Dam Safety Program

Technical Note 6

Downstream Hazard Classification Procedures for Montana Dams

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DAM SAFETY PROGRAM TECHNICAL NOTE 6 (TN6)
DOWNSTREAM HAZARD CLASSIFICATION PROCEDURES FOR MONTANA DAMS

Overview

Technical Note 6 (TN6) is provided 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.

DAM SAFETY PROGRAM TECHNICAL NOTE 6 (TN6)
DOWNSTREAM HAZARD CLASSIFICATION PROCEDURES
FOR MONTANA DAMS

1.0 INTRODUCTION

The **Montana Dam Safety Program** is pleased to provide this **Technical Note 6 (TN6), Downstream Hazard Classification Procedures for Montana Dams**. We hope this publication is helpful in providing technical guidance to professionals engaged in dam safety analysis and design for high hazard dams in Montana. Our intent is to provide relevant and up-to-date information, references and procedures pertinent to the Montana dam safety rules for conducting downstream hazard classifications using a process that has been tested and modified over years of conducting these types of analyses.

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. TN6 will be revised and updated as new procedures are refined and new technical references are made available.

1.1 TECHNICAL NOTE PURPOSE

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.

The Administrative Rules of Montana (ARM) 36.14, Subchapter 2 provide 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 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.

1.2 TARGET AUDIENCE

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.

2.0 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.

2.1 UNDERSTANDING 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.

2.1.1 When is a Hazard Classification Required?

Montana Code Annotated (MCA) section 85-15-209 defines when a hazard classification determination is needed:

> *A person proposing to construct a dam or reservoir with an impounding capacity of 50 acre-feet or more measured at the maximum normal operating pool shall make application to the department for a determination of whether the dam or reservoir is a high-hazard dam. The application must include the information required by the department. The department shall make the determination required by this section within 60 calendar days after a complete application is received by the department.*

In addition, ARM 36.14.206(1-4) provides specific criteria for conducting a hazard classification determination:

> *(1) The department's hazard determination shall be based on the consequences of dam failure--not the condition, probability, or risk of failure. A dam must be classified high-hazard if the impoundment capacity is 50 acre-feet or larger and it is determined that a loss of human life is likely to occur within the breach flooded area as a result of failure of the dam.*

(2) The breach flooded area, for the purpose of this classification only, is the flooded area caused by a breach of the dam with the reservoir full to the crest of the emergency spillway.

(3) The evaluation of the effects of flood inundation, for the purpose of classification, will continue downstream until the flood stage is equal to that of the 100-year floodplain.

(4) The breach flow hydrograph and downstream routing of the breach flows, for the purpose of classification, will be estimated by the department either by visual determination or dam breach modeling techniques.

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 less than 50 acre feet with roads or houses downstream can cause loss of life, but are exempt from classification requirements. A dam that fails during an extreme storm event can have a larger flooded area than the one used in a hazard classification. 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.

2.1.2 Types of State Hazard Classifications

The Montana Dam Safety classification system is relatively simple compared to other states and other jurisdictional entities. Montana classifies dams under its jurisdiction as either high hazard or not high hazard. Criteria for determination of a high hazard dam are found in ARM 36.14.206(1):

The department's hazard determination shall be based on the consequences of dam failure--not the condition, probability, or risk of failure. A dam must be classified high-hazard if the impoundment capacity is 50 acre-feet or larger and it is

determined that a loss of human life is likely to occur within the breach flooded area as a result of failure of the dam.

All other dams, excluding those under the jurisdiction of other governmental agencies, are classified as 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 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.

2.1.3 Reasons for Conducting a Hazard Classification

The ARMs are clear on who shall apply for an application and when an application for a hazard classification is required. ARM 36.14.201 is specific in stating that:

…an application for hazard determination must be made by an owner proposing to construct, including new construction, alteration, repair, enlargement, or removal of, any dam or reservoir that has or could impound to the crest of the dam 50 acre-feet or more. This requirement applies even if the department performed a hazard determination on previous construction to the dam or reservoir and found it not to be a high-hazard dam. This requirement does not apply to the owner who already possesses a valid operation permit for the high-hazard dam.

However, the ARMs are somewhat ambiguous in recommending other reasons for a having a hazard classification completed, even though the reasons are stated in various locations of the ARMs. The primary responsibility of dam owners is to provide reasonable standard of care

for their dams. This ultimately means that an owner is liable for his/her dam and its operation, and he/she is expected to be diligent and conscientious in the maintenance and operation of the dam. ARM 36.14.105 states:

> *These rules do not relieve or lessen the responsibility of any person owning, operating, or controlling any high-hazard dam or reservoir for any damages to persons or property caused by defects. These rules do not affect criminal liability of dam owners or operators pursuant* to *85-15-501, MCA (MCA 85-15-501 has since been repealed and is replaced by 85-15-305).*

MCA 85-15-305 explicitly provides wording related to dam owners' liability for damage in the event of a dam failure:

> *(1) Except as provided in subsections (2) and (3), nothing in this chapter relieves an owner of a dam or reservoir of any legal duty, obligation, or liability incident to its ownership or operation, including any damages resulting from leakage or overflow of water or floods caused by the failure of the dam or reservoir.*
> *(2) The owner of a dam or reservoir that has been permitted by the department in accordance with this chapter or that was designed and constructed under the supervision of an engineer and properly maintained is, in the absence of negligence, not liable for damages to persons or property resulting from flows of water from failure of the dam or reservoir.*
> *(3) In addition, the owner of any dam or reservoir that has been permitted by the department in accordance with this chapter or that was designed and constructed under the supervision of an engineer and properly maintained may, without incurring liability, allow passage through the reservoir of inflows without diminution.*

In other words, under MCA 85-15-305(2), if an owner of a high hazard dam has been diligent in having the dam classified and properly maintained and meeting design standards related to high hazard dams, then the law states that he/she will not be liable for damages because they have not been negligent in the care of their dam. Informally, this is called "negligent liability."

Conversely, if an owner has been negligent in the care and operation of a dam, they incur strict liability. This means they are responsible for damages caused by their dam regardless of fault. 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 less than 50 acre-feet or a not-high-hazard dam of 50 acre-feet or larger does not relieve an owner of liability associated of the dam. They are still subject to strict liability for damages caused by the dam.

2.1.4 Oddities and Limitations of Hazard Classifications

Because of procedures stated in ARM 36.14.206 (see Section 2.1.1 of this technical note) that define how a hazard classification is conducted, it leaves open the possibility that a dam that has been classified as not-high-hazard could 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 the crest of the emergency spillway or the maximum normal reservoir level. 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.

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 (see Section 4.0).

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, strict liability applies and they will ultimately be responsible for damages caused by their dams. Showing due diligence is very important for these owners.

2.2 SUMMARY OF REQUIREMENTS FROM DAM SAFETY RULES

The ARMs provide the details for requirements for a hazard classification determination. The following sections summarize the rules and how they apply to hazard classifications.

2.2.1 What Constitutes a Hazard?

In ARM 36.14.206 (5), specific structures and facilities are identified as being capable of human occupation:

> *Loss of life is assumed to occur if the following structures are present or planned for as a matter of public record or notice in the breach flooded area: occupied houses and farm buildings, stores, gas stations, parks, golf courses, stadiums, ball parks, interstate, principal, and other paved highways, and including railroads, highway rest areas, RV areas, developed campgrounds; and excluding unpaved county roads and all private roads.*

If any of the structures or facilities mentioned above are found to be inundated by the modeled breach flow from a dam, loss of life is assumed to occur.

2.2.2 Who is Required to do a Hazard Classification?

ARM 36.14.201 states:

> *An application for hazard determination must be made by an owner proposing to construct, including new construction, alteration, repair, enlargement, or removal of, any dam or reservoir that has or could impound to the Normal Operating Pool[1] of the dam 50 acre-feet or more. This requirement applies even if the department performed a hazard determination on previous construction to the dam or reservoir and found it not to be a high-hazard dam. This requirement does not apply to the owner who already possesses a valid operation permit for the high-hazard dam.*
>
> *[1] Rule under revision to reflect changes to statute*

The rule applies to private, State, or local government (city, county, irrigation districts) owners of dams. Dams that are exempt from this rule are federally-owned or regulated dams, dams on federal property, and dams under the jurisdiction of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, or Superfund).

Determining the normal storage elevation and assessing if it is over 50 acre-feet can be a challenge, depending on the dam and its appurtenances. However, the descriptions listed below represent the most common types of normal pool conditions:

- For most on-stream reservoirs, normal pool is generally the lowest non-gated spillway; often the drop inlet crest elevation. For off-stream reservoirs, normal operating pool will depend on the configuration of the dam and outlets and may require some judgment. For most flood control structures, normal operating pool is often the auxiliary spillway crest.
- The breach analysis for hazard classification determination for dams that include below-ground surface storage in the 50 acre-feet requirement may, determined on a case by case basis, use the below-ground surface storage in the breach analysis.
- If the total storage of reservoirs of dams in series exceeds 50 acre-feet, even though individually they are less than 50 acre-feet, a hazard classification is still necessary.

2.2.3 Downstream Routing Extent

In ARM 36.14.206(3), routing of the breach flood in a hazard classification determination extends to the point where the peak breach discharge is equal to or less than the peak 100-year discharge for the stream. It is important to note that this extent is regulatory and does not represent a limit of where loss of life could occur. In other words, loss of life could occur if houses or human occupied structures within the 100-year floodplain downstream of the extent of breach flood routing are inundated by the breach flood. Even though human occupied structures within a 100-year floodplain are not considered hazards by state and federal standards, they can be subject to loss of life by a breach flood.

2.2.4 Previously Classified Dams

ARM 36.14.201 states that owners proposing repair on a dam that was previously classified are still required to apply for a hazard classification in case downstream hazards have changed. However, the Dam Safety Program encourages such owners to check with DNRC regional engineers for confirmation of changes in the downstream area. The hazard classification may be waived if no additional downstream development has occurred since the time of the original classification.

2.2.5 Options for Independent Hazard Classifications

ARM 36.14.207 (1) states in part:

> *A high-hazard dam owner may request the department to reconsider a hazard determination. A request for reconsideration must include the data and analyses necessary to show that the dam is not a high-hazard dam.*

Because of the nature and responsibilities of the Dam Safety Program in carrying out the intent of the Dam Safety Act and associated ARMs, hazard classifications conducted by the Program are relatively simplified and conservative. Rules allow dam owners to do an independent analysis of hazard determination using better survey data and more sophisticated modeling.

2.3 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. This should be the appropriate action for dam owners given the strict liability to which they are held. Voluntary compliance, or applying for hazard classification without an order to so, is considered part of expected standard of care.

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

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.

3.0 TECHNICAL COMPONENTS OF A HAZARD CLASSIFICATION

Consistency in hazard classification determinations depends on maintaining similar components within each classification analysis. The following section provides a summary of components common to a hazard classification determination.

3.1 COMPUTER MODELING

While results of some hazard determinations may be obvious and computer modeling is deemed unnecessary, it is usually the case that 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, 2009) in breach flood routing. 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, 2010). 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.

The Dam Safety Program accepts more complex models such as HEC-RAS, FLDWAV (NWS, 2008) or two-dimensional models such as FLO-2D (FLO-2D, 2010). Because of expected computational details and model stability challenges of more sophisticated models, their associated engineering costs may be higher than if 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.

As mentioned at the beginning of this section, some cases may not warrant a modeling effort. 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. This would be the case where hazards are located at an elevation above the invert (low point) of the natural waterway that exceeds the hydraulic height of the reservoir and no obstructions downstream are present to create additional backwater height.

3.2 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.

3.2.1 Starting Water Surface Elevation

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.

3.2.2 Reservoir Elevation-Storage Data

For larger reservoirs, elevation-storage data may be relatively easy to locate, usually with the reservoir's operation and maintenance plan. For smaller reservoirs or reservoirs previously not affected with dam safety analyses, elevation-storage data may be harder to determine. In ARM 36.14.102 (3), it is suggested in the absence of any other available data, the reservoir's storage can be estimated by multiplying the surface area of the reservoir at the level in question by the height of the dam taken at the downstream toe times 0.4.

Another method commonly used is to utilize topographic maps to extrapolate reservoir area-elevation data based on topographic contours at and 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 either digitally or by planimeter. The downstream areal extent is to the dam centerline. An example of this method is depicted in Figure 3-1.

FIGURE 3-1. ESTIMATING A RESERVOIR ELEVATION-AREA RELATIONSHIP BY EXTRAPOLATING A TRENDLINE BELOW THE NORMAL RESERVOIR SURFACE

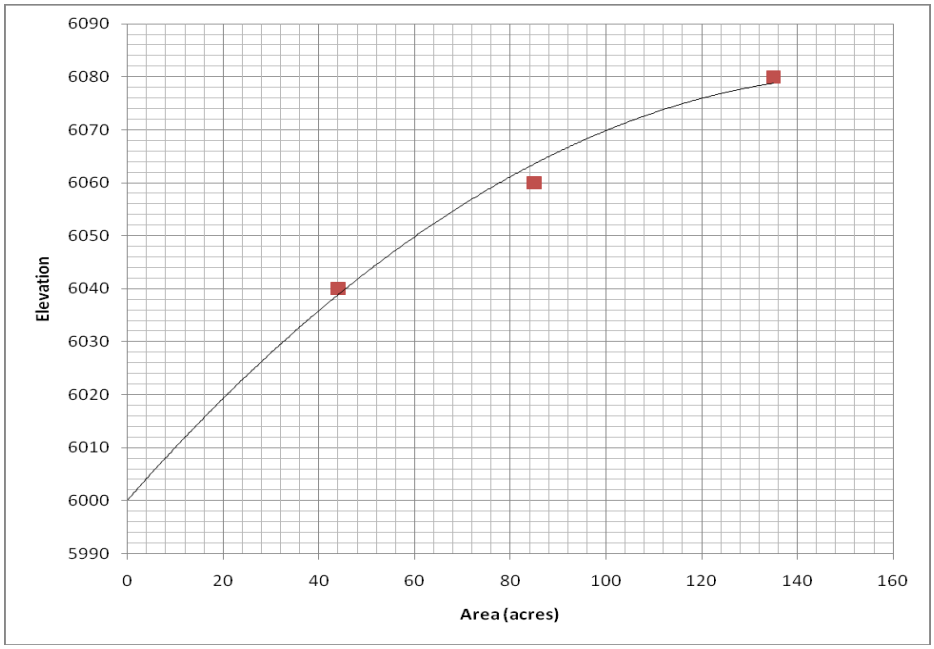


Figure 3-1 represents a reservoir whose normal water surface on a topographic map is shown at elevation 6040. Three area estimates were determined by planimeter or digital delineation at elevation contours 6040 (area = 44 acres), 6060 (area = 85 acres), and 6080 (area = 135 acres) and are represented on Figure 3-1 by small squares. It is also known that the bottom of the reservoir is at or very near elevation 6000. For this example, a polynomial trendline 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.

3.2.3 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.

3.2.4 Minimum Reservoir Storage Capacity

In accordance with ARM 36.14.102, a dam cannot be considered high hazard if its reservoir capacity is less than 50 acre-feet measured to the crest of the dam embankment. Therefore all dams less than 50 acre-feet in capacity are not required to apply for a hazard classification determination.

3.3 DAM

Special consideration is given for the dam and its appurtenances when conducting a hazard classification determination. This is to keep classification analyses consistent and in compliance with the dam safety rules that have been established.

3.3.1 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, no flows from auxiliary spillways will be considered. Principal spillway flows are typically insignificant compared to breach flows from the dam, so they can be neglected as well. Judgment may have to 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.

3.3.2 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 that parameters that best represent actual piping failures are those developed by Froehlich of the U.S. Bureau of Reclamation (2008).

3.4 BREACH FLOOD ROUTING

The main component and 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. The following sections give guidance on determining breach routing parameters and procedures for modeling common features encountered in routing analyses.

3.4.1 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. An inexpensive program called "TOPO! Explorer®" is available from the National Geographic Society to develop a cross section from maps. The user of TOPO! should be aware that the cross section coordinates appear to be X and Y (horizontal distance and height), but they actually represent height and slope distance. The Dam Safety Program has spreadsheets available for public use to assist with modifying the height-slope distance output to be horizontal distance output.

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.

3.4.2 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.

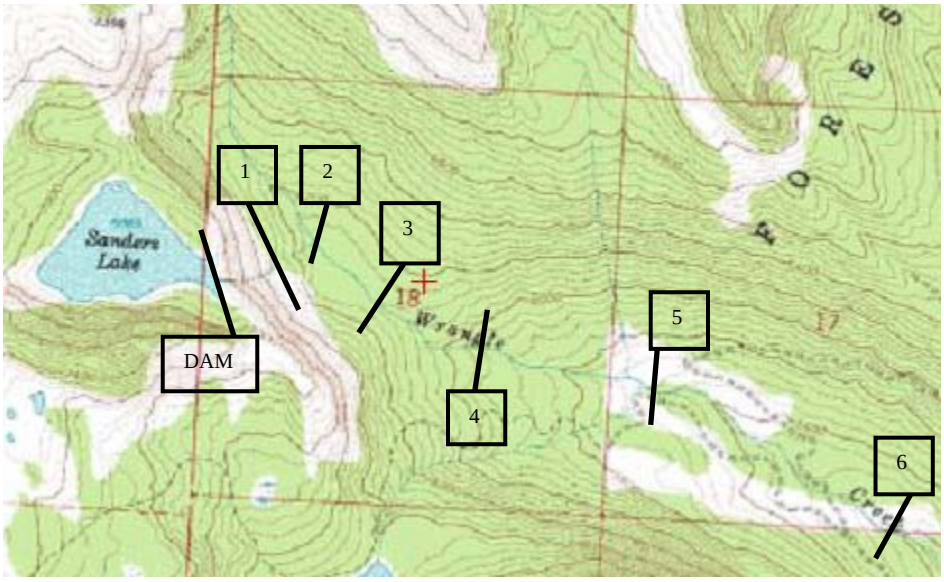
Some mapping tools may help in determining reach length and slope, such as TOPO! Explorer®.

3.4.3 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. Figure 3-2 below gives an illustration of this concept. 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. 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 3-2. SAMPLE PLACEMENT OF CROSS SECTIONS FOR DOWNSTREAM ROUTING



3.4.4 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.

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.

3.4.5 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.

3.4.6 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. Two of the common publications that use pictures to estimate Manning's n coefficients are from the USGS (Arcement and Schneider, 1989) or Chow (1959).

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 larger Manning's n values than regular rainfall-runoff flood flows which are 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.

3.4.7 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 usually 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 water surface elevations because water surface determinations are based only on data at the point only and are not affected by upstream or downstream water surface profiles. So relying only on HEC-HMS routing results may not provide 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. 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 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.

For a bridge, it may be necessary to conduct a HEC-RAS 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 in the HEC-RAS analysis of the bridge. HEC-RAS may require detailed survey data of the bridge and surrounding areas. 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.

For road embankments in the flood routing path, there may be significant ponding or backwater behind road embankments. While this type of backwater is commonly modeled with HEC-RAS because of its backwater surface profile capabilities, it is also possible to model the roads 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, outflow structures, and possibly ditch flow along the road. Flow along the road ditch can be significant. The user is cautioned to model this as accurately as possible because road ditches sometimes have relatively large capacities. It may be useful to model the road ditch as the main downstream flow channel through which flow is routed. Necessary data gathering and input will depend on the applicable situation.

3.4.8 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.

3.4.9 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 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.

3.4.10 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.

One option is to conduct a split flow analysis using the junction split flow optimization methods in HEC-RAS. This method would require the user to assume a steady peak breach flow (using the peak discharge at the location of the upstream point of the split) along the split flow reach, which would be conservative because it would not account for attenuation of the peak flow in the split reach. It would likely require more detailed channel and overbank cross section data than normally expected for a HEC-HMS analysis.

Another method would be to estimate split flow discharges by separately modeling a range of discharges in each split branch. This may only be reasonable for a two-branch split. The flow model for each branch starts at the same water surface elevation at the head of the split. The flow in other branches would be limited to the difference between the total flow at the head of the split and the flow in the modeled branch. The combination of flows that, (a) equal the total flow and (b) end at the same water surface elevation just downstream of the split, would be reasonable estimates of actual flows. This type analysis may be conducted using HEC-HMS and HEC-RAS, the difference being that HEC-RAS would use only one steady state flow and not consider attenuation (this could also be run using the unsteady flow option in HEC-RAS, but as stated earlier, stability of the model presents technical challenges to the user). HEC-RAS may also be more accurate in determining water surface profiles.

3.4.11 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.

3.4.12 100-Year Peak Flood Estimate

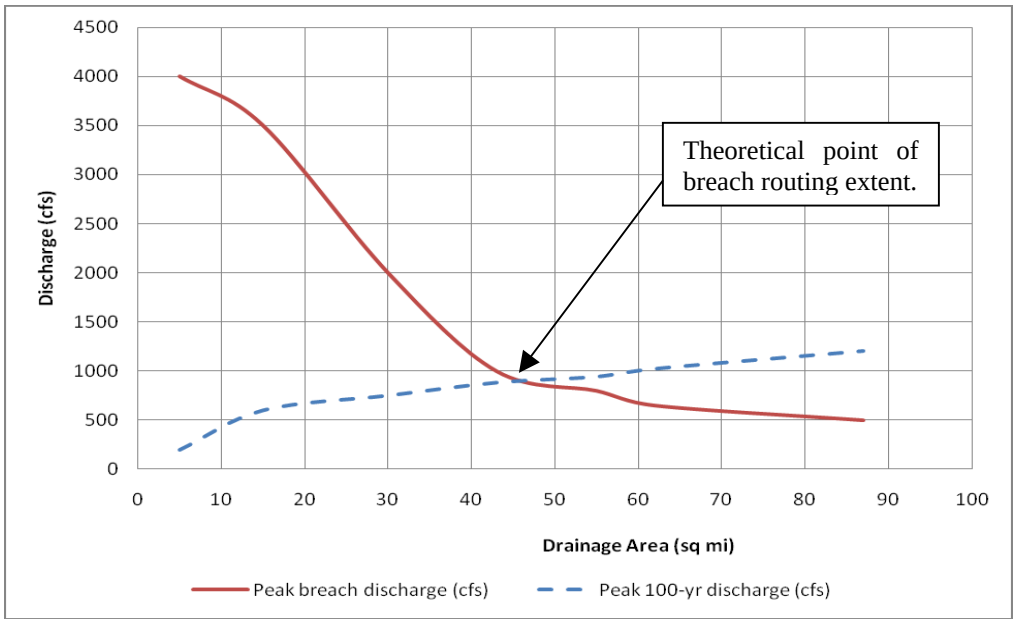
As mentioned above, the extent to which the breach flood is routed is the point at which it falls below the 100-year peak flood estimate for the waterway. However, the 100-year peak discharge on a stream increases as one moves downstream because the contributing drainage area increases. This, combined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

The most convenient and commonly used tools for estimating the peak 100-year discharge for ungaged basins are the U.S. Geological Survey USGS) regression equations for Montana. The equations come from USGS Water-Resources Investigations Report 03-4308, *Methods for Estimating Flood Frequency in Montana Based on Data through Water Year 1998* (Parrett and Johnson, 2004). The USGS has made available an easy-to-use interactive website for using the regression equations at http://mt.water.usgs.gov/freq. The regression results provide average values for peak flows at selected return frequencies.

While the error band of the average estimates can be significant, they are the best estimates available for ungaged basins. Users can use peak flow values in the error range published as long as they look reasonable for the area being analyzed. Conservative estimates may be warranted for the application of hazard classification determinations. It is recommended that gage data be used if available for the watercourse desired.

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



4.0 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.

4.1 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. In Section 2.2.1 of this technical note, the hazards as defined in ARM 36.14.206 (5) were presented. 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.
- Campgrounds and picnic areas.
- 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.

4.2 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

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.

5.0 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.

5.1 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(2) and (3) states:

> *(2) If an upstream dam has the capability to create failure in a downstream high-hazard dam because of its failure flood wave, the upstream dam must be classified as a high-hazard dam.*
> *(3) If the failure flood wave of the upstream dam will cause failure of the downstream dam, and the combined flows will likely cause a loss of life, the upstream dam must be classified as a high-hazard 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.

5.2 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 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.

5.3 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 a sample 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.
- Channel constrictions that tend to raise the upstream water surface elevation due to backwater formation. HEC-HMS, as mentioned previously in this technical note, does not perform standard step backwater computations and will at some locations compute downstream water surface elevations higher than upstream elevations. Judgment is required to determine reasonable backwater elevations upstream of constrictions.
- 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.

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.

FLDWAV – A computer program (Flood Wave) developed by the National Weather Service that a generalized flood routing program with the capability to model flows through a single stream or a system of interconnected waterways. Modeling of steady and unsteady flows is possible, including dam breach flows.

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 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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