Dam Safety Program

Technical Note 6

Downstream Hazard Classification Procedures
for Montana Dams

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REVISION SHEET

DAM SAFETY PROGRAM

TECHNICAL NOTE 6

DOWNSTREAM HAZARD CLASSIFICATION

PROCEDURES FOR MONTANA DAMS

No.	Description of Revision	By	Date
0.0	Original version, Technical Note 6	Hydrometrics, Inc.	December 2010
1.0	Provides updated references, rules, and procedures. Includes more tables and hyperlinked references to streamline content.	Hydrometrics, Inc.	October 2018

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DAM SAFETY PROGRAM
TECHNICAL NOTE 6
DOWNSTREAM HAZARD CLASSIFICATION
PROCEDURES FOR MONTANA DAMS

OVERVIEW

The Montana Dam Safety Program, as part of the Montana Department of Natural Resources and Conservation (DNRC), has provided this Technical Note 6 (TN6) to assist and guide engineers conducting hazard classification determinations for dams in Montana. The procedures outlined in this technical note are standardized processes developed by the Montana Dam Safety Program to classify dams according to downstream hazards that may be flooded during a dam failure.

Hazard classification analyses involve computer modeling of a failure, or breach, flood and routing the flood downstream. If the flood inundates downstream "hazards," such as houses, paved roads, campgrounds, or other areas of human occupancy, then loss of life is assumed. Only one loss of life necessitates a "high hazard" classification. Modeling can become complicated with road crossings, bridges, or other obstructions that can wash out or cause backwater dangers. The differences between hazard designations are explained in more detail in this technical note.

TN6 is organized in a logical format to guide the user through the hazard classification process. It is meant as a guidance document and users are encouraged to follow the recommendation contained herein, but have flexibility to use other methods if they meet the intent of the hazard classification process.

Revision 1.0 modified TN6 by providing updated references, dam safety rules, and procedures since the original version. Revision 1.0 includes more tables and hyperlinked references to streamline content and to provide easier access to reference documents. Included in Revision 1.0 are newly-developed methods for conducting a hazard classification determination.

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DOWNSTREAM HAZARD CLASSIFICATION
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1.0 HAZARD CLASSIFICATION BASICS

This section of TN6 is a brief overview of what constitutes a hazard classification, why they are conducted and some of the limitations of hazard classifications. Many engineers are already familiar with the contents of this section, but for those new to hazard classification determinations, this is a valuable introduction.

1.1 UNDERSTANDING A HAZARD CLASSIFICATION

It is important that engineers engaged in hazard classification determinations have a clear understanding of the meaning and purpose of classifications. The following sections provide information as background to conducting hazard classifications. Table 1-1 provides quick answers and hyperlinked references to the applicable dam safety sections of the Montana Code Annotated (MCA, 2017) and the Administrative Rules of Montana (ARM, 2018) for frequently asked questions related to hazard classifications.

In going through Table 1-1, it is important to note that a classification is nothing more than a break point that dictates permitting requirements. Many dams in Montana having normal capacity of 50 acre-feet or more are not classified as high hazard, even though hazards exist below the dam within the 100-year floodplain of a major river (as discussed below, these hazards are not counted in a classification). Dams that store less than 50 acre-feet with roads or houses downstream can cause loss of life, but are not required to obtain a classification determination. A dam that fails during an extreme storm event can have a larger flooded area than the one used in a hazard classification determination. A classification also does not take into account the condition of the dam; a well-built dam is much less likely to fail than a poorly built one. Because of these reasons, a hazard classification is not a clear indicator of liability, nor is it a complete indicator of what will happen should a dam fail.

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TABLE 1-1. UNDERSTANDING A HAZARD CLASSIFICATION

Question	Description	ARM and MCA Reference
How many hazard categories are there for dams under the jurisdiction of the Dam Safety Program?	Two: high hazard or not-high-hazard.	ARM 36.14.206(2)
Are all dams in Montana under the Dam Safety Program jurisdiction?	No. Dams regulated by other governmental agencies are exempt, as are others detailed in the MCA reference.	MCA 85.15.107
When is a hazard classification determination required?	For dams impounding 50 acre feet or greater at maximum normal operating pool; planning repair or new construction.	ARM 36.14.201(1) MCA 85-15-209
How is maximum normal operating pool defined?	Typically, the reservoir level at the elevation of the lowest uncontrolled spillway. Details are found in the ARM reference.	ARM 36.14.101(12)
On what basis is a determination made?	Determination is based only on consequences of failure; high hazard is when loss of human life is likely as a result of failure.	ARM 36.14.206(1-2)
Does hazard classification have anything to do with the condition of the dam?	Determination is not based on the condition of the dam, nor the probability or risk of failure of the dam.	ARM 36.14.206(1)
What constitutes a downstream hazard?	Loss of life from a dam failure flood is assumed to occur when the structures listed in the ARM reference are inundated.	ARM 36.14.206(2)(a)
How do you apply for a hazard classification?	Application is made to the Dam Safety Program.	ARM 36.14.204
Where is the form for a hazard classification application?	On the Dam Safety Program webpage.	Dam Safety Webpage
What is the determination process?	DNRC personnel conduct the determination. A determination is made within 60 days after a complete application is received.	ARM 36.14.205
If a hazard classification has already been done, is the dam exempt from ever having another classification done?	No. A dam undergoing repairs that had a previous not-high-hazard classification is required to apply to assure downstream conditions have not changed.	ARM 36.14.201(1)
Can a hazard determination be reconsidered?	Yes. DNRC can be requested to do another based on new information or an independent engineer can be hired by the owner to conduct a more detailed analysis.	ARM 36.14.207

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Several types of dams are not required to obtain a classification, as loss of life is unlikely to occur. Table 1-2 summarizes these structures.

TABLE 1-2. STRUCTURES NOT REQUIRED TO OBTAIN A DAM SAFETY HAZARD CLASSIFICATION (ARM 36.14.201(2)(A-F))

Dam Type	Comment
Wastewater pond dams	Typically low head, lined, off stream, stable configuration; Must be subject to regulation under Montana Dept. of Environmental Quality.
Naturally occurring reservoirs	
Canal obstructions / diversions	Generally do not store sufficient water. Diversion structures or canals that impound over 50 acre-feet should obtain a classification.
Levees designed to control floodwaters	
Railroad / road or highway fills not intended to store water	Storage is often controlled by an ungated culvert, thus normal pool is the invert of the culvert. Should these structures have the ability to store water a classification may be required.

1.1.1 Below-Ground Surface Storage / Dead Storage

Many reservoirs have storage below the dams, either from excavation or from a remnant lake present before a dam is added. This is typically referred to as *dead storage*, as it cannot be accessed by gravity flow from an outlet. In 2012, ARM 36.14.209 was modified and dead storage is no longer included in the capacity calculations. This is because since the storage cannot exit during a dam breach and contribute to loss of life. If for some reason, the below ground storage can be released, for example if the reservoir was perched on a hillside, this storage should be included in capacity calculations.

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1.1.2 Other Hazard Classification Categories

As shown in Table 1-1, Montana Dam Safety classifies dams under its jurisdiction as either high hazard or not high hazard. Other hazard classifications commonly used by other jurisdictional government agencies, and used informally by the Montana Dam Safety Program, are:

- *Significant*, where failure of the dam could potentially cause extensive property damage; loss of life from a flood induced breach of dam (described in Section 4.0 of this technical note); loss of life in the 100-year floodplain (also described in Section 4.0 of this technical note); or significant damage to the environment.
- *Low*, where failure of the dam does not cause a loss of life and only minor property damage, such as to fences, rarely traveled dirt roads, unoccupied barns, sheds, etc.

1.1.3 What is the Motivation for an Owner to Obtain a Hazard Classification?

Aside from being a requirement of law, owners have a responsibility to know what happens downstream of their dam in the event of a dam failure. This is considered to be the "Standard of Care" for dam ownership. Should something ever happen to a dam, litigation for damages incurred downstream is common. The dam owner must then prove they were not negligent in operation and maintenance of the dam. The Montana Supreme court has concluded in past dam failure litigation cases that "not knowing is not a defense". Thus, failure to apply for a hazard classification for a dam of 50 acre-feet or more could be construed as a form of negligence.

Also, having a dam that impounds less than 50 acre-feet or is a not-high-hazard dam impounding 50 acre-feet or more does not relieve an owner of liability associated of the dam. They are still potentially liable for damages caused by the dam. Thus, all dams regardless of size or hazard classification are encouraged to keep track of downstream development and operate and maintain their dams in a responsible manner.

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1.1.4 Limitations of Hazard Classifications

There are set criteria on which dams are required to have a hazard classification determination, how a hazard classification is conducted, and how a determination is made (ARM 36.14.206). These rules leave open the possibility that a dam that has been classified as not-high-hazard could still cause loss of life. This is usually the result of two conditions:

1. Hazard classifications are conducted with a "clear weather breach," or a breach of the dam with the pool to maximum normal operating pool. If no houses or other human-occupied structures are in the clear weather breach flood zone, the dam is classified as not high hazard. However, there may be houses or other structures located in the flood zone caused by a storm-induced, or inflow flood-induced, breach of the dam. A storm-induced breach usually results in a wider and deeper downstream flood zone than a clear weather breach.

2. Hazard classification determinations end when the routed breach flood levels become lower than the 100-year flood on any stream reach below the dam. Human-occupied structures located within 100-year floodplain downstream of the end of the hazard determination model could be at risk and loss of life could occur.

As mentioned in Section 1.1.2 of this Technical Note, the Dam Safety Program informally classifies not-high-hazard dams having the potential for causing loss of life (and other dams that could cause extensive property or environmental damage without causing loss of life) as *significant hazard* dams.

In addition, dams less than 50 acre-feet still have the potential to cause loss of life in the event of failure. This fact is sometimes lost to owners because these dams are not required to apply for permits or hazard classifications. Therefore, it is important for owners of dams less than 50 acre-feet to assess their downstream hazards and if loss of life is possible, to voluntarily follow the requirements of high hazard dams.

For owners of dams that are not required to have an operation permit from the Dam Safety Program but whose dams could cause loss of life, liability still applies. Showing due

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diligence is very important for these owners to show they are meeting the standard of care for responsible dam ownership.

1.2 STATE'S PERSPECTIVE ON HAZARD CLASSIFICATIONS

The Montana Dam Safety Program has two main responsibilities:

- To administer and uphold the Montana Dam Safety Act; and
- To safeguard the lives of Montana citizens by requiring proper construction, operation, and maintenance of dams.

To carry out its responsibilities, the Montana Dam Safety Program conducts and oversees hazard classifications with the following principles and guidelines:

1. The Program defines hazard classification regulatory and permitting requirements. Because these requirements have limitations, they do not necessarily accurately represent the actual potential for loss of life.
2. Hazard classifications are conservative. If a determination is borderline high hazard, the Program will error on the side of safety for citizens and assign a high hazard rating to the dam.
3. The Program will use simplified assumptions, such as topographical data from 7.5-minute quadrangle maps. It is not the intent of the Dam Safety Act for the State to bear the responsibility of collecting detailed survey data and conducting an advanced analysis.
4. The Program encourages owners of dams that have no hazard classification to apply for a determination. The nationwide standard of care calls for owners of dams to investigate and determine the potential hazards downstream of their dams. Voluntary compliance, or applying for hazard classification without an order to so, is considered part of the standard of care of responsible dam ownership.
5. The procedures and actions of the Montana Dam Safety Program appear to be in line with what other state dam safety programs are doing. This was verified by a survey of other states' program procedures. Results of the survey concluded Montana's procedures are similar to other states and do not appear to be out of the ordinary. The

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only exception appeared to be Hawaii where hazard classification breach flood routing in all cases ends in the ocean, obviously not a consideration for Montana.

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2.0 CONDUCTING A HAZARD CLASSIFICATION

This section provides guidelines on how to conduct a hazard classification determination. The Montana Dam Safety Program allows various forms of analyses for a determination, based on the characteristics of the dam and reservoir, and the potential hazards that exist downstream of the dam. These different types of analyses are discussed in Section 2.2. There are components of a determination that are common to all hazard classification analyses, as discussed in Section 2.1, and parameters that need to be determined for hazard classification analyses, discussed in Section 2.3.

2.1 COMMON COMPONENTS OF A HAZARD DETERMINATION

In order to assure all hazard classification determinations are conducted similarly, there are common components to each analysis. The following sections discuss in detail how the determination is to be set up prior to actual breach flood analyses.

2.1.1 Reservoir

While the physical characteristics of the reservoir impounded by the dam are important, it is just as necessary to understand the ARMs defining hazard classifications in Montana for starting reservoir levels, how inflow design floods are handled and the minimum reservoir storage requirements for high hazard dams.

2.1.1.1 <u>Starting Water Surface Elevation</u>

For hazard classification determinations, the reservoir starting water surface elevation is at the maximum normal operating level. This means different levels for different types of storage reservoirs. For an on-stream reservoir this is generally the lowest ungated spillway, often the drop inlet elevation. For an off-stream reservoir, normal operating pool may require some judgment and depends on the characteristics of the dam and spillway and/or outlet configuration. For flood control structures, normal operating pool is typically the auxiliary spillway crest.

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2.1.1.2 Reservoir Elevation-Storage Data

If a reservoir does not have available elevation-storage data, there are several ways to estimate it. In the absence of any other available data, ARM 36.14.209 suggests storage can be estimated by multiplying 0.4 times the vertical height of water measured in feet from the downstream toe of the dam to the maximum normal operating pool times the water surface area at that level in acres.

Another method is to utilize topographic data to extrapolate reservoir area-elevation information above the reservoir surface area depicted on the map, and estimate reservoir storage-elevation data below the surface. Using this method, the area within each contour line is estimated digitally. The downstream areal extent is to the dam centerline. An example of this method is depicted in Figure 2-1.

**FIGURE 2-1. ESTIMATING A RESERVOIR ELEVATION-AREA
RELATIONSHIP BY EXTRAPOLATING A TRENDLINE
BELOW THE NORMAL RESERVOIR SURFACE**
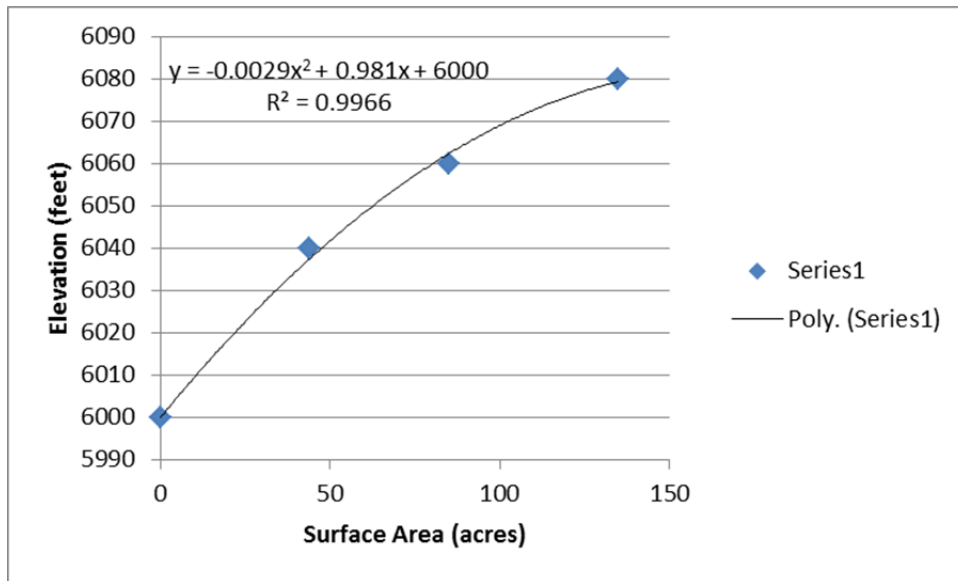
Figure 2-1 represents a reservoir whose normal water surface on a topographic map is shown at elevation 6040. Three area estimates were determined by digital delineation at elevation contours 6040 (area = 44 acres), 6060 (area = 85 acres), and 6080 (area = 135 acres) and are

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represented on Figure 2-1 by the blue diamond symbols. It is also known that the bottom of the reservoir is at or very near elevation 6000, which is typically the elevation of the natural channel at the downstream toe of the dam. For this example, a polynomial trendline (the black line) was added to the graph using an Microsoft Excel® spreadsheet, forcing it through the intercept at elevation 6000. Based on this, an elevation-area relationship can be established for the reservoir between elevations 6000 and 6040 with the extrapolated trendline below elevation 6040. Judgment is needed to determine the appropriate function for fitting a curve to the data. In this case, a second-order polynomial line resulted in a good fit, with an R^2 of 0.9966. R^2 is the coefficient of determination, which is a statistical measure of how close the data are to the fitted regression line. An exact fit would result in R^2 of 1.0.

2.1.1.3 No Inflow Design Storm

Hazard classification analyses are conducted using a clear-weather, or "sunny day," breach simulation of the dam. Therefore, no inflow design storm is considered in the failure analysis.

2.1.2 Dam

Special consideration is given for the dam and its appurtenances when conducting a hazard classification determination.

2.1.2.1 Neglect Auxiliary and Principal Spillway Flows

Because the failure simulation is a clear-weather breach with the reservoir surface at the maximum normal operating level, the auxiliary and principal spillways are not engaged. For flood control structures, the starting water surface elevation can be above the principal spillway (see Photo 2-1 of East Fork Dam near Lewistown, Montana, a flood control structure). Principal spillway flows are typically insignificant compared to breach flows from the dam, so they can be neglected. Judgment may have to be exercised for considering principal spillway flows and the modeler may opt to include principal spillway flows if they comprise a significant portion of the breach flows.

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PHOTO 2-1. EAST FORK DAM, LEWISTOWN, MONTANA.

2.1.2.2 Dam Breach Parameters

The vast majority of dams under DNRC Dam Safety regulation are earthen dams. Failure of earthen dams can be caused by several mechanisms. For a clear-weather breach, the failure mode is typically by piping of the embankment material. The Dam Safety Program has determined the parameters that best represent actual piping failures are those developed by Froehlich (2008). A handy spreadsheet for estimating breach parameters using the Froehlich equation is available to the public through the Colorado Department of Natural Resources (2011).

2.2 BREACH ANALYSIS OPTIONS

The level of effort that must be undertaken for a breach analysis is commensurate with the hazard that a dam may pose, and the complexity of the downstream area. The three (3) levels of analysis that are considered acceptable to the Dam Safety Program, in order of increasing complexity, are:

Screening Level Breach Analysis – Appropriate if it is readily apparent that no hazard exists downstream of the dam, and it is clear that the dam hazard level is not-high-hazard.

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Standard Breach Analysis – Appropriate if hazards may exist within the breach flood inundation zone downstream of the dam and the results are uncertain without a more detailed analysis.

Advanced Breach Analysis – Appropriate when a dam owner disputes DNRC's breach analysis and opts to reanalyze the hazard determination using an independent engineer, or when advanced analysis techniques (unsteady flow, 2D analysis, etc.) are warranted.

The two primary factors that differ for each level of analysis are: (a) the extent of field investigation and data collection; and (b) the sophistication of breach modeling.

2.2.1 Screening Level Breach Analysis

The Screening Level Breach Analysis is appropriate when it seems readily apparent that no hazard exists downstream, and thus the dam hazard level is determined to be not-high hazard. If the Screening Level analysis clearly indicates no hazardous condition exists downstream, then no additional breach analysis is required. One situation where this may be the case is for very steep channels where attenuation of the peak flood flow would be unlikely due to the momentum of the flood and lack of storage capacity in the floodplain. Another situation may be where the only downstream hazards are located at elevations well above the maximum possible stage of the breach flood. An acceptable Screening Level Breach Analysis should demonstrate that the lowest habitable level of all inhabitable structures, recreational areas, etc., located within the breach flood routing reach are at a relative elevation above the adjacent invert, or channel bottom, that is equal to or greater than the hydraulic height of the reservoir and no obstructions downstream are present to create additional backwater height. For example, if a dam is eight (8) feet tall, downstream homes must be at least eight (8) feet higher than the adjacent receiving channel with no structures such as bridges or road crossings between the dam and downstream homes that might fail and cause a higher breach flood than that caused by the dam failure, or if the house(s) are susceptible to backwater from downstream structures.

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An acceptable Screening Level Breach Analysis requires a sufficiently detailed justification of the hazard classification. If justification is not found, then a Standard Breach Analysis should be done. Suggested initial tasks for a Screening Level Breach Analysis are:

1. Use recent aerial photography or satellite images to identify downstream hazards.
2. Verify that downstream hazards are located higher above the adjacent streambed than the height of the dam.
3. Calculate the estimated peak breach flow using Froehlich (2008) equations discussed above.
4. Determine the 100-year peak flow magnitude at locations downstream of the dam as discussed in Section 2.3.12 of this technical note. (Note, the 100-year peak values will increase when the stream on which the dam is located encounters another receiving stream downstream.)   Compare the estimated peak breach flow with the 100-year peak flow. If the peak breach flow is less than the 100-year peak values and no hazards exist between the dam and the location of the 100-year peak flow estimates, the dam is not high hazard.
5. A downstream reservoir or natural lake will provide buffering storage that many times attenuates the breach flood, but a closer investigation or Standard Breach Analysis may be needed to determine the effects of the breach flood on an impoundment. In general, if a downstream impoundment is present and there are structures below the impoundment, a Standard Breach Analysis is needed.

A Screening Level Analysis often can be done in the office. It may be necessary to drive the area downstream of the dam to verify that no occupied dwellings are present. Sometimes it is difficult to assess if structures on aerial photos are barns, sheds, or other unoccupied outbuildings.

Further field investigation or transitioning to a Standard Breach Analysis is needed if the initial tasks are inconclusive for a hazard classification.

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2.2.2 Standard Breach Analysis

Where a Screening Level Breach Analysis is not applicable due to downstream development, factors that complicate the determination such as road crossings, or where the results are uncertain without a more detailed analysis, then a Standard Breach Analysis is appropriate. A Standard Breach Analysis is used when some form of computer modeling will be needed to effectively identify hazards and make a classification determination. The Montana Dam Safety Program accepts and recommends the use of HEC-HMS (Hydrologic Modeling System, USACOE, 2017) for a Standard Breach Analysis. While HEC-HMS is an excellent rainfall-runoff simulation model, it does not include full unsteady flow computations in routing floods like other commonly used software such as HEC-RAS (River Analysis System, USACOE, 2018). However, the methods for routing in HEC-HMS, such as the Muskingum-Cunge method commonly used for natural waterways, are a reasonable simulation of the full St. Venant's equations for unsteady flow. Results from HEC-HMS routing, given reasonably accurate input data, are typically within the error range of any routing method especially with the variables and uncertainty associated with routing of large, sudden unsteady flows, such as debris flow, channel and overbank variations, bridges, and small structures in the floodplain that could be washed downstream.

Where the results of a Standard Breach Analysis indicate that the floodwave inundates the lowest habitable level of a structure or a location of potential human presence, the dam owner has the option to accept the high hazard classification or, alternatively, they may opt to conduct an Advanced Breach Analysis.

Field investigations are typically required to determine fundamental information described further in Section 2.3.

2.2.3 Advanced Breach Analysis

As indicated in Table 1-1 and per ARM 36.14.207, a dam owner has the option to complete an Advanced Breach Analysis. In most situations, the Dam Safety Program will conduct a Standard Breach Analysis, with the level of conservativeness indicated in Section 1.2 of this technical note. Because of expected computational details and model stability challenges of

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more sophisticated models used in an Advanced Breach Analysis, their associated engineering costs may be higher than if a one-dimensional model such as HEC-HMS is used. The Dam Safety Program does not discourage the use of such models if engineers see a need in certain instances to provide a higher level of confidence in the results. The Dam Safety Program will review submitted Advanced Breach Analyses with the same intent as described in Section 1.2.

For an Advanced Breach Analysis, the breach discharge can be routed downstream using a steady flow analysis or an unsteady flow analysis. The analysis can be refined in a number of ways (e.g., steady flow versus unsteady flow, one-dimensional (1D) versus two-dimensional (2D), etc.) and the degree of refinement is at the owner's engineer's discretion, provided it is within accepted engineering practices. The Dam Safety Program accepts more complex models such as HEC-RAS, which offers 1D unsteady flow and 2D steady and unsteady flow analysis, or other 2D models, such as:

FLO-2D© Modeling Software (FLO-2D, 2010), which is a commercially available 2D routing model which has several versions depending the user's need.

MIKE FLOOD© and MIKE 21© (DHI Worldwide, 2010), another commercially available 1D and 2D routing model software. This system has the option to choose between one-dimensional and two-dimensional routing, depending on which integrated model is used.

XP2D© (Innovyze, 2018), a commercially available 2-dimensional overland flow module for xpswmm© and xpstorm©, with multiple capabilities including dam breaches.

An Advanced Breach Analysis often involves a collection of additional field survey data using sophisticated survey equipment.

2.3 BREACH ROUTING PARAMETERS

The following sections give guidance on determining breach routing parameters and procedures for Standard Breach Analysis modeling and common features encountered in

routing analyses. The main component of the analysis that defines a hazard classification determination is the computer simulation of the dam breach flood routing. This is the step where consistent and relatively accurate data, along with engineering judgment and experience, will be instrumental in an effective hazard determination. Additional details describing the requirements of an Advanced Breach Analysis are provided in the subsequent sections.

Since a Standard Breach Analysis utilizes a form of computer modeling, typically HEC-HMS, it is recommended that the engineer conduct an initial HEC-HMS breach analysis from map and on-line data in the office before going to the field. This will allow the engineer to have some basic knowledge of the level and extent of breach flooding that can be compared to field conditions. It is also recommended that an analysis be completed of the 100-year flood values at various locations along the drainage to have an approximate idea of how far the breach analysis will extend downstream.

It is recommended to try to use HEC-HMS as much as possible in the evaluation. Reverting to models such as HEC–RAS introduces complexities that may be more accurate but very time consuming. Some cases will undoubtedly require more accurate analyses but those should be considered on a case-by-case basis.

2.3.1 Downstream Cross Section Data

Routing of a breach flood depends on input data that defines the channel and valley downstream of the dam. Downstream data is input to HEC-HMS by cross sections. Most cross sections identifying the downstream channel can be taken directly off of maps, either manually or digitally, and input into the program.

However, where a hazard such as a house is located, it is recommended to either survey the cross section to maintain accuracy as high as possible, or at a minimum use a hand level to determine the height of the base floor of the house above the stream invert (bottom) at a location directly perpendicular to stream flow direction.

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2.3.2 Stream Reach Length and Slope

HEC-HMS routes the breach flood wave downstream of the dam by simulating flow in a series of reaches along the stream channel. A reach is typically defined as a length of waterway with relatively homogeneous cross section and roughness properties. A designated reach in HEC-HMS will have to be determined by the user based on data taken from maps and field investigations. Data for each reach consists of cross section geometry, roughness estimates (represented by Manning's roughness coefficients, or Manning's "n" values), and bed slope.

The stream reach length in HEC-HMS is the total length of the stream, including meanders, unless the flood is large enough to overwhelm the meanders within the floodplain of the stream. Reach length can be measured from maps. It is important for the user to understand that in HEC-HMS, a reach is defined from an upstream element (such as the dam or the downstream extent of an upstream reach) to the downstream extent of the reach, which is usually another element in the model, unless it is the downstream extent of the model. Cross section data applies along the entire length of the reach, but the downstream end of the reach is where HEC-HMS will calculate flow stage, or the elevation of the peak flow, based on the reach cross section data input to the model. Stage is determined by Manning's equation embedded in the routing equations.

Slope of the reach is the average slope along the stream channel. Slope can be determined from maps by dividing the elevation drop of the reach by the total length of the reach. If the slope varies within the reach, the user may have to subdivide the reach with multiple reaches of different slopes.

Some mapping tools may help in determining reach length and slope, such as Google Earth[©].

2.3.3 Cross Section Locations

As mentioned above, the cross section entered as representing a stream reach will be located at the downstream end of the reach. Once relatively homogeneous reaches have been identified, the cross section locations can be determined and cross section data collected.

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The cross section locations, identifying the downstream extents of the individual reaches, are located to delineate homogeneous reaches. In this case, the homogeneity is generally defined by relatively constant bed slope. If a structure or hazard is within the zone of the breach flood, it is helpful to place the cross section through the hazard, ending the reach at this location. This will allow HEC-HMS to calculate the peak stage at the cross section and help determine if the structure is inundated by the breach flood. Figure 2-2 below gives an illustration of this concept.

FIGURE 2-2. SAMPLE PLACEMENT OF CROSS SECTIONS FOR DOWNSTREAM ROUTING
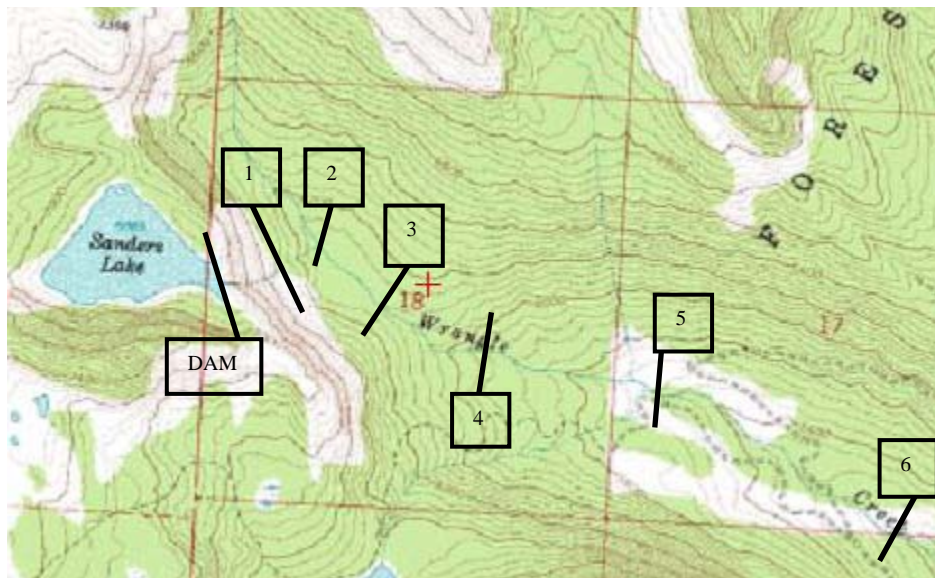
2.3.4 Flood Routing Method

HEC-HMS offers six different methods for routing flows. Each has advantages and disadvantages and a particular method should be selected based on its appropriateness for the application. For hazard classification determinations, breach flood routing will likely occur along a natural stream or river. The only method in HEC-HMS that allows the use of a cross section that attempts to simulate a natural channel and floodplain configuration is the Muskingum-Cunge method, which is recommended by the Montana Dam Safety Program.

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However, within the Muskingum-Cunge method are five options for specifying the cross section shape: circle, eight-point, rectangle, trapezoid, and triangle. Of these, the eight-point option is usually the best to represent a natural channel. The eight-point shape requires a cross section that is simplified by having the entire cross section represented with only eight station-elevation values. Typically, the cross section is configured to represent the main channel and left and right overbank areas. A separate Manning's n value is entered for the channel and each overbank. The cross section should extend vertically from the channel invert up to at least the maximum water surface elevation that will be encountered during a breach flood simulation. HEC-HMS requires creation of the cross section in what is referred to as the Paired Data Manager. The reach routing component reads the Paired Data file during routing simulation.

2.3.5 Base Flow for Routing

Base flow in a stream that is subject to breach flows refers to the stream's normal low flow without storm runoff. In rainfall-runoff models like HEC-HMS, base flow is a common input variable, which is typically necessary for initiating and maintaining routing during flood simulation. The magnitude of base flow can vary but it should be reasonable for the stream being modeled. The Dam Safety Program recommends using the minimum base flow necessary for the model to remain robust and still result in as accurate routing as possible. Note that a hazard classification is a sunny-weather breach, thus using normal base flow is appropriate.

2.3.6 Manning's Roughness Coefficient Determination

The Manning's n roughness coefficients for Muskingum-Cunge routing are assigned to the stream channel and left and right overbanks. Each of the assigned coefficients should be average values for the whole reach according to the placement of cross sections. Manning's n coefficients can be estimated by experience, by calibration, or from pictures of streams with known roughness coefficients. Manning's n can be estimated by several methods. There are many online resources, such as Engineering Tool Box (2001) or Hydrology Studio (2018). Or there are publications that offer guidelines for determining Manning's n, such as

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from the [Federal Highways Administration](#) (1984) and the U.S. Geological Survey (Phillips and Tadayon, 2007).

In general, Manning's n coefficients for breach flows should be higher than those used for other hydraulic computations. Studies have indicated that breach flows contain significant amounts of sediment and debris and discharges may even approach properties of mud flow instead of water flow. Actual breach discharges tend to have higher Manning's n values than regular rainfall-runoff flood flows due to the debris causing an increase in frictional resistance. Models calibrated to actual breach floods have resulted in Manning's n values as high as 0.12 to 0.14. The Dam Safety Program recommends higher n values for breach flows as compared to normal flood flows.

2.3.7 Routing Obstruction Backwater

For obstructions in the routing path of a breach flood, backwater can often be ignored unless potential loss of life exists directly upstream of a bridge, road or other obstruction. Backwater effects of an obstruction can be estimated without use of a HEC-RAS model or HEC-HMS reservoir component with remarkable accuracy. This can be accomplished by simply extending the peak flow stage at the obstruction horizontally upstream until it meets the upstream peak stage line. If inundation of a potential hazard is uncertain, the Dam Safety Program recommends additional HEC-RAS or HEC-HMS reservoir modeling.

2.3.8 Modeling Bridges and Roads

The routing of a breach flood wave becomes more complicated when road embankments or constricted bridge openings are encountered in the downstream routing area. The reason for this is because HEC-HMS does not perform backwater surface profile computations and will not provide accurate results in areas where backwater is likely to occur. The user has to be creative in how this is accomplished and is sometimes faced with modeling the area with HEC-HMS as a reservoir or using HEC-RAS to estimate the backwater profile of the flood.

It is important to remember that because of the limitations of HEC-HMS, it is possible to obtain HEC-HMS water surface elevation results at a point that are higher than upstream

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water surface elevations because water surface determinations are based only on data at the point and are not affected by upstream or downstream water surface profiles. So relying only on HEC-HMS routing results may not provide accurate inundation data for all areas potentially susceptible to flooding.

The first thing the user needs to assess is whether the road crossing in question is paved or not. For the Montana Dam Safety Program, breach flood inundation of a paved road is considered to potentially cause a loss of life, because a paved road indicates higher traffic use. Paved roads on top of bridges or embankments in the floodplain necessitate further investigation and modeling to determine if they are inundated. Unpaved roads do not constitute a potential loss of life if inundated. It is acceptable to assume that unpaved roads are overtopped and washed away, simplifying the analysis. The exception is if the unpaved road has hazards located directly upstream, which may cause backwater inundation of the hazards prior to the road being washed away.

The user should then check the model results as a whole before conducting a more intense modeling effort in the area of backwater. If potential hazards within the backwater area are clearly flooded by dam breach flood wave, or if loss of life exists at other locations along the breach routing reach, no detailed water surface elevation model is necessary.

If no other loss of life potential exists, and it is unclear as to whether or not the road or bridge is overtopped, a more complex analysis may be necessary. The following paragraphs describe how the analysis may be conducted.

2.3.8.1 **Bridge Modeling**

For a bridge, it may be necessary to conduct a HEC-RAS 1D steady flow standard-step water surface profile analysis to determine if the bridge is overtopped. The first step is to determine the peak discharge at the bridge location from the HEC-HMS routing output. The peak discharge will be used as the steady flow input for the HEC-RAS analysis of the bridge. Data requirements are detailed in the latest version of the [HEC-RAS User's Manual](#) (Chapter 6, Entering and Editing Geometric Data, Bridges and Culverts). Bridge opening data is

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required and HEC-RAS requires cross sectional data upstream and downstream of the bridge. Once the analysis is complete, the HEC-HMS routing can continue downstream of the bridge, neglecting any attenuation effects of the bridge or road. Another option, and this is probably more appropriate for bridges with relatively small openings compared to the floodplain area, is to model the bridge as a spillway for a dam and to assume the area upstream of the bridge as a reservoir. This can be input into the basin model of HEC-HMS and included as part of the flood routing. The user will be required to input the road (dam) top elevation, upstream area (reservoir) elevation-area-volume data, and outflow structures (bridge opening). This might require some field surveying to get appropriate data.

2.3.8.2 Road Embankments and Culverts

For road embankments in the flood routing path, there may be significant ponding or backwater behind road embankments, even with culverts in the embankment. Modeling flow through the culvert can be accomplished by several methods. A relatively easy and accessible culvert flow model is the Federal Highway Administration (FHWA) software HY-8® (2016). HEC-RAS also has culvert modeling capabilities. Another option is to model the road embankment and subsequent backwater as a dam with HEC-HMS. Like a bridge analysis described above, this accomplished by identifying the area upstream of the road as a reservoir using elevation-area-volume data, the road (dam) top elevation, and the culvert as an outflow structure.

2.3.9 Flow in Ditches

An issue that is generally ignored during a Standard Breach Analysis is consideration of flow along road ditches, or other ditches that may direct flow laterally away from a main flow channel. Not considering road or lateral ditches is considered conservative and eliminates the complexity introduced by their inclusion in the analysis. Modeling ditches may be considered as part of an Advanced Breach Analysis, but will require additional field data.

2.3.10 Wide Floodplains

For floodplains that are wide and the valley is not well defined, it may be difficult to generate a meaningful 8-point cross section used in the Muskingum-Cunge routing method. The Dam

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Safety Program feels it is acceptable for the user to place artificial vertical walls on each side of a wide floodplain, located reasonable distances apart (which requires professional judgment). The resulting flood stages will be conservative, which in the case of a hazard classification determination fits in with the goal of the Dam Safety Program to protect life and property.

2.3.11 Split Flow

A unique situation that is sometimes encountered when conducting a hazard classification determination is when the breach flow splits and divides the total flow. In general, the overriding concept of modeling a split in flow is the head loss in each branch of the split has to be equal from the point where it splits to the point where flow converges again. So regardless of flow amount, each branch of flow has to start at an equal water surface elevation prior to the split and end at an equal water surface elevation at a point downstream where the split ends. HEC-HMS does not have the capability to model split flow. Other methods need to be employed and the type of method depends on the accuracy required. The user should exercise judgment on when a split flow analysis is required. If no potential hazards exist within the split flow reach, the extra effort to model split flow may not be necessary.

A simplified and conservative method in a reach that has split flow with hazards (houses or other occupied structures) present would be to enter the HEC-HMS cross section for the reach as including only the main channel (the largest channel), ignoring the other split channels. If the modeled flow level does not reach the levels of the hazards, then it is apparent that the hazards will not be inundated. If it indicates that the hazards will be inundated, then a more detailed analysis will be needed.

One option for a more detailed split flow analysis is to conduct it using the junction split flow optimization method in HEC-RAS. This method can be found in the latest version of the HEC-RAS Reference Manual (http://www.hec.usace.army.mil/software/hec-ras/documentation.aspx).

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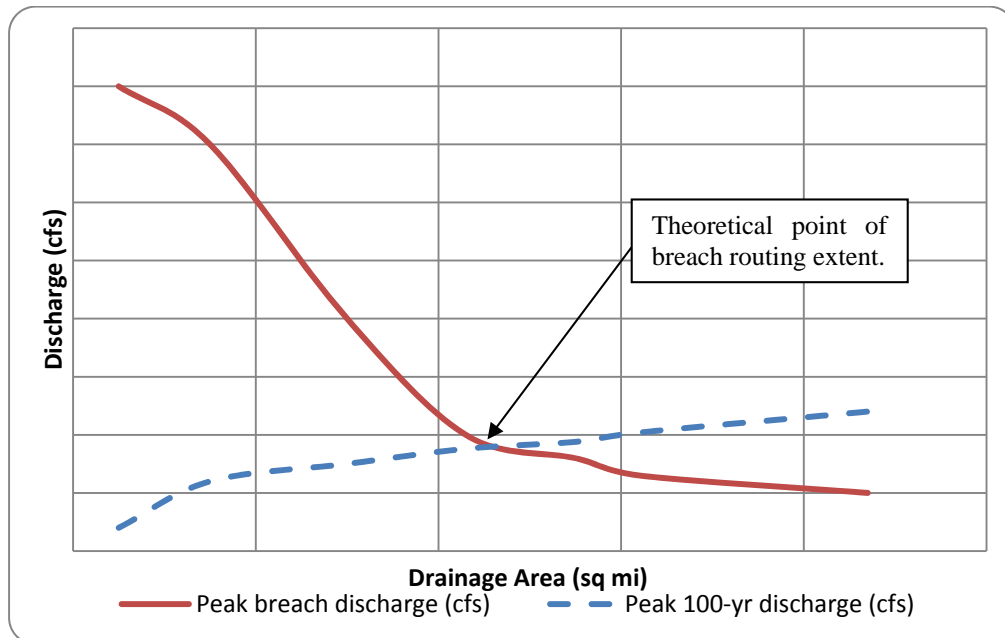
2.3.12 Downstream Routing Extent

In a hazard classification determination, the breach flood is routed to a point on the downstream waterway where the peak breach flow falls below the peak discharge of the watercourse's 100-year flood. If potential hazards exist within the 100-year floodplain (and there are no potential hazards upstream), the Dam Safety Program suggests routing the breach flood further downstream to determine if a "Significant Hazard" classification may be warranted.

2.3.13 100-Year Peak Flood Estimate

As mentioned above, the extent to which the breach flood is routed is the point at which it falls below the 100-year peak flood estimate for the waterway. However, the 100-year peak discharge on a stream increases as one moves downstream because the contributing drainage area increases. This, combined with a decreasing peak breach discharge as the flood moves downstream, creates somewhat of a moving target as far as determining the stopping point for the breach flood routing. Figure 2-3 demonstrates in principle the concept of drainage area to the peak discharges of the breach flood and the 100-year flood.

FIGURE 2-3. CONCEPTUAL RELATIONSHIP BETWEEN PEAK BREACH DISCHARGE AND 100-YEAR PEAK DISCHARGE

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It is recommended that gage data be used to determine a 100-year peak flood value, if available for the watercourse desired. For ungaged streams, the most convenient and commonly used tool for estimating a peak 100-year discharge is the online USGS StreamStats[®] system (USGS, 2018). The equations for StreamStats[®] come from Sando et al. (2016). The regression results provide average values for peak flows at selected return frequencies. While the error band of the average estimates can be significant, the average values should be used.

For an advanced analysis, the modeler may choose to develop a rainfall-runoff model for the basin to more accurately determine the 100-year peak discharge.

It is not recommended to use Federal Emergency Management Agency (FEMA) floodplain studies and maps for determining the 100-year peak flood values. Most maps were published a reasonably long time ago and the peak 100-year flood values and the floodplain delineations may be outdated. A better source is StreamStats[®]. It is more up-to-date with values that were developed with recent data.

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3.0 HAZARDS

In the context of this technical note, a "hazard" is a dwelling, structure, road or location where humans could be present at the time that the area is inundated by a dam breach flood. By virtue of being inundated, the hazard is usually considered to be occupied by humans and loss of life could occur. Exceptions are noted in the narrative that follows.

3.1 LOSS OF LIFE

Regardless of the level of inundation, when a hazard is exposed to water from a breach flood (or modeled by HEC-HMS as such), loss of life is assumed. ARM 36.14.206(2)(a) defines what constitutes a hazard, as indicated in Table 1-1 of this technical note. The following is a list of common hazards where loss of life is assumed when exposed to breach flood flows, and details on how hazards are determined:

- A dwelling whose first floor is inundated, regardless of flow depth and velocity. This includes basements, if occupied. Unoccupied basements are not considered hazards; however these need to be treated on a case-by-case basis. If there is potential for human habitation, an unoccupied basement may be considered a hazard.
- Developed campgrounds. Note: dispersed camping is not considered.
- Paved roads and railroads, regardless of traffic count, flow velocity and depth.
- Barns and outbuildings are not considered occupied dwellings, unless there is reason to assume the outbuildings are occupied in the evening or certain times of the year.

3.2 SIGNIFICANT HAZARD CLASSIFICATION

Officially, the Montana Dam Safety Program only classifies high hazard dams. All other dams are designated as not-high hazard. However, the Program unofficially tracks dams whose failure during a flood event (or, overtopping of the dam during a storm) could potentially cause a loss of life or significant property damage. Significant hazard classification is also applied to dams whose failure flood could potentially cause loss of life beyond the routing limits of a normal hazard classification and within the 100-year

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floodplain. Another significant hazard situation is when the failure flood inundates a well-traveled unpaved road.

The significant hazard classification alerts the Dam Safety Program of dams which may need to be included in owner outreach and education efforts. In some cases, the Dam Safety Program encourages and assists significant hazard dam owners to develop an emergency action plan.

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4.0 OTHER CONSIDERATIONS

There may be situations not covered in this technical note that would present unusual circumstances for hazard classification consideration. These may be added to this technical note at later dates as the circumstances become apparent. But one consideration that is fairly common is when one or more dams are in series. The term "in series" refers to more than one dam on the same watercourse where failure of an upstream dam may cause the failure of a downstream dam. This situation is discussed below.

4.1 DAMS IN SERIES

A hazard classification is necessary if two or more reservoirs are in series and their combined normal reservoir operating capacities exceed 50 acre-feet. This applies even if their individual capacities are less than 50 acre-feet. The analysis would entail modeling the failure of the upstream dam and routing it to a lower reservoir. ARM 36.14.208 indicates that an upstream dam will be classified as high-hazard if its failure causes the failure of a downstream high-hazard dam or if it causes loss of life with or without the failure of a downstream dam. If the breach volume of the upstream dam is contained in the lower reservoir without overtopping the lower dam, the upstream dam is classified as not high hazard. However, if breach flows from the upstream dam do not cause the downstream dam to fail but create spillway discharges at the downstream dam that cause potential loss of life, then the upstream dam would be classified as high hazard. Wastewater ponds that are separated by internal dikes do not constitute dams in series.

4.2 PITS AND FLOOD ROUTING

If a pit, or an impoundment that stores water below the natural ground surface and without an above-ground dam, is encountered in the routing path of a breach flood, it will have to be analyzed to determine if it will contribute to the peak flood discharge of the routed flood. Inclusion of a pit in the routing procedure will depend on the physical characteristics of the pit, most importantly if there is substantial earth separation between the impoundment and a downstream slope to prevent erosion failure during flood overtopping. This may require engineering judgment or the user may opt to model erosion of the soil with an erosion

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software package. If erosion failure appears imminent during the time the pit is overtopped by a breach flood, it should be included as contributing to an increase of the peak flood.

4.3 ENGINEERING JUDGMENT

Familiarity with breach flood routing and experienced judgment on the part of the engineer is a fairly regular part of the hazard classification process. Engineering judgment plays a role in the outcome of a hazard determination. The following are samples of situations where judgment can be expected:

- Adjustment of Manning's n to account for debris flow in the breach flood wave. Increased Manning's n values will increase the flood wave water surface elevation. Heavily forested areas may increase the chance of debris in flood flows and would warrant higher Manning's n values.

- Channel constrictions that tend to cause backwater and raise the upstream water surface elevation. Judgment is required to determine reasonable backwater elevations upstream of constrictions, accompanied by appropriate methodologies to analyze.

- Out-buildings on agricultural operations are generally considered not occupied. However if out buildings have the potential for having human occupation during certain times of the year, such as calving season, they may be classified as a hazard. Local familiarity may be helpful in this case. Engineers will need to obtain more specific information if an out building is under suspicion of being occupied.

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5.0 ACKNOWLEDGEMENTS AND DISCLAIMER

This is the sixth Technical Note developed by the Dam Safety Program and we want it to be a useful document for those engaged in dam safety analyses. We welcome and encourage your feedback on its contents. Please send your comments to:

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The Dam Safety Program operates within the Department of Natural Resources and Conservation (DNRC) Water Resources Division's Water Operations Bureau.

DNRC would like to acknowledge Hydrometrics, Inc. of Helena, Montana for the development and preparation of Technical Note 6. The current version is number 1.0, also developed by Hydrometrics. TN6 will continue to be revised and updated as new procedures are refined and new technical references are made available. Revision 1.0 was implemented in October 2018 to provide simplified methods of determination where more technical methods are not warranted.

The purpose of TN6 is to assist and provide guidance to engineers engaged in conducting hazard classification analyses for dams in Montana. TN6 is not a regulatory document and the references and procedures provided can be modified to suit the needs of the user. Some of the technical resources referenced in TN6 are specific to Montana dams, using data gathered and compiled in Montana.

ARM Chapter 36.14, Subchapter 2 provides specific requirements for hazard classification determinations. The procedures in TN6 are intended as supplemental information to the ARM. TN6 provides more specific guidance on engineering assumptions and analysis techniques. Bringing consistency to hazard classification procedures is important because a classification rating of "high" can have a significant impact on how the dam is operated and

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maintained. The Dam Safety Program recognizes that professionals may use other technical resources and procedures, accompanied with relevant reasons for their use that are not mentioned in TN6. TN6 is written primarily for earthen dams. TN6 can also be used for other types of dams, but breach failure parameters for other dam types need to be adjusted to suit.

DNRC dam safety engineers (or State engineers) perform the majority of hazard classifications. However, there are occasions when non-State engineers will conduct hazard classification determinations. TN6 will benefit non-State engineers by helping them understand the assumptions behind hazard classifications and the techniques used by the Dam Safety Program.

The Dam Safety Program's hazard classification analysis is simplified and conservative, which is the intent of the Montana Dam Safety law and administrative rules. The ARM's allow dam owners to conduct an independent analysis of hazard determination using more detailed survey data and more sophisticated modeling than typically done by the Dam Safety Program. This publication will help provide guidance for such an independent analysis.

Professional judgment is sometimes required in determining hazard classifications, regardless of guidance provided by TN6. Users of TN6 are expected to be familiar with dam safety terminology and common hydrologic and hydraulic computer programs and their appropriate use. DNRC and the Dam Safety Program are not responsible for the use and interpretation of TN6 contents.

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6.0 DEFINITIONS

The following definitions are offered for terms used in Technical Note 6:

Backwater – Water in a stream channel or floodplain that is impeded from its natural flow profile and creates an area of inundation behind an obstruction. The water surface profile of backwater is much flatter than the natural flow profile.

Breach – Failure of a dam caused by an opening through the dam.

Clear-Weather Breach – Failure of a dam due to causes not related to storm inflow flooding. Also called sunny-day breach.

Flood-Induced Breach – Failure of a dam caused by overtopping during storm inflow flooding.

HEC-HMS – A computer program (Hydrologic Modeling System) developed by the U.S. Army Corps of Engineers' Hydrologic Engineering Center that performs rainfall-runoff and flood routing computations. Additional capabilities include dam breach and snowmelt modeling.

HEC-RAS – A computer program (River Analysis System) developed by the U.S. Army Corps of Engineers' Hydrologic Engineering Center that performs water surface profile computations for steady and unsteady flows. Additional capabilities include sediment transport and dam breach modeling.

High Hazard Dam – In Montana, a dam that impounds 50 acre-feet or more in reservoir volume and whose failure would likely cause a loss of life. High hazard dams are under the authority of the Montana Dam Safety Program, a part of the Montana Department of Natural Resources and Conservation.

Hydrograph – A graphical representation of stage, flow, velocity, or other characteristics of water at a given point as a function of time.

Loss of Life – Actual or predicted number of human lives expected to lost in the event of a dam failure. Predicted loss of life (LOL) is based on empirical methodologies derived from historical dam failure data. Typically, LOL is a much lower number than the population at risk (PAR) within a dam breach flood area.

Piping – The action of buried soil erosion by water movement through larger soil pores. For earthen dams, piping is generated by the hydrostatic head of the impounded reservoir. If flow continues unabated, the pore space increases and piping can accelerate rapidly.

Spillway – A hydraulic structure associated with a dam that discharges flow. A spillway can be categorized as principal (discharges normal flows from reservoir); auxiliary (discharges

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flow in excess of the principal spillway capacity); or emergency (discharges flows in excess of the principal and/or auxiliary spillway capacities). Spillways are designed to either regulate flow from the reservoir or provide overtopping protection during extreme flood conditions.

USGS 7.5 Minute Quadrangle Map – Topographic maps developed by the United States Geological Survey that are 1:24,000 in scale, or 1 inch equals 2000 feet. The range of each map covers 7.5 minutes of latitude and longitude.

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