FERC Engineering Guidelines
Risk-Informed Decision Making

Chapter R21

Dam Breach Analysis

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Chapter R21 – Dam Breach Analysis

R21.1 Introduction

Dam breach analyses are used to estimate the potential hazards associated with a failure of a project structure/feature. Dam breach inundation analyses include the following elements: estimation of the dam breach parameters, estimation of the dam breach outflow hydrograph; routing of the dam breach hydrograph downstream; and estimation of downstream inundation extent and severity.

Dam breach prediction models are used to estimate the geometry and formation time of a dam breach. Typically, dam breach prediction models are based on empirical data derived from a number of mostly earth and rockfill dam failures case studies. The available empirical equations relate the dam breach parameters to properties of the dam and reservoir such as height, dam type and its erodibility, volume impounded, and shape of the reservoir.

The most common methods of dam breach outflow hydrograph routing are either one-dimensional or two-dimensional with the latter used when higher levels of accuracy are required or for non-channelized flow situations. For most dam breach analyses, one-dimensional computer software is used. Geographic Information Systems (GIS) are the current state-of-practice for inundation mapping, especially if the dam breach analysis involves populated areas and/or other high potential consequences areas.

The methodologies described in these guidelines are intended to highlight the current state-of-practice tools available to the qualified engineer experienced in hydrology and hydraulics. It remains incumbent on the engineer to exercise sound engineering judgment in selecting the appropriate dam breach analysis type and the required level of detail in modeling and inundation mapping to ensure that they are commensurate with the anticipated consequences, as well as consider how the study results can best be used to aid in determining consequences for a risk-informed decision. Sensitivity analyses for those dam breach analyses with significant impacts are almost always necessary to evaluate the results over the range of credibly possible input parameters. All studies submitted to the FERC should contain a summary of the design assumptions, design analyses, and methodologies used.

R21.2 Dam Breach Analysis Purpose

In the context of risk informed decision making, dam breach analyses are needed for determining the potential consequences of a failure mode's occurrence over a range of loading conditions. It can also be used as part of a dam's remedial design process in the selection of alternatives. The type of analysis as well as the level of accuracy required by the results must be scalable to the potential hazards and complexity of the downstream area being modeled. For risk informed decision making, the dam breach parameters are based on best estimates from similar case studies considering the range of possible values associated with the potential failure mode's specifics and the dam's characteristics.

The results of dam breach analyses are typically tabulated in spreadsheet form and plotted on inundation maps of sufficient detail to understand the potential consequences associated with life loss and economics. These can then be used to formulate estimates of the potential for loss of human life and the economic impacts of resulting damages; however, analysis of social and environmental impacts, damage to national security installations, and political and legal ramifications (which are not easily evaluated and are based on subjective or qualitative evaluation) may be required.

R21.3 Levels of Risk - Scalability

The degree of study and evaluation required to sufficiently define the impacts of dam failure will vary with the extent of existing and potential downstream development, the size of reservoir (depth and storage volume), type of dam, and purpose of the study. Evaluation of the river reach and areas impacted by a dam failure should proceed until sufficient information is generated to reach a sound decision or there is a good understanding of the consequences of failure. To ensure that the proposed study's purpose is accomplished, scalability requirements should also be addressed prior to commencing a dam breach study in a scoping meeting. This discussion should also include sensitivity analyses to address uncertainty. A tiered approach to scalability is outlined in Table 1 that generalizes the different levels of analysis required for each tier. Since the anticipated consequences dictate the level of effort, the levels used should be adjusted as needed for the specifics of the study's purpose.

For screening level consequence estimation, for a dam with little uncertainty in the possible impacts, it could be the case that the existing dam breach models are sufficient. For most other more in-depth analyses new models will need to be run for a particular failure mode. This should be discussed during the scoping meeting discussed above.

Table R21-1: Generalized Scalability for Dam Breach Analysis

Level of Effort	Breach parameter and hydrograph estimation	Computational Methods	Breach Hydrograph Routing	Dam Breach Analysis Output
Screening	Empirical equations or Table 1 from Appendix A of Chapter 2 (FERC, 1993)	SMPDBRK, HEC-1, HEC-HMS, SITES/WinDamB, HEC-RAS	Steady-state Or Hydrologic Routing	Table of critical cross-sections
Typical	Empirical equations or physically based models	Combination or exclusively HEC-RAS and SITES/ WinDamB	Unsteady-State	Table of critical cross-sections, Inundation maps with USGS or GIS base maps
Advanced	Empirical equations, physically based models, or probabilistic approach using a Monte Carlo analysis to determine the dam breach parameters	Combination or exclusively FLO2D, Mike 21 (computational fluid dynamics) for non-channelized areas and HEC-RAS for lower consequences, well channelized areas	Unsteady-State	High resolution GIS base maps created from high resolution survey data

R21.4 Dam Breach Analysis Modeling

Although not an exhaustive discussion, some of the primary considerations in creating the dam breach analysis model are discussed in the following sections.

R21.4.1 Dam Breach Parameter Estimation

Methods used for estimating dam breach hydrographs require selecting the size, shape, and time of breach development to its final dimensions. It is important to note that depending on the type of computer modeling, the treatment of breach development time may be different from the case studies. The shape of the peak breach outflow hydrograph is influenced by the storage in the impoundment at the time of breach, reservoir inflow at the time of breach, size of the dam, and most importantly, the dam type's erodibility and/or mode of assumed failure. For instance, a brittle concrete or structural failure will have a much faster time of breach development as compared to an overtopping failure of a large, cohesive, well compacted, and well vegetated embankment. Since the outflow hydrograph can vary widely depending upon these factors, careful consideration of the dam breach modeling inputs should be agreed upon by the risk team (licensee, consultants, and regulator) prior to commencing the study. Ideally, dam breach analyses should be performed for a specific failure mode, so the breach scenario may be well-understood. For example, if the impacts from a potential failure of a tainter gate are being studied, then breach dimensions would be limited to the dimensions of the gate and the failure mechanism would be based on the potential failure mode. -The breach parameter estimation should strive for realistic assumptions so that the modeling output is useful to risk informed decision making.

For modeling dam breaches associated with structural failure that results in a rapid removal of the project feature, many of these assumptions are straightforward. Potential overtopping and piping failures are more difficult and require the use of empirically based or probabilistic methods. Empirical dam breach parameters are assumed based on comparisons to similar dam failure case studies. For quick and conservative screening or preliminary applications, see Chapter 2 E.3 – Appendix C, Table 1.

The four most widely used and accepted empirically derived enveloping curves and/or equations for predicting breach parameters are: MacDonald & Langridge – Monopolis (1984), USBR (1988), Von Thun and Gillette (1990), and Froehlich (1995a, 1995b, 2008). These methods have reasonably good correlation when comparing predicted values to actual observed values. There are also computer models based on laboratory testing for the breach development such as NWS BREACH, NRCS SITES and WinDamB that can be used as well for the breach prediction process.

Still, the inherent uncertainty in breach parameter estimation should not be overlooked. Historically, this uncertainty was evaluated by running a range of possible breach parameter sets in a sensitivity analysis, to understand the full range of possible dam breach outcomes, and how sensitive those outcomes were to the range of inputs.

In support of risk informed decision making, a probabilistic approach to dam breach modeling may be considered. A probabilistic dam breach parameter evaluation requires the investigator to assign a probability density function (PDF) to each of the uncertain breach parameters. The PDF could be a simple uniform distribution (for example, the piping initiation elevation, where all elevations might be equally probable), or a more common normal (Gaussian) distribution. By examining the breach parameter predictive equations that apply to the subject dam, understanding probable failure modes and site conditions, and using sound engineering judgment, means and variances can be approximated to define the PDFs.

Once the PDFs are assigned, breach parameters are randomly sampled about those predefined distributions, to assemble a breach parameter set. Each set is run through the dam breach model as a single modeled event called a “realization”, and the resulting peak of the breach outflow hydrograph is stored. This procedure is repeated using a Monte Carlo Approach until statistical convergence is achieved in the results (i.e. the mean and standard deviation of the population set of possible outcomes ceases to change with successive realizations). The population set of breach outflow peaks is then ordered and ranked, and each value is assigned an exceedance probability. This then allows the investigator to prepare exceedance probability inundation maps, rather than static deterministic inundation maps. A simple example of an exceedance probability inundation map is shown in Figure 1 below.

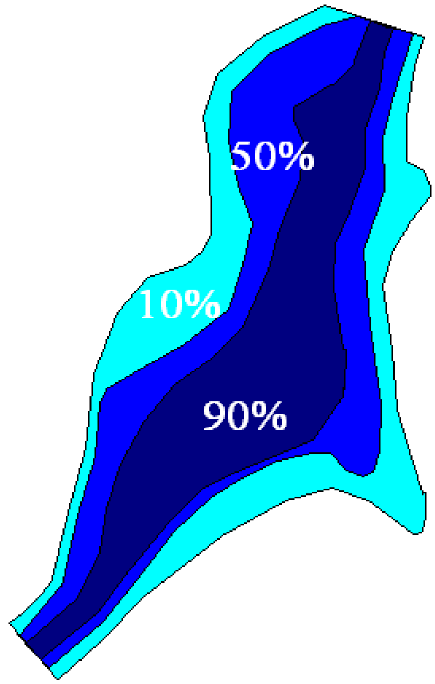

Figure R21-1. Exceedance Probability Inundation Map.

Because of the complexity of this type of analysis, and the large number of realizations required for statistical convergence, the investigator will require significant modeling experience to ensure the dam breach model is efficient and stable over a wide range of breach scenarios. In addition, a basic level of programming experience will help to set up a batch mode run of the dam breach model. More information on probabilistic dam breach modeling can be found in Goodell (2012), Froehlich and Goodell (2012), Froehlich (2008) and Wahl (2004).

Additional information regarding dam breach parameter estimation can be found in Section E.3- Appendix C.

R21.4.2 Dam Breach Model Type

Models to route the flood can be one- or two-dimensional, or can be a combination of both. In general, as the flood plain widens or becomes non-channelized, one-dimensional analysis becomes less reliable. The most commonly used models for estimating both the dam breach outflow hydrograph and routing it downstream are parametric models (HEC-1, HEC-HMS, HEC-RAS, BOSS DAMBRK, FLO 2D, and Mike 21). *Note that the NWS no longer supports DAMBRK and FLDWAV and thus, these computer software programs are not recommended by FERC.* Parametric models can be either hydrologic or hydraulic.

Hydrologic routing programs, such as HEC-1 or HEC-HMS, solve the continuity equation and an analytical or an empirical relationship between storage within the reach and discharge at the model's downstream end. Although they do not account for significant backwater effects, the hydrologic routing models offer the advantages of simplicity, ease of use and computational efficiency. Hydrologic routing models provide attenuated flow hydrographs at locations of interest, but do not provide accurate information on water surface elevations or flow velocities. Also referred to as storage routing, one-dimensional modeling is performed for steady flow conditions ignoring the pressure and acceleration contributions to the total momentum force. Hydrologic routing is typically used in screening level applications.

For most dam breach analyses applications, the recommended method and current state-of-practice involves unsteady flow and dynamic routing. This is known as transient flow or hydraulic routing and is used to predict dam breach wave formation and model downstream progression. The hydraulic routing methods solve and therefore account for the essential momentum forces involved in the rapidly changing flow caused by a dam breach.

For the same outflow hydrograph, the storage or hydrologic routing will usually yields greater attenuation which produces lower discharges and stages downstream than hydraulic or transient flow routing.

R21.4.3 Downstream Floodplain Modeling

Generally speaking, there are two different approaches to simulate the flood inundation caused by a dam breach: one-dimensional (1-D) and two-dimensional (2-D).

Note: Although three dimensional modeling exists, it is not typically used in dam safety practice for dam break modeling.

R21.4.3.1 One-Dimensional Modeling

The 1-D approach to flood inundation modeling only considers one dimension of the flood flow in the direction of x axis (the downstream direction). The unidirectional flow is best represented by the St. Venant formula used for calculating the 1-D flow of the flood wave. Typical modeling software used for calculating the one-dimensional flood flows would include HEC-RAS, and Mike 11 HD.

The modeling of the downstream river conditions in the event of a dam failure using 1-D models requires knowledge of the lateral and longitudinal geometry of the stream and its frictional resistance. This determines how the peak of the flood wave is reduced as it moves downstream (attenuation), the travel time of the flood peak between points of interest, the maximum water stage at points of interest, and the change in shape of the hydrograph as it moves downstream. These effects are governed by factors such as: the channel bedslope; the cross-sectional area and geometry of the main channel, overbank, and backwater areas; the roughness of the main channel and overbank; the existence of storage of floodwaters in off-channel areas from active water conveyance areas; the shape of the flood hydrograph as it enters the channel reach, and the computational solution scheme.

Depending on the level of detail required by the study, field surveys may be needed to verify selected routing parameters and details such as the Manning's number, ineffective flow and overbank areas, bridge constrictions, and off-channel storage. Often a discharge relationship must be obtained for any downstream dams or flow control structures (inline structures). In some cases, some of this information can be obtained from a review of aerial photographs, Flood Insurance Rating Maps, and recent topographic maps.

Depending on scalability requirements, the downstream cross-sectional geometry can be obtained from 10m Digital Elevation Models or topographic maps. In populated areas that introduce high levels of uncertainty, higher quality LiDAR data or actual field surveys may be needed. Field verification should be performed at all cross-sections in the downstream reach where critical information is needed. Also, 10m DEMs and LiDAR do not contain bathymetric data and may have to be augmented by hydrosurveys to obtain riverbed information.

R21.4.3.2 Two-Dimensional Modeling

In the 2-D approach, there are no cross-sections, as with 1-D modeling. Instead, the riverbed is defined by a network field, single grids or mesh, in which the shape can be square (cell based with regular elevation intervals) or polygonal (with irregular intervals) where each individual element has an associated elevation. The single grid has square fields (cells) with constant size, for example, 10 x 10 meters. The flexible mesh has an irregular representation that can be square, rectangular, triangular, or a combination of these shapes; also, the size of the shapes can vary. Typical modeling software used for calculating two-dimensional flood flows would include FLO-2D, Mike 21 HD, Mike Flood (and HEC-RAS version 5.0 which is due end of CY 2013).

Within the 2-D computer model, water propagates by a cell to cell evaluation basis. In contrast to the 1-D model, the Manning coefficient can be variable and applied at every element location (cell). For example, if the element sizes are 5 x 5 meters, and if some elements have dense foliage, where others not, it is possible to define different Manning coefficients for the separate elements at as much as a 5 x 5 meter interval.

The 2-D modeling method is not constrained by the same limitations as the 1-D approach. The limitation to a horizontal water surface at the cross-section locations and the lack of exchange of momentum between the main channels and flooded areas, doesn’t exist in the 2-D approach. Although the water surface is horizontal within an individual cell, when propagating from cell to cell along a cross-section, the water surface can oscillate according to the dynamics of the model. Also, the exchange of impulses between cells is possible, and therefore, the momentum exchange between the main channel and the flood area is possible.

R21.4.4 Boundary Conditions

Boundary conditions both at the upstream and downstream ends of the model are needed in flood routing. Their selection is dependent on the dam breach study’s purpose, their locations relative to the area(s) of interest, and level of sensitivity dependent on the degree of confidence required.

The upstream boundary condition can be defined by a stage-storage relationship, or as a series of cross-sections cut through the reservoir. The method selected normally depends on the shape of the reservoir. Long, riverine reservoirs with relatively fast breach development times should be modeled using bathymetric data and cross sections (dynamic reservoir routing) to account for the hydraulic losses as water in upper portions of the reservoir travels to the dam breach. Dynamic routing is also required when the hydraulic slope of the reservoir is significant and low reservoir rim areas could potentially impact the study results. In larger volume, more compact impoundments, with relatively slow breach development times, where travel time through the reservoir is not critical, the stage-storage method (level pool reservoir routing) requires less effort and has the benefit of accurately modeling the actual storage within the reservoir based on known relationships. Selecting the appropriate reservoir drawdown approach (dynamic or level pool) can be a very important part of the dam breach study. Level pool can save significant time and effort, but if used inappropriately, can greatly overestimate the breach hydrograph.

The assumptions used for the initial reservoir water surface can either be specific to the failure mode being studied, consider a range of possible elevations or annual exceedance probabilities, or for preliminary or screening applications begin with the reservoir at the normal maximum pool elevation especially if there is no allocated or planned flood control storage (e.g. run-of-river). In risk informed decision making, the best estimate should be used for the dam breach scenario being evaluated.

As discussed in the following section, the downstream boundary conditions are not usually an important assumption because routing for risk informed decision making should be continued far enough downstream where impacts are no longer significant. This point could occur when:

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

Additional information regarding dam breach parameter estimation can be found in Chapter 2 Section E.3 of Appendix C.

R21.4.5 Inflow hydrograph, project discharge and concurrent flows

The inflow hydrograph is a straightforward assumption used in the model that is defined by the study's purpose. In risk informed decision making, a range of inflows is usually considered in the analysis. The same can be said of the baseflow condition assumed in the river reach being studied.

The dam's spillway and/or project discharge operations should be modeled as most realistically anticipated for the study's purpose. Debris loading or other spillway blockage situations may require artificially modifying the dam breach model's project discharge rating curve to compensate for the diminished spillway capacity. Gate operations should be modeled depending on normal and flood operation procedures in place at the project, or as described in the failure mode being investigated.

When routing a dam breach flood wave through the downstream floodplain, appropriate local inflows should be considered in the computations, as concurrent floods in a river system may increase the area flooded and also alter the flow velocity and depth of flow as well as the rate of rise of flood flows. These assumptions ultimately affect the estimation of downstream consequences and the level of effort in determining these assumptions should be requisite to the level of detail required and include sensitivities as appropriate. This is an important issue that should be discussed in the scoping phase of the modeling process, so that all the parties are agreed on what assumptions are reasonable.

If historical records are available and the records indicate that the downstream tributaries are characteristically in flood stage at the same time, then concurrent inflows based on historical records should be adjusted so they are compatible with the magnitude of the flood inflow computed for the dam under study. For screening level and sunny-day EAP inundation mapping dam breach applications, the concurrent inflows may be assumed equal to the mean annual flood (approximately bankfull capacity) for the channel and tributaries downstream from the dam. The mean annual flood can be determined from flood flow frequency studies. As the distance downstream from the dam increases, engineering judgment may be required to adjust the concurrent inflows selected.

R21.4.6 Domino Failure Consideration

The possibility of a domino-like failure of downstream dam(s) resulting in a cumulative flood wave large enough to cause adverse impacts should be considered. If one or more dams are located downstream of the dam site under review, the dam breach failure wave should be routed downstream to determine if any of the downstream dams would breach in a domino-like action. While the flood routing of inflows through the dam being studied may be either dynamic or level pool, the routing through all subsequent downstream reservoirs should be dynamic. Tailwater elevations should consider the effect of backwater from downstream constrictions.

Much like concurrent flows, described above in section 5.5, the introduction of downstream dam(s) to the model creates the need for numerous additional variables. If the downstream dam(s) is managed by a different entity than the one performing the dam breach analysis, these variables could be hard to estimate without consultation. This is an important issue that should be discussed in the scoping phase of the modeling process, so that all the parties are agreed on what assumptions are reasonable.

R21.5 Dam Breach Output

The output of the dam breach model for use in risk analysis should be in digital format, such as GIS. There are very few situations where a hand drawn inundation map on a topographic quadrangle map will be acceptable for decision making. The expected outputs from a dam failure analysis for each flood routing are the inundation polygon, the analyzed cross sections and their output data (water surface elevations, hydrograph timing, velocity), and for consequence estimation a grid of the Depth-Velocity of the breach outflow.

R21.6 Accounting for Uncertainty

Analyses of dam failures are complex with many historical dam failures not completely understood. Accounting for uncertainties may not be needed in situations where it can be shown that the complete and sudden removal of the dam would not endanger human life or cause extensive property damage. The principal uncertainties in determining outflow from a dam failure involve the potential failure mode and the selection of the breach size, shape, and time of formation as input parameters for the computations. Uncertainly also exists in the selected flood routing methodology and model input data, concurrent flow estimation, and how reservoir sedimentation may behave during a dam failure. Uncertainty is most often accounted for by performing a sensitivity analysis over a range of best estimates for dam breach modeling input parameters. However, to fully support risk informed decision making, quantification of the uncertainties is required in the outcomes. Quantification of uncertainty requires a probabilistic analysis of the uncertain input parameters; most notably the dam breach parameters, and an exceedance probability index for the full range of possible breach outflow hydrographs. This procedure is introduced in Section R21.5.1, Dam Breach Parameter Estimation.

One of the goals of the pre-analysis scoping meeting is to discuss the range of selected parameters studied and methodology used, and what is the inherent uncertainty of each. A well written account of the uncertainty should include the best estimate of the parameter, the sensitivity of the study to variation in the parameter, an estimate or study of the variation of the parameter, a discussion of how uncertainty has been reduced to the extent practicable, and, if necessary, where future efforts should be focused to further reduce uncertainty.

R21.7 References

R21 – Appendix A – Definitions

Annual Exceedance Probability - The estimated probability that an event (such as a flood) of specified magnitude will be equaled or exceeded in any year.

Dam Failure Inundation Map - A cartographic map depicting the area downstream from a dam that is predicted to be flooded in the event of a failure of the dam.

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

Flood Routing - A process of progressively determining over time the amplitude and speed of a flood wave as it moves past a dam and continues downstream to successive points along a river or stream.

Hazard - A situation which creates the potential for adverse consequences such as loss of life, property damage, or an unexpected or unpredictable event. Adverse impacts in the area downstream of a dam are the impacts resulting from flood waters released through spillways and outlet works or by partial or complete failure of the dam. There may also be impacts upstream of the dam due to backwater flooding or landslides around the reservoir perimeter.

Hydrograph - A graphical representation of the stream flow stage or discharge as a function of time at a particular point on a watercourse.

Incremental Impact Assessment - An assessment of the impacts caused by the increase in flooding due to the failure of a dam or other water impounding structure under a specific flow condition. This assessment evaluates the impacts caused by the passage of a specific flow condition without a dam failure and then considers the same flow condition with a dam failure. The incremental impacts between the non-breach and breach cases on downstream life and property are identified and evaluated.

Outlet Works – An appurtenance in a dam, other than a spillway, that is used to release water (generally controlled) from a reservoir.

Probable Maximum Flood (PMF) - The flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in the drainage basin under study.

Reservoir Regulation Procedure (Rule Curve) - Compilation of operating procedures that govern reservoir storage and releases.

Spillway - A gated or ungated hydraulic overflow structure used to discharge water from a reservoir. Below are several common spillway types:

- **Service Spillway**. 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.

- **Auxiliary Spillway**. Any secondary spillway which is designed to be operated very infrequently; possibly, some degree of structural damage or erosion to the spillway would occur during operation.

- **Emergency Spillway**. A spillway that is designed to provide additional protection against overtopping of dams and is intended for use under extreme flood conditions or mis-operation or malfunction of the service spillway.

Spillway Capacity - The maximum amount of flow a spillway section can pass when the reservoir water level is at the design maximum pool elevation or dam crest elevation.