Chapter 10
Flood-Control Storage

10-1. General Considerations

a. Reservoir flood storage. Where flood damage at a number of locations on a river can be significantly reduced by construction of one or more reservoirs, or where a reservoir site immediately upstream from one damage center provides more economical protection than local protection works, reservoir flood storage should be considered. Whenever such reservoirs can serve needs other than flood control, the integrated design and operation of the project for multipurpose use should be considered.

b. Flood-control features. In planning and designing the flood-control features of a reservoir, it is important that the degree and extent of continuous ensured protection be no less than that provided by a local protection project, if the alternatives of reservoir construction or channel and levee improvement are to be evaluated fairly. This means that the storage space and release schedule for flood control must be provided at all times when the flooding potential exists. In some regions this may be for the entire year, but more commonly there are dry seasons when the flood potential is greatly reduced and storage reservation for flood control can be reduced correspondingly. Except where spring snowmelt floods can be forecasted reliably or where safe release rates are sufficient to empty flood space in a very short time, it is not ordinarily feasible to provide flood-control space only after a flood is forecasted. Space must be provided at all times during the flood season unless it can be demonstrated that the necessary space can be evacuated on a realistic forecast basis. Also, space may be reduced if less storage is needed due to low snowpack, or there is some other reliable basis for long range flood forecasting.

c. Runoff volume durations. Whereas the peak rates of runoff are critical in the design of local protection projects, runoff volumes for pertinent durations are critical in the design of reservoirs for flood control. The critical durations will be a function of the degree of flood protection selected and of the release rate or maximum rate of flow at the key downstream control point. As the proposed degree of protection is increased and as the proposed rates of controlled flows at key damage centers are reduced, the critical duration is increased. If this critical duration corresponds to the duration of a single rainstorm period or a single snowmelt event, the computation of hypothetical floods from rainfall and snowmelt can constitute the principle hydrologic design element. On the other hand, if the critical duration is much longer, hypothetical floods and sequences of hypothetical floods computed from rainfall or snowmelt become less dependable as guides to design. It then is necessary to base the design primarily on the frequency of observed runoff volumes for long durations. Even when this is done, it will be advisable to construct a typical hydrograph that corresponds to runoff volumes for the critical duration and that reasonably characterizes hydrographs at the location, in order to examine the operation of the proposed project under realistic conditions.

d. Hypothetical flood simulations. When hypothetical floods are selected, they must be routed through the proposed reservoir under the operation rules that would be specified for that particular design. In effect, a simulation study of the proposed project and operation scheme would be conducted for each flood. It is also wise to simulate the operation for major floods of historical record in order to ensure that some peculiar feature of a particular flood does not upset the plan of operation. With present software, it is relatively inexpensive to perform a complete period of record simulation once the flood-control storage is set.

10-2. Regulated Release Rates

a. Flood reduction purposes. For flood reduction purposes reservoirs must store only the water that cannot be released without causing major damage downstream. If more water can be released during a flood, less water needs to be stored. Thus, less storage space needs to be planned for flood control. Because reservoir space is costly and usually in high demand for other purposes, good flood-control practice consists of releasing water whenever necessary at the highest practical rates so that a minimum amount of space need be reserved for flood control. As these rates increase, it becomes costly also to improve downstream channels and to provide adequate reservoir outlets, so there is an economic balance between release rates and storage capacity for flood control. In general, it is economical to utilize the full nondamage capacity of downstream channels, and it may pay to provide some additional channel or levee improvements downstream. However, as described in paragraph *f*, full channel capacity may not be available, so analyses should consider the impact of reduced capacity.

b. Channel capacities. Channel capacities should be evaluated by examing water-surface profile data from actual flood events whenever possible. Under natural channel conditions, it will ordinarily be found that floods which occur more frequently than once in two years are not seriously damaging, while larger floods are.

c. Minor versus major damage releases. In some cases, it is most economical to sustain minor damage by releasing flows above nondamaging stages in order to accommodate major floods and thereby protect the more important potential damage areas from flooding. In such situations, a stepped-release schedule designed to protect all areas against frequent minor floods, with provision to increase releases after a specified reservoir stage is reached, might be considered. However, such a plan has serious drawbacks in practice because protection of the minor damage areas would result in greater improvements in those areas; and it soon becomes highly objectionable, if not almost impossible, to make the larger releases when they are required for protection of major damage areas. In any case, it is necessary to make sure that the minor damage areas are not flooded more frequently or severely with the project than they would have been without it.

d. Maintenance and zoning. It is important on all streams in developed areas to provide for proper maintenance of channel capacity and zoning of the floodplain where appropriate. This is vital where upstream reservoirs are operated for flood control because proper reservoir regulation depends as much on the ability to release without damage as it does on the ability to store. Minor inadequacies in channel capacity can lead to the loss of control and result in major flooding. This situation is aggravated because the reduced frequency of flooding below reservoirs and the ability to reduce reservoir releases when necessary often increase the incentive to develop the floodplain and sometimes even remove the incentive for maintaining channel capacity.

e. Forecasted runoff. When a reservoir is located some distance upstream from a damage center, allowance must be made for any runoff that will occur in the intermediate area. This runoff must be forecasted, a possible forecast error added, and the resulting quantities subtracted from project channel capacity to determine per-missible release rates considering attenuation when routing the release from the dam to the damage center and the contribution of flow from the intermediate drainage area. Also, with high intensity rainfall, the added rainfall depth to the total downstream channel flow should be considered.

f. Delaying flood releases. Experience in the flood-control operation of reservoirs has demonstrated that the actual operation does not make 100 percent use of downstream channel capacities. Due to many contributing factors average outflows during floods are less than maximum permissible values. It is usually wise to approach maximum release rates with caution, in order to ascertain any changes in channel capacity that have taken place since the last flood, and this practice reduces operational efficiency. It may be necessary to delay flood releases to permit removal of equipment, cattle, etc., from areas that would be flooded. Releases might be curtailed temporarily in order to permit emergency repairs to canals, bridges, and other structures downstream. If levees fail, releases might be reduced in order to hasten the drainage of flooded areas. Release can be reduced in order to facilitate rescue operations. These and various other conditions result in reduced operation efficiency during floods. To account for this, less nondamage flow capacity than actually exists (often about 80 percent) is assumed for design studies. It is important, however, that every effort be made in actual operation to effect the full non-damage releases in order to attain maximum flood-control benefits.

g. Gradually increasing and decreasing releases. During flood operations, reservoir releases must be increased and decreased gradually in order to prevent damage and undue hardship downstream. Gradually increasing releases will usually permit an orderly evacuation of people, livestock, and equipment from the river areas downstream. If releases are curtailed too rapidly, there is some danger that the saturated riverbanks will slough and result in the loss of valuable land or damage to levees.

10-3. Flood Volume Frequencies

a. Critical durations. Flood volume frequency studies usually consist of deriving frequency curves of annual maximum volumes for each of various specified durations that might be critical in project design. Critical durations range from a few hours in the case of regulating “cloudburst” floods to a few months where large storage and very low release rates prevail. The annual maximum volumes for a specific duration are usually expressed as average rates of flow for that duration. It is essential that these flows represent a uniform condition of development for the entire period of observation, preferably unregulated conditions. Procedures for computing the individual frequency curves are discussed briefly in Chapter 6 herein and are described in detail in EM 1110-2-1415.

b. Flood-control space requirement. Determination of the flood-control space needed to provide a selected degree of protection is based on detailed hydrograph analysis, but a general evaluation can be made as illustrated in Figure 10-1. The curve of runoff versus duration is obtained from frequency studies of runoff volumes or from SPF studies at the location. The tangent line represents a uniform flow equal to the project release capacity (reduced by an appropriate contingency factor). The intercept represents the space required for control of the flood. The chart demonstrates that a reservoir capable of storing

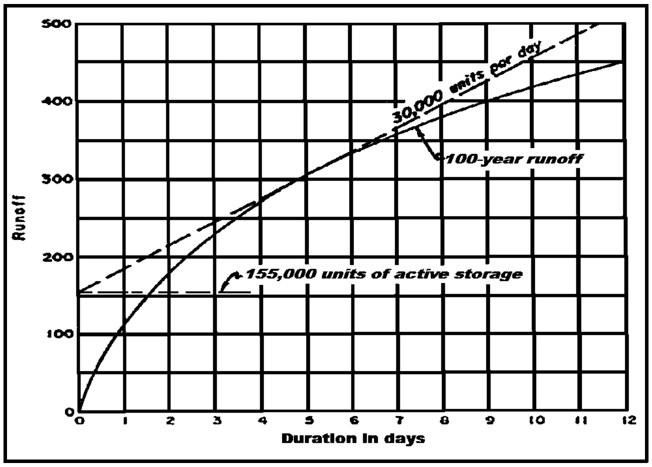

Figure 10-1. Flood-control space requirement

155,000 units of water and releasing 30,000 units per day can control 100-year runoff for any duration, and that the critical duration (period of increasing storage) is about 5 days. The volume-duration curve would be made for each damage area and should include more than 100 percent of the local uncontrolled runoff downstream from the reservoir and above the control point in order to allow for errors of forecast which would be reflected in reduced project releases. If this local runoff appreciably exceeds nondamage flow capacity at the damage centers, the volume over and above the flow capacity is damaging water that cannot be stored in the project reservoir.

10-4. Hypothetical Floods

a. Two classes. Two classes of hypothetical floods are important in the design of reservoirs for flood control. One is a balanced flood that corresponds to a specified frequency of occurrence; the other is a flood that represents a maximum potential for the location, such as the SPF or PMF. ER 1110-8-2(FR) sets forth hydrologic engineering requirements for selecting and accommodating inflow design floods for dams and reservoirs.

b. Specified frequencies. A hypothetical flood corresponding to a specified frequency should contain runoff volumes for all pertinent durations corresponding to that specified frequency. The derivation of frequency curves is as discussed in the preceding section. A balanced flood hydrograph is constructed by selecting a typical hydrograph pattern and adjusting the ordinates so that the maximum volumes for each selected duration correspond to the volumes for that duration at the specified frequency.

c. Longer duration floods. Where flood durations longer than the typical single-flood duration are important in the design, a sequence of flood hydrographs spaced reasonably in time should be used as a pattern flood. In order to represent average natural sequences of flood events, the largest portions of the pattern flood should ordinarily occur at or somewhat later than the midpoint of the entire pattern, because rainfall sequences are fairly random but ground conditions become increasingly wet and conducive to larger runoff as any flood sequence continues.

d. Maximum flood potential. Two types of hypothetical floods that represent maximum flood potential are important in the design of reservoirs. The PMF, which is the largest flood that is reasonably possible at the location, is ordinarily the design flood for the spillway of a structure where loss of life or major property damage would occur in the event of project failure. The SPF, which represents the largest flood for that location that is reasonably characteristic for the region, is a flood of considerably lesser magnitude and represents a high degree of design for projects protecting major urban and industrial areas. These floods can result from heavy rainfall or from snowmelt in combination with some rainfall.

e. Computing hydrographs. SPF and PMF hydrographs are computed from the storm hyetographs by unit hydrograph procedures. In the case of the SPF, ground conditions that are reasonably conducive to heavy runoff are used. In the case of the PMF, the most severe ground conditions that are reasonably consistent with storm magnitudes are used. A general description of these analyses is provided in Chapter 7 of this manual. Detailed methods for performing these computations are described in EM 1110-2-1417. The computer program HEC-1 *Flood Hydrograph Package* contains routines for computing floods from rainfall and snowmelt and also contains standard project criteria for the eastern United States.

10-5. Operation Constraints and Criteria

a. General. As stated earlier, whenever flood releases are required, it is imperative that they be made at maximum rates consistent with the conditions downstream. This means that the outlets should be designed to permit releases at maximum rates at all reservoir levels within the flood-control space. In some cases where controlled releases are very high, such an outlet design is not economical, and releases at lower stages might be restricted because of limited outlet capacity. This constraint, of course, should be taken into account during the design studies.

b. Downstream damage centers. Where damage centers are at some distance downstream from the reservoir, local runoff below the reservoir and above the damage center must be considered when determining releases to be made. This will ordinarily require some forecasting of the local runoff and, consequently, some estimate of the forecast uncertainty. The permissible release at any time is determined by adding a safe error allowance to the forecasted local inflow and subtracting this sum from the nondamaging flow capacity.

c. Rate-of-change of release. The rate-of-change of release must be restricted to the maximum changes that will not cause critical conditions downstream. As a practical matter, these rates-of-change of release should be less than the rates-of-change of flow that occurred before the reservoir was built. After the main flood has passed, water stored in the flood-control space must be released and maximum rates of release will continue until the desired amount of water is released, except that the rate of release should be decreased gradually toward the end of the release period. This reduction in release must be started while considerable flood waters remain in the reservoir in order that water retained for other purposes is not inadvertently released. Schedules for this operation are discussed in Part 3.

10-6. Storage Capacity Determinations

a. Determining required storage capacity. The storage capacity required to regulate a specific flood (represented by a flood hydrograph at the dam) to a specified control discharge immediately downstream of the dam is determined simply by routing the hydrograph through a hypothetical reservoir with unlimited storage capacity and noting the maximum storage. However, there are many special practical considerations that complicate this process. Release rates should not be changed suddenly; therefore, the routing should conform to criteria that specify the maximum rate of change of release. Also, outlet capacities might not be adequate to supply full regulated releases with low reservoir stages. If this is the case, a preliminary reservoir design is required in order to define the relation of storage capacity to outlet capacity.

b. Specified flood. In the more common cases, where damage centers exist at some distance downstream of the reservoir, the storage requirement for a specified flood is determined by successive approximations, operating the hypothetical reservoir to regulate flows at each damage center to nondamaging capacity, and allowing for local inflow and for some forecasting error.

c. Detailed operational study. Although there are approximate methods for estimating storage capacity, it is essential that the final project design be tested by a detailed operational study. The analyses are based on actual outlet capacities and realistic assumptions for limiting rates of release change, forecast errors, and operational contingencies, and include various combinations of reservoir inflow and local flow that can produce a specific downstream flood event. It is also important to route the largest floods of record and synthetic floods through the project to determine that the project design is adequate and that the project provides the degree of protection for which it was designed.

d. Seasonal distribution of storage requirements. Where some of the flood-control space will be made available for other uses during the dry season, a seasonal distribution of flood-control storage requirement should be developed. The most direct approach to this entails the construction of runoff frequency curves for each month of the year. The average frequency of the design flood during the rainy-season months can be used to select flood magnitudes for other months. These could then serve as a basis for determining the amount of space that must be made available during the other months.

e. Further information. Sequential routing in planning, design, and operation of flood-control reservoirs can be accomplished with the computer program HEC-5 *Simulation of Flood Control and Conservation Systems* (HEC 1982c).

10-7. Spillways

Spillways are provided to release floodwater which normally cannot be passed by other outlet works. The spillway is sized to ensure the passage of major floods without overtopping the dam. A general discussion of spillways is provided in Section 4-2 of EM 1110-2-3600. EM 1110-2-1603 describes the technical aspects of design for the hydraulic features of spillways and ER 1110-8-2(FR) sets forth requirements for selecting and accommodating inflow design floods.

a. Spillway design flood. The spillway design flood is usually selected as a large hypothetical flood derived from rainfall and snowmelt. Other methods of estimating extreme flood magnitudes, such as flood-frequency analysis, are not reliable due to limited observations. The selection of a spillway design flood depends on the policies of the construction agency and regulations governing dam construction. Usually, the spillways for major dams, whose failure might constitute a major disaster, are designed to pass the PMF without a major failure; however, the spillways for many small dams are designed for smaller floods such as the SPF.

b. Hydrologic design. The hydrologic design of a spillway is accomplished by first estimating a design and then testing it by routing the spillway design flood. In routing the spillway design flood, the initial reservoir stage should be as high as reasonably expected at the start of such a major flood, considering the manner in which the reservoir is planned to operate or how in the future the reservoir might operate differently from the planned operation. In the case of ungated spillways, it is possible that the outlets of the dam will be closed gradually as the spillway goes into operation, in order to delay damaging releases as long as possible and possibly to prevent them. However, if spillway flows continue to increase, it may be necessary to reopen the outlets. In doing so, care should be exercised to prevent releases from exceeding maximum inflow quantities. The exact manner in which outlets will be operated should be specified so that the spillway design will be adequate under conditions that will actually prevail after project construction. Consideration should be given to the possibility that some outlets or turbines might be out of service during flood periods.

c. Large spillway gates. The operation of large spillway gates can be extremely hazardous, since opening them inadvertently might cause major flooding at downstream areas. Their operation should be controlled by rigid regulations. In particular, the opening of the gates during floods should be scheduled on the basis of inflows and reservoir storage so that the lake level will continue to rise as the gates are opened. This will ensure that inflow exceeds outflow as outflows are increased. The adequacy of a spillway to pass the spillway design flood is tested for gated spillways in the same manner as for ungated spillways described above. Methods for developing spillway-gate operation regulations are described in Chapter 14.

d. Preventing overtopping. To ensure that the spillway is adequate to protect the structure from overtopping, some amount of freeboard is added to the dam above the maximum pool water-surface elevation. This can vary from zero for structures that can withstand overtopping to 2 m or more for structures where overtopping would constitute a major hazard. The freeboard allowance accounts for wind set and wave action. Methods for estimating these quantities are discussed in Chapter 15. Risk analysis should be performed to determine the appropriate top-of-dam elevation.

e. Spillway types. While the spillway is primarily intended to protect the structure from failure, the fact that it can cause some water to be stored above ordinary full pool level (surcharge storage) is of some consequence in reducing downstream flooding. Narrow, ungated spillways require higher dams and can, therefore, be highly effective in partially regulating floods that exceed project design magnitude, whereas wide spillways and gated spillways are less effective for regulating floods exceeding design magnitude. Where rare floods can cause great damage downstream, the selection of spillway type and characteristics can appreciably influence the benefits that are obtained for flood control. Accordingly, it is not necessarily the least costly spillway that yields the most economical plan of development. In evaluating flood-control benefits, computing frequency curves for regulated conditions should be based on spillway characteristics and operation criteria as well as on other project features.

10-8. Flood-Control System Formulation

a. Objectives. The objectives of system formulation are to identify the individual components, determine the size of each, determine the order in which the system components should be implemented, and develop and display the information required to justify the decisions and thus secure system implementation. Section 4-10 describes several formulation strategies.

b. Criteria. Criteria for system formulation are needed to distinguish the best system from among competing alternative systems. The definition of "best" is crucial. A reasonable viewpoint would seem to recognize that simply aggregating the most attractive individual components into a system, while assuring physical compatibility, could result in the inefficient use of resources because of system effects, data uncertainty, and the possibility that all components may not be implemented. It is proposed that the best system be considered to be as follows:

(1) The system that includes the obviously good components while preserving flexibility for modification of components at future dates.

(2) The system which could be implemented at a number of stages, if staging is possible, such that each stage could stand on its own merits (be of social value) if no more components were to be added.

c. General guidance. General guidance for formulation criteria are contained in the Principles and Standards (Water Resources Council 1973). The criterion of economic efficiency from the national viewpoint has been interpreted to require that each component in a system should be incrementally justified, that is, each component addition to a system should add to the value (net benefits) of the total system. The environmental quality criteria can be viewed as favoring alternatives that can be structured to minimize adverse environmental impacts and provide opportunities for mitigation measures. Additional criteria that are not as formally stated as U.S. national policy are important in decisions among alternatives. A formulated flood-control system must draw sufficient support from responsible authorities in order to be implemented. In addition, flood-control systems should be formulated so that a minimum standard of performance (degree of risk) is provided so that public safety and welfare are adequately protected.

d. Environmental and other assessments. Of these criteria, only the national economic efficiency and minimum performance standard have generally accepted methods available for their rigorous inclusion in formulation studies. Environmental quality analysis and social/political/institutional analyses related to implementation have not developed technology applicable on a broad scale. As a consequence, these criteria must guide the formulation studies but, as yet, probably cannot directly contribute in a structured formulation strategy. In discussions that follow, focus is of necessity upon the economic criteria with acceptable performance as a constraint, with the assumption that the remaining criteria will be incorporated when the formulation strategy has narrowed the range of alternatives to a limited number for which the environmental and other assessments can be performed.

e. Degrees of uncertainty. There will be varying degrees of uncertainty in the information used in system formulation. The hydrology will be better defined near gauging stations than it is in remote areas, and certain potential reservoirs will have been more thoroughly investigated than others. In addition, the accuracy of economic data, both costs and value, existing or projected, is generally lower than the more physically based data. Also, since conditions change over time, the data must be continuously updated at each decision point. The practical accommodation of information uncertainty is by limited sensitivity analysis and continuing reappraisal as each component of a system is studied for implementation.

f. Sensitivity analysis. Sensitivity analysis has, as its objective, the identification of either critical elements of data, or particularly sensitive system components, so that further studies can be directed toward firming up the uncertain elements or that adjustments in system formulation can be made to reduce the uncertainty. Because combinations of historic and synthetic floods are typically used to evaluate reservoir flood-reduction performance (i.e., to develop regulated conditions frequency relations at damage index stations), particular attention must be paid to the selection or development of the system hydrology. The problem arises when evaluating complex reservoir systems with many reservoirs above common damage centers. The problem increases with the size and complexity of the basin because the storm magnitudes and locations can favor one reservoir location over another. There are a large number of storm centerings that could yield similar flows at a particular control point. Because of this, the contribution of a specific system component to reduced flooding at a downstream location is uncertain and dependent upon storm centering. This makes the selection or development of representative centerings crucial if all upstream components are to be evaluated on a comparable basis.

g. Desired evaluation. The desired evaluation for regulated conditions is the expected or average condition so that economic calculations are valid. The representative hydrograph procedure is where several proportions (ratios of one or more historic or synthetic events used to represent system hydrology) are compatible with the simulation technique used, but care must be taken to reasonably accommodate the storm centering uncertainty. Testing the sensitivity of the expected annual damage to the system hydrology (event centering) is appropriate and necessary. Even if all historical floods of record are used, there still may be some bias in computing expected annual damages if most historical floods were, by chance, centered over a certain part of the basin and not over others. For instance, one reservoir site may have experienced several severe historical floods, while another site immediately adjacent to the area may, due to chance, not have had any severe floods.

10-9. General Study Procedure

After various alternative locations are selected for a reservoir site to protect one or more damage centers, the following steps are suggested for conducting the required hydrologic engineering studies:

a. Obtain a detailed topographic map of the region showing the locations of the damage areas, of proposed reservoir sites, and of all pertinent precipitation, snowpack, and stream-gauging stations. Prepare a larger scale topographic map of the drainage basin tributary to the most downstream damage location. Locate damage centers, project sites, pertinent hydrologic measurement stations, and drainage boundaries above each damage center, project site, and stream-gauging station. Measure all pertinent tributary areas.

b. Establish stage-discharge relations for each damage reach, relating the stages for each reach to a selected index location in that reach; procedures for doing this are described in *Flood-Damage Analysis Package User's Manual* (HEC 1990b). Where local protection works are considered part of an overall plan of improvement, establish the stage-discharge relation for each plan of local protection.

c. Obtain area- and storage-elevation curves for each reservoir site; select alternative reservoir capacities as appropriate for each site; select outlet and spillway rating curves for each reservoir, and develop a plan of flood-control operation for each reservoir. Determine maximum regulated flows for each damage center.

d. Estimate the maximum critical duration of runoff for any of the plans of improvement, considering the relation of regulated flows at damage centers to unregulated flood hydrographs of design magnitude at those damage centers. Prepare frequency curves of unregulated peak flows and volumes of each of various representative durations, as described for peak flows in Chapter 6, for each damage center index location, and for each reservoir site. If seasonal variation of flood-control space is to be considered, these curves should be developed for each season.

e. The two basic approaches for flood-control simulation are complete period-of-record analysis and representative floods analysis. If flooding can occur during any time of the year, the complete sequential analysis might be favored. However, if there is a separable flood season, e.g., in the western states, then the representative storm approach may be sufficient. For the storm approach, develop data for historical floods with storm centerings throughout the basin and use several proportions of those floods to obtain flows at the damage centers representing the full range of the flow-frequency-damage relationship for base conditions and for regulated conditions. Also, develop synthetic events that have consistency in volumes of runoff and peak flows and are reasonably representative regarding upstream contributions to downstream flows.

f. Perform sequential analysis with the developed hydrology. The period-of-record simulation provides simulated regulated flow which can be analyzed directly to develop flow-frequency relations. The representative flood approach requires an assumption that the regulated-flow frequency is the same as the natural-flow frequency. Frequency curves of regulated conditions at each damage center can then be derived from frequency curves of unregulated flows simply by assuming that a given ratio of the base flood will have the same recurrence frequency whether it is modified by regulatory structures or not. This assumption is valid as long as larger unregulated floods always correspond to the larger regulated flows.

g. Derive a flow-frequency and stage-discharge curve for the index station at each damage center as described in Chapters 6 and 8, for unregulated conditions for each plan of improvement. These can be used for determining average annual damage for unregulated conditions and for each plan of development and would thus form the primary basis for project selection.

h. Develop a PMF for each reservoir site, using procedures described in Chapter 7. These will be used as a possible basis for spillway design. Route the PMF through each reservoir, assuming reasonably adverse conditions for initial storage and available outlet capacity.