sanitary and drinking purposes, cooling water for generators, and water for condensing operations have been estimated to be about 0.06 m^3/s per turbine at some stations in the southwestern United States. Examining operation records for comparable projects in a given study area may also be useful in estimating these losses. If house units are included in a project to supply the project's power requirements, data should be obtained from the designer in order to estimate water used by the units.

(7) The competitive use of water should also be considered when evaluating reservoir losses. When initially estimating yield rates for various project purposes at a multiple-purpose project, competitive uses of water are often treated as losses. For example, consider a proposed project on a stream with an average minimum usable flow of 16 m^3/s. The reservoir of this project is to supply 1.5 m^3/s by pipeline for downstream water supply and 2.0 m^3/s for a fish hatchery in addition to providing for hydroelectric power production. The minimum average flow available for power generation is thus, $16 - (1.5 + 2.0) = 12.5$ m^3/s. Care should be exercised in accounting for all such competitive uses when making preliminary yield estimates.

f. Missing data.

(1) After recorded flows are converted to uniform conditions, flows for missing periods of record at each pertinent location should be estimated by correlation with recorded flows at other locations in the region. Usually, only one other location is used, and linear correlation of flow logarithms is used. It is more satisfactory, however, to use all other locations in the region that can contribute independent information on the missing data. Although this would require a large amount of computation, the computer program HEC-4 *Monthly Streamflow Simulation* accomplishes this for monthly streamflow (HEC 1971).

(2) Flow estimates for ungauged locations can be estimated satisfactorily on a flow per basin area basis in some cases, particularly where a gauge exists on the same stream. In most cases, however, it is necessary to correlate mean flow logarithms (and sometimes standard deviation of flow logarithms) with logarithms of drainage area size, logarithm of normal seasonal precipitation, and other basin characteristics. Correlation procedures and suggested basin characteristics are described in Chapter 9 of EM 1110-2-1415.

g. Preproject conditions. After project flows for a specified condition of upstream development are obtained for all pertinent locations and periods, they must be converted to preproject (nonproject) conditions. Nonproject conditions are those that would prevail during the lifetime of the proposed project if the project was not constructed. This conversion is made by subtracting projected upstream diversions and storage changes and by accounting for evaporation, return flows, differences in channel infiltration, and timing. Where nonproject conditions will vary during the project lifetime, it is necessary to convert to two or more sets of conditions, such as those at the start and end of the proposed project life. Separate operation studies would then be made for each condition. This conversion to future conditions can be made simultaneously with project operation studies, but a separate evaluation of nonproject flows is usually required for economic evaluation of the project.

5-5. Simulation of Streamflow Data

a. Introduction. The term "simulation" has been used to refer to both the estimation of historic sequences and the assessment of probable future sequences of streamflow. The former reference concerns the application of continuous precipitation-runoff models to simulate streamflow based on meteorologic input such as rainfall and temperature. The latter reference concerns the application of stochastic (probabilistic) models that employ Monte Carlo simulation methods to estimate the probable occurrence of future streamflow sequences. Assessment of the probable reliability of water resource systems can be made given the assessment of probable future sequences of flow. Statistical methods used in stochastic models can also be employed to augment observed historic data by filling in or extending observed streamflow records.

b. Historic sequences from continuous precipitation-runoff models. Many different types of continuous simulation runoff models have been used to estimate the historic sequence of streamflow that would occur from observed precipitation and other meteorologic variables. Among the most prominent are the various forms of the Stanford Watershed Model (Mays and Tung 1992) and the SSARR Model used by the North Pacific Division (USACE 1991). For a further description of the application of the models see EM 1110-2-1417 Section 8.

c. Stochastic streamflow models. Stochastic streamflow models are used to assess the probable sequence of future flows. As with any model, a model structure is assumed, parameters are estimated from observed data, and the model is used for prediction (Salas et al. 1980). Typically, stochastic streamflow models are used to simulate annual and/or monthly streamflow volumes. Stochastic streamflow models have not been successfully developed for daily streamflow.

(1) Although many different structures have been proposed in the research literature, regression is most commonly used as the basis for stochastic streamflow models. The regressions involve both correlation between flows at different sites and the correlation between current and past flow periods, termed serial correlation. The correlation between sites is useful in improving parameters estimates from regional information. The serial correlation between periods is important in modeling the persistence, or the tendency for high flow or drought periods. A random error component is added to the regression to provide a probabilistic component to the model.

(2) The model parameters are estimated to preserve the correlation structure observed in the observed data. If the appropriate correlation structure is preserved, then the regression residuals should closely approximate the behavior that would be expected from a random error component.

(3) Model prediction is performed via the application of Monte Carlo simulation. Monte Carlo simulation is a numerical integration technique. This numerical technique is necessary because the stochastic model effectively represents a complex joint probability distribution of streamflows in time and space that cannot be evaluated analytically. The simulation is performed by producing random sequences of flows via a computer algorithm that employs random number generators. These sequences of flows are analyzed to assess supply characteristics, for example the probability for a certain magnitude or duration of drought. The number of flow sequences generated is sufficient when the estimated probabilities do not change significantly with the number of simulations. For further explanation of this point, see "Stochastic Analysis of Drought Phenomena" (HEC 1985b).

d. Assessment of reliability with stochastic streamflow models. The advantage of using a stochastic streamflow model over that of employing only historic records is that it can be used to provide a probabilistic estimate of a water resource system's reliability. For example, the probability that a particular reservoir will be able to meet certain goals can be estimated by simulating the stochastic flow sequences with a reservoir simulation model. Once again, the number of flow sequences used are sufficient when the estimate of the probabilities stabilize.

e. Available software for stochastic streamflow simulation. HEC-4, "Monthly Streamflow Simulation" (HEC 1971), and LAST (Lane 1990) are public domain software for performing stochastic streamflow simulation. HEC-4 performs monthly stochastic streamflow simulation. LAST utilizes a more modern approach where annual and shorter time period (seasonal, monthly, etc.) stochastic streamflow can be co-simulated.

f. Extending and filling in historic records. Statistical techniques can be used to augment existing historic records by either "filling in" missing flow values or extending the observed record at a gauge based on observations at other gauges. The statistical techniques used are referred to as MOVE, maintenance of variance extension, and are a modification of regression based techniques (Alley and Burns 1983, and Salas 1992). MOVE algorithms have been instituted because the variance of series augmented by regression alone is underestimated. The MOVE technology is only generally applicable when serial correlation does not exist in the streamflow records. However, monthly or annual sequences of streamflow volumes usually do exhibit a degree of serial correlation. In these circumstances, the information provided by the longer record station may not be useful in extending a shorter record station. For a discussion of the impact of serial correlation see Matalas and Langbein (1962) and Tasker (1983).

Chapter 6
Hydrologic Frequency Determinations

6-1. Introduction

Frequency curves are most commonly used in Corps of Engineers studies to determine the economic value of flood reduction projects. Reservoir applications also include the determination of reservoir stage for real estate acquisition and reservoir-use purposes, the selection of rainfall magnitude for synthetic floods, and the selection of runoff magnitude for sizing flood-control storage.

a. Annual and partial-duration frequency. There are two basic types of frequency curves used in hydrologic work. A curve of annual maximum events is ordinarily used when the primary interest lies in the very large events or when the second largest event in any year is of minor concern in the analysis. The partial-duration curve represents the frequency of all events above a given base value, regardless of whether two or more occurred in the same year. This type of curve is ordinarily used in economic analysis when there are substantial damages resulting from the second largest and third largest floods in extremely wet years. Damage from floods occurring more frequently than the annual event can occur in agricultural areas, when there is sufficient time between events for recovery and new investment. When both the frequency curve of annual floods and the partial-duration curve are used, care must be exercised to assure that the two are consistent.

b. Seasonal frequency curves. In most locations, there are seasons when storms or floods do not occur or are not severe, and other seasons when they are more severe. Also, damage associated with a flood often varies with the season of the year. In studies where the seasonal variation is of primary importance, it becomes necessary to establish frequency curves for each month or other subdivision of the year. For example, one frequency curve might represent the largest floods that occur each January; a second one would represent the largest floods that occur each February, etc. In another case, one frequency curve might represent floods during the snowmelt season, while a second might represent floods during the rainy season. Occasionally, when seasons are studied separately, an annual-event curve covering all seasons is also prepared. Care should be exercised to assure that the various seasonal curves are consistent with the annual curve.

6-2. Duration Curves

a. Flow duration curve. In power studies, for run-of-river plants particularly and in low-flow studies, the flow-duration curve serves a useful purpose. It simply represents the percent of time during which specified flow rates are exceeded at a given location. Ordinarily, variations within periods less than 1 day are inconsequential, and the curves are therefore based on observed mean-daily flows. For the purposes served by flow duration curves, the extreme rates of flow are not important, and consequently there is no need for refining the curve in regions of high flow.

b. Preparing flow-duration curve. The procedure ordinarily used to prepare a flow duration curve consists of counting the number of mean-daily flows that occur within given ranges of magnitude. The lower limit of magnitude in each range is then plotted against the percentage of days of record that mean-daily flows exceed that magnitude. A flow duration curve example is shown in Figure 6-1.

6-3. Flood-Frequency Determinations

At many locations, flood stages are a unique function of flood discharges for most practical purposes. Accordingly, it is usual practice to establish a frequency curve of river discharges as the basic hydrologic determination for flood damage reduction project studies. In special cases, factors other than river discharge, such as tidal action or accumulated run-off volume, may greatly influence river stages. In such cases, a direct study of stage frequency based on recorded stages is often warranted.

a. Determination made with available data. Where runoff data at or near the site are available, flood-frequency determinations are most reliably made by direct study of these data. Before frequency studies of recorded flows are made, the flows must be converted to a uniform condition, usually to conditions without major regulation or diversion. Developing unregulated flow requires detailed routing studies to remove the effect of reservoir hold-outs and diversions. As damaging flows occur during a very small fraction of the total time, only a small percentage of daily flows are used for flood-frequency studies. These consist of the largest flow that occurs each year and the secondary peak flows that cause damage. However, for most reservoirs studies, the period-of-record flow will be required for analysis of nonflood purposes and impacts.

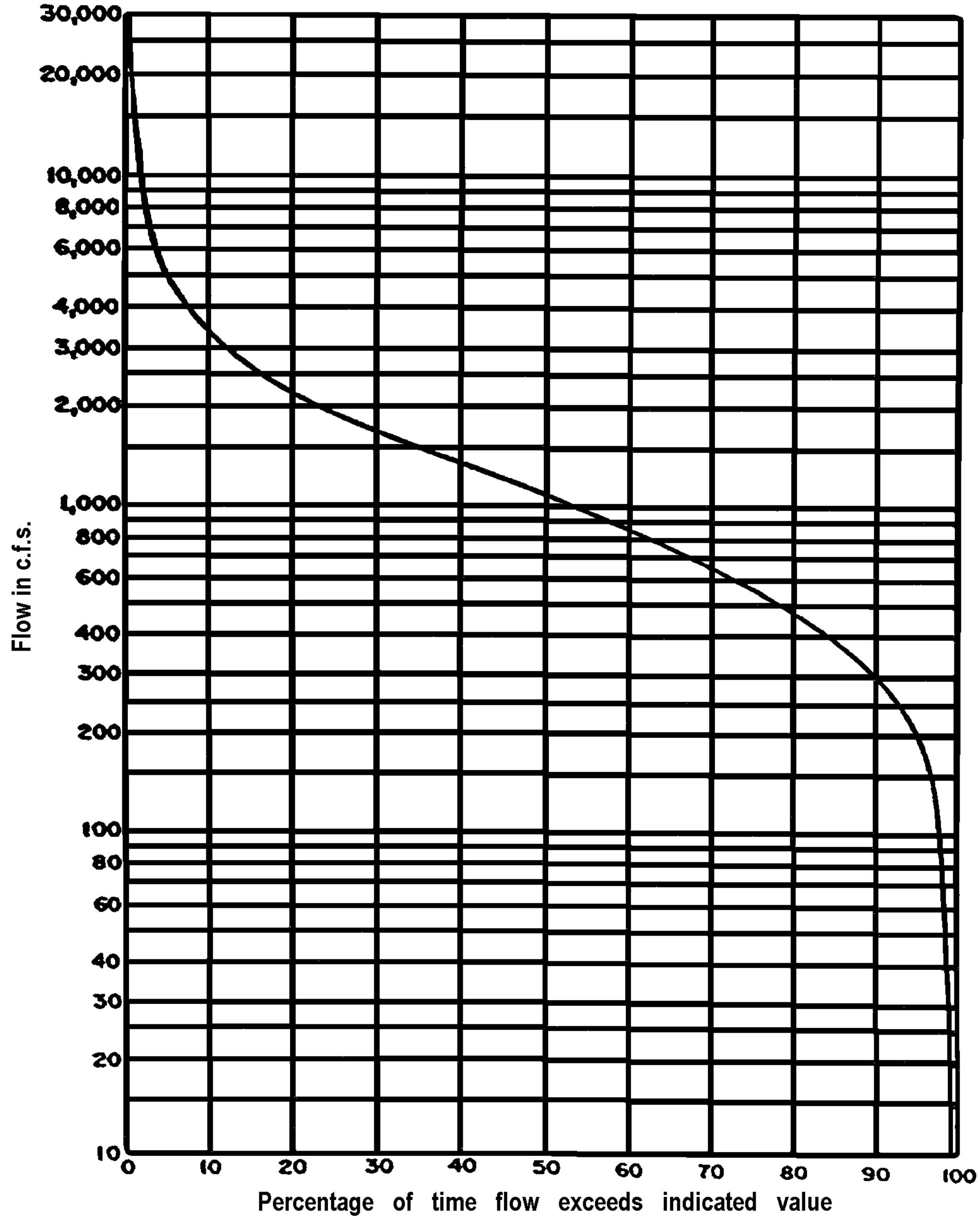

Figure 6-1. Example flow duration curve

b. Historical data. Flood frequency estimates are subject to considerable uncertainty, even when fairly long records are available. In order to increase the reliability of frequency estimates, empirical theoretical frequency relations are used in specific frequency studies. These studies require that a complete set of data be used. In order to comply with this requirement, the basic frequency study ordinarily is based on the maximum flow for each year of record. Supplementary studies that include other damaging events are ordinarily made separately. The addition of historical information can be very important in verifying the frequency of large recorded events. Historical information on large damaging floods can be obtained through standard sources such as USGS water supply series or from newspapers and local museums. The latter sources often are more qualitative but give important insight into the relative frequency of recorded events.

c. Selecting and computing frequency curves. The underlying general assumption made in all frequency studies is that each observed event represents an approximately equal proportion of the future events that will occur at the location, if controlling conditions do not change. Detailed procedures for selecting data and computing flood-frequency curves are presented in EM 1110-2-1415 and HEC-FFA program (HEC 1992c).

d. Regional correlation of data. Where runoff data at or near the site do not exist or are too fragmentary to support direct frequency calculations, regional correlation of frequency statistics may be used for estimating frequencies. These correlations generally relate the mean and standard deviation of flows to drainage basin characteristics and location. Techniques of regional correlation are presented in Chapter 9 of EM 1110-2-1415.

e. Extreme floods. In the analysis of reservoir projects, the project's performance during floods larger than the maximum recorded events is usually required. Extrapolating derived frequency relations is uncertain, so special studies of the potential magnitudes of extreme flood events are usually required. The most practical approach is through examination of rainstorms that have occurred in the region and determination of the runoff that would result at the project location if these storms should occur in the tributary area. This subject is discussed in the following chapter, "Flood-Runoff Analysis."

6-4. Estimating Frequency Curves

a. Approaches. There are two basic approaches to estimating frequency curves--graphical and analytical. Each approach has several variations, but the discussion herein will be limited to recommended methods. The primary Corps reference for computing frequency curves is EM 1110-2-1415.

(1) Graphical. Frequencies are evaluated graphically by arranging observed values in the order of magnitude and representing frequencies by a smooth curve through the array of values. Each observed value represents a fraction of the future possibilities and, when plotting the frequency curve, it is given a plotting position that is calculated to give it the proper weight. Every derived frequency relation should be plotted graphically, even though the results can be obtained analytically. Paragraph 2-4 of EM 1110-2-1415 presents "Graphical Frequency Analysis."

(2) Analytical. In the application of analytical (statistical) procedures, the concept of theoretical populations or distributions is employed. The events that have occurred are presumed to constitute a random sample and are used accordingly to make inferences regarding their "parent population" (i.e., the distribution from which they were derived). The procedure is applied to annual maxima of unregulated flow, which are assumed to be independent random events. The fact that the set of observations could result from any of many sets of physical conditions or distributions leaves considerable uncertainty in the derived curve. However, using statistical processes, the most probable nature of the distribution from which the data were derived can be estimated. Because this in all probability is not the true parent population, the relative chance that variations from this distribution might be true must be evaluated. Each range of possible parent populations is then weighted in proportion to its likelihood in order to obtain a weighted average. A probability obtained from this weighted average is herein referred to as the expected probability P_N. Chapter 3 of EM 1110-2-1415 covers analytical flood-frequency analysis.

(3) Regional. Because of the shortness of hydrologic records, frequency determinations for rare events are relatively unreliable when based on a single record. Also, it is often necessary to estimate frequencies for locations where no record exists. For these reasons, regionalized frequency studies, in which frequency characteristics are related to drainage-basin features and precipitation characteristics, are desirable. Regionalized frequency studies usually develop relationships for analytical frequency statistics. An alternative approach is to develop predictive equations for the flow for specific recurrence intervals. Chapter 9 of EM 1110-2-1415 presents regression analysis and its application to regional studies.

b. Flood volume-duration frequencies. A comprehensive flood volume-duration frequency series consists of a set of: 1, 3, 7, 15, 30, 60, 120, and 183-day average flows for each water year. These durations are normally available from the USGS WATSTORE files, and they are the default durations in the computer program STATS (HEC 1987a). Runoff volumes are expressed as average flows in order that peak flows and volumes can be readily compared and coordinated. Paragraph 3-8 of EM 1110-2-1415 covers flood volumes.

c. Low flow frequencies. Reservoir analysis often requires the evaluation of the frequencies of low flows for various durations. The same fundamental procedures can be used, except that minimum instead of maximum runoff values are selected from the basic data. For low flows, the effects of basin development are usually more significant than for high flow. A relatively moderate diversion may not be very significant during a flood; however, it may greatly modify or even eliminate low flows. Accordingly, one of the most important aspects of low flows concerns the evaluation of past and future effects of basin developments. Chapter 4 of EM 1110-2-1415 describes low-flow frequency analysis.

d. Reservoir level frequency. A reservoir frequency curve of annual maximum storage is ordinarily constructed graphically, using the procedures for flood-flow frequency. Observed storage should be used to the extent available, but only if the reservoir has been operated in the past in accordance with future plans. If historical data are not available, or if it is not appropriate for future use, then reservoir routings should be used to develop data for expected reservoir operations. Stage-duration curves can be constructed from historical operation data or from simulations. These curves are usually constructed for the entire period-of-record, or for a selected wet or dry period. For some purposes, particularly recreational use, the seasonal variation of reservoir stages is of importance, and a set of frequency or duration curves for each month of the year may be required. Reservoir stage (or elevation) curves should indicate significant reservoir levels such as: minimum pool, top of conservation pool, top of flood-control pool, spillway crest elevation, and top of dam.

6-5. Effect of Basin Developments on Frequency Relations

a. Effects of flood-control works. Most hydrologic frequency estimates serve some purpose relating to the planning, design, or operation of water resources management projects. The anticipated effects of a project on flooding can be assessed by comparing the peak discharge and volume frequency curves with and without the project. Also, projects that have existed in the past have affected the rates and volumes of floods, and recorded values must be adjusted to reflect uniform conditions in order for the frequency analysis to conform to the basic assumptions of randomness and common population. For a frequency curve to conform reasonably with a generalized mathematical or probability law, the flows must be essentially unregulated by man-made storage or diversion structures. Consequently, wherever practicable, recorded runoff values should be adjusted to unregulated conditions before a frequency analysis is made. However, in cases where the regulation results from a multitude of relatively small hydraulic structures that have not changed appreciably during the period of record, it is likely that the general mathematical laws will apply as in the case of natural flows, and that adjustment to natural conditions would be unnecessary. The effects of flood control works are presented in paragraph 3-9 of EM 1110-2-1415, and effects of urbanization in paragraph 3-10.

b. Regulated runoff frequency curves. If it is practical, the most complete approach to determining frequency curves of regulated runoff consists of routing flows for the entire period of record through the proposed management works, arranging the annual peak regulated flows in order of magnitude, assigning a plotting position to the peak values, plotting the peak flow values at the assigned plotting position, and drawing the frequency curve based on the plotted data. A less involved method consists of routing the largest floods of record, or multiples of a large hypothetical flood, to estimate the regulated frequency curve. This approach requires the assumption that the frequency of the regulated peak flow is the same as the unregulated peak flow, which is probably true for the largest floods. Paragraph 3-9*d* of EM 1110-2-1415 describes these methods.

c. Erratic stage-discharge frequency curves. In general, cumulative frequency curves of river stages are determined from frequency curves of flow. In cases where the stage-discharge relation is erratic, a frequency curve of stages can be derived directly from stage data. Chapter 6 of EM 1110-2-1415 presents stage-frequency analysis.

d. Reservoir or channel modifications. Project construction or natural changes in streambed elevation may change the relationship between stage and flow at a location. By forming constrictions, levees may raise river stages half a meter for some distance upstream. Reservoir or channel modifications may cause changes in degradation or aggradation of streambeds, and thereby change rating curves. Thus, the effect of projects on river stages often involves the effects on channel hydraulics as well as the effects on streamflow. Consult EM 1110-2-1416 for information on modeling these potential changes.

6-6. Selection of Frequency Data

a. Primary considerations. The primary consideration in selecting an array of data for a frequency study is the objective of the frequency analysis. If the frequency curve that is developed is to be used for estimating damages that are related to instantaneous peak flows in a stream, peak flows should be selected from the record. If the damages are related to maximum mean-daily flows or to maximum 3-day flows, these items should be selected. If the behavior of a reservoir under investigation is related to the 3-day or 10-day rain-flood volume, or to the seasonal snowmelt volume, that pertinent item should be selected. Normally, several durations are analyzed along with peak flows to develop a consistent relationship.

b. Selecting a related variable. Occasionally, it is necessary to select a related variable in lieu of the one desired. For example, where mean daily flow records are more complete than the records of peak flows, it may be desirable to derive a frequency curve of mean-daily flows and then, from the computed curve, derive a peak-flow curve by means of an empirical relation between mean daily flows and peak flows. All reasonably independent values should be selected, but the annual maximum events should ordinarily be segregated when the application of analytical procedures is contemplated.

c. Data selected. Data selected for a frequency study must measure the same aspect of each event (such as peak flow, mean-daily flow, or flood volume for a specified duration), and each event must be controlled by a uniform set of hydrologic and operational factors. For example, it would be improper to combine items from old records that are reported as peak flows but are in fact only daily readings, with newer records where the peak was actually measured. Similarly, care should be exercised when there has been significant change in upstream storage regulation during the period of record so as not to inadvertently combine unlike events into a single series. In such a case, the entire flow record should be adjusted to a consistent condition, preferably the unregulated flow condition.

d. Hydrologic factors. Hydrologic factors and relationships operating during a winter rain flood are usually quite different from those operating during a spring snowmelt flood or during a local summer cloudburst flood. Where two or more types of floods are distinct and do not occur predominantly in mutual combinations, they should not be combined into a single series for frequency analysis. They should be considered as events from different parent populations. It is usually more reliable in such cases to segregate the data in accordance with type and to combine only the final curves, if necessary. For example, in the mountainous region of eastern California, frequency studies are made separately for rain floods, which occur principally from November through March, and for snowmelt floods, which occur from April through July. Flows for each of these two seasons are segregated strictly by cause, those predominantly caused by snowmelt and those predominantly caused by rain. In desert regions, summer thunderstorms should be excluded from frequency studies of winter rain flood or spring snowmelt floods and should be considered separately. Similarly, in coastal regions it would be desirable to separate floods induced by hurricanes or typhoons from other general flood events.

e. Data adjustments. When practicable, all runoff data should be adjusted to unregulated hydrologic conditions before making the frequency study because natural flows are better adapted to analytical methods and are more easily compared within a region. Frequency curves of present-regulated conditions (those prevailing under current practices of regulation and diversion) or of future-regulated conditions can be constructed from the frequency curve of natural flow by means of an empirical or logical relationship between natural and regulated flows. Where data recorded at two different locations are to be combined for construction of a single frequency curve, the data should be adjusted as necessary to a single location, usually the location of the longer record, accounting for differences of drainage area and precipitation and, where appropriate, channel characteristics between the locations. Where the stream-gauge location is somewhat different from the project location, the frequency curve should be constructed for the stream-gauge location and subsequently adjusted to the project location.

f. Runoff record interruptions. Occasionally, a runoff record may be interrupted by a period of one or more years. If the interruption is caused by the destruction of the gauging station by a large flood, failure to fill in the record for that flood would have a biasing effect, which should be avoided. However, if the cause of the interruption is known to be independent of flow magnitude, the entire period of interruption should be eliminated from the frequency array, since no bias would result. In cases where no runoff records are available on the stream concerned, it is possible to estimate the frequency curve as a whole using regional generalizations. An alternative method is to estimate a complete series of individual floods from recorded precipitation by continuous hydrologic simulation and perform conventional frequency analysis on the simulated record.

6-7. Climatic Variations

Some hydrologic records suggest regular cyclic variations in precipitation and runoff potential. Many attempts have been made to demonstrate that precipitation or stream flows display variations that are in phase with various cycles, particularly the well-established 11-year sunspot cycle. There is no doubt that long duration cycles or irregular climatic changes are associated with general changes of land masses and seas and with local changes in lakes and swamps. Also, large areas that have been known to be fertile in the past are now arid deserts, and large temperate regions have been covered with glaciers one or more times. Although the existence of climatic changes is not questioned, their effect is ordinarily neglected because long-term climatic changes generally have insignificant effects during the period concerned in water development projects, and short-term climatic changes tend to be self-compensating. For these reasons, and because of the difficulty in differentiating between fortuitous and systematic changes, it is considered that, except for the annual cycle, the effect of natural cycles or trends during the period of useful project life can ordinarily be neglected in hydrologic frequency studies.

6-8. Frequency Reliability Analyses

a. Influences. The reliability of frequency estimates is influenced by the amount of information available, the variability of the events, and the accuracy with which the data were measured.

(1) In general with regard to the amount of information available, errors of estimate are inversely proportional to the square root of the number of independent items contained in the frequency array. Therefore, errors of estimates based on 40 years of record would normally be half as large as errors of estimates based on 10 years of record, other conditions being the same.

(2) The variability of events in a record is usually the most important factor affecting the reliability of frequency estimates. For example, the ratio of the largest to the smallest annual flood of record on the Mississippi River at Red River Landing, LA, is about 2.7; whereas the ratio of the largest to the smallest annual flood of record on the Kings River at Piedra, CA, is about 100 or 35 times as great. Statistical studies show that as a consequence of this difference in variability, a flow corresponding to a given frequency that can be estimated within 10 percent on the Mississippi River, can be estimated only within 40 percent on the Kings River.

(3) The accuracy of data measurement normally has relatively little influence on the reliability of a frequency estimate, because such errors ordinarily are not systematic and tend to cancel. The influence of extreme events on reliability of frequency estimates is greater than that of measurement errors. For this reason, it is usually better to include an estimated magnitude for a major flood than to ignore it. For example, a flood event that was not recorded because of gauge failure should be estimated, rather than to omit it from the frequency array. However, it is advisable to always use the most reliable sources of data and to guard against systematic errors.

b. Errors in estimating flood frequencies. It should be remembered that possible errors in estimating flood frequencies are very large, principally because of the chance of having a nonrepresentative sample. Sometimes the occurrence of one or two rare flood events can change the apparent exceedance frequency of a given magnitude from once in 1,000 years to once in 200 years. Nevertheless, the frequency-curve technique is considerably better than any other tool available for certain purposes and represents a substantial improvement over using an array restricted to observed flows only. Reliability criteria useful for illustrating the accuracy of frequency determinations are described in Chapter 8 of EM 1110-2-1415.

6-9. Presentation of Frequency Analysis Results

Information provided with frequency curves should clearly indicate the scope of the studies and include a brief description of the procedure used, including appropriate references. When rough estimates are adequate or necessary, the frequency data should be properly qualified in order to avoid misleading conclusions that might seriously affect the project plan. A summary of the basic data consisting of a chronological tabulation of values used and indicating sources of data and adjustments made would be helpful. The frequency data can also advantageously be presented in graphical form, ordinarily on probability paper, along with the adopted frequency curves.

Chapter 7
Flood-Runoff Analysis

7-1. Introduction

Flood-runoff analysis is usually required for any reservoir project. Even without flood control as a purpose, a reservoir must be designed to safely pass flood flows. Rarely are there sufficient flow records at a reservoir site to meet all analysis requirements for the evaluation of a reservoir project. This chapter describes the methods used to analyze the flood hydrographs and the application of hypothetical floods in reservoir projects. Most of the details on methods are presented in EM 1110-2-1417. The dam safety standards are dependent on the type and location of the dam. ER 1110-8-2 defines the requirements for design floods to evaluate dam and spillway adequacy. Requirements for flood development and application are also provided.

7-2. Flood Hydrograph Analysis

a. Unit hydrograph method. The standard Corps procedure for computing flood hydrographs from catchments is the unit hydrograph method. The fundamental components are listed below:

(1) Analysis of rainfall and/or snowmelt to determine the time-distributed average precipitation input to each catchment area.

(2) Infiltration, or loss, analysis to determine the precipitation excess available for surface runoff.

(3) Unit hydrograph transforms to estimate the surface flow hydrograph at the catchment outflow location.

(4) Baseflow estimation to determine the subsurface contribution to the total runoff hydrograph.

(5) Hydrograph routing and combining to move catchment hydrographs through the basin and determine total runoff at desired locations.

For urban catchments, the kinematic-wave approach is often used to compute the surface flow hydrograph, instead of unit hydrograph transforms. Each of the standard flood runoff and routing procedures is described in Part 2 of EM 1110-2-1417. HEC-1 Flood *Hydrograph Package* (HEC 1990c) is a generalized computer program providing the standard methods for performing the required components for basin modeling.

b. Rainfall-runoff parameters. Whenever possible unit hydrographs and loss rate characteristics should be derived from the reconstitution of observed storm and flood events on the study watershed, or nearby watersheds with similar characteristics. The HEC-1 program has optimization routines to facilitate the determination of best-fit rainfall-runoff parameters for each event. When runoff records are not available at or near the location of interest, unit hydrograph and loss characteristics must be determined from regional studies of such characteristics observed at gauged locations. Runoff and loss coefficients can be related to drainage basin characteristics by multiple correlation analysis and mapping procedures, as described in Chapter 16, "Ungauged Basin Analysis" of EM 1110-2-1417.

c. Developing basin models. Flood hydrographs may be developed for a number of purposes. Basin models are developed to provide hydrographs for historical events at required locations where gauged data are not available. Even in large basins, there will be limited gauged data and many locations where data are desired. With some gauged data, a basin model can be developed and calibrated for observed flood events. Chapter 13 of EM 1110-2-1417 provides information on model development and calibration.

d. Estimating runoff. Basin models can estimate the runoff response under changing conditions. Even with historical flow records, many reservoir studies will require estimates of flood runoff under future, changed conditions. The future runoff with developments in the catchment and modifications in the channel system can be modeled with a basin runoff model.

e. Application. For reservoir studies, the most frequent application of flood hydrograph analysis is to develop hypothetical (or synthetic) floods. The three common applications are frequency-storms, SPF and PMF. Frequency-based design floods are used to develop flood-frequency information, like that required to compute expected annual flood damage. SPF and PMF are used as design standards to evaluate project performance under the more rare flood events.

7-3. Hypothetical Floods

a. General. Hypothetical floods are usually used in the planning and design of reservoir projects as a primary basis of design for some project features and to substantiate the estimates of extreme flood-peak frequency. Where runoff data are not available for computing frequency curves of peak discharge, hypothetical floods can be used to establish flood magnitudes for a specified frequency from rainstorm events of that frequency. This approach is not accurate where variations in soil-moisture conditions and rainfall distribution characteristics greatly influence flood magnitudes. In general, measured data should be used to the maximum extent possible, and when approximate methods are used, several approaches should be taken to compute flood magnitudes.

b. Frequency-based design floods. In areas where infiltration losses are small, it may be feasible to compute hypothetical floods from rainfall amounts of a specified frequency and to assign that frequency to the flood event. NOAA publishes generalized rainfall criteria for the United States. They contain maps with isopluvial lines of point precipitation for various frequencies and durations. These point values are then adjusted for application to areas greater that 10 square miles, based on precipitation duration and catchment area. Section 13-4 of EM 1110-2-1417 provides information on simulation with frequency-based design storms.

c. Standard project flood. The SPF is the flood that can be expected from the most severe combination of meteorologic and hydrologic conditions that are considered reasonably characteristic of the region in which the study basin is located. The SPF, which provides a performance standard for potential major floods, is based on the Standard Project Storm (SPS).

(1) The SPS is usually an envelope of all or almost all of the storms that have occurred in a given region. The size of this storm is derived by drawing isohyetal maps of the largest historical storms and developing a depth-area curve for the area of maximum precipitation for each storm. Depth-area curves for storm rainfall of specified durations are derived from this storm-total curve by a study of the average time distribution of precipitation at stations representing various area sizes at the storm center. When such depth-area curves are obtained for all large storms in the region, the maximum values for each area size and duration are used to form a single set of depth-area-duration curves representing standard project storm hyetographs for selected area sizes, using a typical time distribution observed in major storms. EM 1110-2-1411 provides generalized SPS estimates for small and large drainage basins, and projects for which SPF estimates are required. The generalized rainfall criteria and recommended procedures for SPS computations for U.S. drainage basins located east of the 105th longitude are presented.

(2) The SPF is ordinarily computed using the unit hydrograph approach with the SPS precipitation. The unit hydrograph and basin losses should be based on reasonable values for a flood of this magnitude. Part 2 of EM 1110-2-1417 provides detailed information on the unit hydrograph procedure and the simulation of hypothetical floods is described in Chapter 13. The computer program HEC-1 *Flood Hydrograph Package* provides the SPS and SPF computation procedures, as described in the SPF determination manual.

(3) While the frequency of the standard project flood cannot be specified, it can be used as a guide in extrapolating frequency curves because it is considered to lie within a reasonable range of rare recurrence intervals, such as between once in 200 years and once in 1,000 years.

d. Probable maximum flood. The PMF is the flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in the region. The PMF is calculated from the Probable Maximum Precipitation (PMP). The PMP values encompass the maximized intensity-duration values obtained from storms of a single type. Storm type and variations of precipitation are considered with respect to location, areal coverage of a watershed, and storm duration. The probable maximum storm amounts are determined in much the same way as are SPS amounts, except that precipitation amounts are first increased to correspond to maximum meteorologic factors such as wind speed and maximum moisture content of the atmosphere.

(1) Estimates of PMP are based generally on the results of the analyses of observed storms. More than 600 storms throughout the United States have been analyzed in a uniform manner, and summary sheets have been distributed to government agencies and the engineering profession. These summary sheets include depth-area-duration data for each storm analyzed along with broad outlines of storm magnitudes and their seasonal and geographical variations. NWS (1977) Hydrometeorlogical Report No. 51 (HMR 51) contains generalized all-season estimates for the United States, east of the 105th longitude. The PMP is distributed in space and time to develop the PMS, which is a hypothetical storm that produces the PMF for a particular drainage basin.

(2) NWS (1981) HMR No. 52 provides criteria and instructions for configuring the storm to produce the PMF. The precipitation on a basin is affected by the storm placement, storm-area size, and storm orientation. The HMR52 PMS (HEC 1984) computer program uses a procedure to produce maximum precipitation on the basin. However, several trials are suggested to ensure that the maximum storm is produced. The PMS is then input to a rainfall-runoff model to determine the flood runoff.

(3) The HMR52 User's Manual shows an example application with the HEC-1 Flood Hydrograph Package. The storm hyetographs can be written to an output file, in HEC-1 input format, or to an HEC-DSS file. HEC-1 can read the DSS file to obtain the basin precipitation.

(4) Hydrometeorlogical criteria are being updated for various areas of the country. A check should be made for the most recent criteria. Figure 13-3 in EM 1110-2-1417 shows the regional reports available in 1993. The HMR52 computer program does not apply to U.S. regions west of the 105th meridian.

(5) In the determination of both the SPF and the PMF, selection of rainfall loss rates and the starting storage of upstream reservoirs should be based on appropriate assumptions for antecedent precipitation and runoff for the season of the storm. Also, PMF studies should consider the capability of upstream reservoir projects to safely handle the PMF contribution from that portion of the watershed. There could be deficiencies in an upstream project spillway that significantly affects the downstream project's performance.

e. Storm duration. Hypothetical storms to be used for any particular category of hypothetical flood computation must be based on data observed within a region. For application in the design of local flood protection projects, only peak flows and runoff volumes for short durations are usually important. Accordingly, the maximum pertinent duration of storm rainfall is only on the order of the time of travel for flows from the headwaters to the location concerned. After a reasonable maximum duration of interest is established, rainfall amounts for this duration and for all important shorter durations must be established. For standard project storm determinations, this would consist of the amounts of observed rainfall in the most severe storms within the region that correspond to area sizes equal to the drainage area above the project. In the case of hypothetical storms and floods of a specified frequency, these rainfall amounts would correspond to amounts observed to occur with the specified frequency at stations spread over an area the size of the project drainage area. Larger rates and smaller amounts of precipitation would occur for shorter durations, as compared with the longer durations of interest. Once a depth-duration curve is established that represents the desired hypothetical storm rainfall, a time pattern must be selected that is reasonably representative of observed storm sequences. The HEC-1 computer program has the capability of accepting any depth-duration relation and selecting a reasonable time sequence. It is also capable of accepting specified time sequences for hypothetical storms.

f. Snowmelt contribution. Satisfactory criteria and procedures have not yet been developed for the computation of standard project and probable maximum snowmelt floods. The problem is complicated in that deep snowpack tends to inhibit rapid rates of runoff, and consequently, probable maximum snowmelt flood potential does not necessarily correspond to maximum snowpack depth or water equivalent. Snowpack and snowmelt differ at various elevations, thus adding to the complexity of the problem.

(1) Where critical durations for project design are short, high temperatures occurring with moderate snowpack depths after some melting has occurred will probably produce the most critical runoff. Where critical durations are long, as is the more usual case in the control of snowmelt floods, prolonged periods of high temperature or warm rainfall occurring with heavy snowpack amounts will produce critical conditions.

(2) The general procedure for the computation of hypothetical snowmelt floods is to specify an initial snowpack for the season that would be critical. In the case of SPF's a maximum observed snowpack should be assumed. The temperature sequence for SPF computation would be that which produces the most critical runoff conditions and should be selected from an observed historical sequence. In the case of PMF computation, the most critical snowpack possible should be used and it should be considerably larger or more critical than the standard project snowpack. The temperature pattern should be selected from historical temperature sequences augmented to represent probable maximum temperature for the season. Where simultaneous contribution from rainfall is possible, a maximum rainfall for the season should be added during the time of maximum snowmelt. This would require some moderation of temperatures to ensure that they are consistent with precipitation conditions. EM 1110-2-1406 covers snowmelt for design floods, standard project and maximum probable snowmelt flood derivation.

(3) Snowmelt computations can be made in accordance with an energy budget computation, accounting for radiation, evaporation, conductivity, and other factors, or by a simple relation with air temperature, which reflects most of these other influences. The latter procedure is usually more satisfactory in practical situations. Snowmelt, loss rate, and unit hydrograph computations can be made by using a computer program like Flood Hydrograph Analysis, HEC-1. EM 1110-2-1417 has detailed descriptions of each computational component.

Chapter 8
Water Surface Profiles

8-1. Introduction

a. General. Water surface profiles are required for most reservoir projects, both upstream and downstream from the project. Profile computations upstream from the project define the "backwater" effect due to high reservoir pool levels. The determination of real estate requirements are based on these backwater profiles. Water surface profiles are required downstream to determine channel capacity, flow depths and velocities, and other hydraulic information for evaluation of pre- and post-project conditions.

b. Choosing a method. The choice of an appropriate method for computing profiles depends upon the following characteristics: the river reach, the type of flow hydrograph, and the study objectives. The gradually varied, steady flow profile computation (e.g., HEC-2), is used for many studies. However, the selection of the appropriate method is part of the engineering analysis. EM 1110-2-1416 provides information on formulating a hydraulic study and a discussion of the analytical methods in general use. The following sections provide general guidance on the methods and the potential application in reservoir related studies.

8-2. Steady Flow Analysis

a. Method assumptions. A primary consideration in one-dimensional, gradually varied, steady flow analysis is that flow is assumed to be constant, in time, for the profile computation. Additionally, all the one-dimensional methods require the modeler to define the flow path when defining the cross-sectional data perpendicular to the flow. The basic assumptions of the method are as follows:

(1) Steady flow - depth and velocity at a given location do not vary with time.

(2) Gradually varied flow - depth and velocity change gradually along the length of the water course.

(3) One-dimensional flow - variation of flow characteristics, other than in the direction of the main axis of flow may be neglected, and a single elevation represents the water surface of a cross section perpendicular to the flow.

(4) Channel slope less than 0.1 m/m - because the hydrostatic pressure distribution is computed from the depth of water measure vertically.

(5) Averaged friction slope - the friction loss between cross sections can be estimated by the product of the representative slope and reach length.

(6) Rigid boundary - the flow cross section does not change shape during the flood.

b. Gradually varied steady flow. The assumption of gradually varied steady flow for general rainfall and snowmelt floods is generally acceptable. Discharge changes slowly with time and the use of the peak discharge for the steady flow computations can provide a reasonable estimate for the flood profile. Backwater profiles, upstream from a reservoir, are routinely modeled using steady flow profile calculations. However, inflow hydrographs from short duration, high intensity storms, e.g., thunderstorms, may not be adequately modeled assuming steady flow.

c. Downstream profile. Obviously, the downstream profile for a constant reservoir release meets the steady flow condition. Again, the consideration is how rapidly flow changes with time. Hydropower releases for a peaking operation may not be reasonably modeled using steady flow because releases can change from near zero to turbine capacity, and back, in a short time (e.g., minutes) relative to the travel time of the resulting disturbances. Dam-break flood routing is another example of rapidly changing flow which is better modeled with an unsteady flow method.

d. Flat stream profiles. Another consideration is calculating profiles for very flat streams. When the stream slope is less than 0.0004 m/m (2 ft/mile), there can be a significant loop in the downstream stage-discharge relationship. Also, the backwater effects from downstream tributaries, or storage, or flow dynamics may strongly attenuate flow. For slopes greater than 0.0009 m/m (5 ft/mile), steady flow analysis is usually adequate.

e. Further information. Chapter 6 of EM 1110-2-1416 *River Hydraulics* provides a detailed review of the assumptions of the steady flow method, data requirements, and model calibration and application. Appendix D provides information on the definition of river geometry and energy loss coefficients, which is applicable to all the one-dimensional methods.

8-3. Unsteady Flow Analysis

a. Unsteady flow methods. One-dimensional unsteady flow methods require the same assumptions listed in 8-2(a), herein, except flow, depth, and velocity can vary with time. Therefore, the primary reason for using unsteady flow methods is to consider the time varying nature of the problem. Examples of previously mentioned rapidly changing flow are thunderstorm floods, hydroelectric peaking operations, and dam-break floods. The second application of unsteady flow analysis consideration, mentioned above, is streams with very flat slopes.

b. Predicting downstream stages. Another application of unsteady flow is in the prediction of downstream stages in river-reservoir systems with tributaries, or lock-and-dam operations where the downstream operations affect the upstream stage. Flow may not be changing rapidly with time, but the downstream changes cause a time varying downstream boundary condition that can affect the upstream stage. Steady flow assumes a unique stage-discharge boundary condition that is stable in time.

c. Further information. Chapter 5, "Unsteady Flow," in EM 1110-2-1416 provides a detailed review of model application including selection of method, data requirements, boundary conditions, calibration, and application.

8-4. Multidimensional Analysis

a. Two- and three-dimensional modeling. Multi-dimensional analysis includes both two- and three-dimensional modeling. In river applications, two-dimensional modeling is usually depth-averaged. That is, variables like velocity do not vary with depth, so an average value is computed. For deep reservoirs, the variation of parameters with depth is often important (see Chapter 12, EM 1110-2-1201). Two-dimensional models, for deep reservoirs, are usually laterally-averaged. Three-dimensional models are available; however, their applications have mostly been in estuaries where both the lateral and vertical variation are important.

b. Two-dimensional analysis. Two-dimensional, depth-averaged analysis is usually performed in limited portions of a study area at the design stage of a project. The typical river-reservoir application requires both the direction and magnitude of velocities. Potential model applications include areas upstream and downstream from reservoir outlets. Additionally, flow around islands, and other obstructions, may require two-dimensional modeling for more detailed design data.

c. Further information. Chapter 4 of EM 1110-2-1416 provides a review of model assumptions and typical applications.

8-5. Movable-Boundary Profile Analysis

a. Reservoirs. Reservoirs disrupt the flow of sediment when they store or slow down water. At the upper limit of the reservoir, the velocity of inflowing water decreases and the ability to transport sediment decreases and deposition occurs. Chapter 9 herein presents reservoir sediment analysis. Reservoir releases may be sediment deficient, which can lead to channel degradation downstream from the project because the sediment is removed from the channel.

b. River and reservoir sedimentation. EM 1110-2-4000 is the primary Corps reference on reservoir sedimentation. Chapter 3 covers sediment yield and includes methods based on measurement and mathematical models. Chapter 4 covers river sedimentation, and Chapter 5 presents reservoir sedimentation. Section III, of Chapter 5, provides an overview of points of caution, sedimentation problems associated with reservoirs, and the impact of reservoirs on the stream system. Section IV provides information on levels of studies and study methods.

b. Further information. Chapter 7 of EM 1110-2-1416 presents water surface profile computation with movable boundaries. The theory, data requirements and sources, plus model development and application are all covered. The primary math models, HEC-6 *Scour and Deposition in Rivers and Reservoirs* (HEC 1993) and *Open-Channel Flow and Sedimentation* TABS-2 (Thomas and McAnally 1985) two-dimensional modeling package, are also described. The focus for the material is riverine.

Chapter 9
Reservoir Sediment Analysis

9-1. Introduction

a. Parameters of a natural river. Nature maintains a very delicate balance between the water flowing in a natural river, the sediment load moving with the water, and the stream's boundary. Any activity which changes any one of the following parameters:

- water yield from the watershed.
- sediment yield from the watershed.
- water discharge duration curve.
- depth, velocity, slope or width of the flow.
- size of sediment particles.

or which tends to fix the location of a river channel on its floodplain and thus constrains the natural tendency will upset the natural trend and initiate the formation of a new one. The objective of most sediment studies is to evaluate the impact on the flow system resulting from changing any of these parameters.

b. Changes caused by reservoirs. Reservoirs interrupt the flow of water and, therefore, sediment. In terms of the above parameters, the reservoir causes a change in the upstream hydraulics of flow depth, velocity, etc. by forcing the energy gradient to approach zero. This results in a loss of transport capacity with the resulting sediment deposition in the reservoir. The reservoir also alters the downstream water discharge-duration relation and reduces the sediment supply which may lead to the degradation of the downstream channel.

c. Areas of analysis. Sedimentation investigations usually involve the evaluation of the existing condition as well as the modified condition. The primary areas of reservoir sediment analysis are the estimation of volume and location of sediment deposits in the reservoir and the evaluation of reservoir releases' impact on the downstream channel system. Sediment deposits start in the backwater area of the reservoir, which increase the elevation of the bed profile and the resulting water surface profile. However, reservoirs may also cause sediment deposits upstream from the project, which affect the upstream water surface profiles.

d. Further information. The primary Corps reference for sediment analysis is EM 1110-2-4000. Major topics include developing a study work plan, sediment yield, river sedimentation, reservoir sedimentation, and model studies.

9-2. Sediment Yield Studies

a. General. Sediment yield studies determine the amount of sediment that leaves a basin for an event or over a period of time. Sediment yield, therefore, involves erosion processes as well as sediment deposition and delivery to the study area. The yield provides the necessary input to determine sedimentation impacts on a reservoir.

b. Required analysis. Each reservoir project requires a sediment yield analysis to determine the storage depletion resulting from the deposition of sediment during the life of the project. For most storage projects, as opposed to sediment detention structures, the majority of the delivered sediment is suspended. However, the data required for the headwater reaches of the reservoir should include total sediment yield by particle size because that is where the sands and gravels will deposit.

c. Further information. Corps of Engineer methods for predicting sediment yields are presented in Appendix C of EM 1110-2-4000. A literature review, conducted by the Hydrologic Engineering Center under the Land Surface Erosion research work unit, showed numerous mathematical models are available to estimate sediment discharge rates from a watershed and the redistribution of soil within a watershed. An ETL on the methods will be issued soon.

9-3. Reservoir Sedimentation Problems

a. Sediment deposition. As mentioned above, the primary reservoir sediment problem is the deposition of sediment in the reservoir. The determination of the sediment accumulation over the life of the project is the basis for the sediment reserve. Typical storage diagrams of reservoirs, showing sediment (or dead) storage at the bottom of the pool can be misleading. While the reservoir storage capacity may ultimately fill with sediment, the distribution of the deposits can be a significant concern during the life of the project. The reservoir sedimentation study should forecast sediment accumulation and distribution over the life of the project. Sediment deposits in the backwater area of the reservoir may form deltas, particularly in shallow reservoirs. A number of problems associated with delta formations are discussed below.

(1) Deposits forming the delta may raise the water surface elevation during flood flows, thus requiring special

consideration for land acquisition. In deep reservoirs, this is usually not a problem with the reservoir area because project purposes dictate land acquisitions or easements. Deltas tend to develop in the upstream direction. In shallow reservoirs, the increase in water surface elevation is a problem even within the reservoir area. That is, floods of equal frequency may have higher water surface elevations after a project begins to develop a delta deposit than was experienced before the project was constructed. Land acquisition studies must consider such a possibility.

(2) Aggradation problems are often more severe on tributaries than on the main stem. Analysis is complicated by the amount of hydrologic data available on the tributaries, which is usually less than on the main stem itself. Land use along the tributary often includes recreation sites, where aggradation problems are particularly undesirable.

(3) Reservoir deltas often attract phreatophytes due to the high moisture level. This may cause water-use problems due to their high transpiration rate.

(4) Reservoir delta deposits are often aesthetically undesirable.

(5) Reservoir sediment deposits may increase the water surface elevation sufficiently to impact on the groundwater table, particularly in shallow impoundments.

(6) In many existing reservoirs, the delta and backwater-swamp areas support wildlife. Because the characteristics of the area are closely controlled by the operation policy of the reservoir, any reallocation of storage would need to consider the impact on the present delta and swamp areas.

b. Upstream projects. It is important to identify and locate all existing reservoirs in a basin where a sediment study is to be made. The projects upstream from the point of analysis potentially modify both the sediment yield and the water discharge duration curve. The date of impoundment is important so that observed inflowing sediment loads may be coordinated with whatever conditions existed in the basin during the periods selected for calibration and verification. Also, useful information on the density of sediment deposits and the gradation of sediment deposits along with sediment yield are often available from other reservoirs in the basin. Information on the rate of sediment deposition that has occurred at other reservoir sites in the region is the most valuable information when estimating sediment deposition for a new reservoir.

9-4. Downstream Sediment Problems

a. Channel degradation. Channel degradation usually occurs downstream from the dam. Initially, after reservoir construction, the hydraulics of flow (velocity, slope, depth, and width) remain unchanged from pre-project conditions. However, the reservoir acts as a sink and traps sediment, especially the bed material load. This reduction in sediment delivery to the downstream channel causes the energy in the flow to be out of balance with the boundary material for the downstream channel. Because of the available energy, the water attempts to re-establish the former balance with sediment load from material in the stream bed, and this results in a degradation trend. Initially, degradation may persist for only a short distance downstream from the dam because the equilibrium sediment load is soon re-established by removing material from the stream bed.

b. Downstream migratory degradation. As time passes, degradation tends to migrate downstream. However, several factors are working together to establish a new equilibrium condition in this movable-boundary flow system. The potential energy gradient is decreasing because the degradation migrates in an upstream-to-downstream direction. As a result, the bed material is becoming coarser and, consequently, more resistant to being moved. This tendency in the main channel has the opposite effect on tributaries. Their potential energy gradient is increasing which results in an increase in transport capacity. This will usually increase sediment passing into the main stem which tends to stabilize the main channel resulting in less degradation than might be anticipated. Finally, a new balance will tend to be established between the flowing water-sediment mixture and the boundary.

c. Extent of degradation. The extent of degradation is complicated by the fact that the reservoir also changes the discharge duration curve. This will impact for a considerable distance downstream from the project because the existing river channel reflects the historical phasing between flood flows on the main stem and those from tributaries. That phasing will be changed by the operation of the reservoir. Also, the reduced flow will probably promote vegetation growth at a lower elevation in the channel. The result is a condition conducive to deposition in the vegetation. Detailed simulation studies should be performed to determine future channel capacities and to identify problem areas of excessive aggradation or degradation. All major tributaries should be included.

9-5. Sediment Water Quality

a. Sediments and pollutants. When a river carrying sediments and associated pollutants enters a reservoir, the flow velocity decreases and the suspended and bed load sediments start settling down. Reservoirs generally act as depositories for the sediments because of their high sediment trap efficiency. Due to a high adsorption capacity, sediments act as sinks for contaminants in the reservoirs and, in agricultural and industrial areas, may contain PCB's, chlorinated hydrocarbon pesticides, oil and grease, heavy metals, coliform bacteria, or mutagenic substances. Burial of these contaminants by sedimentation may be an important factor and an effective process in isolating potentially toxic substances from surface waters and important biological populations. Toxic inorganic and organic contaminants associated with the sediments can also be bioconcentrated by the aquatic organisms present in reservoirs.

b. Monitoring chemical contaminants. These incoming sediments and associated pollutants significantly affect the water quality of the reservoir pool and downstream releases. Therefore, it is essential that these sediment reservoir interactions be characterized by their depositional behavior, particle size distribution, and pollutant concentrations to successfully plan a management strategy to quantify contaminant movement within reservoirs. Analytical and predictive methods to assess the influence of contaminated sediments in reservoirs have not been developed enough to be used in Corps field offices, but WES Instruction Report E-86-1, "General Guidelines for Monitoring Contaminants in Reservoirs" (Waide 1986), does provide general guidance on the design and conduct of programs for monitoring chemical contaminants in reservoir waters, sediments, and biota.

c. Sedimentation patterns. Sedimentation patterns can often be associated with water quality characteristics. There seems to be a relationship between longitudinal gradients in water quality (a characteristic of many reservoirs) and sediment transport and deposition. High concentrations of inorganic particulates can reduce light availability near inflows and thus influence algal production and decrease dissolved oxygen. The association of dissolved substances, such as phosphorus, with suspended solids may act to reduce or buffer dissolved concentrations, thus influencing nutrient availability.

9-6. Sediment Investigations

a. General. The level of detail required for the analysis of any sediment problem depends on the objective of the study. Chapter 1 of EM 1110-2-4000 describes staged sedimentation studies in Section I. Section II, of that chapter, provides reporting requirements. Problem identification and the development of a study work plan are covered in Chapter 2.

b. Sediment deposits. Considering a dam site as an important natural resource, it is essential to provide enough volume in the reservoir to contain anticipated deposits during the project life. If the objective of a sediment study is just to know the volume of deposits for use in screening studies, then trap efficiency techniques can provide a satisfactory solution. The important information that must be available is the water and sediment yields from the watershed and the capacity of the reservoir. Chapter 3 of EM 1110-2-4000 covers sediment yield. Section 3-7 provides information on reservoir sedimentation, including trap efficiency.

c. Land acquisition. If the sediment study must address land acquisition for the reservoir, then knowing only the volume of deposits is not sufficient. The location of deposits must also be known, and the study must take into account sediment movement. This generally requires simulation of flow in a mobile boundary channel. Sorting of grain sizes must be considered because the coarser material will deposit first, and armoring must be considered because scour is involved. Movable-bed modeling is useful to predict erosion or scour trends downstream from the dam, general aggradation or degradation trends in river channels, and the ability of a stream to transport the bed-material load. The computer program, HEC-6 *Scour and Deposition in Rivers and Reservoirs* (HEC 1993), is designed to provide long-term trends associated with changes in the frequency and duration of the water discharge and/or stage or from modifying the channel geometry.

d. Details of investigations. The details of reservoir sedimentation investigations are covered in Chapter 5 of EM 1110-2-4000. The primary emphasis is on the evaluation of the modified condition, which includes consideration of quality and environmental issues. The levels of sedimentation studies and methods of analysis are presented in Section IV of Chapter 5. Model studies and a short review of HEC-6 and the two-dimensional TABS-2 modeling system are covered in Chapter 6.