Training Aids for Dam Safety

MODULE:

EVALUATION OF HYDROLOGIC ADEQUACY

TADS

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EVALUATION OF HYDROLOGIC ADEQUACY

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PREFACE

There are presently more than 80,000 dams in use across the United States. Like any engineering works, these dams require continual care and maintenance, first to ensure that they remain operational and capable of performing all intended purposes, and then to preclude endangering people and property downstream.

The safety of all dams in the United States is of considerable national, state, and local concern. Given that, the principal purpose of the TADS (Training Aids for Dam Safety) program is to enhance dam safety on a national scale. Federal agencies have responsibility for the safe operation, maintenance, and regulation of dams under their ownership or jurisdiction. The states, other public jurisdictions, and private owners have responsibility for the safety of non-Federal dams. The safety and proper custodial care of dams can be achieved only through an awareness and acceptance of owner and operator responsibility, and through the availability of competent, well-trained engineers, geologists, technicians, and operators. Such awareness and expertise are best attained and maintained through effective training in dam safety technology.

Accordingly, an ad hoc Interagency Steering Committee was established to address ways to overcome the paucity of good dam safety training materials. The committee proposed a program of self-instructional study embodying video and printed materials and having the advantages of wide availability/marketability, low per-student cost, limited or no professional trainer involvement, and a common approach to dam safety practices.

The 14 Federal agencies represented on the National Interagency Committee on Dam Safety fully endorsed the proposed TADS program and have underwritten the cost of development. They have also made available technical specialists in a variety of disciplines to help in preparing the instructional materials. The states, through the Association of State Dam Safety Officials, also resolved to support TADS development by providing technical expertise.

The dam safety instruction provided by TADS is applicable to dams of all sizes and types, and is useful to all agencies and dam owners. The guidance in dam safety practice provided by TADS is generally applicable to all situations. However, it is recognized that the degree to which the methods and principles are adopted will rest with the individual agency, dam owner, or user. The sponsoring agencies of TADS assume no responsibility for the manner in which these instructional materials are used or interpreted, or the results derived therefrom.

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MODULE INTRODUCTION

EVALUATION OF HYDROLOGIC ADEQUACY

MODULE INTRODUCTION

OVERVIEW OF THIS MODULE

This module discusses hydrology as it relates to dam safety, and provides some background information on the analyses that must be conducted to determine if a dam requires remedial action to accommodate floodflows without failing. This information includes:

- The significance of hydrologic safety design.
- The evolution of design practices to identify the inflow design flood (IDF). (Some agencies may refer to this as the safety evaluation flood (SEF), or the safety design flood (SDF). For the purposes of this document, the floodflow above which the incremental increase due to failure is no longer considered to present an unacceptable threat to downstream life and property will be referred to as the IDF.)
- The various modes of failure related to hydrologic events.
- What data must be reviewed in relation to hydrologic considerations.
- Factors to be considered when selecting the IDF.
- Procedures for selecting the IDF and determining the need for remedial action.
- What remedial action may be required to account for hydrologic inadequacy.

As the result of a dam safety evaluation, there may be a question about a dam's ability to safely handle the floodflow from an extreme flood. A study may be required to determine if the dam is capable of safely accommodating floodflows, or whether remedial actions are needed. The studies and analyses should be made by an experienced and qualified engineer, and supported by a hydrometeorologist, when practical.

Many factors may contribute to your assessment of the safety of a dam. Hydrologic adequacy is one of these factors. Hydrologic considerations relative to dam safety include . . .

- Adequacy of spillway or reservoir capacity.
- New or increased development downstream of the dam that may affect the hazard classification.
- Methods used in the original design to determine the size and capacity of the spillway and outlet works that may be ineffective or outdated. Currently, a design flood is determined for a new project based on hydrometeorological data, and the dam is constructed or modified to safely accommodate this flood. However, different methods were used to design older dams, and may not meet current criteria.

Continued . . .

OVERVIEW OF THIS MODULE (Continued)

Based on an evaluation of hydrologic conditions, remedial action may be appropriate. Remedial action for addressing hydrologic inadequacy is discussed in Unit V of this module.

> **NOTE:** There are terms in this module that you may feel need to be defined--terms such as "normal," "appropriate," "reasonable," "maximum," etc. The definition of these terms is dependent on the policies of your specific agency or organization, the hydrologic characteristics of the watershed, the type and purpose of the dam, and your personal engineering judgment.

HOW TO USE THIS MODULE

This module is designed to be used with other Training Aids for Dam Safety (TADS) modules. The TADS Learner's Guide lists all of the TADS modules and presents a recommended sequence for completing the modules. You may want to review the Learner's Guide before completing this module.

CONTENTS OF THIS MODULE

This module is divided into five units, followed by two appendixes:

- **Unit I. Overview:** Presents information on the significance of hydrologic safety design for dams, a brief history of how development of the inflow design flood (IDF) and selection of spillway capacity evolved, and the various modes of failure related to hydrologic conditions.

- **Unit II. Review And Evaluation Of Project Data:** Provides information on the type of data that must be reviewed and evaluated before determining whether a dam is capable of safely accommodating floodflows up through the IDF.

- **Unit III. IDF Selection Factors:** Describes the factors to consider when selecting the appropriate IDF.

- **Unit IV. IDF Selection Procedures:** Describes the procedures used to select the appropriate IDF, including conducting an incremental hazard evaluation.

- **Unit V. Remedial Action:** Presents information on both structural and nonstructural remedial action that may be taken if it is determined that an existing dam cannot safely accommodate the IDF.

- **Appendix A. Glossary:** Defines a number of technical terms used in this module.

- **Appendix B. References:** Lists recommended references that can be used to supplement this module.

DESIGN OF THIS MODULE

This module includes text instruction. There is no accompanying video presentation.

UNIT I

OVERVIEW

I. OVERVIEW: SIGNIFICANCE OF HYDROLOGIC SAFETY DESIGN

INTRODUCTION

Hydrology is one of the earth sciences that encompasses the occurrence, distribution, movement, and properties of the waters of the earth and their environmental relationships.

This unit describes . . .

- The impact hydrology has on dam safety,
- Selection of IDF for dam safety analysis,
- How the philosophy of selecting an IDF has evolved to the current state-of-the-art selection procedures, and
- The various modes of failure that are related to hydrologic inadequacy.

HYDROLOGIC CONCERNS

Many thousands of dams have been constructed in the United States, and new dams continue to add to this total. The proper functioning of these dams to withstand natural forces, including extreme hydrologic events, is an important matter of public safety and concern.

In today's technical world, extreme hydrologic events resulting in dam failures are classified as one of the major "low-probability, high-consequences" events. In addition, the potential for losses due to increased downstream development may increase the consequences of a dam failure.

There has been a growing concern for dam safety over the past two decades, primarily as a result of a number of dramatic dam failures. As a result, the inspection of non-Federal dams authorized by Public Law 92-367, the National Dam Inspection Act, identified some 2,900 unsafe dams of which 2,350 had inadequate spillway capacities. Because of the considerable cost of correcting hydrologically deficient dams, attention is being focused on the proper selection of the appropriate flood a given dam should be capable of safely accommodating. The methodology and processes for selecting this flood are the subject of this module.

The primary objective of hydrologic analyses for dam safety purposes, as presented in this module, is to determine the appropriate IDF a dam should be designed to safely accommodate. The IDF is that floodflow above which the incremental increase due to failure is no longer considered to present an unacceptable threat to downstream life and property.

The IDF is selected based on an evaluation of the additional loss of life and property that would occur if the dam were to fail under a range of inflow conditions from normal up to the probable maximum flood (PMF). (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 drainage basin under study.) The study conducted to make this determination is called the incremental hazard evaluation.

Continued . . .

HYDROLOGIC CONCERNS (Continued)

Sometimes, the incremental increase in hazard due to a failure is evident--a large community, businesses, or other enterprises exist downstream from the dam, and lives and property would be lost in the event of dam failure under all possible flood-induced scenarios. In this case, the incremental hazard evaluation can be made based on a field reconnaissance, and review of topographic maps. In other situations, the potential for damage is not evident because of the location and sparseness of downstream development and because it is not easy to estimate the incremental change in flood depth and area that can be expected as a result of failure. In these cases, it is necessary to conduct detailed dambreak studies to determine the incremental impact of a failure on downstream life and property.

Also, you can use the information resulting from the incremental hazard evaluation to determine or verify the hazard classification assigned to a project. (See Unit III of this module for more information on factors considered when selecting the IDF.)

The appropriate IDF for the project is selected based on the results of the incremental hazard evaluation. This evaluation involves simulating a dam failure during normal and floodflow conditions and routing the water downstream. The additional threat to downstream life and property due to the incremental increase in water surface elevation from dam failure is assessed for each failure scenario.

The dam should be assumed to fail under various flood conditions up through the probable maximum flood (PMF) or the flood above which a failure will no longer result in significant additional loss of downstream life and property. Once these studies are completed, the appropriate IDF for the dam can be selected. The upper limit for the IDF is the PMF. However, there are situations where the IDF may be less than the PMF.

A PMF should be determined if it is needed for use in the evaluation (if a PMF value is already available, it should be reviewed to determine if it is still appropriate). The probable maximum precipitation (PMP) for the area should be determined either through the use of the Hydrometeorological Reports (HMR's) developed by the National Weather Service, or through the services of a qualified hydrometeorologist. (The PMP is, theoretically, the greatest depth of precipitation for a given duration that is physically possible over a particular geographical location during a certain time of the year.) In addition, the hydrologic characteristics of the drainage basin that would affect the runoff from the PMP into the reservoir should be determined. After this information is evaluated, the PMF can be determined.

Once the appropriate IDF for the dam has been selected (whether it be the PMF or something less), it should then be determined whether the dam can safely withstand or pass all floodflows up through the IDF. If it can, then no further evaluation or action is required. If it cannot, then measures must be taken to enable the project to safely accommodate all floods up through the IDF in order to alleviate the incremental increase in adverse consequences a failure may have on areas downstream.

I. OVERVIEW: SIGNIFICANCE OF HYDROLOGIC SAFETY DESIGN

CASE HISTORY AND STATISTICS

It has been estimated that as many as 2,000 dams worldwide have failed since the 12th century. About a third of all dam failures have resulted because of inadequate spillway capacity. There have been about 200 notable dam failures resulting in more than 8,000 deaths in the 20th century alone. Dam failure is not a problem confined to developing countries or due to a compilation of past mistakes that are unlikely to occur again.

Table I-1 on the following page lists some of the dam failures that occurred in the United States due to hydrologic events from 1963 to 1983. These failures resulted in many deaths as well as extensive property damage.

Many dam owners have a difficult time believing that their dams could experience a rainfall event many times greater than any they have witnessed over their lifetimes. Unfortunately, this attitude leads to a false sense of security because floods much greater than those experienced during any one person's lifetime can and do occur.

No one can predict when the next major catastrophic failure will occur. The historical pattern indicates that a dam failure is as likely to occur today or tomorrow as it was on November 6, 1979, when failure of the Kelly Barnes Dam in Toccoa, Georgia, killed 39 people, or on February 26, 1972, when the Buffalo Creek Dam failure in West Virginia killed 125 people and caused major property damage. The Kelly Barnes and Buffalo Creek dam failures occurred as a result of inflows that were only on the order of 10-year and 2-year runoff events, respectively. Continual inspection and review, proper operation and maintenance, and performance of remedial repairs or replacement when necessary will help reduce the potential for failure.

SELECTION OF INFLOW DESIGN FLOOD FOR DAM SAFETY ANALYSES

Ideally, dams should be able to safely accommodate floodflows in a manner that will not increase the danger to life and property downstream. However, this situation is not always the case, and may not always be achievable.

There are various methods or reasons for selecting the inflow design flood and determining whether the dam can safely accommodate the flood. The method chosen may be determined by the amount of time and/or funds available to conduct an evaluation. For example, if time and funds are scarce, a conservative inflow design flood (i.e., the PMF) can be selected.

Sometimes, inflow design flood selection is straightforward (i.e., given certain criteria, a specific inflow design flood must be used) due to political decisions and policies established by government agencies. For example, statutes may require that a flood such as the PMF, a specific fraction of the PMF, or a flood of specific frequency be selected for a dam with a certain hazard classification. Fortunately, the most widely accepted approach involves detailed engineering analyses and investigations to identify the appropriate IDF for a dam.

Continued . . .

I. OVERVIEW: SIGNIFICANCE OF HYDROLOGIC SAFETY DESIGN

SELECTION OF INFLOW DESIGN FLOOD FOR DAM SAFETY ANALYSES (Continued)

TABLE I-1. LOSS OF LIFE AND PROPERTY DAMAGE FROM NOTABLE U.S. DAM FAILURES AS A RESULT OF HYDROLOGIC EVENTS, 1963-1983

Name And Location Of Dam	Year Of Failure	# Of Lives Lost	Damages
Mohegan Park, CT	1963	6	$3 Million
Swift, MT	1964	19	Unknown
Lower Two Medicine, MT	1964	9	Unknown
Lee Lake, MA	1968	2	6 houses destroyed, 20 houses damaged, 1 manufacturing plant damaged or destroyed
Buffalo Creek, WV	1972	125	Caused major property damage
Canyon Lake, SD	1972	33	Unable to assess damage because dam failure accompanied damage caused by natural flooding
Laurel Run, PA	1977	39	6 houses destroyed, 19 houses damaged
Sandy Run and 5 others, PA	1977	5	Unknown
Kelly Barnes, GA	1977	39	9 houses, 18 house trailers, and 2 college buildings destroyed; 6 houses, 5 college buildings damaged
Swimming Pool, NY	1979	4	Unknown
DMAD, UT	1983	1	Unknown

I. OVERVIEW: SIGNIFICANCE OF HYDROLOGIC SAFETY DESIGN

SELECTION OF INFLOW DESIGN FLOOD FOR DAM SAFETY ANALYSES (Continued)

When determining the effect flood inflows will have on dam safety, a hydrologic approach may be used. Simply stated, this approach establishes the IDF for the project, and either:

- Determines whether an existing project can safely accommodate the IDF,

- OR -

- Determines how a new project will be designed to safely accommodate the IDF.

Since the entire spectrum of floods up to the PMF level generally needs to be considered in selecting the IDF, it is usually necessary to determine the probable maximum precipitation (PMP) magnitudes and to develop the PMF based on that information.

The effort involved in conducting PMP and PMF analyses is quite detailed, and will be described later in this module. Depending on the significance of the study being pursued, these analyses should be directed by an engineer and, if necessary, a hydrometeorologist trained and experienced in this specialized field.

Selecting the appropriate IDF is usually based, in part, on the hazard classification of the dam. The hazard classification is based on the consequences of dam failure to life and property downstream, and **not** the likelihood of dam failure. In most hazard classification systems, if more than a few lives are at risk or extensive property damage is likely, then the dam is given a high hazard classification. If no lives will be lost and there will be little or no property damage, the dam will likely be given a low hazard classification. Hazard classification will be discussed in more detail in Unit III.

The procedure presented in this module is the most direct method for selecting an inflow design flood. However, there are times when selection becomes difficult and it may be necessary to conduct further analyses, such as those involved with a risk-based approach. This approach is discussed on pages I-9 and I-10.

I. OVERVIEW: EVOLUTION OF INFLOW DESIGN FLOOD (IDF) PHILOSOPHY

INTRODUCTION

Current practice in the design of dams is to use the inflow design flood (IDF) that is deemed appropriate for the hazard potential of the dam and reservoir, and to design spillways and outlet works that are capable of safely accommodating the floodflow without risking the loss of the dam or endangering areas downstream from the dam. However, many dams exist whose discharge capabilities were designed using methods that are now considered unconservative and potentially unsafe.

PHILOSOPHY OF SELECTING THE INFLOW DESIGN FLOOD

The philosophy of the inflow design flood selection began primarily as a practical concern over the potential loss of a dam and the services it provides.

The early 1900's saw an increase in the nation's social awareness, as demonstrated by various legislative acts designed to protect the public from certain high risk activities. The same era witnessed an increase in the number and size of dams built. When the "big dam" era began in the 1930's, safety clearly became the dominant factor. It was recognized that dams needed to be designed to accommodate water flows that might be greater than the anticipated "normal" flow.

Early Periods

Before 1900, designers of dams had relatively little hydrologic data to indicate flood potential at a proposed dam site. Estimates of flood potential were selected by empirical techniques and engineering judgment based on high water marks or floods of record on streams being studied.

Later, engineers felt that looking at all past flood peaks in a region might give more reliable estimates of maximum flood-producing potentials than a limited record on a single stream. Designers would base their spillway design on these estimates, sometimes providing additional capacity as a safety factor. Some spillways were designed for a particular multiple of the maximum known flood; for example, twice the maximum known flood. The multiples and safety factors were based on engineering judgment; the degree of conservatism in the design was unknown.

By the 1930's, it became apparent that this approach was inadequate, because as longer hydrologic records were obtained, new floods exceeded previously recorded maximum floods. With the introduction of the unit hydrograph concept by Sherman in 1933, it became possible to estimate floodflows from storm rainfall. The design of dams began to be based upon the transposition of major storms that had occurred within a region; i.e., transfer and centering of relevant storm rainfall patterns over the basin above the damsite being evaluated.

It was recognized that flood peaks are dependent on topography, size of individual watersheds, and chance placement of storm centers over the watershed. Also, within meteorologically similar areas, observed maximum rainfall values could provide a better indication of maximum flood potentials than data on flood discharges from individual watersheds. If, in the judgment of the designer, the storm was not representative of what might occur, rainfall amounts were increased to represent a more severe event, and the dam was designed accordingly.

I. OVERVIEW: EVOLUTION OF INFLOW DESIGN FLOOD (IDF) PHILOSOPHY

Transition

Engineers next turned to hydrometeorologists to determine if upper limits for rates of precipitation could be established on a rational basis. Careful consideration was given to the meteorology of storms that produced major floods in various parts of the country. The large scale features of the storm and measures of atmospheric moisture, such as dewpoint temperatures, were considered as well as the rainfall depth-area-duration values produced by these storms. It was then possible to increase the storm dewpoint temperature and other factors affecting rainfall to the maximum appropriate values. This increase resulted in estimates of probable maximum precipitation (PMP), and thus introduced the concept of a physical upper limit to flooding. When translated to floodflows, this estimate is known as the probable maximum flood (PMF).

At first, the terms maximum possible precipitation and maximum possible flood were used. However, the terminology was changed to **probable maximum** to recognize the uncertainties in the estimates of the amount of precipitation, and the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in the region. Today, the probable maximum flood is generally accepted as the standard for the safety design of dams where the consequences of failure are great.

In the late 1940's, the ability to estimate the consequences of dam failure, including the loss of life, was still quite limited. The height of the downstream flood wave and the extent of wave propagation were known to be a function of dam height and reservoir volume. Thus, early standards for dam design were based upon the size of the dam in terms of its height, the reservoir storage volume, and the downstream development.

The practice of setting inflow design flood standards based upon the size of a dam, its reservoir volume, and current downstream development has resulted in an inconsistent level of design throughout the country. The determination of the consequences of a dam failure is more complex than can be evaluated by these simple relationships.

Current Practices

In 1985, the National Academy of Sciences (NAS) published a study of flood and earthquake criteria which contained an inventory of current practices in providing dam safety during extreme floods. The inventory showed considerable diversity in approach by various Federal, State, and local government agencies, professional societies, and private firms. While the inventory shows a fair consensus on spillway requirements for dams having a high hazard potential, there is a wide range of criteria being applied to dams with lower hazard classifications.

Several observations about hydrologic conditions were made in the NAS study. Use of PMP for evaluating spillway capacity requirements for large, high-hazard dams predominates, although some State agencies have standards that do not require such dams to pass the full estimated PMF based on the PMP. The influence of the principal Federal dam-building agencies is evident in the majority of the standards for large, high-hazard dams, but the practices of those agencies have had less effect on current State standards for small dams in less hazardous situations.

Continued . . .

I. OVERVIEW: EVOLUTION OF INFLOW DESIGN FLOOD (IDF) PHILOSOPHY

Current Practices (Continued)

As a result of inspections authorized by Public Law 92-367, the National Dam Inspection Act, and carried out by the Corps of Engineers from 1977 to 1981, several States have adopted the spillway capacity criteria used in those inspections. Several other States have adopted the standards used by the Soil Conservation Service for the design of smaller dams constructed under that agency's programs.

Most agencies draw a distinction between design criteria that are applied to existing dams and those that are applied to new dams. However, since dam failures present the same consequences to life and property, it is desirable that existing dams meet the criteria established for new dams. There may be special considerations at existing dam sites that preclude some options that are available at new dam sites.

Today, hydrologically safe designs should be based on current state-of-the-art criteria. Now that engineers can estimate downstream flood levels resulting from dam failure, safety design standards can be tied specifically to a detailed evaluation of the impacts of a flood if a dam were to fail. Although debate continues over the proper criteria and degree of conservatism warranted when evaluating and designing modifications to existing dams, and when designing new dams, criteria used by dam designers, regulators, and owners now focus on ensuring public safety.

Risk is defined as the probability of occurrence of adverse events. A **risk-based analysis** is one in which the risks and consequences of adverse events are evaluated or compared in a manner that leads to a decision about a particular action to be taken. A risk-based analysis may be a basis for the selection of the IDF for a particular dam.

The American Society of Civil Engineers Task Committee on Spillway Design Flood Selection states that "risk analysis itself is not a single technique, but a collection of related strategies, useful in a wide range of decisionmaking contexts." There are three broad levels of risk analysis:

- **Subjective Assessment.** Where most or all factors relevant to a decision cannot be quantified or otherwise systematically accounted for, a subjective assessment is required. Risk analysis assists this process by offering a framework for analysis and criteria for including or omitting factors. Subjective assessments may not lead to optimal decisions, although experience with similar problems improves the quality of judgment.

- **Index-Based Assessments.** Where at least some important factors in a decision can be quantified, it may be possible to carry out an index-based risk assessment. This type of analysis is more general and complete than a subjective assessment, but it does not permit numerical comparisons of likelihood or expected cost.

Continued . . .

Current Practices (Continued)

- **Quantitative Assessment.** A quantitative (formal) risk assessment requires estimates of occurrence frequencies, relative likelihoods of possible levels of response and damage, and various components of cost and consequences. In its most common form, risk analysis for dam safety design includes the following steps:

  - Events or sequences of events that can lead to dam failure are identified and their likelihood of occurrence estimated.

  - Potential modes of failure that may result from various adverse initiating events are identified.

  - The likelihood that a particular dam failure will occur under a particular set of circumstances is evaluated.

  - The consequences of failure are determined for each potential failure mode.

  - Risk costs (the sum of expected losses: economic, social, and environmental) are calculated for each set of possible failure consequences.

The incremental hazard evaluation is, in essence, a risk-based approach. It is the most direct method for selecting the appropriate IDF for a project. Therefore, the majority of this module deals with the incremental hazard evaluation.

I. OVERVIEW: MODES OF FAILURE

INTRODUCTION

As mentioned earlier, many dam failures have resulted because of inadequate spillway capacity. Failures caused by hydrologic conditions can range from sudden, with complete breaching or collapse, to gradual, with progressive erosion and partial breaching.

The most common modes of failure associated with hydrologic conditions include overtopping, erosion of earth spillways, and overstressing the dam or its structural components. Other TADS modules address specific modes of dam failure in detail. The following paragraphs describe briefly each of the modes of failure caused by hydrologic conditions.

OVERTOPPING

Overtopping of a dam occurs when the water level in the reservoir exceeds the height of the dam and flows over the crest. Overtopping by itself will not necessarily result in a failure. Failure depends on the type, composition, and condition of the dam and the depth and duration of flow over the dam.

Embankment dams are usually the most susceptible to failure when overtopped because of erosion. If the erosion is severe, it can lead to a breach and failure of the dam. Also, during overtopping, the foundation and abutments of concrete dams can be eroded leading to a loss of support and failure from sliding or overturning. In addition, when a concrete dam is subjected to overtopping, the loads can be substantially higher than those for which the dam was designed. If the increased loading on the dam itself due to overtopping is too great, a concrete dam can fail by overturning or sliding.

EROSION IN EARTH SPILLWAYS

High or large flows through earthen spillways adjacent to dams can result in erosion that progresses to the dam and threatens it. Erosion can also cause a downcutting that progresses toward the spillway crest and eventually leads to a breach. Discontinuities in slope, non-uniform vegetation or bed materials, and concentrated flow areas can start headcuts and accelerate the erosion process. Flood depths that exceed the safe design parameters can produce erosive forces that may cause serious erosion in the spillway.

Erosion that occurs due to flow concentrations can start where roads or trails are devoid of vegetation or have ruts that run parallel to the spillway flow. A varied mix of earth materials, unlevel cross sections, uneven stands of vegetation, and obstructions such as trash accumulations can cause turbulent, concentrated flow conditions that start gullies that can widen and migrate upstream to breach the spillway crest.

Runoff brought into a spillway channel by a side inlet may also disrupt the desirable uniform flow pattern and increase the erosion in the channel.

The probability of failure of an earthen auxiliary spillway due to erosion is increased when the capacity of the principal spillway inlets (outlet works) or gates is reduced due to trash accumulations. These accumulations reduce the available capacity through these appurtenances and increase the volume, depth, frequency, and duration of flow in the auxiliary spillway.

I. OVERVIEW: MODES OF FAILURE

OVERSTRESSING OF STRUCTURAL COMPONENTS

As floods enter the reservoir, the reservoir will normally rise to a higher elevation. Even though a dam (both concrete and earth embankment dams) may not be overtopped, the reservoir surcharge will result in a higher loading condition. If the dam is not properly designed for this flood surcharge condition, either the entire dam or the structural components may become overstressed, resulting in an overturning failure, a sliding failure, or a failure of specific structural components (such as the upstream face of a slab and buttress dam).

I. OVERVIEW: SUMMARY

SUMMARY: OVERVIEW OF HYDROLOGIC CONSIDERATIONS

Unit I described the evolution of hydrologic consideration in the design of dams, and the selection of an IDF for dam safety analyses.

The hydrologic approach used when determining the effect flood inflows will have on dam safety simply establishes the IDF for the project and either:

- Determines whether an existing project can safely accommodate the IDF, or
- Determines how a new project will be designed to safely accommodate the IDF.

Since the entire spectrum of floods up to the PMF level generally needs to be considered in selecting the IDF, it is usually necessary to determine the probable maximum precipitation (PMP) magnitudes and to develop the PMF based on that information.

This unit also described overtopping, erosion in earth spillways, and overstressing of structural components as those modes of dam failure relate to hydrologic problems.

UNIT II

REVIEW AND EVALUATION OF PROJECT DATA

II. REVIEW AND EVALUATION OF PROJECT DATA: OVERVIEW

WHY REVIEW PROJECT DATA?

In order to accurately determine whether a dam is capable of safely passing its inflow design flood, certain data must be reviewed. Reviewing project data will help you identify . . .

- The hazard classification assigned to the dam,
- The effects of a flood on the downstream area,
- The flood used for the original design (IDF), and the hydrologic parameters,
- What criteria are used for operating the project in the event of a flood,
- Site characteristics that would have an effect on flood flows and reservoir storage capacity, and
- The capacity of hydraulic structures.

IDENTIFY AND REVIEW DOWNSTREAM HAZARD CLASSIFICATION

Downstream hazards are defined as the potential for loss of life or property damage downstream from a dam due to waters released in the event of failure of the dam. Hazard classification is not associated with the existing condition of a dam and its appurtenant structures, or the anticipated performance or operation of a dam. Rather, hazard classification indicates existing potential for adverse impact on human life and downstream developments should a dam failure occur.

Many dams were initially assigned a hazard classification by the Army Corps of Engineers during a program authorized by Congress in 1972, in Public Law 92-367, the National Dam Inspection Act. Many of these classifications have been reviewed by the appropriate Federal and State agencies, and have been updated, as necessary. Current hazard classifications may be available from the appropriate Federal or State agency having jurisdiction over the dam.

Hazard classification serves as a management tool for prioritizing and selecting levels of dam safety program activities, and for scheduling frequency of dam safety reassessments. Hazard potential is used to determine the criteria that are adopted for use in design of project modifications or remedial actions, including the magnitude of the inflow design flood (IDF).

In reviewing the hazard classification of a dam, the methodology for determining downstream flood depths should be assessed. Determine whether the methodology used is still appropriate and accurate. Also, identify whether changes have occurred in downstream development and how these changes affect the hazard classification.

II. REVIEW AND EVALUATION OF PROJECT DATA: ORIGINAL DESIGN DATA

REVIEW THE FLOOD USED FOR THE ORIGINAL DESIGN

Before performing any new hydrologic studies, you should review all available design studies and records. The scope of the review will depend upon what procedures were used in selecting the IDF:

- If hydrometeorological methods were not used in the original design, reevaluate the original IDF.

- If hydrometeorological methods were used, review the design storm and the method of modeling basin runoff.

Design Storm

For the design storm estimate, there are two basic considerations to address:

1. Have all currently available storm data been reflected in the existing hydrometeorological study? This should generally involve determining whether the appropriate and most current hydrometeorological reports for the region were used in the design. If not, the differences in probable maximum precipitation (PMP) values should be determined. In 1980, the National Weather Service published a study that recorded and updated the greatest observed rainfalls in the United States and compared these estimates with the current estimates of point and areal PMP (see the Glossary in Appendix B). This report and any other recent reports should be reviewed to determine whether the existing storm study reflects all currently available data that are relevant.

2. If the design storm study is dated, was appropriate methodology used to determine the design storm? The general practice of some agencies from about the 1940's to the late 1960's was to transpose a number of observed storms from nearby meteorologically compatible areas to the basin being studied. The moisture generated by observed storms were maximized using meteorological procedures, and a design storm was then developed. This estimate needs to be compared with the results obtained using current procedures.

Modeling Basin Runoff (Hydrologic Analysis)

Many of the original IDF studies for dams performed back in the 1920's and 1930's applied techniques that are no longer considered acceptable. Some of these procedures were discussed in Unit I. Currently, the most common runoff modeling techniques consist of the use of unit hydrographs and loss rate parameters. When reviewing a study for adequacy, examine information from the old study to determine whether the unit hydrograph that was used is compatible with more recent studies in the area (in some instances, more than one unit hydrograph may be used).

Continued . . .

II. REVIEW AND EVALUATION OF PROJECT DATA: ORIGINAL DESIGN DATA

Modeling Basin Runoff (Hydrologic Analysis) (Continued)

Certainly more sophisticated and complex computer models for converting rainfall to runoff have become available. However, as the complexity of computer models increases, many more site-specific data are needed. Attempts to estimate needed input data can lead to inaccuracies and may produce unwarranted confidence in the results. As a practical matter, the unit hydrograph approach, which requires a limited number of assumptions about input parameters, continues to be a valid technique for developing extreme flood hydrographs.

The antecedent conditions assumed to occur prior to the IDF are also important. Initial basin moisture conditions will affect infiltration and runoff rates during the IDF storm event. Since storms tend to occur in series, an antecedent flood is generally part of the inflow series. For drainage areas where snowmelt contributes to flood conditions, the incorporation of snowmelt along with the rainfall-runoff component is important. Make sure to review the adequacy and reasonableness of all assumed antecedent conditions.

If it is evident that the basis for the original design gave results that are substantially in accord with current practice, further investigation may be unnecessary. If, however, the basis used, such as design storms, is considerably different from what would be acceptable today, then a revised flood study is required.

II. REVIEW AND EVALUATION OF PROJECT DATA: OPERATIONAL DATA

REVIEW RESERVOIR OPERATIONS

Reviewing reservoir operations will provide you with information on how the project is operated, problems that may have occurred, and how the project performs under various reservoir water levels. Review the following types of information: operating criteria, records of operation, and operating criteria for flood control.

Operating Criteria

The following documents will give you an understanding of how projects are to be operated under both normal conditions and flood conditions, and will be useful in evaluating dam safety:

- Reservoir operating criteria,
- Water control or regulation manuals,
- Standing operating procedures,
- Designers' operating criteria,
- Maintenance records, and
- Any other pertinent documents.

Records Of Operation

Evaluate past reservoir operating records to obtain specific information on past water level fluctuations in the reservoir. Historical flood data or data on unusual flood events, including hydrographs and operation of gates and valves, are useful in evaluating current hydrologic conditions and in predicting future performance during floods. If no reservoir operation or maintenance records exist, you can usually obtain information on approximate minimum and maximum reservoir levels from the personal experience of concerned individuals. Items of particular interest associated with reservoir levels include . . .

- High water marks of major floods,
- Duration of spillway flows and overflows, if any,
- Time required to draw down the reservoir to the normal reservoir level, and
- Operations and maintenance problems that affect spillway capacity, such as persistent trash accumulation or similar problems.

Any history of flood damages and resultant repairs and modifications to the dam will also be helpful. This background information allows comparisons between recorded hydrologic events and computed hypothetical events that may be helpful in assessing project safety.

Reservoir Operations For Flood Control

If flood control is a project purpose, review the reservoir operating criteria during flood flows. If there was Federal cost sharing for the flood control feature, a reservoir regulation manual containing operating criteria should be available. Many reservoirs without dedicated flood control storage may still have operating rules or schedules that regulate drawdown and filling. These schedules may be based on ability to predict inflows for snowmelt, and could provide a significant operational consideration.

II. REVIEW AND EVALUATION OF PROJECT DATA: OTHER SITE DATA

REVIEW DRAINAGE BASIN AND SITE DATA

Review contributing watershed area information to determine . . .

- If the topographic maps and photographs are adequate.
- If any assumptions were made regarding natural or manmade diversions.
- If karst, pothole, or disturbed areas contribute to water losses.
- If upstream storage conditions have changed, such as the addition of new reservoirs or changes in operating schemes.

Review the basis used to determine the reservoir storage capacity to determine . . .

- If the original estimate of available floodwater capacity is still valid.
- If sediment yields exceeded those predicted and impact on storage or release capacities.
- If water is being stored for other uses that might conflict with the original floodwater storage requirements.

REVIEW CAPACITY OF HYDRAULIC STRUCTURES

In most cases, assessment of the safety of an existing dam will require that the IDF be routed through the reservoir and spillway, including other outlet structures available to release water from the reservoir during extreme events.

The dimensions, location, and structural condition of these hydraulic structures determine the quantity of water that can be discharged safely. Operation of gated spillways is generally not as reliable as ungated spillways, and is a factor in determining whether releases during flood periods can be assured.

Assumed release capacity as a result of operation of gates, outlet works, and power facilities should be reviewed for reasonableness during flood conditions. A major concern is the accessibility of the gate controls during a major flood. For example, could the operator get across the spillway once it started discharging if the controls were on the other side and needed to be operated? In some cases, very small floods preclude crossing the spillway or dam. The assumptions should be compatible with IDF conditions and with historical operations. The assumption that significant releases will be made through the outlet works may be appropriate, but only if operation data indicate that significant releases are commonly done during flood periods.

The TADS module entitled Evaluation Of Hydraulic Adequacy provides further information on this topic.

II. REVIEW AND EVALUATION OF PROJECT DATA: OTHER SITE DATA

REVIEW DOWNSTREAM FLOODPLAIN STUDIES

In assessing the hazard involved in the potential failure of a dam, an estimate of the downstream flood that would be produced by such failure is needed. Many dam owners have developed an Emergency Action Plan (EAP) for their dams. These EAP's usually contain dam failure inundation maps. Review the following hydraulic factors to evaluate the reliability of the results of downstream floodplain studies:

- The assumed dam failure parameters (including breach size, time to breach, and various flood conditions)
  - Sensitivity analysis
  - Previous incremental hazard evaluations
- The method of flood routing
- The method of calibrating the flood routing model
- The method of determining flood profiles
- The parameters used to determine the flood profiles
  - The distance between cross sections
  - The selected Manning's "n" value
- The parameters used to determine the inundated area
  - The contour interval for floodplain mapping

Evaluations should be conducted by an engineer trained and experienced in this specialized field.

II. REVIEW AND EVALUATION OF PROJECT DATA: SUMMARY

SUMMARY: REVIEW AND EVALUATION OF PROJECT DATA

Unit II described the types of data that should be reviewed in order to accurately determine whether a dam is capable of safely passing its inflow design flood. Table II-1 summarizes the types of data to review and the information obtainable from each type.

TABLE II-1. TYPES OF DATA TO REVIEW FOR DETERMINING DAM SAFETY

REVIEW THE . . .	TO . . .
Downstream Hazard Classification	. Help select and prioritize levels of dam safety program activities. . Schedule frequency of downstream reassessments. . Help determine criteria that are adopted for use in design of project modifications or remedial action.
Flood Used For The Original Design	. Determine what procedures were used in selecting the inflow design flood (IDF).
Reservoir Operations	. Determine how the project is operated, what problems have occurred, and how the project performs under various reservoir water levels.
Drainage Basin And Site Data	. Determine what physical aspects of the water-shed contribute to inflow of water to the reservoir, or to water losses. . Determine whether conditions exist that might affect reservoir storage capacity.
Downstream Floodplain Studies	. Help evaluate the reliability of the results of downstream floodplain studies. . Assess the hazard involved in the potential failure of a dam by estimating the flood that would be produced, and examining the area that would be inundated by the flood.

UNIT III

INFLOW DESIGN FLOOD (IDF) SELECTION FACTORS

III. IDF SELECTION FACTORS: OVERVIEW

WHAT ARE THE IDF SELECTION FACTORS?

Dams should be designed to withstand or safely accommodate floodflows up to the floodflow above which the incremental increase due to failure is no longer considered to present an unacceptable consequence to downstream life and property. This design standard will reduce the hazard posed by the water impounded by a dam. This flood is called the **inflow design flood (IDF).** The upper limit for the IDF is the **probable maximum flood (PMF).**

The IDF should be determined during the design stage of a new dam. However, for existing projects, studies may need to be conducted to determine the appropriate IDF for the dam and whether the dam can safely accommodate the IDF. If not, either structural or procedural remedial action may be required to alleviate the possible effects of a failure.

The purpose of this unit is to describe the factors that should be considered in determining the appropriate IDF for a particular dam. These factors include . . .

- The hazard potential and/or hazard classification of the dam and the impacts of dam failure.
- Potential inundation of the downstream area caused by dam failure during various floodflow events.
- The probable maximum precipitation (PMP) and probable maximum flood (PMF) for the drainage basin.
- Whether the consequences of dam failure are acceptable or not acceptable if the IDF is less than the PMF.
- Whether the dam provides vital community services, such as municipal water supply or energy.

Finally, once the IDF has been established, this hypothetical flood is routed through the reservoir and downstream to determine the effects of the flood. This procedure will help determine where flood waters will go, what damage they will leave behind, whether spillways and other flow control appurtenances are adequately sized, and if the current operating procedures are adequate to accommodate the flood.

III. IDF SELECTION FACTORS: HAZARD EVALUATION

INTRODUCTION

Once a dam is constructed, the downstream hydrologic regime is permanently changed. This change could alter land use patterns and permit and encourage new encroachment on the downstream floodplain that would otherwise not happen without the dam. Consequently, evaluation of the impacts of dam failure must be based upon the dam being in place, and must include comparing the impacts of with-failure and without-failure conditions on existing as well as prospective developments. This evaluation is known as the **incremental hazard evaluation.**

DETERMINING THE HAZARD POTENTIAL

The hazard potential of a dam pertains to potential for loss of human life or property damage in the area downstream of the dam in the event of failure or incorrect operation of a dam. Hazard potential does not refer to the structural integrity of the dam itself, but rather the effects if a failure should occur.

The hazard potential of a dam is based on consideration of the effects of a failure during both normal and floodflow conditions, and includes consideration of recreational development and use. The hazard potential of a dam can be classified as low, significant, or high. **The hazard classification assigned to a dam should be based on failure consequences resulting in the greatest hazard potential.**

Low Hazard

Dams classified in the **low hazard** potential category generally either are located in rural or agricultural areas where the increased flooding due to failure may damage farm buildings, limited agricultural land, or township and country roads, or have a small storage capacity whereby the release from a failure would represent no danger to human life.

Significant Hazard

Dams classified in the **significant hazard** potential category are usually located in predominantly rural or agricultural areas where damage from the increased flooding due to failure would be limited to isolated homes, secondary highways and/or minor railroads, and may cause interruption in the use of relatively important public utilities, and/or some increased flooding of structures with possible danger to human life.

High Hazard

Dams classified in the **high hazard** potential category are those located where the increased flooding due to failure could cause major damage to homes, extensive damage to agricultural, industrial, and commercial facilities, and/or damage to important public utilities, main highways, or railroads, and pose danger to human life.

III. IDF SELECTION FACTORS: HAZARD EVALUATION

EVALUATING THE IMPACTS OF DAM FAILURE

The possible consequences resulting from dam failure include loss of human life, economic, social, and environmental losses, damage to national security installations, and political and legal ramifications.

Loss Of Human Life

To estimate the potential for loss of life, evaluate the following factors:

- The number and location of habitable structures in the area that would be inundated by dam failure.

- The presence of public facilities that attract people on a temporary basis within the area that would be inundated if the dam failed (e.g., improved campgrounds, organized or unorganized recreation areas, State or national parks, etc.).

- Type of flow conditions based on water depths, velocities, rate of rise and flood wave travel time, duration of floodflow, and special hazardous conditions such as the presence of surface waves, debris flow, or terrain conditions that may increase the potential for loss of life.

- Emergency response capability, and warning and evacuation that would likely take place.

Economic Impacts

To estimate the economic impacts of damage resulting from dam failure, evaluate the following factors:

- Residences

- Commercial property

- Industrial property

- Public utilities and facilities including transmission lines and substations

- Community water supplies

- Transportation systems

- Agricultural buildings, lands, and equipment

- The dam, and loss of production and other benefits from the operation of the dam and reservoir

III. IDF SELECTION FACTORS: HAZARD EVALUATION

Social Impacts

Social impacts are extremely important and in some cases may exceed property losses, but these impacts cannot easily be evaluated in economic terms. To evaluate the social impacts, consider the following:

- Real income
- The health and well-being of individuals (psychological and physical injury)
- The community (both family and larger), including destruction of educational, historical, and cultural facilities and values
- The general way of life (e.g., disruptions and inconveniences)

Environmental Impacts

Environmental impacts are also important, but some cannot be easily evaluated in economic terms. To evaluate the environmental impact, consider the following:

- Damage to or loss of wildlife and habitat
- Loss of fishery and riparian habitat
- Reduced aesthetic qualities
- Extreme changes in the channel regime and floodplain characteristics

National Security Installations

When evaluating the impacts of dam failure, also consider damage to national security installations.

Political Considerations

Remember to also take into account political considerations. Certain projects may be politically sensitive. Should a failure be a catastrophic event affecting a large number of people, it can be politically unacceptable.

Legal Ramifications

If failure of a dam causes property damage and loss of life, the owner of the dam may be subject to serious liability problems. Remember to identify the legal ramifications that may result from a dam failure.

III. IDF SELECTION FACTORS: HAZARD EVALUATION

SELECTING A HAZARD CLASSIFICATION

In selecting a hazard classification for a dam, the classification is based on failure consequences resulting from the failure condition that will result in the greatest hazard potential for loss of life and property damage. For example, a failure during normal operating conditions may result in the released water being confined to the river channel, indicating a low hazard potential. But, if the dam were to fail during a floodflow condition, the result may be serious damage to life and property, representing a high hazard potential. The appropriate hazard classification for the dam would, therefore, be high.

In most cases, the hazard potential can be determined by field investigations and a review of available data, including topographic maps. A field investigation may involve a visual inspection of the downstream area to see if there have been changes in development or land use. When determining the hazard classification, consider if there are new housing developments, businesses, or changes in land uses (such as the development of camping areas, etc.). Also consider any activity upstream of the dam that might affect the inflow of water to the reservoir during flood conditions.

When the hazard potential is not readily apparent from a field investigation, dambreak studies must be performed. Dambreak studies involve developing different floodflow scenarios, assuming failure of the dam under each flood, and clearly identifying the consequences of each scenario.

How The Hazard Classification Relates To The IDF

Selection of the appropriate IDF for a dam is related to the hazard classification for the dam. The IDF for a dam having a low hazard potential is selected primarily to protect against loss of the dam and its benefits should a failure occur. The IDF for a dam with a high hazard potential is the maximum flood above which there are no significant incremental impacts on downstream life and property, and the IDF can vary up to the probable maximum flood (PMF), which is discussed later in this unit. The IDF for a significant hazard potential dam must be carefully selected to ensure adequate protection of life and property downstream of the dam, and the IDF can also be the PMF under certain circumstances.

Detailed studies may be required for various floodflow conditions to evaluate the incremental increase in consequences resulting from a failure in order to identify the flood level above which the consequences of failure become acceptable--that is, the floodflow condition above which the incremental increase due to failure is no longer considered to present an unacceptable threat to downstream life and property. The selection of the appropriate IDF for a dam is the result of this hazard evaluation.

III. IDF SELECTION FACTORS: HAZARD EVALUATION

EVALUATING INCREMENTAL INCREASE IN CONSEQUENCES DUE TO DAM FAILURE

The detail of study required to sufficiently define the impact of dam failure in order to select an appropriate IDF will vary with the extent of existing and potential downstream development, the size of the reservoir (depth and storage volume), and type and use of the dam. Evaluation of the areas impacted by a dam failure should proceed only until enough information has been gathered to reach a sound decision. In some cases, it may be apparent from a field inspection or an inspection of aerial photographs and topographic maps that loss of life and economic impacts caused by failure of the dam would be unacceptable. In other cases, detailed studies including dambreak analyses will be required.

The downstream consequences attributable to dam failure are determined based on the extent of downstream flooding with and without dam failure. This determination requires defining the flood profiles and flooded areas downstream from the dam for a given flood with and without dam failure.

Figure III-1 illustrates the incremental increase due to failure, and Figure III-2 illustrates the incremental area flooded by dam failure.

The area affected is the area inundated by the incremental increase in flooding levels caused by dam failure over flooding with the dam in place. Key elements in determining the area affected by a flood wave resulting from a theoretical dam breach are the height of the flood wave, the length and width of the river reach over which it will travel, and the travel time of the flood wave.

The key elements in determining the area affected by a flood are primarily a function of the . . .

- Channel and floodplain geometry and roughness,
- Channel slope,
- Hydraulic head at the dam,
- Volume of stored water and reservoir inflow, and
- Size, shape, and rate of the dam breach.

Also consider special cases where dam failure could cause domino-like failure of downstream dams.

When conducting dambreak studies, consider the incremental consequences of failure under both normal (full reservoir with normal streamflow conditions prevailing) and floodflow conditions up to the point where a dam failure would no longer significantly increase the threat to life or property. For each flood condition, determine water surface elevations with and without dam failure, flood wave travel times, and rates of rise. Since computations of dambreaks and flood routings are not precise, **your evaluation of the consequences of failure should be reasonably conservative.**

Continued . . .

III. IDF SELECTION FACTORS: HAZARD EVALUATION

EVALUATING INCREMENTAL INCREASE IN CONSEQUENCES DUE TO DAM FAILURE (Continued)

FIGURE III-1. ILLUSTRATION OF INCREMENTAL INCREASE DUE TO DAM FAILURE

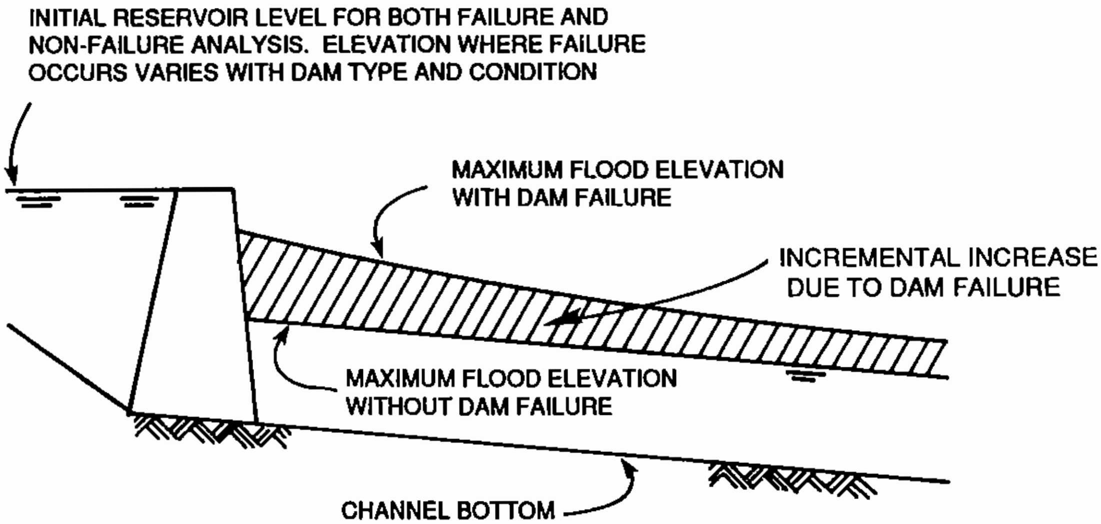
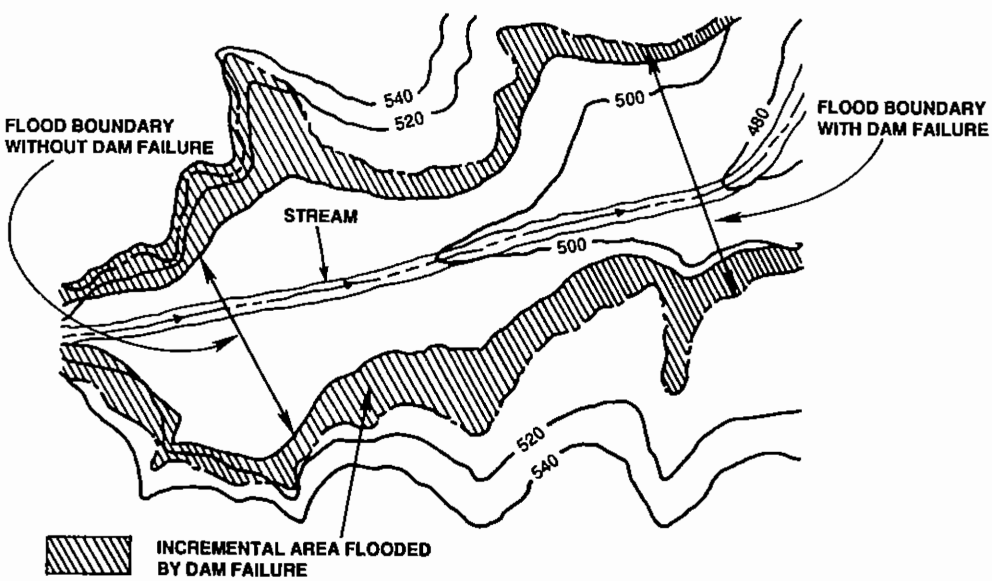


FIGURE III-2. ILLUSTRATION OF INCREMENTAL AREA FLOODED BY DAM FAILURE



III. IDF SELECTION FACTORS: HAZARD EVALUATION

EVALUATING INCREMENTAL INCREASE IN CONSEQUENCES DUE TO DAM FAILURE (Continued)

Start with the normal inflow condition and the reservoir at normal full reservoir level with normal streamflow conditions prevailing. That condition should be routed through the dam and downstream areas, with the assumption that the dam remains in place. The same flow should then be routed through the dam with the assumption that the dam fails.

The upper limit of flood magnitude to be considered in an IDF evaluation is the **probable maximum flood (PMF).** The flood wave for each condition should be routed downstream to the point where there is no longer a significant increase in flooding because of dam failure.

Determine the incremental increase in downstream water surface elevation between the with-failure and without-failure conditions (in other words, how much higher was the water downstream when the dam failed than when the dam did not fail?), and identify the amount of damage that could result. If the incremental rise in flood water downstream indicates an additional threat to downstream life and/or property, assess the need for remedial action.

To determine the greatest unacceptable threat to downstream life and/or property, identify the consequences of failure under incrementally larger inflow conditions to determine the appropriate IDF for the project. For each assumed flood inflow condition (which can be percentages of the PMF) . . .

- Assume the dam remains in place during the non-failure condition, and
- Assume the dam fails when the peak reservoir elevation is attained for the assumed inflow condition.

INUNDATION ASSOCIATED WITH DAM FAILURE

The next step is to hypothetically fail the dam under progressively greater floodflows (up to the PMF, if necessary), until a flood is identified such that a failure at that flow or larger flows will no longer pose an unacceptable threat to life and property in the event of a dam failure. The determination of what is unacceptable is based on an incremental analysis and on engineering judgment. This floodflow is then considered to be the appropriate IDF for the project. It is important to investigate the full range of floodflow conditions to verify that a failure under floodflows larger than the selected IDF up through the PMF will not result in any additional incremental increase in hazard.

There are many potential causes and modes of dam failure, depending on the type of structure and its foundation characteristics. There are also varied degrees of failure (partial to complete), and rates of failure (gradual to sudden). Determine the most likely mode of dam failure under the most adverse conditions and the resulting peak outflow at the time of the failure. The mode and degree of dam failure involves considerable uncertainty, so conservative failure hypotheses or sensitivity analyses of the breach parameters should be made.

Continued . . .

INUNDATION ASSOCIATED WITH DAM FAILURE (Continued)

Whenever dam failures are assumed, several factors should be evaluated. The type of dam and the mechanism that could cause failure require careful consideration if a realistic breach is to be assumed. Also, give special consideration to the . . .

- Size and shape of the breach,
- Time of breach formation,
- Hydraulic head, and
- Storage in the reservoir.

Most of the methods used for estimating dambreak hydrographs require a choice of size, shape, and the time from the dam breach to be input to the computations. Therefore, sensitivity analyses are considered necessary. Sensitivity analyses, varying flood inflow conditions and breach parameters, should be performed only to the extent necessary to make a decision.

Many Federal agencies have developed methods for determining dam failure hydrographs and for routing them downstream that are available upon request. These procedures may be obtained from the following agencies:

- National Weather Service (NWS)
- Bureau of Reclamation
- Soil Conservation Service
- Army Corps of Engineers
- Tennessee Valley Authority
- Geological Survey
- Federal Emergency Management Agency

The dambreak (DAMBRK) computer model developed by the NWS is the most widely used.

When routing a dambreak flood through the downstream reaches, consider appropriate local inflows in the computations. There are three methods that can be used to evaluate downstream concurrent inflows:

- Base concurrent inflows on historical records, if these records indicate that the tributaries contributing to the reservoir volume are characteristically in flood stage at the same time that flood inflows to the reservoir occur. Concurrent inflows based on historical records should be adjusted so they are compatible with the magnitude of the flood inflow computed for the dam under study.

- Use concurrent inflows developed during flood studies for downstream reaches when they are available. However, since these concurrent floods often represent inflows to a downstream reservoir, suitable adjustments must be made to properly distribute flows among the tributaries.

Continued . . .

INUNDATION ASSOCIATED WITH DAM FAILURE (Continued)

- Use the mean annual flood (approximately bankfull capacity) for the channel and tributaries downstream from the dam. The mean annual flood can be determined from flow frequency studies. As the distance downstream from the dam increases, engineering judgment may be required to adjust the concurrent inflows selected.

To avoid unnecessary study time and costs, terminate dambreak routings at a point where adequate real-time flood forecasting warning information can be provided. In general, the study should be terminated when the potential for loss of life and significant property damage caused by routing floodflows appears limited. This point could occur when . . .

- There are no habitable structures, and anticipated future development in the floodplain is limited,
- Floodflows are contained within a large downstream reservoir,
- Floodflows are confined within the downstream channel, or
- Floodflows enter a bay or ocean.

Inundation Mapping

It is important to prepare inundation maps showing the extent of flooding to downstream areas as a result of a dam failure. Inundation maps should show an outline of the area covered by the dambreak flood in enough detail to clearly identify the areas that would be flooded, as well as to identify dwellings and other significant features that are likely to be directly affected. Inundation maps are created by superimposing the flood outline on an existing map. Additional data included on the maps are estimated flood travel time and depth at selected locations. Clarity and simplicity are important.

Since local officials are likely to use inundation maps for evacuation purposes, a note should be included on the map to advise that, because of the method, procedures, and assumptions used to develop the flooded areas, the limits of flooding shown and flood wave travel times are approximate, and should be used only as a guideline for establishing evacuation zones. Actual areas inundated will depend on actual failure conditions and may differ from areas shown on the map.

Also develop water surface profiles and summary tables showing the elevations for the with and without dam failure condition, flood wave travel times, rates of rise, and locations of structures for the flood conditions investigated to supplement the information shown on the inundation map.

You can use the information on the maps, water surface profiles, and tables as tools for selecting the appropriate IDF.

III. IDF SELECTION FACTORS: PROBABLE MAXIMUM FLOOD (PMF)

INTRODUCTION

The flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in a particular drainage basin is known as the **probable maximum flood** (PMF). A deterministic approach is recommended to compute the PMF as opposed to a probabilistic methodology. A deterministic approach is used to generate a flood hydrograph by modeling the physical atmospheric and drainage basin hydraulic and hydrologic processes. The PMF methodology attempts to represent the most severe combination of critical meteorologic and hydrologic conditions considered reasonably possible for a given area or drainage basin.

MODELING THE PROBABLE MAXIMUM FLOOD (PMF)

In modeling the PMF phenomena, the most prominent features of the rainfall-runoff process are modeled separately and then combined to form the flood hydrograph. These features include the . . .

- Probable maximum precipitation (PMP),
- Antecedent and/or subsequent precipitation,
- Snowmelt,
- Infiltration and surface depression losses,
- Base flow,
- Interflow,
- Flood hydrograph determination, and
- Routing through upstream channels and reservoirs.

Make sure to give consideration to upstream releases and diversions into and out of the basin, as appropriate.

DETERMINING THE PROBABLE MAXIMUM FLOOD (PMF)

The PMF is developed by combining the appropriate sequences of meteorologic events (such as rainstorms and snowmelts). The appropriate sequence of meteorologic events for developing the appropriate PMF will vary, depending on the region and the season. Where snowmelt is not a consideration, the principal storm in combination with appropriate antecedent storms produces the PMF on the watershed. The occurrence of this sequence of events is called the PMF series, and is normally assumed because this series is typical of severe meteorological events in most regions.

The antecedent storm depths and time intervals between storms will vary with season, type of storm, and region. Where snowmelt contributes significantly to produce floodflows, the appropriate PMF may result from the PMP occurring on an appropriate snowpack, or precipitation falling on a probable maximum snowpack. On small watersheds, the PMF usually results from large summer thunderstorms that typically cover small areas, while on larger watersheds, more general spring or fall storms are normally most critical.

Continued . . .

III. IDF SELECTION FACTORS: PROBABLE MAXIMUM FLOOD (PMF)

DETERMINING THE PROBABLE MAXIMUM FLOOD (PMF) (Continued)

Any combination of rainfall and snowmelt events that are considered when developing the probable maximum condition should be meteorologically and hydrologically compatible with the definition of the PMF. The magnitude and timing of the antecedent event should be consistent with conditions that could reasonably occur. When appropriate, it is important to consider the effects of frozen ground on runoff, since this condition can greatly increase the runoff potential and the resulting floodflows.

Include releases from upstream reservoirs as part of the PMF inflow hydrographs. When storms serve as a basis for determining inflows, adopt the storm centering pattern that maximizes the inflow to the site being evaluated.

PROBABLE MAXIMUM PRECIPITATION (PMP)

Many hydrometeorological documents discuss the notion that the probable maximum precipitation (PMP) represents an upper limit to the level of precipitation the atmosphere can produce. At times, it is necessary to revise PMP estimates because of new or additional storm data, increased understanding of severe storm meteorology, or new developments in hydrometeorological techniques. Such revision requires the services of an experienced and qualified hydrometeorologist.

The commonly used approach in deterministic PMP development for non-orographic regions (regions that are flat or without mountains) is to determine observed storm and limiting surface dewpoint temperatures (used to obtain the moisture maximization factor) from a "sufficient" sample of extreme storms. The extreme storm samples are obtained through a method known as "storm transposition," which is the adjustment of maximum moisture for a storm at its actual site of occurrence to the corresponding maximum moisture level at the site for which the PMP is to be determined.

Storm transposition is based on the concept that all storms within a meteorologically homogeneous region could occur at any other location within that region as long as appropriate adjustments for the effects of topography and related moisture supply are made. The maximized transposed storm values are then enveloped both depth-durationally and depth-areally to obtain PMP estimates for a specific basin. By looking at different durations of PMP, you can ensure that the critical duration is selected.

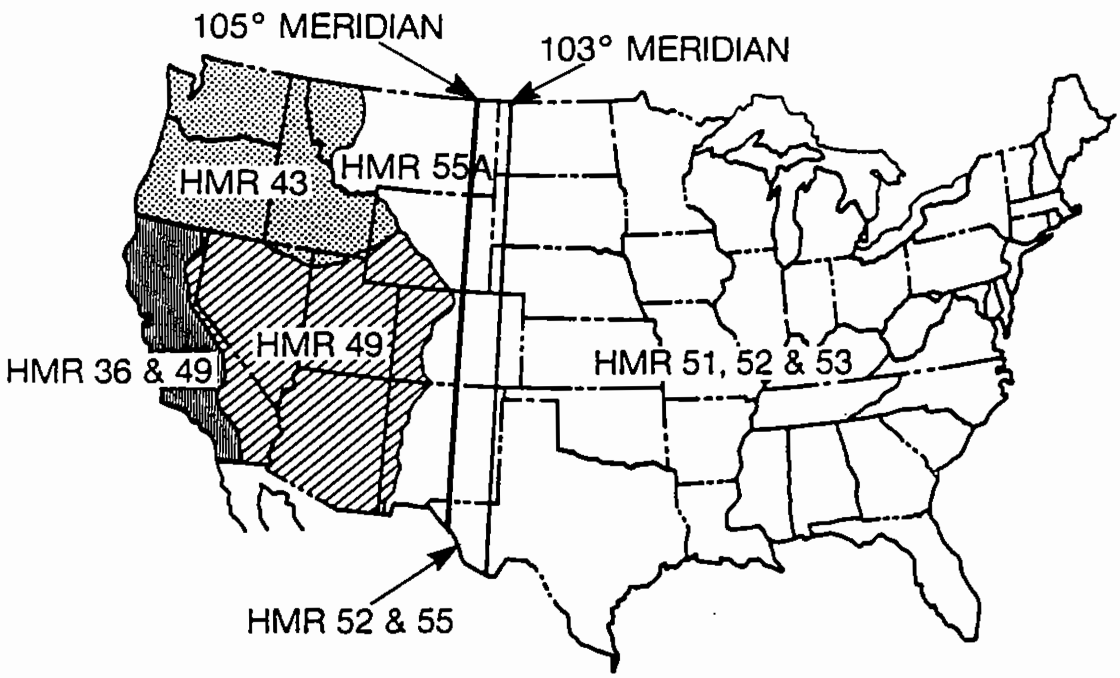
In orographic (mountainous) regions, where local influences affect the delineation of meteorological homogeneity, transposition is generally not appropriate. Alternative procedures are offered for those regions that are less reliant on the adequacy of the storm sample. Most of these procedures involve development of both non-orographic and orographic components of PMP (sometimes an orographic intensification factor is used). Orographic and non-orographic PMP's are then combined to obtain total PMP estimates for various durations for an orographic basin. To date, no single orographic procedure has been developed that may be used on a universal basis. These techniques have been discussed at length in various NWS reports. Currently, PMP estimates are available for the entire continental United States, as well as for Alaska, Hawaii, and Puerto Rico (see Figure III-3).

Continued . . .

III. IDF SELECTION FACTORS: PROBABLE MAXIMUM FLOOD (PMF)

PROBABLE MAXIMUM PRECIPITATION (PMP) (Continued)

FIGURE III-3. REGIONS COVERED BY GENERALIZED PMP STUDIES



HMR 39 HAWAII
HMR 54 SOUTHEAST ALASKA
TP 42 PUERTO RICO AND VIRGIN ISLANDS
TP 47 ALASKA

KEY

HMR = Hydrometeorological Report

TP = Technical Paper

Precipitation Losses

When computing the PMF, it is general practice to assume that an antecedent storm has already partially or completely satisfied the water loss due to interception, evaporation, surface depression losses, and interflow. These losses can then be eliminated from further consideration, **except** in areas that include geologic features such as glacial potholes, lava bases, and karst topography, where antecedent precipitation may not be enough to satisfy the losses.

Where geologic phenomena occur, such as underlying impervious strata overlaid by relatively coarse superficial material, the precipitation may infiltrate rapidly to the impervious strata and then flow horizontally as interflow to a defined watercourse. If the drainage network is sufficiently dense (a short subsurface flow distance to a defined watercourse) or the formation is extremely permeable (e.g., limestone), the contribution of interflow to the flood may be significant.

Interflow must be considered on a site-specific basis. In determining the appropriate infiltration rates for use in PMF determinations, it is generally assumed that antecedent storm events of sufficient magnitude have occurred to satisfy initial losses associated with the higher and steeper part of the infiltration curve, and to reduce infiltration rates to their ultimate long-term values. The estimated losses should be appropriate for the season.

Basin Runoff Modeling

The difference between the probable maximum storm rainfall and the infiltration rate is the excess precipitation. Use the excess precipitation to develop the PMF hydrograph representing surface runoff at the catchment concentration point. There are a number of techniques or models available for developing this flood hydrograph. The unit hydrograph technique is the basic tool used by most dam construction and regulatory agencies.

The **unit hydrograph** is the hydrograph that would result from one inch of direct runoff distributed uniformly over the basin and occurring at a constant rate over a specific unit time duration. The response to a storm of unit time duration, but non-unit depth, is the product of the unit hydrograph and the storm's precipitation excess. A complex storm can be represented as a sequence of unit-duration storm segments. The response to this storm is the sum of the sequence of corresponding individual storm-segment responses. A typical example is shown in Figure III-4.

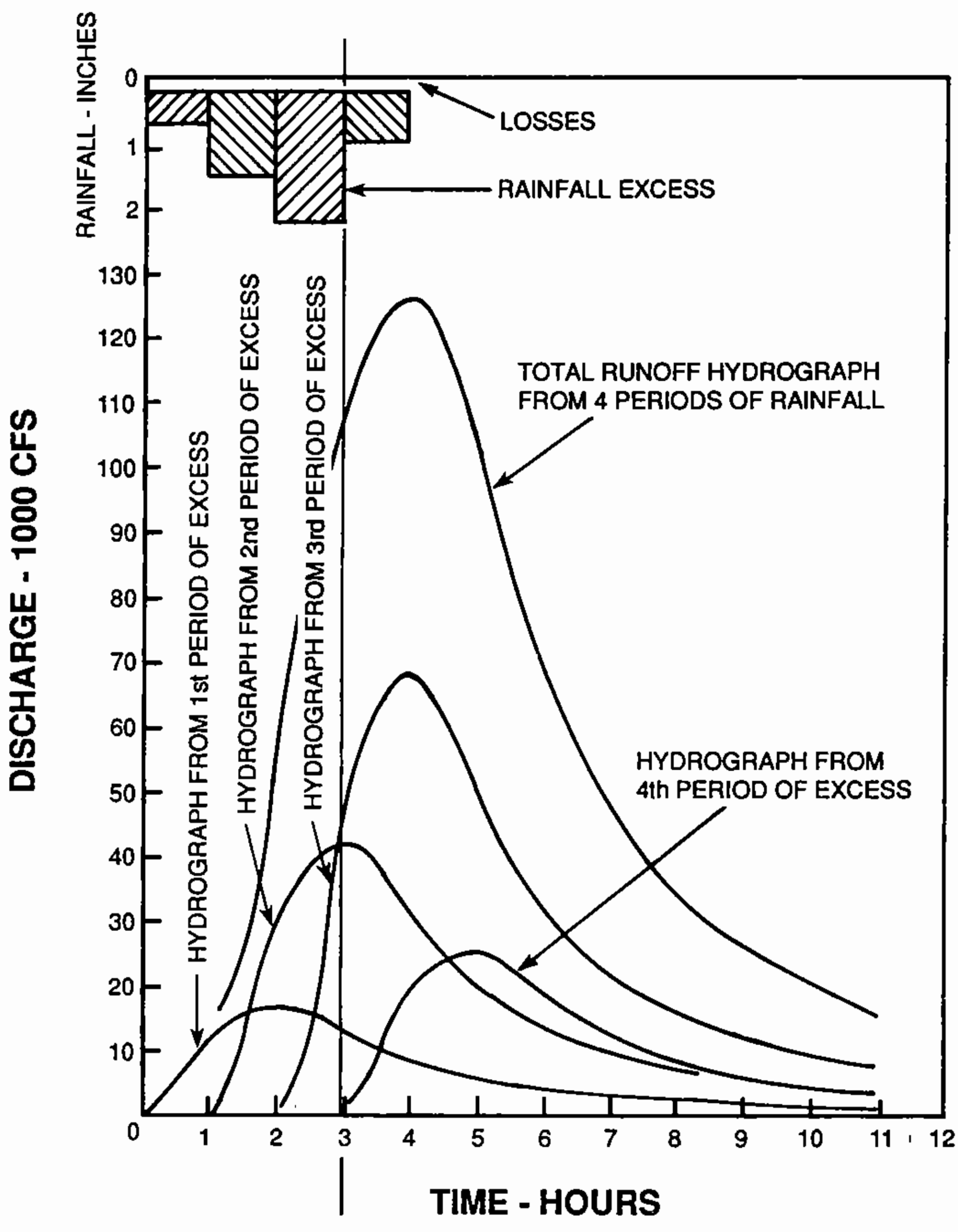
In some cases, you might find a stream gauge located at the basin's concentration point. Sometimes one or more significant flood events have been recorded at the gauge and associated storm rainfall data collected. If such is the case, you can develop an appropriate unit hydrograph by reconstituting the observed flood or flood events. Ensure that the underlying assumptions of unit hydrograph theory are closely met by the historic event, or errors in the PMF computations will occur. The PMF may then be determined by application of the unit hydrograph (based on observed data) to the precipitation excess, resulting from occurrence of the PMP over the basin.

Continued . . .

III. IDF SELECTION FACTORS: PROBABLE MAXIMUM FLOOD (PMF)

Basin Runoff Modeling (Continued)

FIGURE III-4. EXAMPLE OF A FLOOD HYDROGRAPH



Basin Runoff Modeling (Continued)

In many cases, however, no flood records will exist for the site being studied or within the same drainage basin, and a "synthetic unit hydrograph" must be developed. A "synthetic unit hydrograph" is a unit hydrograph generated for an ungauged drainage basin using an acceptable technique that generally makes use of relationships developed from unit graph studies of gauged areas relating unit graph parameters to physical features of the watershed. Fortunately, a large number of unit graph studies of actual floods presently exist. These studies have allowed the compilation of unit hydrographs for a wide variety of basins representing a diverse combination of geographic, climatic, topographic, and vegetative conditions.

A runoff model translates precipitation excess over a watershed into its resulting flood hydrograph. In order to accurately reflect the watershed's response to rainfall, subdivide large watersheds into homogeneous sub-areas on the basis of size, topography, drainage pattern, installed and proposed regulation facilities, land use, vegetative cover, soil type, and precipitation characteristics. The lag times and times of concentration should also be selected and evaluated for reasonableness. The sub-area flood hydrographs are combined by streamcourse modeling, and routed through the project reservoir.

Verify deterministic simulation models, including unit hydrographs, by comparing results of the simulation with historic floods of record for which suitable precipitation data are available. Use at least three of the largest floods of record for verification and any additional calibration of the model.

> **NOTE:** If a unit hydrograph has been derived from historic floods, it may be appropriate in some cases to increase the ordinates near the peak (preserving hydrograph volume) when applying it to the PMF. This adjustment compensates for the lack of nonlinearity inherent in the basin when extrapolating application of the unit hydrograph extreme magnitude events.

For ungauged basins, verify the adopted relationships between basin parameters and characteristics of the synthetic unit hydrograph by regional study. For example, you can develop synthetic coefficients from derived unit hydrographs for similar basins in the region under study which have similar characteristics.

There is no way to precisely verify a streamcourse model for the PMF condition. However, a model derived from valley cross sections and stage discharge relationships that have successfully reproduced historical events is a reasonable tool for use in estimating PMF conditions. Where appropriate, include releases from upstream reservoirs in the streamcourse model.

III. IDF SELECTION FACTORS: APPROPRIATE INFLOW DESIGN FLOOD (IDF)

INTRODUCTION

Selecting an appropriate IDF for the design of a dam requires consideration of the consequences of dam failure. Adopt the PMF as the IDF in those situations where the incremental consequences of dam failure during flood conditions less than the PMF are unacceptable.

IDF LESS THAN PMF

A flood less than the PMF may be adopted as the IDF in those situations where the incremental consequences of dam failure are acceptable. In such situations, usually detailed studies conclude that no significant increase in loss of life or property damage is created by failure under flood conditions exceeding the adopted IDF. Therefore, losses due to failure under floodflows exceeding the IDF will generally be limited to the dam owner's facilities. In these situations, define the IDF as the floodflow condition where a dam failure at that flood condition or larger floods up to the PMF would not significantly increase the threat to life and property beyond that occurring without dam failure.

Consider the consequences of failure acceptable when evaluation of the area affected shows one of the following conditions:

- There are **no** permanent human habitations, or commercial, industrial, or national security installations, nor are such developments projected to occur within the potential incremental dambreak floodplain in the foreseeable future, and the transient population is not expected to be endangered.

- There are **only a few** permanent human habitations within the potential hazard area that would be affected by failure of the dam, and there would be no significant incremental increase in the losses resulting from the occurrence of floods larger than the proposed IDF up to the PMF. (For example, where the impoundment storage is small and failure would not add appreciable volume to the outflow hydrograph, and, consequently, the downstream inundation would be essentially the same with or without failure of the dam.)

The consequences of dam failure may not be acceptable if the threat to these habitations is increased appreciably by the failure flood wave or level of inundation. When a dambreak analysis shows that downstream incremental increases in flooding due to failure are small, engineering judgment and additional analysis may be necessary to evaluate the need for remedial action. Sensitivity analyses are useful in making such judgments.

IDF FOR LOW HAZARD DAMS

The IDF for low hazard dams can be based on a percentage of the PMF or be determined by a flood frequency analysis. The magnitude of the IDF should provide adequate protection against the loss of benefits during the life of the project and should be consistent with acceptable economic risks to the owner of the dam. There is often the possibility that downstream development may increase over time and change the hazard classification. Consideration should be given to designing a dam having a low hazard potential for a flood frequency of at least 100 years.

Continued . . .

III. IDF SELECTION FACTORS: APPROPRIATE INFLOW DESIGN FLOOD (IDF)

IDF FOR LOW HAZARD DAMS (Continued)

Dams identified as having a low hazard potential should be designed to some minimum standard to . . .

- Protect against the risk of loss of benefits during the life of the project;
- Hold operation and maintenance costs to a reasonable level;
- Maintain public confidence in owners and agencies responsible for dam safety; and
- Be in compliance with local, State, or other regulations applicable to the facility.

IDF FOR SPECIAL CONSIDERATIONS

Dams that provide vital community services, such as municipal water supply or energy, may require protection against failure to ensure uninterrupted provision of those services (this should be investigated). For example, loss of water supply for domestic purposes may not be an acceptable public health risk in some cases. Dams in this category would need to be designed for the PMF. If the social and economic risk of losing such services is acceptable, the IDF can be less conservative.

III. IDF SELECTION FACTORS: RESERVOIR FLOOD ROUTING

INTRODUCTION

Use site-specific considerations to establish hydrologic flood routing criteria for each dam and reservoir. The criteria for routing the IDF or any other flood should be consistent with the reservoir regulation procedure that is to be followed in actual operation.

INITIAL RESERVOIR ELEVATION

Initial reservoir levels for routing runoff through reservoirs should be based on the hydrologic characteristics of the basin and project operational considerations. The assumed initial levels should be reasonable for the season when the PMF may occur and generally should be based on reservoir system regulation studies that reflect basin runoff conditions and releases for specific project purposes. In some cases, it may be necessary to examine seasonal variations in reservoir levels and the corresponding seasonal variations in rainfall to be sure that the appropriate reservoir levels for the IDF are determined.

Consider reservoir regulation rule curves and forecasting procedures established for the forecasted components of the IDF (usually only the snowmelt portion) when establishing initial reservoir elevations. Hydrologic characteristics and operation objectives will vary significantly from one reservoir or reservoir system to the next. General guidelines for establishing initial elevations should be based on one of the following three storage allocations:

- If there is no allocated or planned flood control storage (e.g., run-of-river), the flood routing usually begins with the reservoir at the normal maximum reservoir elevation. If regulation studies show that reservoir levels would either be higher or lower than the normal maximum reservoir elevation during the critical PMF season, analyze these studies to determine the appropriate initial reservoir level for routing the IDF.

- If a project has flood storage space allocated, the flood routing usually begins with the reservoir at the normal maximum reservoir elevation and an antecedent storm is included in the routing procedure. If an antecedent flood is not included in the routing, select a conservative initial reservoir level based on hydrologic considerations. In special cases, reservoir levels higher or lower than the normal maximum reservoir level may be selected when results of regulation studies clearly show such conditions would prevail during the critical IDF season.

- Joint-use storage is usually established as exclusive flood control storage during a specific time of year and as conservation storage during the remainder of the year. The flood routing usually begins with the reservoir at the bottom of the specifically allocated flood storage space (including joint use) or as determined from regulation studies.

III. IDF SELECTION FACTORS: RESERVOIR FLOOD ROUTING

RESERVOIR CONSTRAINTS

Flood routing criteria should recognize constraints that may dictate the maximum desirable or allowable water elevation. Prescribed maximum water surface elevations reached during routing of the IDF can be achieved by providing spillways and outlet works with adequate discharge capacity. Backwater effects in the reservoir must be considered when appropriate.

Reservoir constraints may include:

- Topographic limitations on reservoir storage that exceed the economic limits of dike construction.
- Public works around the reservoir rim that will not be relocated, such as water supply facilities and sewage treatment plants.
- Dwellings, factories, and other developments around the reservoir rim that will not be relocated.
- The possible loss of significant storage capacity caused by sediment accumulation in the reservoir; a factor to account for in routing the IDF. Deposition in reservoir headwater areas may build up a delta that can increase flooding in that area, as well as reduce flood storage capacity.
- Geologic features such as terrain that may become unstable when inundated and result in landslides that could threaten the safety of the dam or appurtenances, dwellings, factories, and/or other developments, or displace needed storage capacity.

RESERVOIR ROUTING REQUIREMENTS

Consider the following factors when establishing flood routing criteria:

- Operation requirements to meet project purposes;
- The need to provide a maximum permissible release rate to prevent flooding or erosion of downstream areas and control the rate of drawdown;
- The need to provide a minimum release rate to recover flood control storage for use in regulating subsequent floods; and
- The practicability of evacuating the reservoir for emergencies and for performing inspection, maintenance, and repair.

Continued . . .

RESERVOIR ROUTING REQUIREMENTS (Continued)

Spillways, outlet works, and penstocks for powerplants are sized to satisfy project requirements and must be operated in accordance with specified regulating instructions when the reservoir is within the allocated storage levels. Rely on these facilities to make flood releases subject to the following limitations:

- Only those release facilities that can be expected to operate reliably under the assumed flood condition should be assumed to be operational for flood routing. Reliability depends upon structural competence and availability for use, such as the reliability of trash racks, gates, etc. to hold or pass trash without blocking flow. Availability of a source of auxiliary power for gate operation, accessibility of controls, design limits on operating head, reliability of access roads, and availability of operating personnel at the site during flood events are factors to consider in determining whether to assume release facilities would be operational.

- A positive way of making releases to the natural watercourse by use of a bypass or wasteway must be available if canal outlets are to be considered available for making flood releases.

- A specific evaluation of expected flood conditions should be made before considering penstocks for powerplants available for making flood releases. Grounded transmission lines, loss of substations, and powerload interruptions could prevent operation of turbines.

- Bypass outlets for generating units may be used if they are or can be isolated from the turbines by gates or valves.

- In flood routing, regulated releases are generally limited to maximum values determined from:

    - Project uses,
    - Availability of outlet works,
    - Tailwater conditions including effects of downstream tributary inflows and wind tides, and
    - Downstream nondamaging discharge capacities until allocated storage elevations are exceeded.

- During normal flood routing, the rate of outflow from the reservoir should not exceed the rate of inflow until the maximum inflow exceeds the spillway discharge capacity, or until the maximum inflow has occurred. Also, the maximum rate of increase of outflow should not exceed the maximum rate of increase of inflow, to prevent outflow conditions from being more severe than predam conditions. An exception to the preceding would be the case where streamflow forecasts are available and high early flood releases could serve to reduce maximum flood releases.

III. IDF SELECTION FACTORS: FREEBOARD ALLOWANCES

INTRODUCTION

Freeboard provides a margin of safety against overtopping failure of dams. It is generally not necessary to prevent splashing or occasional overtopping of a dam by wind waves under extreme conditions. The number and duration of such occurrences, however, should not threaten the structural integrity of the dam, interfere with project operation, or create hazards to personnel.

Freeboard provided for concrete dams can be less conservative than for embankment dams because of their resistance to damage or erosion. If studies show concrete dams can withstand the PMF while overtopped without significant erosion of foundation or abutment material, then don't require freeboard for the PMF condition. However, special consideration may be required in cases where a powerplant is located near the toe of the dam.

WHAT IS FREEBOARD?

Normal freeboard is the difference in elevation between the top of the dam and the normal maximum reservoir elevation. **Minimum freeboard** is the difference in reservoir elevation between the top of the dam and the maximum reservoir water surface that would result from routing the IDF through the reservoir. **Intermediate freeboard** is the difference between intermediate storage level and the top of the dam. Intermediate freeboard may be applicable when there is exclusive flood control storage.

FREEBOARD GUIDELINES

The following are guidelines for determining appropriate freeboard allowances:

- Base freeboard allowances on site-specific conditions and type of dam (concrete or embankment).
- Evaluate both normal and minimum freeboard requirements when determining the elevation of the top of the dam, and adopt the resulting higher top of dam elevation for design.
- Base freeboard allowances for wind-wave action on the most reliable wind data available that are applicable to the site. The significant wave should be the minimum used in determining wave runup, and the sum of wind setup and wave runup should be used for determining requirements for this component of freeboard.

Continued . . .

III. IDF SELECTION FACTORS: FREEBOARD ALLOWANCES

FREEBOARD GUIDELINES (Continued)

- Computations of wind-generated wave height, setup, and runup should incorporate selection of a reasonable combined occurrence of reservoir level, wind velocity, wind direction, and wind durations based on site-specific studies.

  - It is highly unlikely that maximum winds will occur when the reservoir water surface is at its maximum elevation resulting from routing the IDF, because maximum levels generally persist only for relatively short periods of time (a few hours). Consequently, winds selected for computing wave heights should be appropriate for the short period the reservoir would reside at or near maximum levels.

  - Normal reservoir levels persist for long periods of time. Consequently, maximum winds should be used to compute wave heights.

- Apply freeboard allowances for settlement to account for consolidation of foundation and embankment materials when uncertainties exist in computational methods, or data used yield unreliable values for camber design. Freeboard allowance for settlement should not be applied where an accurate determination of settlement can be made and is included in the camber.

- Consider freeboard allowance for embankment dams for estimated earthquake-generated movement, resulting seiches, and permanent embankment displacements if a dam is located in an area with potential for intense seismic activity.

- Consider freeboard allowance for wave and volume displacement due to potential landslides that cannot be economically removed or stabilized if a reservoir is located in a topographic setting where the wave or higher water resulting from displacement may be destructive to the dam or may cause serious downstream damage.

- Total freeboard allowances should include only those components of freeboard that can reasonably occur simultaneously for a particular water surface elevation. Components of freeboard and combinations of those components which have a reasonable probability of simultaneous occurrence are listed in the following paragraphs for estimating minimum, normal, and intermediate freeboards. Establish the top of the dam to accommodate the most critical combination of water surface and freeboard components from the following combinations.

III. IDF SELECTION FACTORS: FREEBOARD ALLOWANCES

Minimum Freeboard

For minimum freeboard combinations, add the following components, when they can reasonably occur simultaneously, to determine the total minimum freeboard requirement:

- Wind-generated wave runup and setup for a wind appropriate for maximum reservoir stage for the IDF.
- Effects of possible malfunction of spillway and/or outlet works during routing of the IDF.
- Settlement of embankment and foundation not included in crest camber.
- Landslide-generated water waves and/or displacement of reservoir volume (only cases where landslides are triggered by the occurrence of higher water elevations and intense precipitation associated with the occurrence of the IDF).

Normal Freeboard

For normal freeboard combinations, use the most critical of the following two combinations of components for determining normal freeboard requirements:

- **Combination 1**

  (1) Wind-generated wave runup and setup for maximum wind, and

  (2) Settlement of embankment and foundation not included in camber.

- **Combination 2**

  (1) Landslide-generated water waves and/or displacement of reservoir volume,

  (2) Settlement of embankment and foundation not included in camber, and

  (3) Settlement of embankment and foundation or seiches as a result of the occurrence of the maximum credible earthquake.

Intermediate Freeboard

For intermediate freeboard combinations, in special cases, evaluate a combination of intermediate winds and water surface between normal and maximum levels to determine whether this condition is critical. This evaluation may apply where there are exclusive flood control storage allocations.

III. IDF SELECTION FACTORS: SUMMARY

SUMMARY: INFLOW DESIGN FLOOD (IDF) SELECTION FACTORS

Unit III discussed the specific factors to consider when determining the IDF for a particular dam. These factors are summarized below.

Hazard Evaluation

Evaluation of the impacts of dam failure must be based upon the dam being in place. The evaluation must include comparing the impacts of with-failure and without-failure conditions on existing as well as prospective developments. Conducting an incremental hazard evaluation involves . . .

- Determining the hazard potential
- Evaluating the impacts of dam failure
- Selecting a hazard classification
- Evaluating the incremental increase in consequences due to dam failure
- Evaluating inundation associated with dam failure

Probable Maximum Flood (PMF)

The PMF methodology attempts to represent the most severe combination of critical meteorologic and hydrologic conditions considered reasonably possible for a given area or drainage basin. Computing the PMF involves . . .

- Modeling the PMF
- Determining the PMF
- Determining the PMP by computing precipitation losses and basin runoff modeling

Appropriate Inflow Design Flood (IDF)

Selecting an appropriate IDF for the design of a dam requires consideration of the consequences of dam failure. The PMF should be adopted as the IDF in those situations where the incremental consequences of dam failure during flood conditions less than the PMF are unacceptable. Selecting the appropriate IDF involves evaluating . . .

- An IDF less than the PMF
- An IDF for low hazard dams
- An IDF for special considerations

Reservoir Flood Routing

Use site-specific considerations to establish hydrologic flood routing criteria for each dam and reservoir. These considerations include . . .

- The initial reservoir elevation
- Specific constraints of the reservoir
- Reservoir routing requirements

Continued . . .

III. IDF SELECTION FACTORS: SUMMARY

Freeboard Allowances

Freeboard is essentially the difference in elevation between the top of a dam and the reservoir elevation. Freeboard is categorized as normal, minimum, and intermediate. This unit provided guidelines for determining appropriate freeboard allowances.

UNIT IV

INFLOW DESIGN FLOOD (IDF) SELECTION PROCEDURES

IV. IDF SELECTION PROCEDURES: OVERVIEW

HOW IS THE IDF SELECTED?

The purpose of this unit is to describe the procedures used to select the appropriate inflow design flood (IDF) for a dam, and to determine the need for remedial action. These procedures are presented in two flowcharts. The first flowchart describes the steps needed to determine . . .

- If the probable maximum flood (PMF) was used in the original design of the dam,
- If the PMF or some lesser flood is the appropriate IDF, and,
- Whether remedial action at the dam is needed to enable it to safely accommodate the appropriate PMF and/or IDF.

In order to determine whether the PMF or some lesser flood is the appropriate IDF, it may be necessary to conduct an incremental hazard evaluation. This process is presented in the second flowchart.

Following each flowchart is a breakdown of the procedures. Each block is presented individually, and includes an explanation of the steps taken.

This unit identifies the need for remedial action; the actual types of remedial action are described in Unit V.

IV. IDF SELECTION PROCEDURES: DETERMINING THE APPROPRIATE IDF

INTRODUCTION

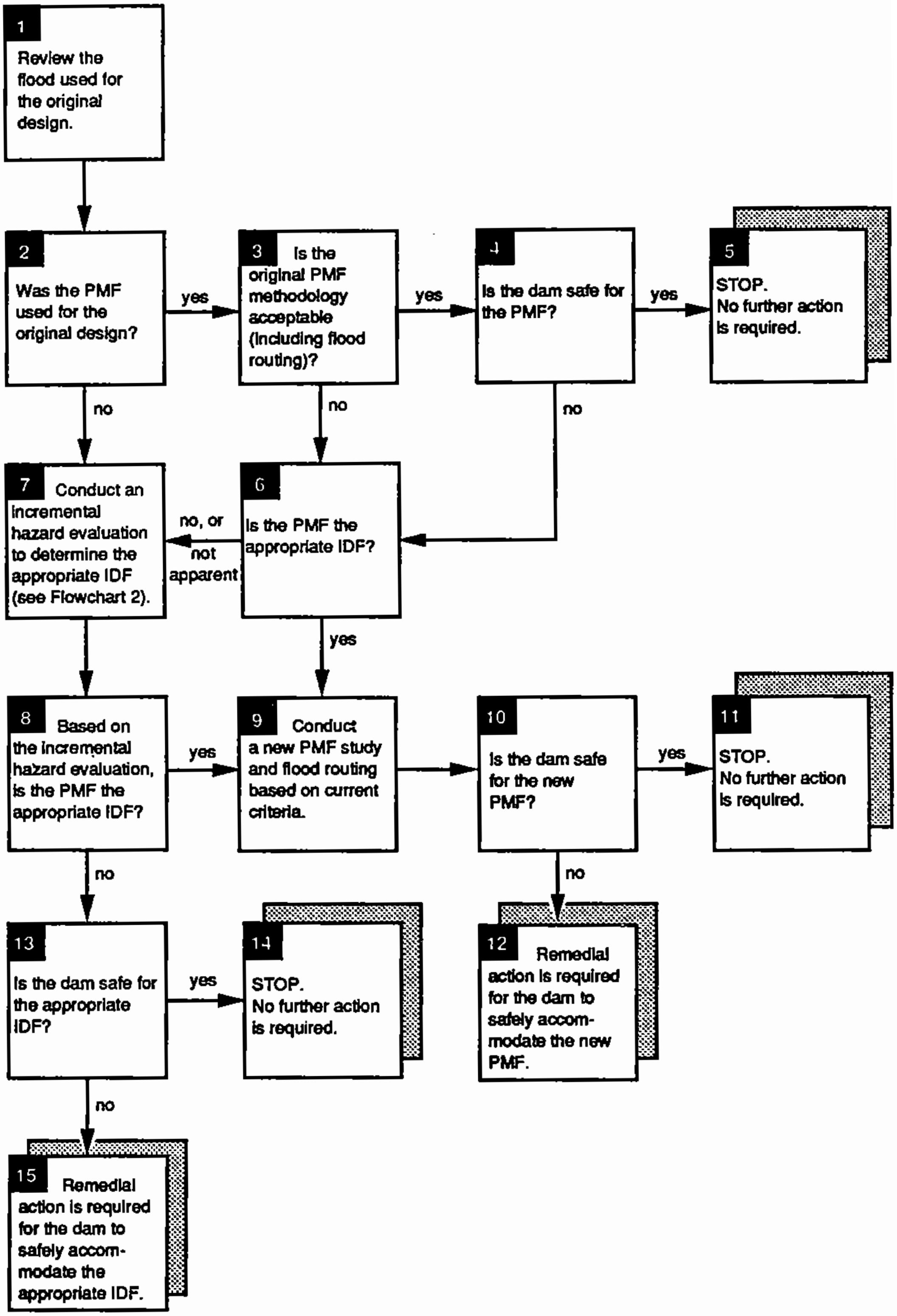
Based on the findings of a dam safety evaluation, the individual or agency responsible for the evaluation may request that further studies be conducted to determine whether a dam will safely pass flood flows during an extreme flood. Based on a review of available information, it may be necessary to conduct studies to determine the hydrologic safety of the dam. These studies should be conducted by an experienced and qualified engineer. The services of an experienced and qualified hydrometeorologist may also be required.

PROCEDURES FOR DETERMINING THE APPROPRIATE IDF AND THE NEED FOR REMEDIAL ACTION

Flowchart 1 in Figure IV-1 presents a logical, step-by-step approach for evaluating the hydrologic design of an existing dam, and determining the appropriate IDF for the dam and whether remedial action is needed in order for the dam to safely accommodate the IDF.

Now, review Flowchart 1 on the next page.

FIGURE IV-1. FLOWCHART 1--PROCEDURES FOR DETERMINING THE APPROPRIATE INFLOW DESIGN FLOOD (IDF) AND THE NEED FOR REMEDIAL ACTION



IV. IDF SELECTION PROCEDURES: DETERMINING THE APPROPRIATE IDF

EXPLANATION OF FLOWCHART 1

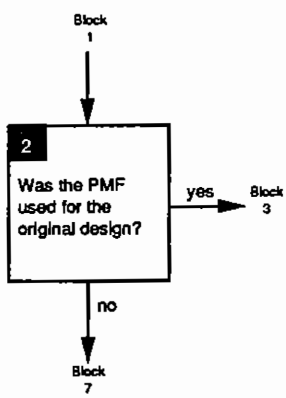
An explanation of the IDF flowchart is presented below.

Block 1

The initial step in selecting the appropriate IDF and determining the need for dam safety modification is to review the basis for the original hydrologic design of an existing dam. This information will provide valuable insight regarding whether the flood originally used for design purposes satisfies current criteria or whether detailed investigations and analyses will be required to determine the appropriate IDF for the dam.

In those situations where the original design information has been lost, detailed investigations and analyses will normally be required.

Block 2

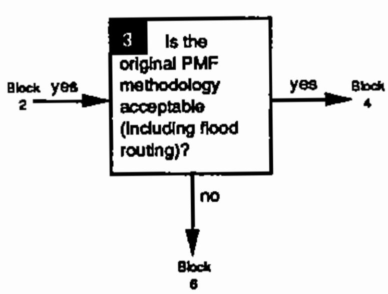


Once you have identified the basis for the original hydrologic design, the next step is to determine if the flood used for the original design is the probable maximum flood (PMF). This question is important, since the upper limit of the IDF is the PMF.

If your answer is **YES**, continue to Block 3.

If your answer is **NO**, go to Block 7. In Block 7 you will perform an incremental hazard evaluation to determine the appropriate IDF.

Block 3



To ensure the reliability of the original PMF study or the assumptions made on the various parameters affecting the study, it is necessary to determine if the PMF methodology originally used is still acceptable under current criteria.

If your answer is **YES**, continue to Block 4.

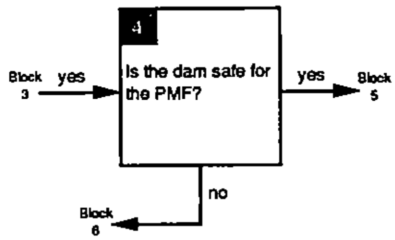
If your answer is **NO**, go to Block 6. In Block 6, you will answer the question: Is the PMF the appropriate IDF?

Continued . . .

IV. IDF SELECTION PROCEDURES: DETERMINING THE APPROPRIATE IDF

EXPLANATION OF FLOWCHART 1 (Continued)

Block 4

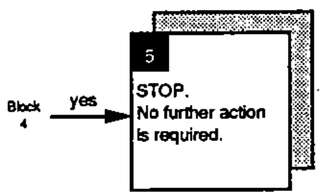


Determine if the dam is safe for the PMF. Your answer to this question will indicate whether remedial action will be required.

If your answer is **YES**, continue to Block 5.

If your answer is **NO**, go to Block 6. In Block 6, you will answer the question: Is the PMF the appropriate IDF?

Block 5



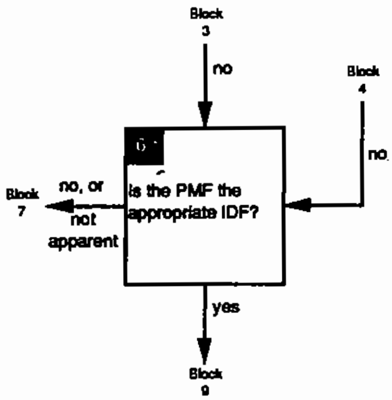
If the PMF is considered to be the appropriate IDF for the dam, no further investigations or remedial work for hydrologic conditions will be required.

Continued . . .

IV. IDF SELECTION PROCEDURES: DETERMINING THE APPROPRIATE IDF

EXPLANATION OF FLOWCHART 1 (Continued)

Block 6



IF . . .

In Block 3 you determined that the original PMF methodology is **NOT** acceptable,

OR . . .

In Block 4 you determined that the dam is **NOT** safe for the PMF,

THEN . . .

You need to determine if the PMF is the appropriate IDF.

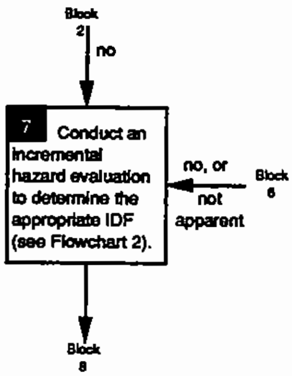
In some cases, such as when the dam is totally submerged during the PMF, it may be obvious that the appropriate IDF is something less than the PMF. In other cases, it will not be apparent whether the IDF should be the PMF or something less. In these two cases, it will be necessary to perform an incremental hazard evaluation to determine the appropriate IDF for the dam. Continue to Block 7.

Sometimes, based on the size and volume of the dam and reservoir, the proximity of the dam to downstream communities, or even because of political decisions, it will be obvious that the IDF should be the PMF. If this is the case, a new PMF study will be required. Go to Block 9.

Continued . . .

EXPLANATION OF FLOWCHART 1 (Continued)

Block 7



IF . . .

In Block 2 you determined that the flood used in the original design is **NOT** the PMF,

OR . . .

In Block 6, you determined that it is **obvious** that the IDF should be less than the PMF or it is **not apparent** if the IDF should be the PMF or something less,

THEN . . .

You need to perform an incremental hazard evaluation to determine the appropriate IDF. Performing the incremental hazard evaluation involves:

- Conducting dambreak sensitivity studies,
- Reviewing incremental rises between with-failure and without-failure conditions for a range of flood inflows (see Flowchart 2).
- Selecting the appropriate IDF on the basis of the dambreak studies and incremental impacts on downstream areas.

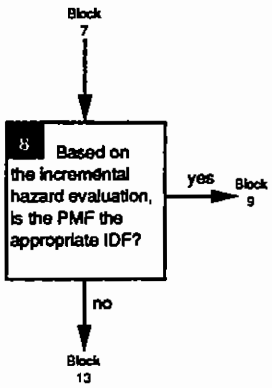
A procedural flowchart for performing a hazard evaluation appears in Flowchart 2 (Figure IV-2), followed by an explanation of the procedure.

Continued . . .

IV. IDF SELECTION PROCEDURES: DETERMINING THE APPROPRIATE IDF

EXPLANATION OF FLOWCHART 1 (Continued)

Block 8



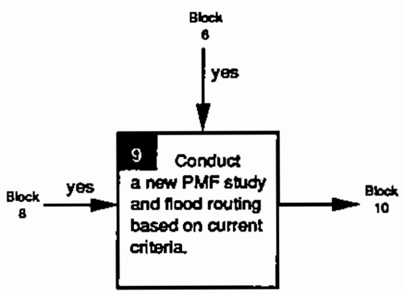
You should use the results of the incremental hazard evaluation and dambreak studies conducted in Block 7 to determine if the PMF is the appropriate IDF.

The IDF should be the PMF when the incremental consequences of failure are unacceptable, regardless of how large the assumed flood inflow becomes.

If your answer is **YES**, continue to Block 9.

If your answer is **NO**, go to Block 13. In Block 13 you will answer the question: Is the dam safe for the appropriate IDF?

Block 9



IF . . .

In Block 6 you determined that the PMF is obviously the appropriate IDF,

OR . . .

If, based on the incremental hazard evaluation conducted in Block 8, the PMF is the appropriate IDF,

THEN . . .

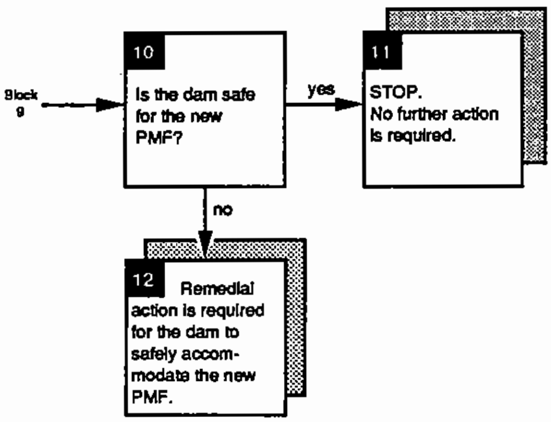
You should conduct a new PMF study and flood routing based on current criteria.

Continued . . .

IV. IDF SELECTION PROCEDURES: DETERMINING THE APPROPRIATE IDF

EXPLANATION OF FLOWCHART 1 (Continued)

Blocks 10, 11, And 12

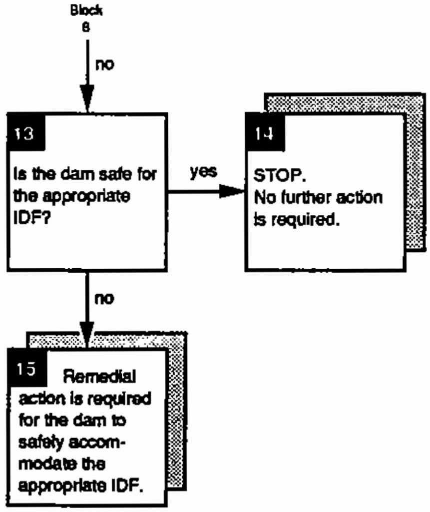


Once the new PMF is calculated, you should determine if the dam is safe for the new PMF.

If the dam is **SAFE** for the new PMF, no further investigations or remedial actions for hydrologic conditions are required.

If the dam is **NOT SAFE** for the new PMF, remedial action is required for the dam to safely accommodate the PMF. Remedial action, as described in Unit V, can be both structural and nonstructural.

Blocks 13, 14, And 15



IF . . .

In Block 8 you determined that the PMF is **NOT** the appropriate IDF,

THEN . . .

You need to determine if the dam is safe for the appropriate IDF.

If the dam is **SAFE** for the appropriate IDF, no further investigations or remedial action for hydrologic conditions are required.

If the dam is **NOT SAFE** for the appropriate IDF, remedial action is required for the dam to safely accommodate the appropriate IDF. Again, remedial action can be structural or nonstructural.

Depending on the type of remedial action considered, it may be necessary to reevaluate the IDF to ensure that the appropriate IDF has been selected for the design of any modification.

IV. IDF SELECTION PROCEDURES: PERFORMING A HAZARD EVALUATION

INTRODUCTION

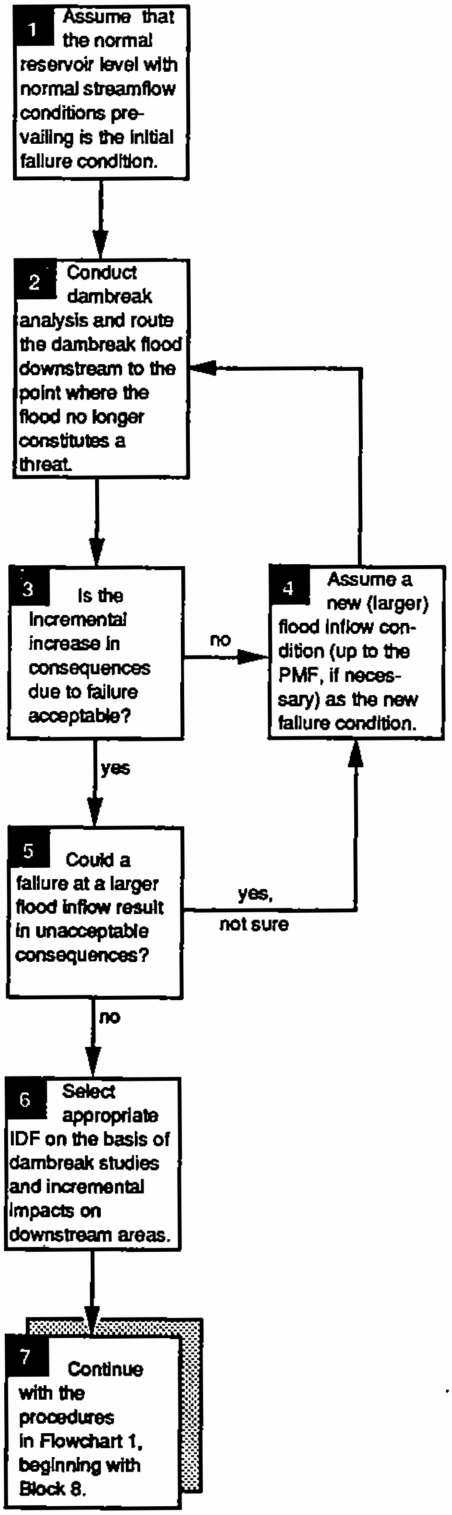
As stated previously, if the PMF was not used for the original design of a dam, or if the PMF is not the appropriate IDF, an incremental hazard evaluation must be performed to determine the appropriate IDF.

PROCEDURES FOR CONDUCTING AN INCREMENTAL HAZARD EVALUATION

Flowchart 2 in Figure IV-2 shows the procedures for performing an incremental hazard evaluation. This flowchart is an expansion of Block 7 in Flowchart 1, Figure IV-1.

Now, review Flowchart 2 on the next page.

FIGURE IV-2. FLOWCHART 2--PROCEDURES FOR CONDUCTING AN INCREMENTAL HAZARD EVALUATION

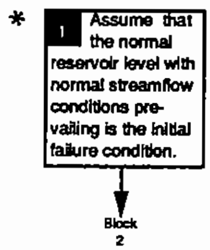


IV. IDF SELECTION PROCEDURES: PERFORMING A HAZARD EVALUATION

EXPLANATION OF FLOWCHART 2

An explanation of the Hazard Evaluation Flowchart is presented below.

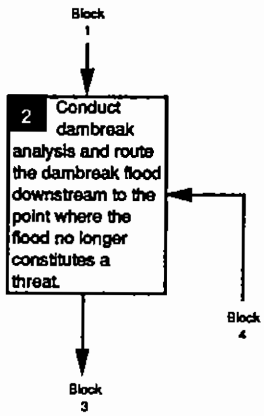
Block 1



Assume that the normal reservoir level with normal streamflow conditions prevailing is the initial failure condition. Starting at this point will ensure that the full range of flood inflow conditions will be investigated and will include the "sunny day" failure condition. It will also assist in verifying the initial hazard rating assigned to the dam. Using the normal maximum water surface level as the initial condition is particularly important if the initial hazard rating was low.

* Some agencies or organizations select a flood that just overtops the dam as the initial failure condition. If so, the steps presented in Blocks 2 through 7 are still the same, although the initial hazard rating assigned to the dam will not be verified.

Block 2



Next, conduct dambreak sensitivity studies (of various breach parameters) and route the dambreak flood to the point downstream where it no longer constitutes a threat to downstream life and property. The steps for performing an incremental hazard evaluation presented in Unit III of this module should be followed.

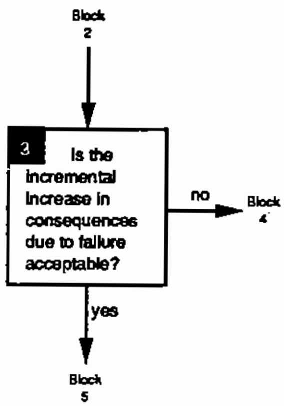
It is important to remember that the incremental increases should address the differences between the nonfailure condition with the dam remaining in place and the failure condition. Also, the dam should not be assumed to fail until the peak reservoir water surface elevation is attained for the assumed flood inflow condition being analyzed. Dams should be assumed to fail as described in Unit III.

Continued . . .

IV. IDF SELECTION PROCEDURES: PERFORMING A HAZARD EVALUATION

EXPLANATION OF FLOWCHART 2 (Continued)

Block 3

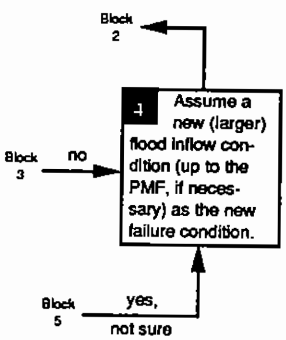


Now, determine if the additional increase in consequences due to failure is acceptable. Answering this question is critical in the incremental hazard evaluation, and doing so involves an estimate of loss of life and property with and without dam failure.

If the consequences of failure under the assumed floodflow conditions are **NOT ACCEPTABLE,** go to Block 4.

If the consequences of failure **ARE ACCEPTABLE,** continue to Block 5.

Block 4



IF . . .

In Block 3 it was determined that the consequences of failure under the assumed floodflow conditions are **NOT ACCEPTABLE,**

THEN . . .

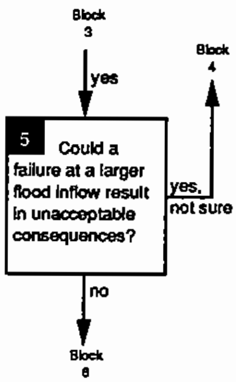
Assume a new (larger) flood inflow condition (e.g., some percentage of the PMF) and perform a new dambreak analysis (see Block 2). This procedure should be repeated until an acceptable level of flooding is identified, or the full PMF has been reached.

Continued . . .

IV. IDF SELECTION PROCEDURES: PERFORMING A HAZARD EVALUATION

EXPLANATION OF FLOWCHART 2 (Continued)

Block 5



IF . . .

In Block 3 you determined that the consequences of failure under the assumed floodflow conditions are **ACCEPTABLE;** i.e., failure of the dam under "sunny day" conditions was insignificant,

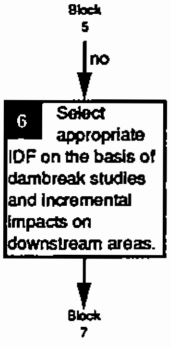
THEN . . .

Determine if failure at a larger flood inflow condition will result in unacceptable consequences. This question is very important. For example, situations exist where a failure during normal water surface conditions results in the flood wave being contained completely within the banks of a river and obviously would not cause a threat to life and property downstream. However, under some floodflow conditions, the natural river flows may go out-of-bank, and a failure on top of that flood condition will result in an additional threat to downstream life and property.

If failure at another flood level will result in **UNACCEPTABLE** consequences, or if you are **NOT SURE,** return to Block 4. Assume larger flood inflow conditions and perform new dambreak studies. This procedure should be repeated to determine the acceptable level of flooding.

If failure at another flood level will **NOT** result in unacceptable consequences, continue to Block 6.

Block 6



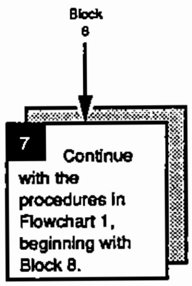
You should now select the appropriate IDF based on the results of dambreak studies and incremental impacts on downstream areas.

Continued . . .

IV. IDF SELECTION PROCEDURES: PERFORMING A HAZARD EVALUATION

EXPLANATION OF FLOWCHART 2 (Continued)

Block 7



Continue this process with the steps in Flowchart 1, Figure IV-1, starting with Block 8. In Block 8 you will answer the question: Based on the incremental hazard evaluation, is the PMF the appropriate IDF?

SUMMARY: INFLOW DESIGN FLOOD (IDF) SELECTION PROCEDURES

Unit IV described the procedures used to select the appropriate IDF for a dam and to determine the need for remedial action.

The steps involved to select the appropriate IDF for a dam were presented in Flowchart 1. If you determine that the PMF was used for the original design of the dam, and that the PMF is the appropriate IDF, further investigation or remedial action for hydrologic conditions is not necessary.

If you determine that the PMF was not used for the original design of the dam, or if the PMF was not the appropriate IDF, conduct an incremental hazard evaluation to determine the appropriate IDF. Flowchart 2 presented the procedures for conducting an incremental hazard evaluation.

Then, if it is determined that the dam is not safe for the new PMF or the appropriate IDF, remedial action must be taken.

UNIT V

REMEDIAL ACTION

V. REMEDIAL ACTION: OVERVIEW

REMEDIAL ACTION CONSIDERATIONS

Earlier units discussed what to consider when determining whether a dam, reservoir, and spillway have the capacity to safely accommodate the appropriate inflow design flood (IDF). This unit describes some of the remedial measures available when a project cannot accommodate the IDF.

During the recent emphasis on dam safety, it has become apparent that many dams are unsafe because of inadequate spillway capacity. Such projects must be considered unsafe because the reservoir and spillway, acting together, are not capable of safely accommodating the IDF. This situation creates a potential for dam failure, with the uncontrolled release of stored water in the event of failure endangering persons and properties downstream. When determining the effects of an inadequate spillway, consider the spillway, the dam, the reservoir, and the uses being made of the upstream and downstream areas. Taking an overall view of the situation will help you decide what remedial action must be taken.

Each dam that is hydrologically inadequate is a unique case. When trying to determine the appropriate remedial measure, you need to consider several aspects of the project, such as the . . .

- Nature of the site,
- Type and condition of the project,
- Benefits produced by the project,
- Mode of operation,
- Technical and financial resources available to the dam owner,
- Policies of the dam regulatory agencies, and
- Legal and moral responsibilities of the dam owner to those endangered in the event of failure.

It is not feasible to establish a list of alternative remedial measures and state under what circumstances a particular measure should be used; rather, the appropriate remedial action must be determined on a project-specific basis.

V. REMEDIAL ACTION: OVERVIEW

TYPES OF REMEDIAL ACTION

Most projects that are hydrologically inadequate would be endangered only during very rare flood events. Therefore, the most acceptable remedial action may involve operations (i.e., releasing extremely high floodflows, or sustaining damage) that could not be tolerated on a more frequent basis.

The approaches that have been used to address hydrologic inadequacy can be:

- **Structural.** Structural measures involve making some physical change to the dam, appurtenances, and/or reservoir. Structural measures are generally preferred because they provide the most effective long-term solution.

- **Nonstructural.** Nonstructural measures are generally changes to procedures. Some form of nonstructural measure may be implemented early on at limited cost while the ultimate solution is developed. However, situations do exist where either a combination of structural and nonstructural measures may be necessary, or entirely nonstructural measures may be satisfactory.

Some of the available structural and nonstructural measures are discussed on the following pages.

V. REMEDIAL ACTION: STRUCTURAL MEASURES

INTRODUCTION

Structural remedial measures involve making a physical change to the project. Some of the more common structural measures include . . .

- Increasing the discharge capacity
- Increasing the reservoir storage capacity
- Diverting runoff upstream of the dam
- Modifying the dam to permit overflow
- Removing the dam
- Changing other structural features, based on site-specific considerations

INCREASING DISCHARGE CAPACITY

Increasing discharge capacity is the most direct approach to solving the problem of inadequate spillway capacity, though it is not always feasible. The required spillway capacity may vary from the capacity to pass the peak of the IDF to only a fraction of the peak, depending on the balance between discharge capacity and temporary surcharge storage capacity. Some approaches to providing more spillway capacity include:

- Increasing the crest length of ungated spillways. Provided that the approach and exit channels are hydraulically sufficient, nonlinear (in plan) control sections such as a labyrinth may substantially increase discharge capacity.

- Adding bays to gated spillways.

- Lowering the crest of the existing spillway. If needed to maintain reservoir levels for project operation, gates or other measures can be considered.

- Improving the hydraulic efficiency of the existing spillway. At some projects, such measures as removal of land masses projecting into approach, exit, or downstream channels, removal of debris and deposits from such channels, or provision of guide walls or improved pier noses may add significantly to the discharge capacity of the spillway. Often, the last two or three spillway bays on each end of a spillway are less efficient or have less flow capacity than the other bays. Severe flow angle of approach can cause flow separations and flow drawdown along the piers of these spillway bays. In some cases the flow reductions are as much as 20 percent in each bay. With proper guide walls or with modified pier noses to guide the incoming flow, uniform flow distributions across the bay may be achieved. Another benefit could be the reduction of structural vibration and cavitation or erosion damage.

- Constructing a new spillway. This modification could involve reconstruction of a section of the dam to serve as an auxiliary or emergency spillway or locating a new spillway in an abutment area or away from the dam in a low saddle in the reservoir rim. A new remote saddle spillway could introduce new problems if it would discharge floodflows into areas or a stream that would otherwise have been unaffected by floodflows.

Continued . . .

INCREASING DISCHARGE CAPACITY (Continued)

- Providing a fuseplug levee or dike. A fuseplug levee or dike has a crest lower than the top of the dam, and is designed to wash out when overtopped, and act as an emergency spillway. However, fuseplugs should be considered only in those locations where the emergency discharge will not endanger the main dam or other important facilities. The operation of a fuseplug is like a dam failure--it must be planned such that it will not present a threat to life and property downstream. Stoplogs, flashboards, or other closure devices for spillway structures can provide the same type of emergency spillway capacity, but with better control of the spillway operation, if attended.

INCREASING RESERVOIR STORAGE CAPACITY

In some cases the problem of inadequate spillway capacity can be alleviated by making more reservoir storage available. Raising the top of the nonoverflow section of the dam, which provides storage above operating reservoir levels, can increase reservoir storage capacity. Also, increasing the height of a dam can effectively increase the flow capacity not only of the spillway, but also of the other flow conveyance structures.

Before such measures can be implemented, it is necessary to check whether the structures and geologic conditions downstream can withstand the additional energy of discharge without detrimental erosion, and whether an increase in reservoir stages would create problems with stability of other structures. Also, it is necessary to check whether raising the structure would create a problem in upstream channels or around the reservoir due to the increased water level. Increasing the effective height of dams can be accomplished by:

- Increasing the actual height of the dam. Concrete mass may be placed on top and on the downstream face of a masonry dam for height increases. For embankment sections, fill may be placed on the top and downstream slope of the embankment.

- Adding or increasing height of parapet walls on the upstream side of the dam. On a masonry dam, the upstream handrail may be removed and replaced by a solid concrete parapet of the same height or slightly higher. On an embankment dam, a concrete or masonry parapet could be used.

- Using flashboards on top of a concrete dam.

- Installing an inflatable dam similar to the "Faber" type on top of the dam. The inflatable dam is inflated by pumping water to fill the tubing.

- Increasing the height of a concrete dam by adding a concrete cap on top and installing posttensioned cables, tying old and new structures to the foundation.

- Driving steel sheet piles in certain types of embankment dams to increase height.

V. REMEDIAL ACTION: STRUCTURAL MEASURES

DIVERTING RUNOFF UPSTREAM FROM THE DAM

At some projects, it may be feasible to direct runoff from the reservoir or upstream from the reservoir to alleviate an inadequate spillway capacity. Usually such opportunities will be feasible only at impoundments in relatively flat terrain or at relatively small impoundments. The possible danger to others as well as the legal implications of diverting runoff from natural channels or out of the basin should be considered before adopting such a plan.

MODIFYING DAMS TO PERMIT OVERFLOW

For some existing dams, it is not physically or economically feasible to accommodate large floods by conventional means. For these situations consider low-cost, innovative solutions to allow overtopping without failure. The capabilities of embankment and concrete dams to withstand overtopping are very different, so the two types of dams are discussed separately.

Embankment Dams

Overtopping of embankment dams, with or without slope protection, has not been a popular solution for accommodating a portion of floodflows because of the potential for overflow erosion. While considerable guidance is available on designing for overtopping of rockfill dams, there still is a significant lack of knowledge about the resistance of various types of earth embankments to erosion from overtopping.

In the past several years, embankment overtopping protection has been used as a cost-effective alternative to the more traditional alternatives discussed in previous paragraphs. Erosion protection is provided on the crest, and at the abutments, downstream slope, and downstream toe of the dam, so that water can flow over the embankment without eroding and breaching it. Two types of embankment protection that have proven successful are discussed below.

- **Portland Cement Mixtures**

  Roller-compacted concrete (RCC) is a no-slump concrete with a normally low cement content. RCC may be made onsite, spread by earthmoving equipment, and compacted with vibratory rollers. RCC is effective in providing overflow protection for embankment dams up to about 50 feet in height. Studies are currently being carried out utilizing RCC for modification of embankment dams that have heights exceeding 200 feet. Designs for overtopping protection have normally consisted of horizontal lifts placed in a stairstep fashion on the downstream slope. Early dam restoration projects using RCC have shown it to be economical, quick to apply, and as reliable as more traditional modifications.

  Soil cement is a mixture of soil with small amounts of gravel, Portland cement, and water. In a hardened state, soil cement has the strength of lean concrete. It can prevent erosion from wave action along the upstream face of dams and along channel slopes. Research tests have shown that soil cement can be effective in preventing overflow erosion of embankments.

Continued . . .

Embankment Dams (Continued)

- **Cable-Tied Concrete Blocks**

  Cable-tied concrete blocks are gaining recognition in preventing overflow erosion of relatively low embankments where the depth and duration of overtopping are not excessive. Several patented systems are available, including Armorflex, Dycel, and Petraflex. Each system consists of precast open cell concrete blocks, which are joined together to form large, flexible mattresses that are linked by cables running through conduits in the blocks. The blocks are not generally solid, but contain some open area to dissipate hydrostatic pressure and allow grass to grow through the blocks.

  When used for overtopping protection, the individual mattresses are laid on the surface, tied together, and anchored in the embankment. The anchors typically consist of soil anchors that are driven or screwed into place and then connected to the cables. Tests performed in England have shown that such installations can withstand flow velocities of 26 ft/sec on a slope of 3H:1V. Key design considerations include: selection of cable and anchorage materials, whether cables are to be placed in one or two directions, use of a geotextile below the mattresses, and anchorage at the upstream edges. Materials should be selected to provide a working life that is appropriate for the life of the dam.

Concrete And Masonry Dams

It is generally accepted that concrete and masonry dams can withstand overflow if the increased loading does not endanger the stability of the structure, and if the overflow does not erode the abutments or foundation. However, damage to appurtenant structures such as outlet and hydropower works or their controls is another consideration.

The ability of concrete and masonry dams to resist overturning and sliding forces resulting from high reservoir stages and overflow can be improved by installation of posttensioned anchors through the dam into the foundation. Armoring abutments and the the foundation area at the toe can improve resistance to erosion at these critical locations. Buttressing of older concrete and masonry dams with RCC has recently been used to rehabilitate many of these structures.

REMOVING THE DAM

Removing the dam is usually considered only as a last resort. While failure is alleviated, project benefits are lost when a dam is removed. Also, the owner may be liable for any loss of life or any property damage that might occur downstream in the event flooding occurs because of dam removal. Environmental impacts must also be considered.

When a dam is removed, the site should be left in such a condition that there is no significant impediment to the free passage of flood waters.

V. REMEDIAL ACTION: NONSTRUCTURAL MEASURES

INTRODUCTION

Nonstructural remedial measures essentially involve procedural issues. Some of the more common nonstructural measures involve . . .

- Developing and implementing an enhanced Emergency Action Plan (EAP), perhaps with an automated warning system
- Modifying project operations
- Modifying the use of downstream areas
- Taking other steps, based on site-specific considerations

DEVELOPING ENHANCED EMERGENCY ACTION PLANS

EAP's should be prepared for any dam which, if it were to fail, would likely cause loss of life or extensive property damage. For dams that are hydrologically inadequate, EAP's must be enhanced because they must address specific actions in response to the known dam safety problem. A greater level of detail should be used in the preparation of EAP's when the potential for loss of life from a specific threat is known.

One means of enhancing an EAP is to combine it with a warning system. Rainfall, snowpack, streamflow, reservoir levels, and the dam itself can each be monitored as part of a warning system. The data can be transmitted by telephone lines, radio, or satellite to a location where they are immediately processed by computer. Such a system can provide valuable information on expected inflow and an early indication about when critical or emergency conditions are likely.

Early identification of emergency situations allows the initiation of efforts to prevent or delay dam failure, and provides additional time for issuing warnings to floodplain occupants. The ability to predict or detect dam failure early in the failure process can save many lives because widespread warning and evacuation can precede the actual dam failure. However, only a small reduction in property damage may be realized. In addition, an EAP must be continually maintained, updated, and tested if it is to remain effective, whereas a structural modification is a one-time action. Although this module points out the importance and need for prediction/detection systems or processes, the development and presentation of such information is beyond the scope of this module. (See the TADS module entitled How To Develop And Implement An Emergency Action Plan.)

MODIFYING PROJECT OPERATIONS

In some instances, it may be feasible to modify project operations to substantially increase the reservoir storage space that would be available to regulate the IDF. In considering such a plan, be sure to appraise the effect of the modified operations on project benefits, the effectiveness of the increased storage in alleviating spillway capacity problems, and the assurance that the storage would be available when needed.

V. REMEDIAL ACTION: NONSTRUCTURAL MEASURES

MODIFYING DOWNSTREAM AREAS

Seldom will it be feasible for the owner of an unsafe dam to reduce the hazard of dam failure by changing the uses of downstream areas, but this situation might arise if the dam and the downstream area have the same owner. Downstream damage potentials can often be greatly reduced by just a little forethought in developing downstream areas.

SUMMARY: REMEDIAL ACTION

Unit V described structural and nonstructural remedial action that can be taken to address the problem of hydrologic inadequacy of a dam.

Structural Measures

Structural measures involve making some physical change to the dam, appurtenances, or reservoir. The measures described in this unit were:

- Increasing the discharge capacity
- Increasing the reservoir storage capacity
- Diverting runoff upstream of the dam
- Modifying the dam to permit overflow
- Removing the dam

Nonstructural Measures

Nonstructural remedial action essentially involves procedural issues. Some of the more common nonstructural remedial measures include:

- Developing and implementing an enhanced Emergency Action Plan (EAP), perhaps with an automated warning system
- Modifying project operations
- Modifying the use of downstream areas

APPENDIX A

GLOSSARY

GLOSSARY

ANTECEDENT - Going before in time; prior; anterior; preceding. References to antecedent events in this module refer to all of those hydrometeorological events that precede or are likely to precede the particular event being discussed.

BREACH - An eroded opening through a dam that drains the reservoir. A controlled breach is a constructed opening. An uncontrolled breach is an unintentional opening that allows uncontrolled discharge from the reservoir.

CONTOUR INTERVAL - The vertical distance between the elevations represented by adjacent contour lines on a map.

DAM FAILURE - The catastrophic breakdown of a dam, characterized by the uncontrolled release of impounded water. There are varying degrees of failure.

DETERMINISTIC METHODOLOGY - A method in which the chance of occurrence of the variable involved is ignored and the method or model used is considered to follow a definite law of certainty, and not probability.

DEWPOINT TEMPERATURE - The temperature at which dew begins to form or vapor begins to condense into a liquid.

EMBANKMENT DAM - Any dam constructed of excavated natural materials (includes both earthfill and rockfill dams).

EMERGENCY ACTION PLAN (EAP) - A formal plan of procedures designed to minimize consequences to life and property in the event of an emergency at a dam.

EROSION - The wearing away of the earth's surface, as by floods, glaciers, waves, wind, or any other natural process.

FLASHBOARDS - Individual boards or panels supported by vertical pins or stanchions anchored to the spillway crest to increase storage.

FLOOD - A temporary rise in water levels resulting in inundation of areas not normally covered by water. Hypothetical floods may be expressed in terms of probability of exceedance per year such as one percent chance flood, or expressed as a fraction of the probable maximum flood or other reference flood.

FLOOD HYDROGRAPH - A graphical representation of the flood discharge with respect to time for a particular point on a stream or river.

FLOODPLAIN - The downstream area that would be inundated or otherwise affected by the failure of a dam or by large floodflows.

FLOOD PROFILE - Plot of water surface elevations versus stream location for a given discharge.

GLOSSARY

FLOOD ROUTING - The process of determining, progressively over time, the amplitude of a flood wave as it moves past a dam or downstream to successive points along a river or stream.

FLOOD STORAGE - The retention of water or delay of runoff either by planned operation, as in a reservoir, or by temporary filling of overflow areas, as in the progression of a flood wave through a natural stream channel.

FOUNDATION - The portion of the valley floor that underlies and supports the dam structure.

FREEBOARD - The vertical distance between a specified water level and the top of a dam or spillway crest.

FUSEPLUG - An embankment of erodible material placed across a spillway which is designed to fail in a controlled manner during rare, severe flooding when overtopping occurs.

GATE - A movable, watertight barrier for the control of water in a waterway.

HAZARD CLASSIFICATION - A rating (e.g., low, moderate, significant, or high hazard) that is representative of the probable loss of life and property damage downstream from a dam based on the results of breaching studies of the dam, and an identification of the area downstream that would be inundated.

HAZARD EVALUATION - An evaluation of a situation which creates the potential for adverse consequences such as loss of life, property damage, and adverse social and environmental impacts.

HYDROLOGY - One of the earth sciences that encompasses the occurrence, distribution, movement, and properties of the waters of the earth and their environmental relationships.

HYDROMETEOROLOGIST - An individual who specializes in hydrometeorology.

HYDROMETEOROLOGY - The study of the atmospheric and land-surface phases of the hydrologic cycle with emphasis on the interrelationships involved.

INFLOW DESIGN FLOOD (IDF) - The flood hydrograph used in the design of a dam and its appurtenant structures, particularly the spillway and outlet works, for determining maximum temporary storage and height of dam requirements. The IDF is the floodflow above which the incremental increase due to failure is no longer considered to present an unacceptable threat to downstream life and property.

INTAKE STRUCTURE - Placed at the beginning of an outlet works waterway, the intake structure establishes the ultimate drawdown level of the reservoir by the position and size of its opening(s) to the outlet works. Intake structures may be vertical or inclined towers, drop inlets, or submerged, box-shaped structures. Intake elevations are determined by the head needed for discharge capacity, storage reservation to allow for siltation, the required amount and rate of withdrawal, and the desired extreme drawdown level.

GLOSSARY

INUNDATE - To overflow; to move in waves; to flood.

INUNDATION MAP - A map showing areas that would be affected by flooding from an uncontrolled release of a dam's reservoir or passage of floodflows through the spillway.

KARST TOPOGRAPHY - A region characterized by distinctive features such as caverns, sinkholes, "lost" rivers, large springs, barren uplands and thin soils. Such topography usually exists in areas of limestone bedrock which has formed these features due to solutioning and weathering of the bedrock.

MANNINGS "N" VALUE - The coefficient of roughness in the Manning formula for open channel flow.

METEOROLOGY - The science that deals with the atmosphere and atmospheric phenomena; the study of weather and climate.

METEOROLOGICAL EVENT - The occurrence of any form of precipitation related to a hydrologic event.

METEOROLOGICAL HOMOGENEITY - Climates and orographic influences that are alike or similar.

NORMAL RESERVOIR LEVEL - The maximum elevation of the water surface in the reservoir under normal operating conditions.

OROGRAPHIC PRECIPITATION - Precipitation due to physical geography that pertains to mountains and to features directly connected with mountains.

PROBABLE MAXIMUM FLOOD (PMF) - The flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in the drainage basin under study.

PROBABLE MAXIMUM PRECIPITATION (PMP) - Theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location during a certain time of the year. Point values are generally accepted as representing average PMP over a few square miles (1 - 10). Areal values denote PMP averaged over a designated size storm area.

PROBABILISTIC METHODOLOGY - A method in which the time dependence and sequence of occurrence of the variables is ignored and the chance of their occurrence is assumed to follow a definite probability distribution in which the variables are considered purely random.

RESERVIOR REGULATION RULE CURVE - Refers to a compilation of operating criteria, guidelines, and specifications that govern the storage and release function of a reservoir. It may also be referred to as operating rules, flood control diagram, or water control schedule. These are usually expressed in the form of graphs and tabulations, supplemented by concise specifications. In general, they indicate limiting rates of reservoir releases required during various seasons of the year to meet all functional objectives of the project.

GLOSSARY

RESERVOIR RIM - The boundary of the reservoir including all areas along the valley sides above and below the water surface.

SEICHE - An oscillating wave in a reservoir caused by a landslide into the reservoir or earthquake-induced ground accelerations or fault offset.

SENSITIVITY ANALYSIS - An analysis in which the relative importance of one or more of the variables thought to have an influence on the phenomenon under consideration is determined.

SETTLEMENT - The vertical downward movement of a structure.

SLIDE - The unplanned descent (movement) of a mass of earth or rock down a slope.

SPILLWAY - A structure that passes normal and/or floodflows in a manner that protects the structural integrity of the dam.

STOPLOGS - Large logs, timbers, or steel beams placed on top of each other with their ends held in guides on each side of a channel or conduit to provide an inexpensive and easy means of closure.

STORM CENTERING - Location of the storm pattern such that the precipitation falls on a specific drainage basin to create the maximum runoff at the site under consideration.

STORM TRANSPOSITION - The application of a storm from its actual location of occurrence to some other area within the same region of meteorological homogeneity. Storm transposition requires the determination of whether the particular storm could have occurred in the area to which it is to be transposed.

SURCHARGE - The volume or space in a reservoir between the controlled retention water level and the maximum water level. Flood surcharge cannot be retained in the reservoir but will flow over the spillway until the controlled retention water level is reached.

SYNOPTIC - Seeing the whole together, from a general view (e.g., synoptic features of a storm).

SYNTHETIC UNIT HYDROGRAPH - A hydrograph with a volume of one inch of direct runoff resulting from a storm of a specified duration and areal distribution based upon physical features of the basin rather than directly from flow records of a gauged stream.

TOE OF DAM - The junction of the downstream slope or face of a dam with the ground surface; also referred to as the **downstream toe.** For an embankment dam, the junction of the upstream slope with the ground surface is called the **upstream toe.**

TOPOGRAPHIC MAP - A detailed graphic delineation (representation) of natural and man-made features of a region with particular emphasis on relative position and elevation.

TRIBUTARY - A stream that flows into a larger stream or body of water.

GLOSSARY

UNDERMINE - To erode away at the base or foundation; to undercut; to excavate ground from under, so as to form a tunnel or hole.

UNIT HYDROGRAPH - A hydrograph with a volume of one inch of direct runoff resulting from a storm of a specified duration and areal distribution. Hydrographs from other storms of the same duration and distribution are assumed to have the same time base but with ordinates of flow in proportion to the runoff volumes.

WATERSHED - The area drained by a river or river system.

APPENDIX B

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REFERENCES

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