JUSTIFYING INFLOW DESIGN FLOOD FOR DAM HYDROLOGIC SAFETY: HOLISTIC COMPARISON OF METHODS

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Abstract: The approach of selecting adequate inflow design floods (IDFs) is critical to verifying the existing or implementing designing acceptable hydrologic safety for dams. The purpose of this paper is to present state-of-the-methods for selecting an IDF in a technically defensible fashion by way of: (1) Clarifying the hypothetical dam failure scenarios between both hazard-classification based preliminary IDF determination and the more refined potential failure modes (PFMs) based IDF determination; (2) Discerning the iterative process needed for an optimal IDF determined from the refined incremental consequence approach (ICA); and (3) Recognizing the merits of the refined risk-informed decision making (RIDM) approach as a more advanced method and its challenges as well. Two example application cases are provided to illustrate and compare the IDF selection processes of those methods which are addressed in this paper.

Note: The opinions and views offered here are those of the author, and are not necessarily those of the Federal Energy Regulatory Commission, individual Commissioners, or other members of the Commission's staff.

BACKGROUND INFORMATION

Federal and State agencies bring commitment to public safety. The Federal Emergency Management Agency (FEMA) published the P-94 guidance document entitled, "Selecting and Accommodating Inflow Design Floods for Dams" in August 2013. It provides updated guidance for the analysis, evaluation, and assessment of the hydrologic safety for new and existing dams. Its release was 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. To be consistent and stable over time, the basic philosophy and principles are described, but not all procedures provided, in order to adequately manage the hydrologic safety risk to dams by passing a required minimum magnitude flood flow for the sake of public safety.

The methodologies of both deterministic and probabilistic approaches, shown in Fig. 1 Methodologies of IDF Selection: Deterministic vs. Probabilistic Methodology, are correctly being used to facilitate dam safety risk management for evaluating hydrologic safety of dams. The deterministic approach includes the prescriptive approach based solely on a dam's hazard potential class, and the ICA is based on the incremental upstream/downstream inundation situations. The more advanced probabilistic approach is a quantitative risk oriented RIDM process to meet a defined tolerable risk level.

To illustrate the merits and shortcomings of the deterministic and probabilistic approaches as described, two case studies are presented as examples (for reference only) to demonstrate an optimal hydrologic safety protection for a dam. Non-structural solutions to IDF issues such as considering the effectiveness of Emergency Action Plan (EAP) execution on dam failure consequences, removing dam, land acquisition, structure abandonment, etc. are not discussed in this paper.

IDF BASED HYDROLOGIC SAFETY STRATEGY

Prescriptive method, ICA method and RIDM approach are available techniques to develop a quantified hydrologic safety strategy for dams to accommodate the wide variety of situations, available resources, and conditions. The IDF analysis starts from hypothetical dam failure assumptions under various flood loading conditions for dam failure potential consequence magnitude estimations. The PFMs of a dam system including dam and appurtenant structures can be identified through a PFM analysis (PFMA) exercise. In practice, the dam breach assumptions are evaluated to use the most conservative parameters resulting in a worst downstream inundation scenario for the relatively simpler prescriptive approach but more realistic, physically based PFMs parameters are used for the refined ICA and RIDM approaches. Thus, the prescriptive method's assumed parameters are often greater than the ICA/RIDM methods'. The subsequent consequence (life and property losses, environmental damage, etc.) are estimated basically based on dam failure-induced flood flow inundation levels at the downstream impact areas.

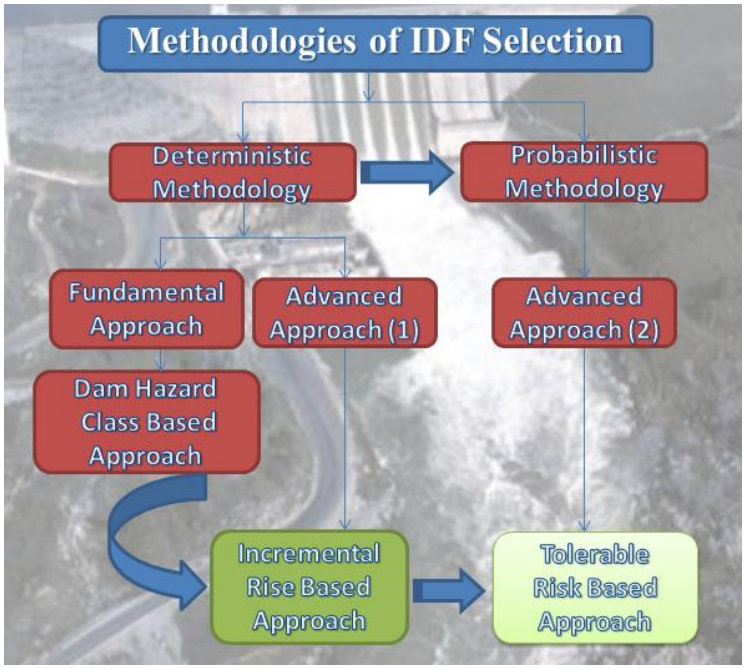


Fig. 1 Methodologies of Inflow Design Flood Selection: Deterministic vs. Probabilistic Methodology

In general, a PFM is defined as a process (i.e., dynamic mechanism) in which the dam could reasonably and logically be expected to fail under a certain adversarial condition equal to or greater than its failure threshold. The most common hydrologic PFMs include overtopping erosion of embankments/abutments, erosion and back-cutting of earthen channel spillways,

cavitation of chute channels, internal erosion (seepage and piping), dam overturning/sliding, and overstressing of the structural components of the dam, all of which may be caused by high reservoir levels due to extreme hydrological events. To attempt to avoid these PFMs, spillways are designed to safely pass the justified IDF based on the analysis results of any of the above mentioned alternative approaches.

Guiding Definitions of IDF: An IDF can technically be defined in three ways. The first is by the dam hazard class based prescriptive IDF. The second is the flood flow above which the incremental increase in downstream inundation water surface elevation due to failure of a dam is no longer considered to present an unacceptable additional downstream threat. The first and second definitions are based on deterministic approach results. The third is probability based and the IDF is the flood flow above which the consequence risk due to failure of a dam does not exceed a given level of "tolerable risk". For instance, some agencies using two tolerable risk indices to justify the IDF selection such as averaged annual failure probability (AFP) of a dam and a resulting averaged annual life loss (ALL).

Inundation Loss Rating Factors: For an IDF study, it is required to perform and provide a precise assessment of the downstream adverse impact potentials as the consequences of upstream dam failure caused by various hydrologic loading conditions. In assessing the consequences, the likelihood of loss of human life and property damage must be evaluated using dam failure analysis results and sound engineering judgment. Two rating factors commonly used to determine such likelihood are inundation depth and associated flow velocity. The references of theoretical and experimental data for building vulnerability (from Karvonen et al., 2000) and on humans and monoliths (after Lind/Hartford, 2000) can be used as a judgment basis for harmful rating factors.

Vital Importance of Implementation of the IDF Requirement: The IDF is utilized as the flood hydrograph entering a reservoir that is used as a basis to design and/or modify a specific dam and its appurtenant works; particularly for such as sizing the spillway and outlet works, and for determining the maximum flood overtopping prevention height of a dam, freeboard, and flood storage requirements. Thus, appropriate selection of the IDF is the first step in evaluating or designing a specific dam to address hydrologic PFMs and reduce risks to the public to an acceptable degree of hydrologic safety. As a result, seeking such an IDF for a dam is important to balance the risks due to its potential hydrologic failure with resulting downstream consequences and the benefits derived from the dam.

SUITABLE HYPOTHETICAL DAM FAILURES FOR HAZARD CLASSIFICATION AND REFINED IDF APPROACHES

The prescriptive approach is the method for a planned or existing dam to be evaluated for a prescribed standard, based on the hazard potential classification of the dam. This method's IDF criteria are intended to be conservative through a more conservative hypothetical dam failure scenario. It is a relatively simpler approach than other two refined approaches. But it is not

intended to assure that there is an economical marginal benefit from designing for such a conservative IDF. For some cases, specifically, this approach's IDF may be just a preliminary value and could be further reduced by the PFMs based refined ICA or RIDM approaches as shown in Fig. 2 Methodologies of IDF Selection: Preliminary Study vs. Refined Study. The basic cause is due to different dam failure assumptions as addressed below.

<u>Failure assumptions for Hazard Classification Based Preliminary IDF Determination</u>: The hazard potential classification of the dam is performed with the philosophical idea that is all about a dam's hypothetical worst failure case scenario. Namely, the existing dam conditions are not considered. A dam must be assumed to fail by any magnitude flood event for the purpose of evaluating its associated worst hazard potential. Thus, a hypothetical dam failure is estimated using worst dam breach parameters which are not necessarily based on the dam's PFMs. Table 1 Recommended Prescriptive Approach IDF Requirements for Dams under Flood Loadings illustrates the IDF requirements using the prescriptive approach.

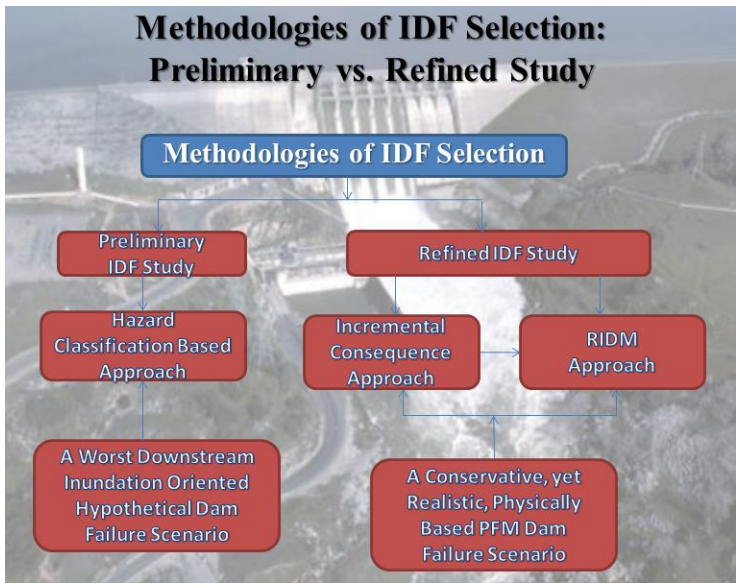


Fig. 2 Methodologies of Inflow Design Flood Selection: Preliminary Study vs. Refined Study

Table 1 Recommended Prescriptive Approach Inflow Design Flood Requirements for Dams under Flood Loadings

Hazard Potential Classification	Definition of Hazard Potential Classification	Inflow Design Flood (IDF)
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
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)

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 (i.e. 100-year flood) or a Smaller Flood Justified by Rationale

Failure assumptions for PFMs Based Refined IDF Determination: The philosophical idea and engineering concepts for refined IDF approaches are a direct contrast to dam hazard classification based IDF approach. The philosophical idea is about a dam's realistic capability to safely pass a required flood event given the existing dam conditions. Whether or not a dam is assumed to fail depends upon its PFMs under extreme hydrologic loading conditions. The engineering concept is that a hypothetical dam failure should be estimated using reasonably conservative, realistic, physically based dam breach parameters related to the dam conditions.

A Hybrid Case of Hazard Classification and PFM Based Failures: In dam hazard classification studies, only the most severe dam failure scenario is assumed. However, the most likely mode of dam failure for the selection of IDF is not always the most severe. For example, the concrete portion of a composite dam system (e.g., composed of concrete and embankment dams) is assumed to fail to produce the largest uncontrolled flow downstream to classify the dam's hazard potential. On the contrary, for a refined IDF analysis, the PFM of the embankment portion should be considered since it is most likely to fail during a critical overtopping event.

ICA METHOD'S ITERATIVE PROCESS TO OPTIMIZE IDF

Conceptual Scheme: As indicated above, the IDF selection using ICA is the flood above which there is a negligible increase in downstream inundation depth, flow velocity, and/or consequences due to failure of the dam when compared to the same flood without dam failure. Figure 3 Schematic Illustration of ICA for the selection of IDF presents a schematic of such a comparison. This process is continued until the flood of greatest magnitude that causes incremental consequences is identified.

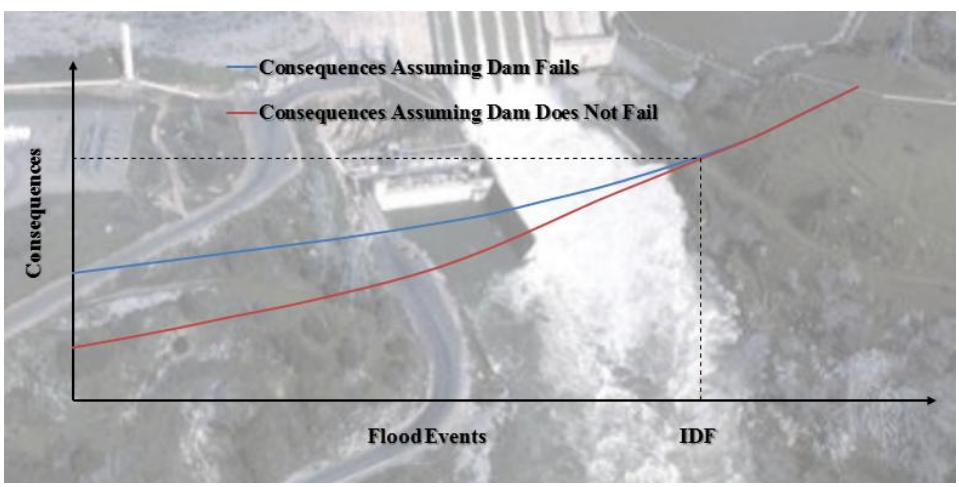


Figure 3. Schematic Illustration of Incremental Consequence Approach for the selection of IDF

Good Engineering Practices (GEPs): The GEPs consist of proven and accepted engineering methods, procedures, and practices that provide appropriate, cost-effective, and well-documented

solutions to meet user-requirements and compliance with applicable regulations. In GEPs, an appropriate measure needs to be studied to modify a dam to increase its conveyance capacity to safely pass the derived initial IDF value. For some cases, moreover, it must go through an iterative process as shown in Fig. 4 Incremental Consequence Approach: A Complete Iterative Process to Further Refine the Initial IDF's flow chart. The resulting IDF can be further refined by taking into account the hypothetically added spillway capacity. Thus, a comprehensive measure to modify a dam to increase its conveyance capacity to safely pass an adequate IDF must go through such an iterative process. The Case 1 example provided later illustrates the process of repeating the analysis until convergence to attain a minimum acceptable IDF.

Potential New Adverse Impacts: In the iterative process for the IDF selection and implementation, several hydraulically advantageous measures may be utilized to improve the spillway capacity to meet requirements while some disadvantages described below could also exist which should be identified and avoided by performing a supplemental PFMA (SPFMA) exercise:

- Raising the crest of dam: It can increase the downstream consequences should the dam fail by creating a larger dam breach flood wave or it may increase upstream inundation consequence during extreme flood events.
- Widening the spillway, or lowering the crest of the spillway and installing crest gates: It may actually increase the risk to the downstream public by increasing the spillway flows during hydrologic events that occur more often.
- The above measures could also introduce new PFMs, thus increasing dam failure risk.

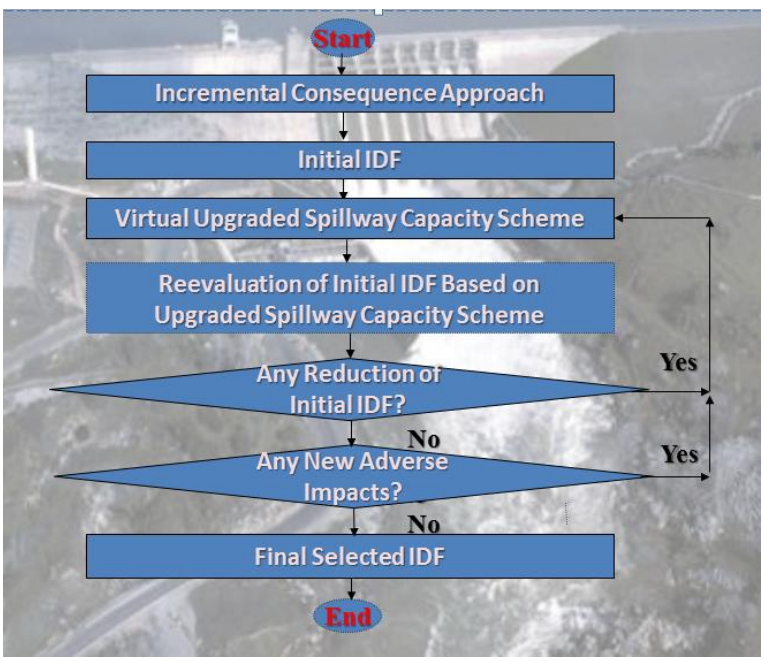


Fig. 4 Incremental Consequence Approach: A Complete Iterative Process to Further Refine the Initial Inflow Design Flood

PROBABILISTIC APPROACH TO SELECTING IDF

Risky Society toward a New Modernity: We live in a contemporary "high risk society" in which risk is everywhere. We may estimate either the cost-effectiveness between the well-being and risk or the risks to compare with tolerable risk levels by means of probabilistic risk assessment (PRA). The pursuit of absolute safety or zero risk is impractical, and self-deception. A risk assessment is not the sole basis for a decision, but rather it provides a systematic way of understanding a dam's PFMs, quantitative probabilities of loadings and structural failures, and the potential consequences and associated uncertainties. Current complementary use of the probabilistic method of RIDM approach to the deterministic method can be significantly expanded by state-of-art risk-based analysis for more realistic dam hazard potential assessment. Such a RIDM process provides a defensible basis for making decisions and helps to identify the greatest risks and prioritize efforts to minimize to a tolerable risk level or even eliminate them if it is possible.

Risk-informed Process: The RIDM approach in a risk-based system synthesizes the ICA with risk estimation through using information and reports available for the dam under study, historical performance of comparable dams, and experience based engineering judgment, etc. Specifically, RIDM is a decision making process to decide on a course of action for dam safety improvement. Qualitative and quantitative information about dam safety risks are considered along with other project-specific information. Risk-informed hydrologic hazard analysis includes a site-specific evaluation of the probabilities of a full range of extreme hydrological events and performance of the dam during those events, and evaluates in more detail the social, economic, and environmental consequences of failure. In short, RIDM is a tool for evaluating hydrologic events in a risk-based context and the level of effort is proportion to safety issues.

Quantitative Risk Indexes: Risk can be expressed in terms of life-safety and economic consequences on an annualized basis. The units of measure for dam safety risk are such as loss-of-life per year for life-safety, and costs (dollars) per year for property damages and economic losses. For instance, the RIDM process can include specifically 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 (See F-N Chart of Fig. 5 A commonly recognized standard for life loss tolerable risk), and societal incremental life safety risk expressed as an averaged ALL. As an example, some agencies use two major tolerable risk indices to justify the IDF selection including averaged AFP of a dam (e.g., AFP $\leq 1.0 \times 10^{-4}$/year), and a resulting ALL (e.g., ALL $\leq 1.0 \times 10^{-4}$ lives/year). As examples, some merits of RIDM approach compared to the ICA method are illustrated in Table 2 Examples of Advantages of RIDM Approach over ICA Method from a practical perspective on how this approach works more realistically for an advanced IDF study.

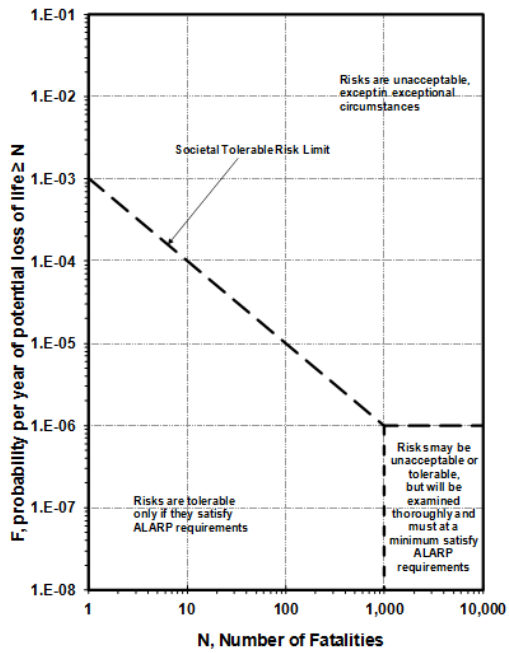


Fig. 5 A commonly recognized standard for life loss tolerable risk ("ALARP": As Low As Reasonably Practical" - the residual risks can be cost effectively reduced further)

Table 2.1 One Example of Advantages of RIDM Approach over Incremental Consequence Approach Method

ITEM	RIDM APPROACH	ICA METHOD
Dam Failure Mechanism Rationalization		
Consideration and evaluation of dam PFMs on critical uncertain sequential factors	More realistically sequential occurrence probabilities estimated as needed based on a flood event tree risk model in which loading, response and consequence of dam failure are represented by levels of branching	Subjective, conservative overall assumptions usually made on one single PFM without specifically describing the failure mode's sequential physical process
Measurement of a PFM parameter's variation	The variation considered by an uncertainty analysis (i.e., risk analysis)	A deterministic way used through sensitivity analyses
Judgment on likelihoods of PFMs occurrence	Numerical engineering judgment by quantified risk analysis based on reasonable representation of probabilities of "System Response Probability (SRP)"	Best engineering judgment on likelihoods of PFM categories I/II (most or considered but not most significant PFMs) but lacking consistency without clear criteria
Assumption on dam overtopping failure depth (i.e. the "threshold inflow flood" depth) based on factors of duration, down-stream slope protection, flow velocity, etc.	Assuming several most likely overflow depths with varied probabilities to fail the dam matching various flood magnitudes of the rising limb of a flood hydrograph regardless its frequency magnitude	Assuming a single flood frequency based conservative overtopping flow depth, some even overly conservatively assuming at a reservoir peak level

Dam breach size	Varied cases of multiple assumed sizes with individual probabilities while actual size remains uncertain	A method simplified as one single size causing a worst inundation scenario through a sensitivity analysis which may be overly conservative
Uncertainties on structural component functions	Gate reliability, spillway debris plugging, etc. driven by probabilities based on historical records	Dam structural component functions usually assumed as designed without flexibility

Table 2.2 Three Examples of Advantages of RIDM Approach over Incremental Consequence Approach Method

ITEM	RIDM APPROACH	ICA METHOD
Consequence Estimation		
Consequence model of life and property loss estimates in terms of downstream structures	Life and property loss estimates associated with each end node of the probability based event trees	Life and property loss estimates as a lump sum figure
Life loss estimation	Uniform ALL risk basis	One life loss considered equivalent to significant life loss consequence
Justification of IDF		
Risk reduction decision making basis for a selected IDF	Quantitative risk reduction measurements allowing uncertainties judgment and flexibility of IDF by ALARP principle	No overtopping allowed for IDF
Final justified solution	Tolerable risk levels of such as APF/ALL to be satisfied	Analysis result of insignificant inundation incremental rise
Sensitivity analyses for structural and non-structural measures to reduce dam failure hazard potential	Exploring the effects of modifying dam structure and adjusting the evacuation effectiveness	Exploring the effects of adjusting parameters of dam structure breach rather than including evacuation effectiveness
Solutions for Achieving Required IDF		
Justification solutions to an inadequate spillway system	Both structural/non-structural measures such as improving evacuation effectiveness	Structural measures only as a common approach
Risk reduction assessment for acceptable life and property safety risks	Using ALARP principle to evaluate the strength (i.e., adequacy and degree) of justification of risk reduction options (e.g., USBR uses increasing justification to reduce the APF)	Only the required IDF based spillway capacity upgrading as the solution

CASE STUDIES ON SELECTING IDF

Case I study on Incremental Consequence Approach: The ICA initial IDF could be reduced by taking into account the hypothetically added spillway capacity through an iterative process.

Refer to the paper by D. Steines, etc. (2003), which discusses the case of Otter Rapids Dam (Fig. 6 Otter Rapids Dam Built in 1908). The dam was classified as a high hazard potential impounding structure so the prescriptive approach resulting IDF was the PMF of 35,600 cfs. The

reason for a selected relatively smaller IDF than an initial one is that the iterative process of ICA was used to reevaluate the IDF. The IDF is influenced by routing extreme flood events through a hypothetical upgraded total spillway capacity, and vice versa the determined new spillway design is dependent on the reexamined IDF.

In this specific case by adding spillway capacity, through lowering the crest, the reservoir storage would be reduced and the discharge increased for a given flood magnitude. The reduced storage would result in lower reservoir elevations. The increased discharge would result in higher downstream river stages. The differential head between the reservoir and the tailwater would be reduced significantly. Therefore, the incremental rise in the downstream flood elevation due to a dam failure would be reduced. As summarized in Table 3 Example of a Selected IDF through an Iterative Refined Process, the adopted converged IDF is reduced 50% or 13.2% from 35,600 cfs or 20,500 cfs to 17,800 cfs, respectively. Lowering the spillway in this case would not increase the risk to the public by more frequent flooding events.

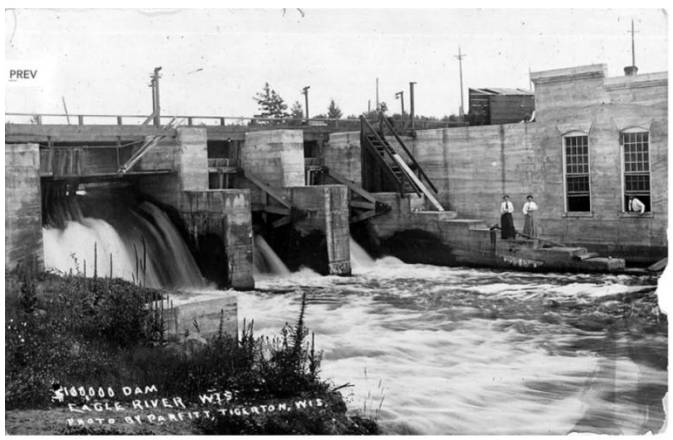


Figure 6. Otter Rapids Dam Built in 1908

Table 3. Example of a Selected Inflow Design Flood through an Iterative Refined Process

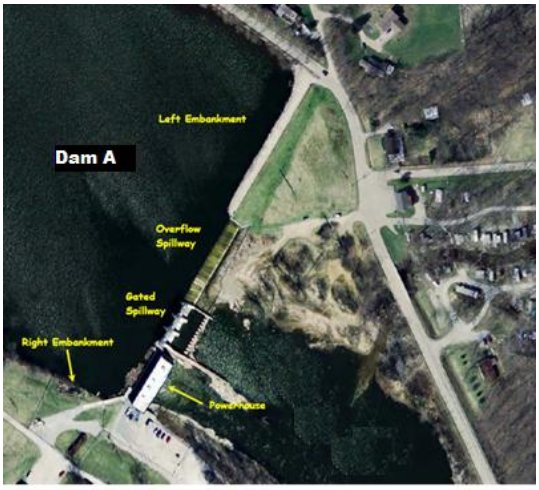
Hazard Classification Based Preliminary IDF (i.e. PMF) (cfs)	ICA's Refined Initial IDF (cfs)	Selected Converged IDF (cfs)	Reduction (%) by Selected Converged IDF	
			Preliminary IDF	Refined Initial IDF
35,600	20, 500	17,800	50.0	13.2

<u>Case II study on RIDM Approach</u>: The PFM based probabilistic consequence driven risk assessment is applied as a tool for the selection of IDF.

Refer to the paper by J. Hedien (2013), which discusses the case of two concrete core-wall earth embankments on the same river (Fig. 7 Upstream and Downstream Tandem Dams A & B Located on a Same River) which have insufficient spillway capacities to pass the preliminary IDFs of PMFs without overtopping and failing the dams. By applying the ICA, a key result in

Table 4 shows the comparison of determined IDFs between based on hypothetical dam failures occurring at dam crest overtopping depths of 10 feet (i.e. at the reservoir peak level) and two feet (best judgment). Another key result shows the comparison of selected IDFs between the ICA and the RIDM method.

The RIDM approach assesses both the probability of the flood loading and the probability of the resulting adverse response to evaluate AFP of each dam. The estimated total risk is the summation of risk from the identified PFMs. Based on the noted acceptable tolerance risk standards in the table, the IDFs of 60,000 cfs and 65,000 cfs were selected for the upstream and downstream dams, respectively. A 99% evacuation effectiveness was assumed (i.e. 1% not evacuated). Reductions from the prescriptive method's to the ICA's and RIDM approach's IDFs are 53% and 71%, respectively as shown in Table 4 IDF Study Results by ICA and RIDM Process for Two Tandem Dams.



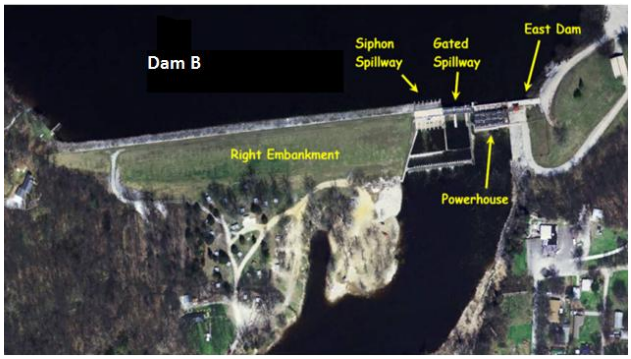


Figure 7. Upstream and Downstream Tandem Dams A & B Located on a Same River

Table 4. Inflow Design Flood Study Results by Incremental Consequence Approach and RIDM Process for Two Tandem Dams (IDF unit: 10^3 cfs)

Tandem Dams	**Preliminary IDF by Prescriptive Method: Governing PMF (Cool Season)**	**ICA Refined IDF: Assumed Overtopping Failure Depths**		**RIDM Approach Refined IDF to Meet Tolerable Risk Levels***	**Final Adopted IDFs**	***For this example, the accepted **Tolerable Risk Levels** set by an agency and a foreign country committee : AFP ≤ 1.0 x 10^{-4}/year (BOR) & ALL ≤ 1.0 x 10^{-4} lives/year (ANCOLD)
		10 feet at Peak Reservoir level	Two Feet			
U/S Dam A	223	129	70	60	60	
D/S Dam B	230	230	135	53	65	

ADVANTAGES AND CHALLENGES OF IDF SELECTION METHODS

The FEMA P-94 guidance document (2013) should be utilized for the appropriateness and applicability of hydrologic safety design criteria for dams. The basic philosophy and principles are described in sufficient detail to promote a compatible approach among state and federal agencies in the design and evaluation of dams from the standpoint of hydrologic safety. Considering many engineering analyses are based on limited information, estimation results may not be fixed but inherently will have a margin of uncertainty and are subject to change as new information is obtained. Whichever IDF selection approach is applied needs to include a periodic review of information such as dam conditions, present and reasonably anticipated future upstream and/or downstream developments for hydrologic characteristics/regime and potential hazard changes, etc. to ensure the validity of the conducted IDF analysis results.

Either a deterministic or probabilistic approach can be used to effectively select the IDF to accommodate a wide variety of situations, available resources, and conditions which might be encountered in practice for a specific dam. For the purpose of comparison, three IDF selection approaches' advantages and challenges are summarized below:

Prescriptive Method: The conventional prescriptive approach is well understood in the dam safety community as a simple and efficient approach intended to be conservative to allow for effectiveness of resource utilization while providing reasonable assurance of the public safety.

Advantages: The intent of this method is to provide straightforward definitions that can be applied uniformly by all federal and state dam safety agencies and can be readily understood and easily accepted by the public for its conservative result. When other two methods described below are costly, risky and challenging to analyze and tackle challenges in a manner outside the normal convention, the prescriptive IDF criteria are recommended.

Challenges: Dam failure assumptions are not based on physical conditions but a worst downstream inundation scenario. As a result, it may be cost prohibitive to design for an overly conservative IDF. The required IDFs in Table 1 are not suitable for the sunny-day failure governed hazard classification cases so that adequate IDFs should be separately studied.

ICA Method: An incremental procedure can provide a framework for evaluating the benefits of mitigating hazards presented by hydrologic deficiencies by routing a wide range of extreme flood magnitudes through the dam. When warranted, engineers can perform additional investigations using advanced analytical tools and methods to more precisely evaluate incremental consequences.

Advantages: 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.

Challenges: A comprehensive iterative process is not usually performed. In addition, the uncertainty associated with the analysis is not quantified, so the resulting IDF is usually more conservative than further realistically based RIDM result.

RIDM Process Method: The risk driven resulting IDF is often determined using a sliding scale between a lower threshold flood event and the maximum theoretical event.

Advantages: Applying this method is an unconventional approach to assess how safe a dam is and is also able to compare with other public safety risks in an understandable, consistent fashion. The uncertainty associated with the analysis is specifically reflected as a probability based consideration and analysis of information rather than conservative unquantified assumptions. Thus, the RIDM selected IDF is often smaller than the other two methods. The computed risks for various hydrologic loading conditions are compared against tolerable risk guidelines. The objective is to reduce risks below a tolerable risk limit. Better data would enable to reduce subjectivity significantly in risk analysis and decision-making. The consequence risk may be more reliably estimated considering the potential inundated structure has been evacuated before the failure of a dam by assuming a certain evacuation effectiveness.

Challenges: Although the present trend appears to be in such a direction of practice, major challenges of RIDM approach include below:
(1) Technical Challenges: Many agencies have to overcome the deterministic mindset and may not have the resources or training necessary to conduct or review such a comprehensive probable flood hazard analysis (PFHA); opposite to data based statistical objective probability, quantitative risk is largely subjective and almost entirely a matter of judgment by limited experts; reliable data on dams, dam components, and operations are generally not available to meet specific needs of risk assessments for individual dams or even components of dam systems;
(2) Difficult to Administer: The considerable variety in risk-based analysis criteria will complicate any precise comparisons between criteria used by different agencies. It will also result in a variation or imbalance of risk tolerances with regards to dam safety throughout the country. Thus, widely acceptable, defensible guidelines for consistent methods and uniform risk tolerance need to be established. Moreover, because risk may change with time, reevaluating risk on a periodic basis is needed; and
(3) Resources Consuming: The staff, cost and time resources required are much more than the other two IDF study methods.

CONCLUSIONS AND SUGGESTIONS

- Each of three IDF selection methods has its individual concepts, principles, merits and disadvantages. However, if the IDF value resulting from the ICA method may have a potential to be significantly reduced from the prescriptive method, then an iterative process needs to be completed, or a full range of risks based RIDM method can be used, in order to ensure an optimal IDF value.
- Each agency has a unique authority, mission, and management practice. The FEMA P-94 guidance points to individual agency processes for agency specific guidance on the definition of IDF based on incremental consequences and how to use risks to inform decisions. However, the consistency and uniformity of guidance between them is needed in the long run for a same standard of dam safety risk management across the nation.
- RIDM based on qualitative and quantitative risk assessments is the process of using information about risk to assist in decision-making with regards to a wide variety of dam safety activities. This would include decisions regarding a variety of actions such as: IDF selection; frequency of inspection; need for increased instrumentation; need for additional technical studies; assessment of how uncertainties affect the level of risk; sufficiency of evidence to support the need for remedial action; selection of a remedial action to address an

identified deficiency; prioritization of projects or actions; the sequence in which remedial actions are taken at a given dam or group of dams, etc.

- Risk is all about uncertainties, so all sources of uncertainty should be considered. Risk assessment should be unbiased and risk reduction should make economic sense or life loss reduction ALARP. The application of RIDM is a technical challenge but also an opportunity to deliberate more realistic conditions for obtaining a more refined IDF value. A requirement for acceptance of the estimated IDF 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.
- There are certain principles that are held in common for consistency and correctness about the urgency of completing required dam safety actions which should be commensurate with the level of risk for varied safety aspects such as adequate interim risk reductions before upgrading existing spillways to accommodate required IDFs. However, what the defined level is needs collaborative efforts between agencies. (Available references: the USACE – DSAC (Dam Safety Action Classification) and USBR – DSPR (Dam Safety Priority Rating)).
- Hazard potential classification is based on consequences of dam failure irrespective the cause of failure. The FEMA P-94 document's Table 2, "IDF Requirements for Dams Using a Prescriptive Approach" and its foot notes indicate required and recommended minimum IDFs. The notes can clarify that this table is based on flood scenarios, not sunny-day failures. Or the table title can be clarified as "under Flood Loadings" like Table 1 in this paper.
- Some agencies use the term "spillway design flood" (SDF) as IDF. In application, both terminologies can mean differently for some cases. For instance, if the derived IDF for an existing or planned dam is smaller or greater than the flood used for the design of spillway capacity, then the used design flood should be appropriately called SDF rather than IDF.
- Climate change concerns are addressed in the P-94 document. Experts argue that engineers can improve climate change resiliency incrementally by making small changes with minimal additional investment to the projects they are already planning or constructing. In addition, because the effects of climate change won't be the same in all areas and funding for infrastructure projects is limited, it would be advisable to determine the areas of highest risk to critical infrastructure when deciding how to allocate adaptation and mitigation spending.

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