APPLICATION OF THE INFLOW DESIGN FLOOD ANALYSIS ALTERNATIVE TO NRCS TR-60 DESIGN STORM CRITERIA FOR HIGH HAZARD DAMS

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Abstract

The United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) publication Earth Dams and Reservoirs TR-60 (2005) describes design procedures and provides requirements for planning and designing earth dams and associated spillways to ensure consistent performance of these dams. For high hazard dams, TR-60 specifies that the probable maximum precipitation (PMP) event be used to generate the freeboard hydrograph (FBH) storm. The FBH is used to analyze the integrity (erosion) of the earthen materials in the auxiliary spillway and set the height of the dam.

TR-60 requirements may not be suitable for all sites, particularly where physical site constraints may preclude construction or rehabilitation of a high hazard dam with the capacity to pass the PMP generated FBH. For these situations, TR-60 permits the use of an inflow design flood (IDF) analysis to determine the FBH design storm based on an event smaller than the PMP for high hazard dams, "provided downstream land use controls exist to prevent voiding incremental risk assumptions after the dam is completed" (NRCS 2005). IDF should not be considered unless there is a limiting site constraint and may not be used solely for the purpose of building a smaller dam. Neither should IDF be considered if the inundation area downstream of a dam based on failure (breach) of the dam during a PMP rainfall event cannot be zoned or otherwise protected from development.

IDF analysis is described in the Federal Emergency Management Agency (FEMA) Publication 94, Federal Guidelines for Dam Safety – Selecting and Accommodating Inflow Design Floods (FEMA 2004). FEMA 94 guidelines provide thorough and consistent procedures for selecting and accommodating the IDF. In IDF analysis, intensive and rigorous hydrologic evaluations are made of the dam for a without-failure condition and a with-failure condition. The results of these evaluations are compared to determine if the incremental increase in water surface elevation downstream due to failure of a dam presents an unacceptable threat. It is an iterative process whereby the procedure is repeated until the flood inflow condition is identified such that a failure at that flow, or larger flows (up to the probable maximum flood, or PMF), no longer result in unacceptable additional consequences. The resultant flood flow is the IDF for the project. The maximum IDF is always the PMF, but in many cases the IDF will be less than the PMF. In both TR-60 design and IDF analysis, it is taken to be understood that when translated to runoff, the estimated flood flow from the PMP rainfall is known as the PMF.

In order to ensure consistency with NRCS policy, the NRCS approach to IDF analysis differs slightly in comparison to what is described in FEMA 94. This paper provides suggestions to aid

the modeler in making an IDF analysis consistent with NRCS policies, addresses the considerations that should be given to using an IDF approach, and suggests appropriate documentation.

BACKGROUND

Since the Flood Control Act of 1944 (PL78-534) and Watershed Protection and Flood Control Act of 1953 (PL83-566) were enacted, the Natural Resources Conservation Service (NRCS) has assisted with the design and installation of over 11,000 small floodwater retarding dams in 47 states. Agency policy for design has evolved since 1944 and is currently found in Technical Release No. 60, Earth Dams and Reservoirs (TR-60) which contains the hydrologic requirements for analyzing the erosion resistance of the earthen materials in the auxiliary spillways and determining height of dams based on hazard classification. Dam hazard classification describes the potential for property damage and/or threat to loss of life downstream of the dam in the event of dam failure.

The original watershed dams built in the 1940s, 1950s and 1960s are reaching the end of their economic lives. The majority of these dams were originally constructed as low hazard dams with a design life of 50 years. In the 50 years or more since many of these dams were built, changes in the watershed and aging of the dam components have resulted in public safety concerns. An NRCS fact sheet titled, “Overview - Rehabilitation of Aging Dams” (NRCS 2003) describes some of the common problems and concerns associated with aging dams. Those problems and concerns are summarized in Table 1.

Table 1. Problems and Concerns of Aging Dams

Problem	Concern
Deteriorating metal pipes and structural components [including concrete components]	Metal rusts and fails which could lead to failure of the embankment as a result of internal erosion
Sediment-filled reservoirs	Sediment displaces storage of floodwaters
	Some sediments may have contaminants from chemicals in runoff from upstream areas
Development both up- and down-stream of the dams	Roofs and concrete streets and sidewalks increase the volume of runoff to the dam resulting in insufficient floodwater storage behind the dam putting the dam at risk for overtopping and failure

Development in the watershed both up-and downstream of the dams is perhaps the greatest problem of those listed in Table 1. Most dams originally built in rural areas with the intent of protecting agricultural, and not residential, areas, do not meet current high hazard design criteria. Additionally, over the years, population growth and urban sprawl have led to development in the areas surrounding the water upstream of the dam, sometimes encroaching on the defined flood pool; and in areas downstream of the dam in the potential breach inundation zone, or in areas that would have otherwise been flooded if the dam were not in place. Oftentimes, residents downstream of a dam are unaware of the hazard this presents in the event the dam were to fail.

In order to address public health and safety the Watershed Rehabilitation Amendments to the Watershed Protection and Flood Prevention Act were authorized by Congress in 2000. Through this program, the dams are analyzed to determine the potential for rehabilitation which can

include extending the life of the dam; addressing and making repairs to deteriorated components; repairing damage from catastrophic storm events; upgrading the dam to meet dam safety requirements (most often a conversion from a low or significant hazard dam to a high hazard dam); or decommissioning and removing the dam.

CURRENT TR-60 CRITERIA FOR HIGH HAZARD DAMS

According to NRCS policy found in 210-V-NEM (National Engineering Manual), Part 520, Subpart C, DAMS (NRCS 1982), "Dams are classified according to the potential hazard to life and property if the dam should suddenly breach or fail. Existing and future downstream development including controls for future development must be considered when classifying the dam. The classification of a dam is determined only by the potential hazard from failure, not by the criteria." Table 2 defines the hazard classes, low, significant, and high (NRCS 2005). It is important to note that the potential of loss of a single life is sufficient to classify a dam as high hazard under NRCS policy. This differs slightly in comparison to policies of some other Federal agencies. It is also important to note that breach analysis is not a required component in determining hazard classification under NRCS policy. However, if a breach routing is used as part of the classification process, it should be included with the documentation of the classification.

Table 2. NRCS - Hazard Classes of Dams

Hazard Class	Description
Low	Dams located in rural or agricultural areas where failure may damage farm buildings, agricultural land, or township and country roads
Significant	Dams located in predominantly rural or agricultural areas where failure may damage isolated homes, main highways or minor railroads, or cause interruption of use or service of relatively important public utilities.
High	Dams located where failure may cause loss of life, serious damage to homes, industrial and commercial buildings, important public utilities, main highways, or railroads.

Each hazard class has a unique set of hydrologic criteria, found in TR-60, for sizing the dam spillways and determining the top of dam elevation. The NRCS hydrologic criteria for analysis and design of all single and/or multiple purpose high hazard dams are found in Table 3. In general, the principal spillway hydrograph (PSH) is used to determine the elevation of the auxiliary spillway, accounting for flow through the principal spillway. The auxiliary spillway hydrograph, or stability design hydrograph (SDH), is used to size the auxiliary spillway and evaluate the stability of the vegetation (resistance to stripping by water flow) in the spillway. And the freeboard hydrograph is used to analyze the integrity (resistance to erosion) of the earthen auxiliary spillway materials and set the top of dam elevation.

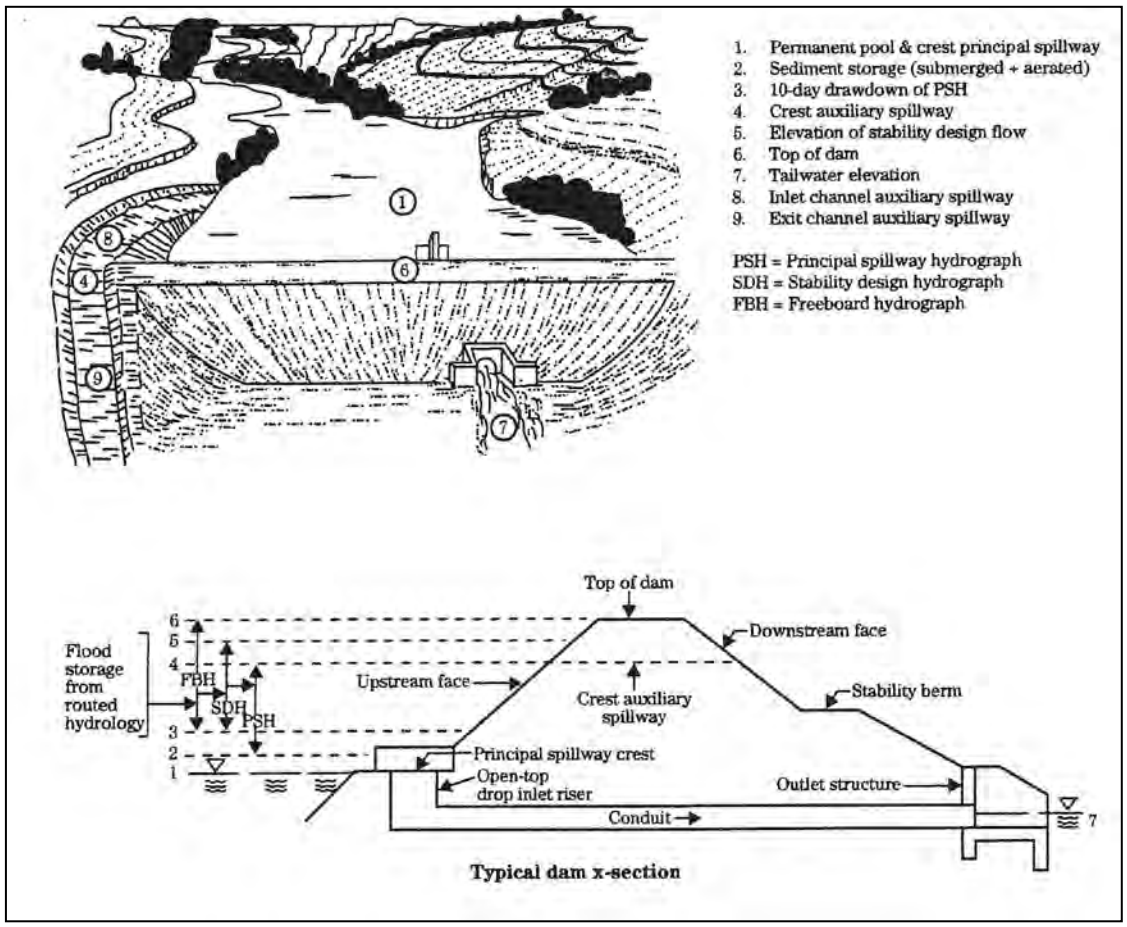
Routing of the PSH starts at the elevation of total sediment storage in the dam, while the routing of both the SDH and FBH starts at a 10-day drawdown elevation determined by routing the PSH storm and then allowing the dam to drawdown for a period of 10-days prior to routing the SDH and/or FBH events. This concept is illustrated in Figure 1. NRCS' National Engineering Handbook, Part 630, Hydrology, Chapter 21, Design Hydrographs (NEH 630.21), (NRCS 2008) defines the technical procedures used in developing the runoff hydrographs for these precipitation events.

Table 3. NRCS Hydrologic Criteria for Analysis and Design of High Hazard Dams

	Precipitation data	Purpose
Principal Spillway Hydrograph (PSH)	1% chance (or P100[1/])	Used to set auxiliary spillway elevation
Auxiliary Spillway Hydrograph (SDH)	P100+0.26(PMP[2/]-P100)	Used to evaluate the strength of vegetation (resistance to stripping) in the auxiliary spillway and to set the width of the auxiliary spillway
Freeboard Hydrograph (FBH)	PMP	Used to evaluate the integrity (resistance to erosion) of earth spillway materials and to set top of dam elevation

[1/] P100 = Precipitation for 100-year return period or 1% chance event.
[2/] PMP = Probable maximum precipitation

Figure 1. NRCS Dam Terminology
Source: SITES 2005 - Water Resources Site Analysis Computer Program User Guide (NRCS 2007)



Where site constraints prohibit modification of the dam and spillway to safely pass the FBH, TR-60 permits the IDF analysis procedure. IDF analysis is described in the Federal Emergency Management Agency (FEMA) Publication 94, Federal Guidelines for Dam Safety – Selecting and Accommodating Inflow Design Floods (FEMA 2004). While the NRCS approach to IDF is slightly different than that described in FEMA 94, through an IDF analysis, it is possible to justify the use of a storm smaller than the PMP to size the auxiliary spillway and determine dam height for High Hazard dams, "provided downstream land use controls exist to prevent voiding incremental risk assumptions after the dam is completed" (NRCS 2005).

FEMA 94 GUIDELINES FOR INFLOW DESIGN FLOOD ANALYSIS

FEMA 94 was developed by the Interagency Committee on Dam Safety (ICODS), consisting of representatives from all Federal agencies with authority to design, construct, and/or maintain dams. FEMA 94 is intended, "...to provide thorough and consistent procedures for selecting and accommodating Inflow Design Floods (IDFs);" and further defines the IDF as, "..the flood flow above which the incremental increase in water surface elevation downstream due to failure of a dam or other water retaining dam is no longer considered to present an unacceptable additional downstream threat."

It is important to understand the meaning of the terms, incremental increase, consequences of failure, and acceptable or unacceptable consequences. Incremental increase is the difference between the flood wave elevation for the storm event under analysis and the breach wave for that same storm event. For example, the PMP event, the incremental increase is the difference between the flood wave elevation caused by the PMP event and the breach wave elevation caused by failure of the dam during the PMP event. Incremental increase may also be referred to as incremental effects, or incremental rise.

In general, if the incremental increase is less than 2 feet for the entire stream reach downstream of the dam under review, the incremental increase may be considered acceptable. Some engineering judgment and further evaluations may be necessary to determine whether or not differences of greater than 2 feet are acceptable, but in most circumstances an incremental increase of greater than 2 feet will not be considered acceptable by NRCS.

Consequences of dam failure are defined by the incremental increase together with the number of houses or inhabitable structures impacted by the breach wave compared to the number of houses or inhabitable structures impacted by the flood wave from the same storm event. For purposes of this paper, consequences of failure will be taken to refer specifically to the number of houses or other inhabitable structures impacted by the breach wave compared to the number of houses or inhabitable structures impacted by the flood wave from the storm event.

Acceptability may be judged by looking at the consequences of failure. According to FEMA 94, Acceptable additional consequences occur where "There are permanent human habitations within the potential hazard area that would be affected by failure of the dam, but there would be no significant incremental increase in the threat to life or property resulting from the occurrence of a failure during floods larger than the proposed IDF." In short, acceptability might best defined as that point where a smaller design storm results in the same, but not less, damages than are caused by the PMP event.

Depending upon the types and numbers of houses or inhabitable structures impacted by the storm flood wave and the storm breach wave, consequences may be considered unacceptable with as little as 0.5 feet difference between the flood wave and breach wave. One indicator of acceptability is the number of homes impacted by the larger storm event in comparison to a smaller storm event. For example, if the PMP flood evaluation shows a total of 30 homes impacted by the flood and an additional 5 impacted by the breach; and a 0.75PMP evaluation shows a total of 10 homes impacted by the flood and an additional 10 impacted by the breach,

the consequences of using the smaller event would be unacceptable because the larger storm, impacts so many additional homes.

FEMA 94 conditions the acceptability by further saying that "..no permanent human habitations, known national security installations or commercial or industrial development, nor are such habitations or commercial or industrial developments projected to occur within the potential hazard area in the foreseeable future." In other words, a storm event smaller than the PMP may be used, but there must be no less damages in the breach inundation zone compared to what will occur during the PMP event so long as no changes will occur in the breach inundation zone. The best way to assure that no such changes will occur is to zone the breach inundation zone for no further development. Unless the area can be zoned or otherwise protected from development, use of an IDF smaller than the PMP will be considered unacceptable by NRCS.

APPLICATION OF FEMA 94 GUIDELINES TO NRCS PROJECTS

The following guidance is given as a step-by-step procedure for making an IDF analysis for NRCS projects. These steps are illustrated in the flowchart in Figure 2. The decision points in Figure 2, as represented by the diamond shapes, define those locations where decisions on stopping the analysis or continuing with further analysis is beneficial during the IDF analysis process.

Step 1: Route the PMP event through the dam starting at the 10-day drawdown elevation and normal streamflow conditions prevailing at the start of the storm. Develop a flood wave profile to determine flood wave elevations and an inundation map to determine the number of structures (houses and other buildings) impacted by the event.

Step 2: Conduct breach analysis of the dam for the PMP event, starting at the 10-day drawdown elevation and assuming normal streamflow conditions prevail at the start of the storm. Route to a point downstream where the flood is no longer considered a threat. (One suggestion is this point be defined as that location where the flood wave is contained within the 1% chance - 100-year - floodplain as defined on FEMA Flood Insurance Rate Maps -FIRMs.) Develop a breach wave profile to determine breach wave elevations and an inundation map to determine the number of structures impacted by the event.

Step 3: Determine the difference between the flood wave elevations from Step 1 and the breach wave elevations from Step 2. This represents the incremental increase.

Compare the numbers of structures impacted by the PMP storm event to the number of structure impacted by the breach analysis of the dam during the PMP event. This represents the consequences of failure of the dam.

If the difference between the breach wave elevation and the flood wave elevation is less than or equal to two feet along the entire stream reach downstream of the dam, a smaller storm may be justified. Continue to Step 4.

If the difference between the breach wave elevation and the flood wave elevation is greater than 2 feet anywhere along the stream reach downstream of the dam, use of a smaller storm is not justified if any residences or other inhabitable buildings are impacted and the PMP event is identified as the design storm.

Step 4: Select an increment of the PMP event as the proposed IDF (for example 0.75 PMP) as the selected storm event. Route that storm event through the dam starting at the 10-day drawdown elevation and normal streamflow conditions prevailing at the start of the storm. Develop the flood wave profile to determine flood wave elevations and an inundation map to determine the number of structures impacted by the event.

Step 5: Conduct a breach analysis of the dam for the increment of the PMP event from Step 4, assuming 10-day drawdown elevation water surface level behind the dam and normal streamflow conditions prevail at the start of the storm. Route to a point downstream where the flood is no longer considered a threat. Develop a breach wave profile to determine breach wave elevations and an inundation map to determine the number of structures impacted by the event.

Step 6: Determine the difference between the flood wave elevations from Step 4 and the breach wave elevations from Step 5 to determine the incremental increase.

Compare the numbers of structures impacted by the selected storm event to the number of structure impacted by the breach analysis of the dam during the selected storm event to determine the consequences of failure of the dam.

If the incremental increase along entire stream reach below the dam is less than two feet continue to Step 7.

If the difference between the breach wave elevation and flood wave elevation is greater than 2 feet anywhere along the stream reach below the dam, use of the selected storm is not justified. However, use of a storm larger than the currently selected event, but smaller than the PMP may still be justified. Return to Step 4 and select a different increment of the PMP.

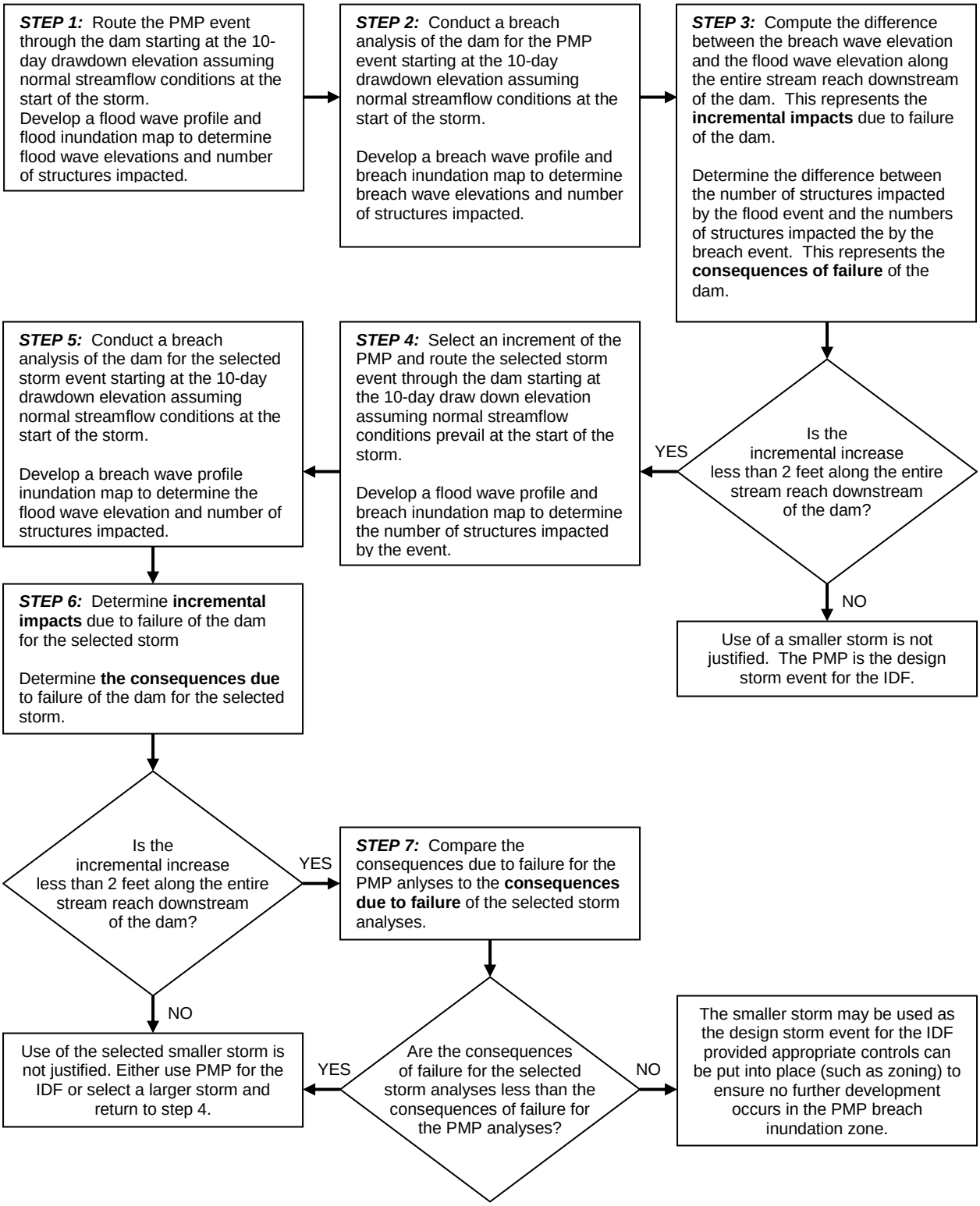
Step 7: Compare the consequences of failure from the PMP analyses to the consequences of failure from the analyses of the selected storm.

If consequences of failure for the selected storm are less than the consequences of failure for the PMP event, the PMP event is the IDF. Note that a storm larger than the selected interval but smaller than the PMP may still be justified. If desired, return to Step 4 and select a different increment of the PMP to evaluate.

If the consequences of failure for the selected storm interval are the same as the consequences of failure for the PMP analyses, the selected interval may be used as the IDF event.

Figure 2 presents a flowchart illustrating the steps in making an inflow design flood including the decision points for determining whether or not to proceed with further analysis.

Figure 2. Flowchart for Inflow Design Flood analysis and Decision Matrix for NRCS projects



NRCS APPROACH TO IDF COMPARED TO FEMA 94 GUIDELINES

With many NRCS rehabilitation projects, increasing the top of dam elevation results in inundation of homes or other inhabitable dwellings built above the dam during design floods. In many cases rehabilitation projects have included principal spillway and/or auxiliary spillway modifications to accommodate design flows without raising the top of dam elevation; but often, even with modifications to the principal and/or auxiliary spillways, the top of dam elevation does increase with the PMP design storm. It is those situations where utilization of IDF as an alternative to TR-60 criteria has most often been pursued.

The NRCS approach to IDF differs somewhat in comparison to the recommendations found in the FEMA 94 guidelines. To properly utilize the IDF concept according to FEMA 94, a breach analysis is required. This is unlike the NRCS procedure which strictly defines the design event as the flood event resulting from the PMP, or the probable maximum flood (PMF).

FEMA 94 presents suggested guidance for determining the IDF assuming one starts with a storm smaller than PMP and increases the size of the storm until the point that the larger flood could result in unacceptable consequences. FEMA 94 does not specify a lower limit, but does specify an upper limit with the guidance that it is not necessary to use a storm event larger than the PMP as the design storm. This differs from the NRCS interpretation because the standard NRCS design flood for high hazard dams is the PMP. Therefore, IDF analysis in NRCS starts with the PMP event and works backwards to the point where the smaller storm has approximately the same impact as the PMP. There must be a limiting site constraint to justify using an IDF approach. IDF cannot be used simply to build a smaller dam.

With this in mind, the modeler needs to make certain that the selected IDF storm event is not smaller than the NRCS requirement for the SDH storm of the high hazard dam or the FBH storm of a significant hazard dam. As an example, take the case of an area where the 24-hour PMP event is 35” and the P100, 24-hour event is 7”. The SDH design storm requirement for a high hazard dam as given in TR-60 is: P100 + 0.26 (PMP - P100) = 7 + 0.26 (35 - 7) = 14.28” which equates to about 41% of the PMP event. For this same area, the FBH design storm requirement for a significant hazard dam as given in TR-60 is: P100 + 0.40 (PMP - P100) = 7 + 0.40 (35 - 7) = 18.2”, which equates to 52% of the PMP event. For this location, the minimum IDF could be no smaller than 18.2 inches for a 24-hour storm.

In general, FEMA 94 guidelines recommend starting the design storm routing with the reservoir at the normal maximum pool elevation. NRCS criteria require starting the design storm routing at the 10-day draw down elevation.

Table 4 summarizes some of the differences between the FEMA 94 design storm analysis recommendations and the NRCS design storm analysis.

Table 4. Differences between NRCS Design Storm Analysis and FEMA 94 Recommendations for Inflow Design Flood Analysis

	NRCS Design Storm Analysis	**FEMA 94 Recommendations**
Breach Analysis	Not required. However, should be included with supporting documentation if used in determining hazard classification.	Required as part of making the IDF determination.
Determination of appropriate design storm	Start with PMP event and work backwards to smaller storms.	Start with smaller storms and work upwards to PMP (maximum event).
	Selected IDF can be no smaller than SDH storm for high hazard dam, nor smaller than FBH for significant hazard dam.	No lower limit.
Reservoir water surface elevation from which to start routing	10-day drawdown elevation	Normal maximum pool elevation (typically lowest ungated auxiliary spillway elevation).

DOCUMENTATION OF IDF ANALYSIS

IDF analysis can be and has successfully been used within NRCS to document the use of a design storm smaller than the PMP for high hazard dams. To do so, states must submit a request for concurrence to NRCS headquarters along with supporting documentation to support the decision to use a storm smaller than PMP as the IDF. Appropriate documentation includes the following information:

- A brief statement describing the history of project and the dam under consideration addressing specifically why it is necessary that a storm event smaller than the PMP be considered.
- Flood wave profile and flood inundation map for the PMP storm event.
- Breach wave profile and breach inundation map for the PMP storm event.
- Identification of all houses and inhabitable structures within the flood wave and breach wave inundation below the dam for the PMP storm event along with water surface elevations at those structures for the flood and breach events.
- Flood wave profile and flood inundation map for the proposed IDF storm event.
- Breach wave profile and breach inundation map for the proposed IDF storm event.
- Identification of all houses and inhabitable structures within the flood wave and breach wave inundation areas below the dam for the proposed IDF storm event along with water surface elevations at those structures for the flood and breach events.
- Summary of the consequences of failure for the PMP event compared to the consequences of failure for the proposed IDF storm event.

SUMMARY / CONCLUSIONS

The USDA - NRCS publication TR-60 describes design procedures and provides requirements for planning and designing earth dams and associated spillways in order to ensure consistent performance of these dams. For high hazard dams, TR-60 specifies the probable maximum precipitation (PMP) event for FBH which is used to analyze the integrity (erosion) of the earthen materials in the auxiliary spillway and set the height of the dam. For sites where the PMP criteria as the FBH storm event cannot be met, an IDF analysis may be appropriate bearing in

mind that IDF may not be used solely for the purpose of building a smaller dam. A limiting site constraint must exist to consider using IDF for an NRCS project. Additionally, unless the area can be zoned or otherwise protected from development, use of an IDF smaller than the PMP will be considered unacceptable by NRCS.

IDF analysis, as described in FEMA 94, provides a thorough and consistent procedure for selecting and accommodating an IDF storm. However, the NRCS approach to IDF differs slightly from that described in FEMA 94. For NRCS projects states must submit a request for concurrence and supporting IDF analysis documentation to NRCS headquarters to use a storm smaller than PMP as the design event.

In preparing documentation, the modeler must be aware of the technical requirements for using an IDF approach including the requirement to evaluate both the flood event and flood with breach event for the PMP and proposed IDF events; starting with evaluation of the PMP storm and PMP with breach storm as the basis for the IDF analysis and working backwards to smaller storms; checking to ensure the selected IDF is not smaller then the NRCS SDH storm for a high hazard dam, nor smaller than NRCS FBH storm for a significant hazard dam; and starting reservoir routings at the 10-day drawdown elevation.

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