Selecting and Accommodating Inflow Design Floods for Dams

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Preface

In September 2010, the Federal Emergency Management Agency's National Dam Safety Program sponsored development of this document under the supervision of James E. Demby, Jr., P.E. of FEMA[1].

During the initial phase of the study, research was completed regarding the history of the hydrologic design of dams as well as the current state of the practice. This effort included conducting a comprehensive survey of all state and federal dam safety agencies that own, regulate, and/or assist in the design or evaluation of dams and reviewing their current policies and guidelines. The findings of this research effort are summarized in FEMA P-919: *Summary of Existing Guidelines for Hydrologic Safety of Dams* (FEMA, 2012).

The main objectives of this document are to recommend appropriate procedures for selecting and accommodating the Inflow Design Flood for dams based on current and accepted practices and to promote a reasonable degree of consistency and uniformity among state and federal agencies. The wide variety of dams and watersheds require a variety of approaches that can achieve a reasonable balance of public protection, efficiency of evaluation, and efficiency of project operation.

The quality and scope of this document have been significantly improved by the efforts and knowledge of an independent Steering Committee composed of the following dam safety experts:

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In addition to the Steering Committee, this document has been reviewed by the Research Work Group, state and federal dam safety agencies, and the National Dam Safety Review Board.

The document *Guidelines for Selecting and Accommodating Inflow Design Floods for Dams* was last published in 2004 by FEMA. Some of the content in these updated guidelines was taken directly from the previous guidelines.

Readers of this document are cautioned to use sound engineering judgment when applying the guidelines herein. This publication is intended solely for use by professional personnel who are competent to evaluate the significance and limitations of the information provided herein, and who will accept total responsibility for the application of this information. Anyone making use of this information assumes all liability from such use.

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[2] Mr. Mahoney retired from FERC in October 2011. His involvement with the Steering Committee was limited to the initial research phase of the effort. Subsequent to Mr. Mahoney's retirement, Mr. Lin (also of FERC) was appointed to the Steering Committee.

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EXECUTIVE SUMMARY

The main objectives of these guidelines are to recommend appropriate procedures for selecting and accommodating the Inflow Design Flood based on current and accepted practices and to promote a reasonable degree of consistency and uniformity among state and federal agencies. Appropriate selection of the Inflow Design Flood is the first step in evaluating and designing a dam to address hydrologic potential failure modes and reduce risks to the public.

Existing guidelines of most state and federal agencies for evaluating the hydrologic safety of dams were written in the late 1970s. Since that time, significant technological and analytical advances have led to better watershed and rainfall information, improvements in the analysis of extreme floods, greater sophistication in means to quantify incremental dam failure consequences, and tools for evaluating hydrologic events in a risk-based context. Lead agencies and professionals in the nation's dam safety community recognize the need for updated guidelines for evaluating the hydrologic safety of dams and, in particular, for selecting an appropriate Inflow Design Flood.

This document is intended to provide a flexible framework within which both federal and state agencies can develop and update guidelines according to their varied goals and resources. The guidelines herein are not intended to be a mandate for uniformity nor provide a complete manual of all procedures available for estimating or accommodating Inflow Design Floods. The basic philosophy and principles are described in sufficient detail to promote common and/or compatible approaches among state and federal agencies in the design and evaluation of dams from the standpoint of hydrologic safety.

The guidelines include the following important recommendations to dam safety agencies and professionals:

1. It is recommended that Inflow Design Flood selection guidelines either be based on the estimated risks associated with hydrologic events, or the hazard potential classification system outlined in Table 1 of Section 2.2, "*Dam Classification System,*" and described in detail in FEMA's *Federal Guidelines for Dam Safety: Hazard Potential Classification System for Dams* (2004).

2. It is recommended that Inflow Design Flood selection guidelines using any classification system based on the size of a dam be discontinued.

3. Selection of an Inflow Design Flood for a new dam or a dam undergoing significant modifications should take into account both current conditions and reasonably anticipated future development. Development within the upstream watershed can cause increased runoff and peak flows, while development within the downstream inundation area can alter hazard potential classification and specific estimates of consequences of hydrologic events.

4. It is recommended that the practice of prescribing an Inflow Design Flood using arbitrarily selected composite criteria (i.e. prescribing an Inflow Design Flood by an equation that includes both a frequency event and some fraction of the probable maximum event) or percentages of hydrologic events (e.g. 50% Probable Maximum Flood) be discontinued.
5. The indiscriminate application of less stringent, prescriptive hydrologic design criteria for all existing, “grandfathered” dams should be discontinued.
6. When the cost of more detailed methods such as incremental consequence analysis, a site-specific probable maximum precipitation study, or risk-informed hydrologic hazard analysis is prohibitive, prescriptive Inflow Design Flood criteria for High, Significant, and Low Hazard dams are recommended as shown in Table 2 of Section 2.3.3, “*Inflow Design Flood Requirements Using a Prescriptive Approach.*”

In addition to Inflow Design Flood selection, the guidelines also address the accommodation of flood events up to and including the Inflow Design Flood. This includes the consideration of spillway type, flood routing design criteria, and freeboard criteria. Such criteria play a significant role in the hydrologic safety of a dam.

1. INTRODUCTION

1.1. Authorization

Existing guidelines of most state and federal agencies for evaluating the hydrologic safety of dams were written in the late 1970s. Since that time, significant technological and analytical advances have led to better watershed and rainfall information, improvements in the analysis of extreme floods, greater sophistication in means to quantify incremental dam failure consequences, and tools for evaluating hydrologic events in a risk-based context. Lead agencies and professionals in the nation's dam safety community recognize the need for updated guidelines for evaluating the hydrologic safety of dams and, in particular, for selecting an appropriate Inflow Design Flood (IDF). The IDF is the flood hydrograph entering a reservoir that is used to design and/or modify a specific dam and its appurtenant works; particularly for sizing the spillway and outlet works, and for evaluating maximum storage, height of dam, and freeboard requirements.

In September 2010, the Federal Emergency Management Agency (FEMA) authorized the development of this document as part of an effort titled: *Development of Guidelines for the Evaluation of Risk-Based Hydrologic Safety of Dams*. The objective of this effort was to develop and publish a guidance document for the evaluation of the hydrologic safety of dams, including guidelines for selecting the IDF for new and existing dams that could be applied nationwide.

1.2. Purpose and Scope

The engineering profession, dam owners, and others involved in dam safety continue to deliberate the appropriateness and applicability of hydrologic design criteria for dams. Meanwhile, several state and federal agencies have recently updated their dam safety regulations, including the sections relating to hydrologic safety. Despite these updates, dam classification systems and spillway capacity criteria remain inconsistent and non-uniform between the various federal and state agencies throughout the nation.

Some degree of non-uniformity between these agencies is expected and is, in fact, appropriate. The selection of procedures and design criteria is often dependent on variables such as the availability of hydrologic data, individual watershed characteristics, the likelihood of extreme hydrologic events in different locations, dam type and purpose, etc. Guidelines also differ according to agency type (e.g. state vs. federal), location and geography of the agency's jurisdiction, agency role (e.g. regulator, dam owner, designer), or available budget and staff. All of these factors contribute to the disparity of current guidelines.

In light of these expected differences, this document is intended to provide a flexible framework within which both federal and state agencies can develop and update guidelines according to their varied goals and resources. The guidelines herein are not intended to be a mandate for uniformity nor provide a complete manual of all procedures available for estimating or accommodating IDFs. The basic philosophy and principles are described in sufficient detail to promote a reasonable degree of consistency and uniformity among state and federal agencies in the design and evaluation of dams from the standpoint of hydrologic safety.

Over the past few decades, prescriptive hydrologic guidelines have been commonly accepted and used by both state and federal dam safety agencies. While this guidance document provides for such an approach, it also acknowledges the vast improvement in available precipitation, terrain, land use and census data, and in analysis tools that facilitate detailed consequence assessment and risk analysis in selecting an IDF. This document is not intended to either promote or discourage the use of newer methods such as incremental consequence analysis or risk assessment. It does, however, recognize that the cost of these advanced approaches may prove valuable in selecting an IDF which is more in alignment with the levels of risk generally accepted by society and ensure efficient use of available economic resources.

The main objectives of these guidelines are to recommend appropriate procedures for selecting and accommodating IDFs based on current and accepted practices and promote common and/or compatible approaches among state and federal agencies. Selection of the IDF is the first step in evaluating and designing a dam to address hydrologic potential failure modes and reduce risks to the public.

1.3. Hydrologic Safety of Dams

A well-designed, constructed, and operated dam can reduce flood risk in developed areas downstream by temporarily impounding flood waters and attenuating the observed peak flood flows in vulnerable low lying areas, even if the dam is not specifically designed for flood mitigation. However, impounding water behind a dam also creates risk to downstream areas because of the potential for an uncontrolled release of the reservoir pool caused by dam failure which could result in a peak flow discharge that greatly exceeds any possible natural flood event. There are several potential causes of dam failure including hydrologic, hydraulic, geologic, seismic, structural, mechanical, and operational. These guidelines consider only hydrologic failure modes and are limited to the selection of the IDF for the hydrologic design of a dam to reduce risks to the public. However, decisions to invest in risk reduction actions based on these guidelines should be made in the context of all risks at a dam to ensure that the proposed modifications are not providing a false sense of safety by not addressing other risks or failure modes which may be more likely.

One of the most common causes of dam failures is the inability to safely pass flood flows. Failures caused by hydrologic conditions can range from sudden failure, with complete breaching or collapse of the dam, to gradual failure, with progressive erosion and partial breaching. The most common potential failure modes associated with hydrologic conditions include overtopping erosion, erosion of spillways, internal erosion (seepage and piping) at high reservoir levels, and overstressing the structural components of the dam.

1.4. History of Design Flood Selection for Spillways

Although laws related to the performance of dams have existed since before 1700 BC (King, 1910), dam designs during the early period of dam building in the United States were based solely on the judgment of the design engineer. Estimates of flood potential were selected by empirical techniques and engineering judgment using high water marks or floods of record on streams. IDF selection began primarily as a practical concern for protection of a dam and the benefits it provides.

By about 1900, the field of surface water measurement had advanced enough to support the development of empirical equations to transpose maximum regional discharges to the drainage area of interest and predict peak flood discharges. At about the same time, several dams across the United States catastrophically failed including Mill River Dam (Massachusetts) in 1874, South Fork Dam (Pennsylvania) in1889, Walnut Grove Dam (Arizona) in 1890, Austin Dam (Pennsylvania) in 1911, and St. Francis Dam (California) in 1928. These failures led to an increase in social awareness prompting various legislative acts designed to protect the public from certain high risk activities.

Systematic nationwide collection of surface water data began in earnest by the U.S. Geologic Survey in 1934 when the New Deal Federal Public Works Administration obtained funds to perform detailed studies of floods, rainfall, and runoff. The 1930s and 1940s saw many significant advances in the science of hydrology including the innovation of the unit hydrograph which enabled the estimation of flood flows from storm rainfall.

Even with these improvements in flood estimation, regulatory guidelines and design standards for the hydrologic safety of dams prior to 1950 were still based mainly on judgment and experience. As of 1964, a fourth of the states exercised no supervision over dams at all, and a third exercised no responsibility over operation and maintenance of a dam once it was constructed. This same year, Franklin F. Snyder, Hydraulic Engineer with the U.S. Army Office of the Chief of Engineers (U.S. Army Corps of Engineers), published a proposed dam classification system that included recommended spillway design floods based on dam height, storage, and damage potential.

The 1950s and 1960s also saw the development of elegant theoretical and mathematical approaches to solve hydrologic problems. This, along with the subsequent advancement of computers to perform computationally demanding analyses, led to greater use of watershed modeling using unit hydrographs and precipitation. During this period, engineers turned to meteorologists to establish limiting rates of precipitation for design purposes. Between 1963 and 1999, a series of Hydrometeorological Reports (HMRs) were developed and updated by NOAA’s National Weather Service (NWS) to establish Probable Maximum Precipitation (PMP) estimates for the majority of the country (NOAA, 2011). Deterministic approaches to the hydrologic design of dams using these HMRs have been commonly accepted over the past few decades.

In the early 1970s, a series of dam failures including Buffalo Creek Dam (West Virginia) in February 1972 and Canyon Lake Dam (South Dakota) in June 1972 caused significant loss of life.

Following these events, Congress enacted the National Dam Inspection Act (PL 92-367) which became law on August 8, 1972. In the early 1970s, many states still did not have laws regarding dam safety and often did not require a review of dam design prior to construction, construction inspection, or post-construction inspection. Most states had inadequate dam safety programs with a wide variation of practices, regulations, and capabilities of the agencies supervising dam safety. The subsequent loss of human life from the failure of Teton Dam (Idaho) in 1976, Kelly Barnes Dam (Georgia) in 1977, and Laurel Run Dam (Pennsylvania) in 1977 provided significant impetus to implement the National Dam Inspection Act.

In an effort to coordinate the nation's dam safety efforts, Congress charged the U.S. Army Corps of Engineers (USACE) with implementing the provisions of PL 92-367. In addition to carrying out a national program of inspection of dams for the purpose of protecting human life and property, the act also required: (1) an inventory of all dams located in the United States; (2) a review of each inspection made; and (3) recommendations for a comprehensive national program for the inspection and regulation of dams, and the respective responsibilities which should be assumed by federal, state, and local governments, and by public and private interests. Because of the scale of the program, the USACE developed a classification system to screen the adequacy of spillway capacity. The selected dam classification system was similar to that proposed by Snyder in 1964. It was during the years following the enactment of PL 92-367 that many states formally adopted dam safety regulations for the first time.

As a result of the inspections authorized by Public Law 92-367 and carried out by the USACE from 1978 to 1981, many states adopted the provisional dam classification and spillway design criteria used in that inspection program. Other states adopted standards used by the Natural Resources Conservation Service (formerly the Soil Conservation Service) or other federal agencies, such as the Bureau of Reclamation. The establishment of spillway design criteria was further complicated by distinctive design criteria applied to existing versus new dams; by different temporal rainfall distribution and duration criteria; by diverse assumed initial watershed and reservoir conditions; and by dissimilar freeboard requirements.

In 1979, FEMA and the ad hoc Interagency Committee on Dam Safety issued *Federal Guidelines for Dam Safety*. This document provided the first national guidelines for federal agency dam owners and dam owners regulated by federal agencies. For flood selection design or evaluation, the federal guidelines supported the use of risk analysis. The guidelines were clear that the spillway design standard to be adopted for dams where loss of life or major property damage could occur was a design flood that has virtually no chance of being exceeded. Many interpreted this to be the Probable Maximum Flood (PMF). Some engineers, owners, and state regulators supported the PMF standard while others felt that although the PMF was easily calculated, it was not risk-based and ultimately diverted critical resources away from other potential failure modes that could be more likely to cause dam failure and life loss.

In 1986, FEMA published *Federal Guidelines for Selecting and Accommodating Inflow Design Floods for Dams* as a supplement to the *Federal Guidelines for Dam Safety*. The primary purpose of the document was to provide guidelines on procedures for selecting and accommodating IDFs for use by federal agencies in developing agency criteria and to foster nationwide consistency in application.

Several other guidance documents relating to the hydrologic safety of dams were published in the decades that followed by agencies such as FEMA, the American Society of Civil Engineers (ASCE), and the National Research Council. These documents included numerous recommendations supporting both deterministic and risk-informed approaches to spillway design. The guidance documents also identified several inconsistencies in the state-of-the-practice.

In the past two decades, there has been progress in developing and applying risk analysis to select the IDF. The U.S. Bureau of Reclamation appears to be the first agency to seriously apply a form of risk analysis in the evaluation of a dam's safety, including selecting the appropriate IDF. Beginning around 1995, the Bureau of Reclamation adopted risk-informed decision making as the primary framework for dam safety decision-making. In 1997, the USACE supplemented their IDF selection policy with an incremental procedure to provide a framework for evaluating the benefits of mitigating hazards presented by hydrologic deficiencies. The strict use of a prescriptive IDF standard was supplemented to provide an analysis of the benefits versus costs of design as compared to a lesser flood and recognition of the fact that a dam designed to pass the PMF does not result in zero risk (Eiker et al, 1998). The revised USACE policy was a step toward providing a risk-informed analysis of the benefits gained from mitigating the hazard while maintaining the traditional engineering standard of requiring a design that is capable of safely passing the prescriptive IDF. In 1998, FEMA published the initial version of *Selecting and Accommodating Inflow Design Floods for Dams* which permitted federal agencies to use incremental consequence analysis or other risk-informed analyses to select an appropriate IDF (FEMA, 2004).

The transition to risk-informed analyses is taking place in some states. Methodologies developed and adopted by California, Washington, and Montana are not the equivalent of formal risk analysis as used by the Bureau of Reclamation; they do, however, reflect a desire in those states to make site-specific, risk-informed dam safety decisions and designs.

Today, many professionals consider the formal risk analysis approach adopted by the lead federal agencies to be a useful way to evaluate dam safety because it requires dam owners to investigate potential failure modes and consequences in detail, identify the greatest risks, and explicitly consider uncertainties. The traditional standards-based approach remains popular among the majority of the state regulatory agencies. Deterministic standards typically take a conservative approach, are easy to understand, are relatively inexpensive to conduct evaluations, and are easier to communicate the state of jurisdictional dams relative to the standards. Risk-informed analyses require estimates of probabilities for extreme flood events that are based on limited available data and techniques that do not lend themselves to traditional statistical analysis used in hydrologic analysis. Risk analysis does, however, explicitly evaluate the degree of confidence in both the magnitude of the IDF and its probability of occurrence which is consistent with the federal guidelines urging the use of sound professional judgment. The greater effort required for risk-based methods is frequently justified to allow more integrated consideration of water resources management objectives and tradeoffs.

1.5. Current State-of-the-Practice

The current hydrologic guidelines vary widely from state to state and between federal agencies in many respects. Many of the state guidelines have not been updated since they were first adopted and are based on the provisional hydrologic guidelines established by the USACE to implement the National Dam Inspection Act between 1978 and 1981. In estimating the magnitude of the IDF, most states follow a prescriptive approach in which the design flood is specified based on the size and/or hazard classification of the dam.

Both probabilistic and deterministic criteria are prescribed by regulatory agencies. Probabilistic criteria are based on either floods or rainfall events which have specified probabilities or return periods (such as the 1% annual chance exceedance flood). Deterministic criteria are based on PMP estimates. These are typically derived from the HMRs which were developed by the NWS. Most of the HMRs use regional analyses of individual storm depth-area-duration rainfall patterns to evaluate spatial and temporal rainfall distributions with adjustments to account for orographic effects. Some of the HMRs include stippled regions which indicate areas where orographic effects have not been accounted for. PMP estimates developed using HMRs in conjunction with watershed models to compute flood runoff have been widely accepted over the past few decades as the basis for the evaluation and design of dams where failure of the structure cannot be tolerated.

At present, the use of composite criteria (i.e. prescribing an IDF by an equation that includes both a frequency event and some fraction of the probable maximum event) as well as specifying percentages of the PMP, PMF, or various frequency events is fairly common among both state and federal agencies, especially for significant hazard dams. In 1985, the National Research Council’s Committee on Safety Criteria for Dams questioned the use of composite criteria and percentages of various hydrologic events for selecting the IDF:

> “*The problem with such a criterion, based on an arbitrary percentage of a derived flood or an arbitrary combination of floods developed from differing concepts, is that it permits no direct evaluation of the relative degree of safety provided*” (NRC, 1985).

The issue was further expounded on in 1988 by the ASCE Task Committee on Spillway Design Flood Selection which stated,

> “*Studies by the NWS indicate that the occurrence of a storm producing PMP is not equally probable nationwide. Thus, using a fraction of the PMF results in selecting a safety design flood which varies widely in exceedance probability… As long as the PMF is used to define*

> *a probable upper limit to flooding for use in a safety design, this is not a major concern… When selecting a safety design flood less than the PMF, use of a fraction of the PMF produces a variation in exceedance probability that results in an inconsistent national safety standard*" (ASCE, 1988).

In order to apply consistent, safe hydrologic design standards across the nation, it is recommended that the practice of prescribing an IDF using arbitrarily selected composite criteria or percentages of hydrologic events be discontinued.

Additional variation is present in methodologies related to the transformation of a PMP to a PMF as well as in required freeboard and other IDF accommodation criteria. Of those agencies that have incorporated some form of risk-informed analysis in the selection of the IDF, the accepted risk tolerances and risk analysis methodologies also differ.

Recent and ongoing technical advances are improving the assessment of the likelihood of extreme hydrologic events as well as the prediction of the characteristics of hydrologic events and potential dam failure consequences. These include improved computer models to simulate watershed runoff and dam failure flood waves; increased availability of high resolution terrain, census, and land use data; improved understanding of rare hydrologic events; consideration of geologic evidence of ancient flood events; and site-specific PMP studies. These advances provide engineers with the ability to perform sophisticated evaluations of dam designs to more precisely evaluate risks associated with hydrologic events through better understanding of hydrologic events, potential hydrologic failure modes, and the consequences of a dam failure. When warranted, engineers can perform additional investigations using advanced analytical tools and methods to more precisely evaluate incremental consequences and dam failure probabilities. This information can be used to select an IDF that reduces risk to the public without spending limited resources on conservative designs that result in marginal reduction of flood risk.

2. INFLOW DESIGN FLOOD SELECTION

2.1. General

Over 88,000 dams have been constructed in the United States, and new dams continue to be added to this total. Additionally, new development downstream of existing dams, a phenomenon referred to as risk creep (also commonly called hazard creep), is resulting in increased potential consequences that would occur if a dam were to fail. This evolution can result in the reclassification of many dams to a higher hazard category which requires greater spillway capacity and/or reservoir storage volume, often at substantial cost to the dam owner. As a result, the design of dams to withstand natural forces, including extreme hydrologic events, is an increasingly important matter of public safety and concern.

In any design scenario, it is important to consider the full range of hydrologic events to which a dam will be subjected. When contemplating modifications to a dam to increase the conveyance capacity to pass extreme hydrologic events, some modifications, like widening the spillway or lowering the crest of the spillway, may actually increase the risk to the downstream public by increasing the spillway flows during hydrologic events that are more likely to occur. Other modifications, like raising the dam to increase spillway capacity, can increase the downstream consequences should the dam fail during an extreme flood event by creating a larger dam breach flood wave. The goal of selecting the IDF should be to balance the risks of a hydrologic failure of a dam with the potential downstream consequences and the benefits derived from the dam.

Selection of an IDF can involve tradeoffs in trying to satisfy multiple objectives including:

1. Providing acceptable safety to the public.
2. Effectively applying the resources of the dam owner.
3. Maintaining the credibility of the regulator in representing the interest of the public.
4. Assessing the desire of the public for the benefits of a dam in exchange for the inherent risks that come from living downstream of a dam.

No single approach to the selection of an IDF is adequate for the unique situations of thousands of existing or planned dams. The following alternative approaches to defining the IDF are recommended to accommodate the wide variety of situations, available resources, and conditions which might be encountered in practice:

> ***Prescriptive Approach*** – In this initial phase, a planned dam is designed or an existing dam is evaluated for a prescribed standard based on the hazard potential classification of the dam. This approach is intended to be conservative to allow for efficiency of resource utilization while providing reasonable assurance of the safety of the public. It is not intended to assure that there is an economical marginal benefit from designing for a conservative IDF.

Site-specific PMP Studies (Refinement of the Prescriptive Approach) – The prescriptive approach relies upon determination of a PMF for high hazard dams which requires assessment of the PMP. The most common sources of the PMP information are the regional HMRs published by the NWS. These reports provide generalized rainfall values that are not basin-specific and tend to represent the largest PMP values across broad regions. Most of these reports have not been updated to reflect current state-of-the-art knowledge and technology. A site specific study of the PMP/PMF using current techniques can result in a more appropriate estimate of the PMF for consideration as the IDF.

Incremental Consequence Analysis – The volume of many reservoirs may be small in comparison to the volume of the hydrologic events to which they may be subjected. In these cases, the IDF can be established by identifying the flood for which the downstream consequences with and without failure are not significantly different.

Risk-informed Decision Making – This method allows a dam owner or regulator to consider the risk associated with hydrologic performance of dams relative to other dam safety risks at the same dam, across a portfolio of dams, or in comparison to societal risks in general. In this method, the IDF is selected as the design flood which assures that a given level of "tolerable risk" is not exceeded. The strengths of this method include providing dam owners and regulators the ability to assess the marginal value of increasing levels of flood protection, balancing capital investment in risk reduction across a number of different failure modes, and prioritizing risk reduction actions across a portfolio of dams.

2.2. Dam Classification System

All state and federal agencies use some type of dam classification system to categorize dams according to the probable damages or adverse consequences caused by a dam failure. Under a prescriptive approach, the IDF is often specified based solely on the dam classification system. Given the limited resources of many states and federal agencies and the fact that they have hundreds or thousands of dams under their jurisdictions, use of a generalized dam classification system based on hazard to select the IDF is both practical and reasonable.

Significant variations of dam classification systems exist among state and federal dam safety agencies. Despite these differences, it is apparent that each system attempts to classify dams according to the potential impacts that would result from a dam failure. One significant problem with these various systems is the use of terms that lack clear definition (e.g. "will cause loss of life," "may cause loss of life"). The various dam classification systems also use different terminology to define similar concepts (e.g. "Significant Hazard," "Moderate Hazard," "Class II," "Class B"). This hinders consistency and communication between the various federal and state agencies and understanding by the public. **More consistent use of the existing hazard potential classification system is therefore recommended to support consistent application of IDF selection guidelines.**

FEMA's *Federal Guidelines for Dam Safety: Hazard Potential Classification System for Dams* (2004) was developed to address inconsistencies between the various federal and state agencies and provide recommended guidelines regarding the hazard classification of dams. This hazard potential classification system for dams is simple, clear, concise, and adaptable to any agency's current system. The intent of this classification system is to provide straightforward definitions that can be applied consistently and uniformly by all federal and state dam safety agencies and can be readily understood by the public.

It should be understood that the "hazard potential" is the possible adverse incremental consequences that result from the release of water or stored contents due to failure or misoperation of the dam. Incremental consequences are defined as the impacts that would occur due to failure or misoperation of the dam over those that would have occurred without failure or misoperation of the dam. The hazard potential assigned to a dam is based on consideration of the incremental adverse effects of failure during both normal and flood flow conditions. Hazard potential does not indicate the structural integrity of the dam itself, but rather the consequences should dam failure occur.

The three qualitative hazard potential classes of dams identified in *Federal Guidelines for Dam Safety: Hazard Potential Classification System for Dams* are:

1. **HIGH HAZARD POTENTIAL:** Dams assigned the high hazard potential classification are those where failure or misoperation will probably cause loss of human life.
2. **SIGNIFICANT HAZARD POTENTIAL**: Dams assigned the significant hazard potential classification are those dams for which failure or misoperation results in no probable loss of human life but can cause economic loss, environmental damage, disruption of lifeline facilities, or can impact other concerns. Significant hazard potential dams are often located in predominantly rural or agricultural areas but could be located in areas with population and significant infrastructure.
3. **LOW HAZARD POTENTIAL:** Dams assigned the low hazard potential classification are those dams for which failure or misoperation results in no probable loss of human life and low economic and/or environmental losses. Losses are principally limited to the dam owner's property.

These hazard potential classes are also summarized in Table 1.

Table 1 Recommended Dam Classification System Based on Hazard Potential

Hazard Potential Classification	Loss of Human Life	Economic Loss, Environmental Loss, and/or Disruption of Lifeline Facilities
High	Probable (one or more expected)	Yes (but not necessary for this classification)
Significant	None expected	Yes
Low	None expected	Low and generally limited to owner

This dam classification system is recommended to be used with the understanding that the failure of any dam, no matter how small, could represent a danger to downstream life and property. **It is recommended that the hazard potential classification system be used as the basis for IDF selection guidelines and that use of any classification system based on the size (height or storage volume) of a dam for IDF selection be discontinued.** The size of a dam has historically been used as a simplified indicator for estimating hazard potential because of the unavailability of data or inability to conduct more detailed analyses. It is recognized that size classification has been helpful in reducing the number of dams impacted by risk or hazard creep; however, a formal assessment of future development should also be sufficient to select an appropriate level of design while limiting the potential for risk creep. Data and analytical approaches are now available that are economical to perform and provide a more precise assessment of the hazard potential. By using a classification system that is based on the size of the dam, a small dam located in a heavily populated area may in fact be subject to less stringent requirements than a very large dam in a remote, undeveloped location or a location where downstream development is not likely. Therefore, dam size is not always indicative of potential consequences due to failure and should not be the basis for evaluating hydrologic design requirements.

It is also recognized that any quick release of water whether controlled or uncontrolled can result in loss of life. In assessing hazard potential, the likelihood of “loss of human life” should be evaluated using dam failure analysis results and sound engineering judgment. Such judgments can be significantly aided by depth-velocity flood lethality relationships.

2.3. Guidelines for Selecting the Inflow Design Flood

The guidelines presented herein are intended to provide a balance between the objectives mentioned in Section 2.1. Where that balance is relatively obvious, a simple and efficient prescriptive approach based on the hazard potential classification may suffice. For dams for which there are significant tradeoffs between the potential consequences of failure and the cost of designing to the recommended prescriptive standard, the guidelines provide alternatives for more rigorous and detailed analytical investigations to evaluate the potential for selecting a lower IDF while reducing risks to the public. In other words, an alternative to the simplified prescriptive approach is appropriate where an investment in more precisely understanding the tradeoffs in selection of an IDF can result in better use of resources. Advanced methodologies such as site-specific PMP studies, incremental consequence analysis, or risk-informed hydrologic hazards analysis are described in Sections 2.3.4 thru 2.3.6 and should be used at the discretion and judgment of dam safety regulators and owners. This approach includes such provisions in an effort to strike a balance between what is theoretically desirable and what is practical based on current technologies.

2.3.1. Requirements for Existing Dams

Many existing dams were constructed prior to the development of current guidelines and/or regulations for safely passing an appropriate IDF. Additionally, many of these dams were designed using hydrologic information or technologies that differ from those that are currently available. For these reasons, it is common for existing dams to not meet current regulatory IDF requirements. Current guidelines and/or regulations in several states allow for indiscriminate "grandfathering" of older, existing dams in recognition of the fact that upgrading such dams to pass the IDF can be difficult and expensive. Such guidelines often prescribe less stringent design criteria for all dams built prior to a specified date. This practice does not equitably address public safety, which is the primary goal of establishing IDF guidelines. **The indiscriminate application of less stringent, prescriptive criteria for all existing, "grandfathered" dams should be discontinued.** Rather than doing so indiscriminately, guidelines and/or regulations should include considerations of safety and risk (e.g. hazard potential and incremental risk reductions to be achieved) when determining whether dam owners are required to upgrade existing dams to comply with updated regulatory requirements. Even if a regulator decides not to require upgrades to a dam to fully meet new conditions, there may be cost-effective alternatives for partially upgrading the dam and lowering the risk exposure of downstream populations below commonly accepted levels of risk tolerance which should be considered.

When dam owners have made a good faith effort to accommodate an appropriate IDF based on the applicable engineering practice, hydrologic data, and regulatory guidelines in place at the time the dam was designed and constructed or rehabilitated, a new regulatory guideline related to spillway discharge capacity or new hydrologic information may not be sufficient by itself to require the dam owner to modify their dam to meet the revised regulatory guideline. Several principles should be considered before requiring a dam owner to apply updated guidelines to an existing dam.

- If significant modifications are otherwise required to the dam and appurtenant structures, the IDF should be updated to reflect the new guidelines and/or hydrologic data.
- If the IDF for an existing dam is not in accordance with current guidelines and hydrologic data, consideration should be given to the risk exposure of the population downstream of the dam. If the risk exposure exceeds commonly accepted levels of risk tolerance, a new IDF should be established and the dam should be modified to accommodate the IDF.
- If the IDF for an existing dam is shown to be inadequate to address the guidelines, known hydrologic conditions, or commonly accepted engineering practices in place at the time of design and construction of the dam, the IDF should be revised to meet current guidelines and the dam should be modified as necessary to accommodate the new IDF.

2.3.2. Consideration of Future Development

Selection of an IDF for a new dam or a dam undergoing significant modifications should take into account both current conditions and reasonably anticipated future development. This is especially important when the hazard classification of the dam is low or significant and when the IDF selection is based on methods that are dependent upon the magnitude of the downstream consequences.

Primary sources of information for future development are local land use planning organizations. Upstream development in the watershed should be considered to the extent that it could alter the hydrologic characteristics used in determining the IDF for the dam. Downstream development should be considered to the extent that it could alter dam hazard classification and/or estimates of risk that may indicate a need for a larger IDF.

If there are uncertainties about future development, the dam owner may wish to consider designing the dam to include provisions for accommodating a larger IDF with minimal additional investment. Choosing designs that can substantially increase storage or discharge capacity with minimal investment may result in considerable savings if a larger IDF becomes necessary at a later date.

2.3.3. Inflow Design Flood Requirements Using a Prescriptive Approach

For dams where the balance between the objectives mentioned in Section 2.1 is relatively obvious, a simple and efficient prescriptive approach based on hazard potential classification may suffice. Prescriptive IDF criteria corresponding to the hazard potential classification described in Section 2.2 are summarized in Table 2.

This approach requires minimal analysis and the selection of the IDF is intended to be conservative; however, the limitations of a simple prescriptive approach also need to be recognized and considered if such an approach is used to select an IDF and require modifications to a dam to satisfy this criteria. In some cases, modifications to a dam to accommodate a prescriptive IDF, such as increasing dam height or spillway capacity, can increase potential consequences or introduce potential failure modes that could significantly increase rather than decrease risks to the public. Consequently, a prescriptive approach to IDF selection and implementation should be applied judiciously with full consideration of its overall risk and public safety implications.

The prescriptive IDF for a High Hazard Potential dam is the PMF. For the purpose of flood evaluation for dams classified as having Significant Hazard Potential, extrapolation of the flood frequency relationship to the 0.1% annual chance exceedance flood (1,000-year flood) is generally accepted as the upper limit of the range of credible extrapolation for annual exceedance probability using available flood frequency techniques based on regional streamflow or precipitation data (Reclamation, 2010; CDA, 2007). At the time of publication of this document, NOAA Atlas 14 precipitation frequency estimates were being updated to include the 0.1% annual chance exceedance precipitation (NOAA, 2012). Extrapolation for annual exceedance probabilities beyond the 0.1% annual chance exceedance flood event has been performed using combinations of regional data sets and paleoflood data (Reclamation, 2010).

Table 2 IDF Requirements for Dams Using a Prescriptive Approach

Hazard Potential Classification	Definition of Hazard Potential Classification	Inflow Design Flood
High	Probable loss of life due to dam failure or misoperation (economic loss, environmental damage, or disruption of lifeline facilities may also be probable, but are not necessary for this classification)	PMF[1]
Significant	No probable loss of human life but can cause economic loss, environmental damage, or disruption of lifeline facilities due to dam failure or misoperation	0.1% Annual Chance Exceedance Flood (1,000-year Flood)[2]
Low	No probable loss of human life and low economic and/or environmental losses due to dam failure or misoperation	1% Annual Chance Exceedance Flood (100-year Flood) or a smaller flood justified by rationale

(1) Incremental consequence analysis or risk-informed decision making may be used to evaluate the potential for selecting an IDF lower than the prescribed standard. An IDF less than the 0.2% annual chance exceedance flood (500-year flood) is not recommended.

(2) Incremental consequence analysis or risk-informed decision making studies may be used to evaluate the potential for selecting an IDF lower than the prescribed standard. An IDF less than the 1% annual chance exceedance flood (100-year flood) is not recommended.

Dams identified as having a Low Hazard Potential should be designed to at least meet a 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, federal, or other regulations applicable to the facility. In general, the prescriptive IDF for a dam having a Low Hazard Potential should be the 1% annual chance exceedance flood (100-year flood) unless otherwise justified by appropriate rationale.

In some cases, selecting an IDF greater than the IDF specified in Table 2 may be justified. The incremental cost of providing additional conveyance capacity at a new dam or as part of dam rehabilitation is often nominal and may be a favorable investment in lowering risks associated with hydrologic potential failure modes. For example, selecting the minimum IDF specified in Table 2 does not eliminate the risk of litigation should the dam fail as a result of not being designed to safely pass floods in excess of the selected IDF. Furthermore, selection of the appropriate magnitude of the IDF may also include consideration of whether a dam provides vital community services such as municipal water supply, sole water source for firefighting capability, or energy production. Additional risk reduction may be required to ensure those services are continued during and following extreme flood conditions when alternate services are unavailable.

When selecting an IDF based on either probabilistic or PMP concepts, it should be recognized that these values are derived using limited information. Accordingly, such estimates are not fixed but inherently have a margin of uncertainty. As science evolves and additional data is collected, precipitation estimates and frequency of floods can change. The occurrence of events greater in magnitude than had been previously recorded in a specific location or region can cause such estimates to increase. This uncertainty in the foundation data is combined with the uncertainty inherent in modeling a postulated, rather than actual, event. Practitioners should be aware of this and, when possible, select IDFs that consider this reality. In all cases, an appropriate IDF selection should be performed, or directed and reviewed by a registered professional engineer experienced in hydrology and hydraulics.

2.3.4. Site-Specific Probable Maximum Precipitation Studies

The PMP represents the theoretically greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographic location at a certain time of the year (NOAA, 1999). The PMP is used to estimate the PMF inflow hydrograph and peak spillway discharge capacity needed at a dam. Using the prescriptive approach outlined in Section 2.3.3, the IDF for a high hazard potential dam is the PMF which is derived using the PMP. Generalized PMP estimates have been developed by the NWS for the entire United States including Alaska, Hawaii, and Puerto Rico. The commonly used approach in deterministic PMP development for non-orographic regions is to select the storm representative dew point temperature at the surface or Sea Surface Temperatures (used to compute the moisture maximization factor) and to collect a "sufficient" sample of extreme storms. These extreme storms are moved to other parts of the study area with similar climatic and topographic characteristics (WMO, 2009) where they could have potentially occurred through a method known as storm transposition (i.e. the adjustment of moisture observed in a storm at its actual site of occurrence to the corresponding moisture level at the site for which the PMP is to be evaluated). The maximized transposed storm values are then enveloped both depth-durationally and depth-areally to obtain PMP estimates for a specific basin. Several durations of PMP are normally considered to ensure the most appropriate duration is selected. If more than one storm type produces PMP for various area sizes and/or durations, PMP values for each storm type may be provided.

Site-specific PMP studies have been performed by the NWS and by private consultants recognizing that the published HMRs provide generalized rainfall values that are not basin-specific and tend to represent the largest PMP values across broad regions. Many recent site-specific studies have produced PMP values significantly different from HMR published values. Reasons for the differences (mostly reductions) are attributed to using basin characteristics that are specific to the topography and local climate of the watershed being studied, new storm data like NWS Next Generation Radar (NEXRAD), improved analysis procedures, and technology advances such as new computer models and geographic information system (GIS) software to analyze depth-area-duration tables. Site-specific PMP values are often 5 to 25 percent lower than values from the published HMRs, although some studies have shown minimal reductions or even slight increases. Other studies have shown even larger reductions (greater than 50 percent). The largest PMP reductions from site-specific studies vary with storm type, watershed size, and location. For example, in Nebraska, larger reductions have been produced for small area sizes and short durations than for large area sizes and long durations. Reductions also vary by location throughout the state with larger reductions from the HMR values for long durations and large drainage areas in the western part of the state than in the eastern part of the state. For shorter durations and small area sizes, there is less variation across the state (Tomlinson & Kappel, 2009; Tomlinson et al, 2008).

As understanding and the availability of hydrometeorological data increase, updated PMP estimates can better define the PMP for a site-specific basin or region. Nebraska has adopted a recent statewide PMP study that supersedes HMR 51. Other states including Arizona, Wyoming, and Ohio are also conducting state-wide PMP studies to replace the existing regional HMRs. In Michigan and Wisconsin, the FERC has accepted a PMP study for use in computing the PMF in those states. Refining the PMP estimate for a specific watershed or dam project may be a consideration.

At present, no industry standard associated with developing site-specific PMPs exists, and the methodologies and assumptions used by practitioners are varied. Many state and federal agencies do not have the resources to administer or review a site-specific PMP study. In those cases, a condition for acceptance of the study could include provisions for the dam owner to engage an independent peer review or review board consisting of experts in this area of study to oversee the study and approve the analyses and final results. This approach has been used by FERC on several large hydropower dam projects as well as numerous state-regulated dams.

2.3.5. Incremental Consequence Analysis

Adverse incremental consequences are defined as the difference in negative impacts that would occur due to failure or misoperation of a dam during a specified flood event over those that would occur without failure or misoperation. An incremental consequence analysis can be performed to select an appropriate IDF based upon the potential consequences of dam failure. *The IDF selected using incremental consequence analysis is the flood above which there is a negligible increase in downstream water surface elevation, velocity, and/or consequences due to failure of the dam when compared to the same flood without dam failure.* Figure 1 presents a schematic of such a comparison. Typically, incremental consequence analysis considers the potential for loss of human life and economic loss or property damage. The analysis could also consider consequences such as lifeline disruption and environmental impacts. For a High Hazard Potential dam, the recommended lower limit for an IDF estimated using incremental consequence analysis is the 0.2% annual chance exceedance flood. The recommended lower limit for a Significant Hazard Potential dam is the 1% annual chance exceedance flood. If incremental consequence analysis is used to define the IDF, upstream and downstream conditions and development should be periodically reviewed to ensure that changes in prospective consequences do not lead to a different recommendation for the IDF.

It is also important to understand that once a dam is constructed, the downstream hydrologic regime may change, particularly during flood events. The change in hydrologic regime could alter land use patterns to encroach on a floodplain that would otherwise not be developed without the dam. Consequently, evaluation of the consequences of dam failure must be based on the dam being in place, and should compare the impacts of with-failure and without-failure conditions on existing development and known and prospective future development. **Comparisons between existing downstream conditions with and without the dam are not recommended when analyzing incremental consequences.**

A hypothetical dam failure should be estimated using conservative yet realistic dam breach parameters. If it can be shown that the PMF dam failure event would not cause additional loss of life or significant property damages greater than the PMF non-failure event, a flood of lesser magnitude can be analyzed in the same comparative manner. This process is continued until the flood of greatest magnitude that causes incremental consequences is identified.

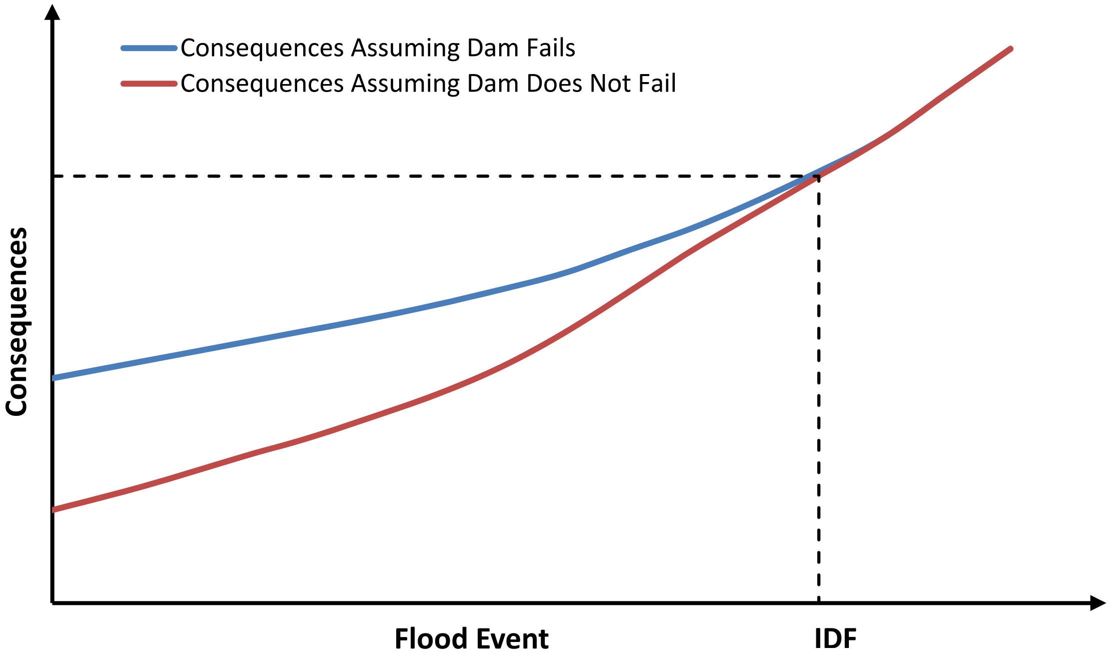

Figure 1 Conceptual Comparison of Incremental Consequences

Generally, acceptable consequences exist when evaluation of the area affected indicates one of the following:

1. There are no human habitations or major infrastructure, commercial, or industrial developments within the dam failure inundation area.
2. There are human habitations or major infrastructure, commercial, or industrial developments within the dam failure inundation area, but there would be no significant incremental increase in the threat to life or property.

There is much debate regarding what qualifies as a "significant incremental consequence." Methods of assessing the incremental increase in consequences vary from examining individual structures in the inundation zone to applying general criteria along the entire downstream inundation reach (FERC, 1993; Hoeft & Locke, 2010). Such criteria should not be viewed as absolute decision-making thresholds. Rather, sensitivity analyses and engineering judgment must be applied. Since dam failure analyses and flood routing studies do not provide certain results, evaluation of the consequences of failure should be reasonably conservative. The application of more detailed methods such as two-dimensional flow modeling may justify a less conservative conclusion. Other emerging technologies such as flood impact and life loss analysis software (e.g. HEC-FIA, LifeSim) may prove useful in consequence estimation and comparison (DHS, 2011). More detailed evaluation criteria such as depth-velocity flood lethality relationships could also be considered.

2.3.6. Risk-Informed Hydrologic Hazard Analysis

Risk-informed hydrologic hazard analysis includes a site-specific evaluation of the probability of hydrologic events and performance of the dam during those events, and evaluates in more detail the social, economic, and environmental consequences of failure. A formal quantitative risk assessment can be used to select an appropriate IDF. Such an assessment requires an evaluation of a full range of hydrologic loading conditions and possible dam failure mechanisms tied to consequences of failure. Estimates of hydrologic loading occurrence frequencies, relative likelihoods of possible levels of response and damage, and various components of cost and consequences are assessed. In its most common form, a formal quantitative risk analysis for selecting the IDF includes the following steps:

1. ***Develop a Hydrologic Hazard Curve.*** The flood loading input in a risk analysis is a hydrologic hazard curve developed for a hydrologic hazard analysis. Hydrologic hazard curves are defined as graphs of peak flow and volume for specific durations versus annual exceedance probability. The Bureau of Reclamation has developed guidelines on methods to develop hydrologic hazard curves (Swain et al, 2006).
2. ***Develop Hydrologic Loads.*** The resulting hydrologic loads from the hydrologic hazard curve for risk analysis can consist of peak flows, hydrographs, or reservoir levels and their

annual exceedance probabilities. The Bureau of Reclamation has developed and applied numerous methods to estimate extreme flood magnitudes and probabilities for dam safety and to address uncertainty. A conservatively estimated PMF is normally used to define the upper bound to the hydrologic hazard curve (Reclamation, 2010).

3. ***Identify Hydrologic Potential Failure Modes.*** Potential failure modes that may result from various adverse hydrologic events are identified. These normally include but are not limited to overtopping erosion, internal erosion (seepage and piping) at high reservoir levels, erosion in earth spillways, cavitation, mechanical system malfunction, and overstressing structural components.

4. ***Assess Hydrologic Potential Failure Mode Probabilities.*** The likelihood that a particular dam failure scenario will occur under a particular set of hydrologic circumstances is evaluated.

5. ***Quantify Consequences of Dam Failure.*** The consequences of a dam failure are estimated for each hydrologic potential failure mode and hydrologic event.

6. ***Quantify Dam Safety Risks.*** Event trees are normally chosen as the basic tool for computing dam safety risks. For each identified potential failure mode, event trees are developed to represent the sequence or progression of events and potential states of nature that could result in dam failure. Risks are computed as the product of the hydrologic load probability, the failure probability given the load, and the consequences given that failure occurs.

7. ***Select the IDF Based on Public Risk Tolerance and Risk Guidelines.*** The computed risks for various hydrologic loading conditions or flood events are compared against tolerable risk guidelines. This process can include assessing individual incremental life safety risk using probability of loss of life, societal incremental life safety risk expressed as a probability distribution of potential life loss (f-N chart), and societal incremental life safety risk expressed as an Annualized Life Loss. In general, the objective is to reduce risks below a tolerable risk limit. The tolerable risk limit is based on a principle of equity. The risk can be further reduced to satisfy “As Low As Reasonably Practicable” (ALARP) principles, whereby a judgment is made whether the residual risks can be cost effectively reduced further. The ALARP decision is based on an assessment of cost efficiency.

When using risk analysis to select the IDF for a dam, the uncertainty associated with the analysis needs to be considered. If the results are sensitive to assumed or extrapolated values that have significant uncertainty, conservative assumptions within the confidence limits of the analysis should be used to select the IDF. Because risk may change with time, a periodic review of conditions at the dam as well as upstream and downstream conditions and development should be performed to ensure the validity of the analysis.

While the practice of using quantitative risk analysis is not new, the application of the approach is fairly recent in comparison with other approaches to selecting an IDF. The U.S. Bureau of Reclamation and USACE have both published risk-based decision making guidelines for such an analysis (Reclamation, 2010; USACE, 2011). Current USACE policy does not allow use of a risk analysis to select an IDF. Because the use of risk-informed decision making continues to evolve, it is recommended that the most current risk analysis practices and risk tolerance guidelines adopted by the Bureau of Reclamation and the USACE be followed if a risk-informed approach to IDF selection is adopted.

Many state and federal agencies may not have the resources or training necessary to review a risk-informed IDF selection. In those cases, a condition for acceptance of the hydrologic design should include provisions for the dam owner to engage an independent peer review or review board consisting of experts in this area of study to oversee the study and approve the analyses and final results.

2.3.7. Potential Impacts of Climate Change on Estimates of Probable Maximum Precipitation

While significant research efforts regarding the magnitude and impacts of climate change are ongoing, the Intergovernmental Panel on Climate Change's Fourth Assessment Report has projected a warming climate (Ray, 2007). Accordingly, several recent studies have been performed to estimate the potential impacts that climate change may have on extreme precipitation events. Dr. Ken Kunkel of NOAA's National Climatic Center has focused his recent research on climate variability and change, particularly related to extreme events, such as heavy precipitation, heat waves, cold waves, and winter storms (Easterling & Kunkel, 2011). He noted that the PMP is estimated "by assuming that all possible factors contributing to heavy rain (upstart speed, moisture content, duration) come together at the same time and place." Even though there were some data quality issues, Kunkel showed evidence that the peak moisture content has increased over time across most of the United States. The climate models are consistent in showing increases of 10 percent every few decades that would correspond to 10 percent increases in PMP.

Others have also concluded that due to likely changes to maximum moisture and maximum storm efficiency, PMP estimates would increase under a warming climate (Jakob et al, 2009). This would lead directly to substantial increases in PMP values. Given the potential catastrophic consequences of dam failure, these findings should be considered carefully in future design activities. It should be noted, however, that the research currently being performed is inconclusive as to the next step and ultimately concludes that for the present time it would be difficult to quantify the increase in the PMP due to climate change.

Even though it is projected that the increases in the temperature of the planet will continue in the future, the pattern is far from being uniform. It is anticipated that the spatial and temporal patterns of rainfall and evaporation will be altered and that the occurrence of extreme events (e.g. floods and droughts) will increase, but it is not yet possible to quantify these changes. While research is occurring in this domain, no generally accepted methodology currently exists to evaluate the effect of climate change on flood frequencies or extreme precipitation depths. Until such methodologies are identified, extreme precipitation should be evaluated in a conservative yet realistic manner. In addition, flood frequency and PMP estimates should be updated frequently as additional information becomes available such as after the occurrence of a very large precipitation event or when new advances on climate modeling become available (CDA, 2007). All such new modeling/methods should be thoroughly documented and justified.

3. INFLOW DESIGN FLOOD ACCOMMODATION

3.1. Spillway Characteristics

In addition to design flood selection, the accommodation of the IDF is critical to the hydrologic safety of a dam. IDF accommodation includes the consideration of spillway type, flood routing design criteria, and freeboard criteria. Spillways and flood outlets should be designed to safely convey major floods to the watercourse downstream of the dam. They are selected for a specific dam and reservoir on the basis of dam safety, dam type and purpose, release requirements, topography, geology, project economics, and other possible factors.

It is recognized that the procedures and design criteria for IDF accommodation vary significantly based on these and other factors. The guidelines contained in this document are not intended to provide a complete manual of all such criteria, but are intended to act as a baseline from which dam safety agencies can develop criteria suitable to their varied objectives, jurisdictions, and resources. The basic philosophy and principles are described in sufficient detail to promote a reasonable degree of consistency and uniformity among state and federal agencies in the design or evaluation of dams from the standpoint of hydrologic safety.

Due to the importance of safely accommodating the IDF and floods of lesser magnitude, all spillway designs and analyses should be performed, or directed and reviewed by a registered professional engineer experienced in hydrology and hydraulics.

3.1.1. Controlled versus Uncontrolled Spillways

By definition, an uncontrolled spillway releases water whenever the reservoir elevation exceeds the spillway crest level. Conversely, a controlled spillway can regulate releases over a range of water levels through the use of gates and/or valves. Each of these spillway types has specific design implications which should be considered when designing a spillway.

The selection of a controlled or uncontrolled type of spillway for a specific dam depends on site conditions, project purposes, the magnitude of the IDF, economic factors, costs of operation and maintenance, and other considerations. The following considerations influence the use of either a controlled or uncontrolled spillway:

- ***Discharge capacity*** – For a given spillway crest length and maximum allowable water surface elevation, a controlled spillway can be designed to release higher discharges than an uncontrolled spillway if the spillway crest elevation is lower than the normal reservoir storage level. This can impact spillway design selection when there are limitations on spillway crest length or maximum water surface elevation.

- ***Project objectives and flexibility*** – Controlled spillways permit a wide range of releases and have capability for pre-flood drawdown.

- ***Operation and maintenance*** – Uncontrolled spillways are typically more reliable and self-maintaining than controlled spillways. Controlled spillways may experience more operational problems and are more expensive to construct and maintain than uncontrolled spillways. Constant attendance or several inspections per day by an operator during high water levels is highly desirable for reservoirs with controlled spillways, even when automatic or remote controls are provided. However, access to the dam during a major flood event might be difficult or even impossible. Controlled spillways require regular maintenance and periodic testing of gate operations.
- ***Reliability*** – The nature of uncontrolled spillways reduces dam failure potential associated with improper operation and maintenance. Where forecasting capability is unreliable, or where time from the beginning of runoff to peak inflow is only a few hours, uncontrolled spillways are more reliable, particularly for high hazard potential structures. Consequences of failure of operation equipment or errors in operation can be severe for controlled spillways. Susceptibility to plugging due to debris can also impact the reliability of both controlled and uncontrolled spillways.
- ***Data and control requirements*** – Operational decisions for controlled spillways should be based upon real-time hydrologic and meteorologic data to make proper regulation possible.
- ***Emergency drawdown*** – Typical uncontrolled spillways cannot be used to evacuate a reservoir during emergencies. The capability of controlled spillways to draw down pools from the top of the gates to the spillway crest can be an advantage when rapid reduction of load on the dam is required.
- ***Economics*** – Economic considerations often influence whether controlled or uncontrolled spillways are selected. Controlled spillways are typically more expensive than uncontrolled spillways.

The selection of a combination of more than one type of spillway is also a possibility. Final selection of the type of crest control should be based on a comprehensive analysis of all pertinent factors.

3.1.2. Additional Spillway Types

Dams and their appurtenant structures should be designed to give satisfactory performance. In addition to distinguishing between controlled and uncontrolled spillways, these guidelines identify three specific types of spillways: (1) service or principal spillways, (2) auxiliary spillways, and (3) emergency spillways. Outlet works can also be used to lower reservoir levels in anticipation of a flood event or to pass floodwaters.

> ***Service spillways*** should be designed for frequent use and should safely convey releases from a reservoir to the natural watercourse downstream of the dam. A service spillway

should exhibit excellent performance characteristics for frequent and sustained flows, such as up to the 100-year flood event. In general, service spillways should pass design flows without sustaining any damage.

Auxiliary spillways are usually designed for infrequent use. It is acceptable for an auxiliary spillway to sustain limited damage during passage of the IDF provided it does not jeopardize the structural integrity of the dam or the function of the spillway. Reference to these spillways as "emergency spillways" should be discontinued. Media references to flow through "emergency spillways" often leads to a misconception by the public that an emergency condition exists at a dam when the dam is safely functioning as designed.

Emergency Spillways are not intended to be used for the routing of the IDF. They are provided where there is a desire to protect against a malfunction of another feature required to safely pass the IDF.

3.2. Routing the Inflow Design Flood

Site-specific considerations should be used to establish flood routing criteria for each dam and reservoir. The criteria for routing any flood should be consistent with the reservoir regulation procedure that is to be followed in actual operation. The general guidelines to be used in establishing criteria are presented below and should be used if applicable.

3.2.1. Guidelines for Initial Reservoir Elevation

It may be helpful to conduct an antecedent flood study to inform selection of the starting reservoir water surface elevation. In general, if there is no allocated or planned flood control storage, the flood routing begins with the reservoir at the normal maximum pool elevation. If regulation studies show that pool levels would be lower than the normal maximum pool elevation during the critical IDF season, then the results of those specific regulation studies should be analyzed to select the appropriate initial pool level for routing the IDF.

3.2.2. Reservoir Constraints

Flood routing criteria should recognize constraints that may exist on the maximum desirable water surface elevation. A limit or maximum water surface reached during a routing of the IDF can be achieved by providing spillways and outlet works with adequate discharge capacity. Backwater effects of flood flow into the reservoir must specifically be considered when constraints on water surface elevation are evaluated. Reservoir constraints may include the following:

- Topographic limitations on the reservoir stage which exceed the economic limits of saddle-dike construction.
- Public works around the reservoir rim, which are not to be relocated, such as water supply facilities and sewage treatment plants.

- Dwellings, factories, and other development around the reservoir rim, which are not to be relocated.
- Sediment deposits in reservoir headwater areas which may build up a delta and can increase flooding in that area, as well as reduce flood storage capacity.
- Geologic features that may become unstable when inundated and result in landslides, which would threaten the safety of the dam, domestic and/or other developments, or displace reservoir storage capacity.
- Flood plain management plans and objectives established under federal, state, or municipal regulations.

3.2.3. Reservoir Regulation Requirements

To ensure the hydrologic safety of a dam, several reservoir regulation requirements need to be followed. For example, maximum and minimum regulated releases from a dam should be specified. The maximum regulated release rate should be specified to prevent flooding or erosion of downstream areas and control the rate of reservoir drawdown. A minimum regulated release capacity facilitates the recovery of flood control storage for use in regulating subsequent flood events. It is also important to allow for the evacuation of the reservoir in the event of an emergency and for performing inspections, maintenance, and repairs.

Spillways, outlet works, penstocks for power plants, and navigation locks are sized to satisfy project requirements and must be operated in accordance with specific instructions if these project works are relied upon to make flood releases. These are subject to the following conditions and limitations in deciding whether to assume release facilities are operational:

- Structural competence and availability for use
- Availability and reliability of generating units for flood release during major floods
- Availability of a source of auxiliary power for gate operation
- Effects of reservoir debris on operability and discharge capacity of gates and other facilities
- Accessibility of controls
- Design limits on operating head
- Reliability of road network for access to the site
- Availability of operating personnel at the site during floods
- Any other condition or situation that limits the operation of facilities at design capacity

Only those release facilities which can be expected to operate reliably under the assumed flood condition should be assumed to be operational for flood routing.

A positive way of making releases to the natural watercourse by use of a bypass or waste way must be available if canal outlets are to be considered available for making flood releases. 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, assumed releases are generally limited by several factors including project uses, availability of outlet works, tailwater conditions including effects of downstream tributary inflows and wind tides, and downstream non-damaging discharge capacities until allocated storage elevations are exceeded. When a reservoir's capacity in regulating flow is exceeded, other factors including the safety of the dam will govern releases.

During flood routing, the rate of outflow from the reservoir should not exceed the maximum projected rate of inflow, to the extent possible, until the outflow approaches the maximum project discharge capacity, nor should the maximum rate of increase of outflow exceed the maximum rate of increase of inflow to the extent possible. This is to prevent flooding impacts downstream of the dam from being more severe than they would have been had the same flood occurred prior to the dam’s existence. This only applies to the rising limb of a flood hydrograph. Once inflows and downstream flows have receded, the dam must release the water it has stored which will result in outflow exceeding inflow. Another exception to the above would be those uncommon cases where reliable streamflow forecasts are available and sufficient time exists for pre-flood releases to reduce reservoir levels to provide appreciable storage for flood flows.

3.2.4. Evaluation of Domino-like Failure

If one or more dams are located downstream of the site under review, the flood wave that could result from failure of the dam should be routed to evaluate if any of the downstream dams would potentially breach in domino-like action. The flood routing of flows entering the dam being reviewed may be either dynamic or level pool depending on site specific conditions. For instance, a dynamic pool routing should be used in cases with significant backwater effect, flat channel slope, rapidly rising inflow hydrographs in long and narrow reservoirs, or irregularly shaped reservoirs. The routing through all subsequent downstream reservoirs should also be dynamic. Tailwater elevations should consider the effect of backwater from downstream constrictions. If failure of the dam being reviewed could contribute to failure of a downstream dam, the minimum hazard classification of the upstream dam should be the same as the classification of the downstream dam.

3.3. Freeboard Requirements

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 waves under extreme hydrologic conditions. However, the number and duration of such occurrences should not threaten the structural integrity of the dam, interfere with project operation, or create hazards to personnel.

Freeboard should be evaluated on a case-by-case basis considering many factors including the magnitude of the selected IDF; predicted duration of high water levels during the design flood; the effective wind fetch and reservoir depth available to support wave generation; the probability of high wind speed occurring from a critical direction; the potential wave run up based on roughness and slope; the potential for debris plugging and/or misoperation of a spillway; and the ability of the dam to resist erosion from overtopping waves.

Freeboard allowance for settlement should be applied to account for consolidation of foundation and embankment materials when uncertainties exist in computational methods or data used yield uncertain values for camber design. Freeboard allowance for settlement is not necessary when an accurate estimate of settlement can be made and is accounted for with camber. Freeboard allowance for embankment dams for estimated earthquake-generated movement, resulting seiches, and permanent embankment displacements or deformations should be considered if a dam is located in an area with potential for seismic activity. Reduction of freeboard allowances on embankment dams may be appropriate for small fetches, obstructions that impede wave generation, special slope and crest protection, and other factors.

Freeboard provided for concrete and masonry dams can be less than for embankment dams because of their resistance to wave damage or erosion. If studies demonstrate that dams can withstand the IDF while overtopped without significant erosion of foundation or abutment material, then no freeboard should be required for the IDF condition. Special consideration may be required in cases where a power plant or other feature is located near the toe of the dam.

The U.S. Bureau of Reclamation has developed *ACER Technical Memorandum No. 2* which includes criteria for freeboard computations[3] (Reclamation, 1981).

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[3] At the time of publication of this document, representatives from the Bureau of Reclamation indicated that a new design standard for freeboard and selection of the IDF was in draft form. The new design standard will supersede the criteria included in *ACER Technical Memorandum No. 2*.

4. DEFINITIONS OF TERMS

4.1. Glossary

Adverse consequences. Negative impacts that may result from the failure of a dam. The primary concerns are loss of human life, economic loss (including property damage), lifeline disruption, and environmental impacts.

Annual Chance Exceedance Probability. The likelihood that a random event will exceed a specified magnitude in a one year period.

Appurtenant structure. Ancillary features of a dam such as outlets, spillways, power plants, tunnels, etc.

Breach. An opening through a dam that allows the uncontrolled draining of a reservoir. A controlled breach is a constructed opening. An uncontrolled breach is an unintentional opening caused by dam failure. An uncontrolled breach is generally associated with the partial or total failure of the dam.

Consequences. Potential loss of life or property damage downstream of a dam caused by floodwaters released at the dam or by waters released by partial or complete failure of dam. Also, in-lake flooding caused by misoperation or the effects of landslides upstream of the dam on property located around the reservoir.

Dam. An artificial barrier that has the ability to impound water, wastewater, or any liquid-borne material, for the purpose of storage or control of water.

Dam failure. Catastrophic full or partial collapse of a dam structure characterized by the sudden, rapid, and uncontrolled release of impounded water. It is recognized that there are lesser degrees of failure and that any malfunction or abnormality outside the design assumptions and parameters that adversely affect a dam's primary function of impounding water is properly considered a failure. These lesser degrees of failure can progressively lead to or heighten the risk of a catastrophic failure. They are, however, normally amenable to corrective action.

Dam safety. Dam safety is the art, engineering science, and enactment and implementation of public policy ensuring the integrity and viability of dams such that they do not present unacceptable risks to the public, property, and the environment. It requires the collective application of engineering principles and experience, and a philosophy of risk management that recognizes that a dam is a structure whose safe function is not explicitly determined by its original design and construction. It also includes all actions taken to identify or predict deficiencies and consequences related to failure, and to document, publicize, and reduce, eliminate, or remediate to the extent reasonably possible, any unacceptable risks.

Deterministic methodology. A method in which the chance of occurrence of the variables involved is not explicitly included in the computations and the method or model used is considered to follow a definite law of certainty, and not probability.

Flood. A temporary rise in water surface elevation 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.

> **Flood hydrograph.** A graph showing, for a given point on a stream, the discharge, height, or other characteristic of a flood as a function of time.
>
> **Flood, Inflow Design (IDF).** The flood hydrograph entering the reservoir that is used to design and/or modify a specific dam and its appurtenant works; particularly for sizing the spillway and outlet works, and for evaluating maximum storage, height of dam, and freeboard requirements.
>
> **Flood, Probable Maximum (PMF).** The flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that is reasonably possible in the drainage basin under study.
>
> **Flood, Spillway Design (SDF).** The flood hydrograph leaving the reservoir that is used to design and/or modify a specific dam and its appurtenant works (also referred to as the outflow hydrograph). The SDF is estimated by routing the appropriate IDF through a dam's spillway, outlet works, and attendant surcharge storage.

Floodplain. An area adjoining a body of water or natural stream that may be covered by floodwater. Also, the downstream area that would be inundated or otherwise affected by the failure of a dam or by large flood flows. The area of the floodplain is generally delineated by a frequency or magnitude of flood.

Freeboard. Vertical distance between a specified stillwater reservoir surface elevation and the top of the dam, without camber.

f-N Chart. A plot of the Annual Probability of Exceedance of Life Loss (f, greater than or equal to) vs. Incremental Loss of Life (N) for all failure scenarios for a particular reservoir. f-N charts display the entire estimated probability distribution of life loss for a reservoir encompassing all potential failure mode-exposure scenarios. They are used for societal tolerable risk guidelines in many countries (Bowles, 2007).

Grandfather Clause. A legislative or regulatory provision that permits an exemption based upon a specified pre-existing condition. Some regulatory agencies provide such exemptions for dams constructed prior to a specified date.

Hazard. A situation that creates the potential for adverse consequences such as loss of life, property damage, or other adverse impacts.

> **Hazard potential.** The possible adverse incremental consequences that result from the release of water or stored contents due to failure of the dam or misoperation of the dam or appurtenances. Impacts may be for a defined area downstream of a dam from flood waters released through spillways and outlet works of the dam or waters released by partial or complete failure of the dam. There may also be impacts for an area upstream of the dam from effects of backwater flooding or landslides around the reservoir perimeter.

> **Hazard potential classification.** A system that categorizes dams according to the degree of adverse incremental consequences of a failure or misoperation of a dam. The hazard potential classification does not reflect in any way on the current condition of the dam (i.e., safety, structural integrity, flood routing capacity).

Hydrograph, flood. A graph showing, for a given point on a stream, the discharge, height, or other characteristic of a flood as a function of time.

> **Hydrograph, breach or dam failure.** A flood hydrograph resulting from a dam breach.

> **Hydrograph, unit.** A flood hydrograph with a volume of one inch of 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.

Hydrologic hazard curves. Graphs of peak flow and volume for specific durations versus annual exceedance probability.

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

Incremental consequence. Under the same conditions (e.g., flood, earthquake, or other event), the difference in impacts that would occur due to failure or misoperation of the dam over those that would have occurred without failure or misoperation of the dam and appurtenances.

Inflow Design Flood (IDF). The flood hydrograph entering the reservoir that is used to design and/or modify a specific dam and its appurtenant works; particularly for sizing the spillway and outlet works, and for evaluating maximum storage, height of dam, and freeboard requirements.

Normal reservoir level. For a reservoir with a fixed overflow sill the lowest crest level of that sill. For a reservoir whose outflow is controlled wholly or partly by moveable gates, siphons or other means, it is the maximum level to which water may rise under normal operating conditions, exclusive of any provision for flood surcharge.

Potential Failure Mode. A potential failure mode is a physically plausible process for dam failure resulting from an existing inadequacy or defect related to a natural foundation condition, the dam or appurtenant structures design, the construction, the materials incorporated, the operations and maintenance, or aging process, which can lead to an uncontrolled release of the reservoir.

Probable. Likely to occur; reasonably expected; realistic.

Probable Maximum Flood (PMF). The flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that is 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.

Reservoir. A body of water impounded by a dam and in which water can be stored. In the case of mine tailings facilities, it can include the solids as well as the water retained.

Risk. A measure of the likelihood and severity of adverse consequences. Risk is estimated by the mathematical expectation of the consequences of an adverse event occurring, i.e., the product of the probability of occurrence and the consequence, or alternatively, by the triplet of scenario, probability of occurrence, and the consequence.

Risk analysis. A procedure to identify and quantify risks by identifying potential failure modes, providing numerical estimates of the likelihood of an event, and estimating the magnitude of the consequences. The risk analysis should include all potential events that would cause unintentional release of stored water from the reservoir.

Risk assessment. The process of deciding whether existing risks are tolerable and present risk control measures are adequate and, if not, whether alternative risk control measures are justified. Risk assessment incorporates the risk analysis and risk evaluation phases.

Risk evaluation. A procedure concerned with assessing likelihood or probability and impact of individual risks based on risk analysis results, taking into account any interdependencies or other factors outside the immediate scope under investigation.

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

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.

Spillway. A structure over or through which flow is discharged from a reservoir. If the rate of flow is controlled by mechanical means, such as gates, it is considered a controlled spillway. If the geometry of the spillway is the only control, it is considered an uncontrolled spillway.

Spillway, auxiliary. Any secondary spillway that is designed to be operated infrequently, possibly in anticipation of some degree of structural damage or erosion to the spillway that would occur during operation.

Spillway, emergency. A spillway provided where there is a desire to protect against a malfunction of another feature required to safely pass the IDF or account for uncertainty in the selection of the IDF. An emergency spillway is not intended to be used for the routing of the IDF.

Spillway, service. A spillway that is designed to provide continuous or frequent regulated or unregulated releases from a reservoir, without significant damage to either the dam or its appurtenant structures. This is also referred to as principal spillway.

Spillway capacity. The maximum spillway outflow that a dam can safely pass with the reservoir at its maximum level.

Spillway channel. An open channel or closed conduit conveying water from the spillway inlet downstream.

Spillway crest. The lowest level at which water can flow over or through the spillway.

Spillway Design Flood (SDF). The flood hydrograph leaving the reservoir that is used to design and/or modify a specific dam and its appurtenant works (also referred to as the outflow hydrograph). The SDF is estimated by routing the appropriate IDF through a dam's spillway, outlet works, and attendant surcharge storage.

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.

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 out of the reservoir until the controlled retention water level is reached.

Watershed. The area drained by a river or river system or portion thereof. The watershed for a dam is the drainage area upstream of the dam.

4.2. Acronyms

ALARP. As Low As Reasonably Practicable

ALL. Annualized Life Loss

ANCOLD. Australian National Committee on Large Dams

ASCE. American Society of Civil Engineers

CDA. Canadian Dam Safety Association

EAP. Emergency Action Plan

FEMA. Federal Emergency Management Agency

FERC. Federal Energy Regulatory Commission

FIA. Flood Impact Analysis

GIS. Geographic Information Systems

HEC. Hydrologic Engineering Center

HMR. Hydrometeorological Report

ICODS. Interagency Committee on Dam Safety

IDF. Inflow Design Flood

NEXRAD. Next Generation Radar

NOAA. National Oceanic and Atmospheric Administration

NWS. National Weather Service

NRC. National Research Council of the National Academy of Sciences

NRCS. Natural Resources Conservation Service, formerly SCS

PMF. Probable Maximum Flood

PMP. Probable Maximum Precipitation

SDF. Spillway Design Flood

SCS. Soil Conservation Service, currently known as the NRCS

USACE. United States Army Corps of Engineers

WMO. World Meteorological Organization

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