Guidance for Completing a Dam Breach Analysis for Small Ponds and Dams in Maryland

DRAFT

MARYLAND
DEPARTMENT OF THE ENVIRONMENT
1800 Washington Boulevard, Suite 540
Baltimore MD 21230-1718

May 2018

Forward

Dams and waterway impoundments provide public benefits through the storage of water for flood control, recreation, drinking water, generation of hydroelectric power, stormwater management, wildlife habitat creation, and irrigation. However a dam's basic function - to store water - creates a potential hazard. Dam failures can result in loss of life and significant property damage. Dam failures occur for a variety reasons including seepage, overtopping, and structural collapse, during both severe weather events and normal periods. At all times the risks associated with the storage of water must be managed to reduce the probability of failure. Design engineers and dam owners are inherently liable for the potential serious consequences of dam failures.

Determining the hazard classification of a dam or waterway impoundment is essential to understanding its threat posed to public safety. Dams in Maryland are classified as low, significant, or high hazard structures. The hazard classification dictates what criteria shall be used to design and construct the dam, and what actions must be taken in the event of an impending failure. This is the case for proposed new dams as well as for the repair or retrofit of existing structures. Thus, one of the first steps in embankment design is to perform a hazard classification analysis.

The Maryland Department of the Environment (Department) receives many requests for detailed information and technical assistance on how to design dams. Ultimately, the primary responsibility for proper dam design lies with the design engineer. This document has been developed by the Department to provide guidance to the design engineer on completing a dam breach analysis and determining its hazard classification. This guidance references some technical manuals and modeling tools that are outside the scope of this document. The design engineer will need to become familiar with the use of these tools, including HEC-RAS, National Weather Service (NWS) Simple Dam Break Equation, HMR-521, HEC-1, HEC-HMS and spreadsheet calculators that can be found on the Department's website.

This document presents a hazard classification system for dams that is simple, clear, and concise. The process is equally appropriate for large dams, smaller pond embankments, or waterway impoundments. A stepped approach is used with increasing levels of technical analysis as the downstream areas become more complex and/or a higher classification becomes appropriate.

This document represents sound engineering practice for most typical situations. Adherence to this guidance, however, does not necessarily guarantee approval of the analysis. The determination on the acceptability of the analysis will continue to be made on a case-by-case basis. Where unusual conditions exist and these guidelines are not applicable, it is the duty of the design engineer to recommend to the Department deviations from the guidelines. The primary responsibility of proper dam design shall continue to be that of the design engineer.

This guidance is a living document and will be updated from time to time with new information as it becomes available. This current version is to be considered a working draft and is available for use by the design community. The Department welcomes comments and questions to help clarify or improve this document. Please direct all questions and comments in writing to Scott Bass at Scott.Bass@maryland.gov.

1. Introduction

This document provides guidance for conducting a breach analysis for the purpose of determining the hazard classification of a dam in Maryland. The breach analysis defines the depth, velocity, and extent of the dam breach floodwave in the downstream inundation area, known as the “danger reach.” The hazard classification of a dam is based on the incremental consequences of a dam failure, including loss of life and property damage, and not its condition or the probability of dam failure. The incremental consequences are assessed based on the increase in hazard when comparing the depth and velocity of the floodwave resulting from a dam breach to the downstream conditions present without a dam failure. The spillway design flood, the inspection frequency, the need for an Emergency Action Plan (EAP), and certain design and approval criteria are based on the hazard classification of the dam. Permit applications to construct, reconstruct, repair or alter a dam or reservoir (lake, pond, etc.) must include a breach analysis and hazard classification determination.

Dam failures occur all the time across the country, and for many different reasons. A failure may be triggered by a large flood that results in overtopping and erosion, uncontrolled seepage through the dam, a sudden structural breakdown, misoperation of the dam, inadvertent excavations within or near the embankment, an earthquake, sabotage, etc. Different failure mechanisms may present different breach discharges and downstream damages, and thus the hazard classification is based on the worst-case condition that can be reasonably expected for a range of hydrologic loading conditions.

There are three hazard classifications for dams in the State of Maryland:

- Low Hazard (loss of life is unlikely and damage is limited);
- Significant Hazard (small possibility of loss of life, damage causes property loss and/or interrupts use of public utilities or roads); and
- High Hazard (loss of life is probable, serious damage to structures, important roads, public utilities or railroads).

Hazard classification categories, low, significant and high are synonymous with Natural Resources Conservation Service (NRCS) Pond Code MD-378 hazard classes “a”, “b”, and “c”, respectively.

2. Determining a Hazard due to Dam Breach

The factors that must be considered in order to determine the hazard classification of a dam include, but are not limited to:

- The population-at-risk (PAR);
- Depth and velocity of flow against habitable buildings;
- Depth and velocity of flow over roads;
- Depth and velocity of flow in the presence of unprotected persons;
- Isolation of a population from emergency services;
- Damage to critical infrastructure;
- Economic loss; and
- Environmental damage.

In Maryland, PAR is often the controlling factor for deciding the appropriate hazard classification of a dam. PAR includes those people present in the inundation flood zone at the time of failure, including permanent residents and transient individuals such as recreationist or the traveling public, who, if they took no action to evacuate, may experience an increased hazardous flooding condition due to dam breach based on depth and velocity of the floodwave. Hazardous conditions associated with depth and velocity of flow to houses, cars, and unprotected persons are defined by the U.S. Bureau of Reclamation in its document, ACER Technical Memorandum No. 11 (ACER 11) *Downstream Hazard Classification Guidelines* (USBR, 1988). Those relationships have been adopted by the Department and form the basis for hazard classification. In some cases, the Department may classify a dam as a significant or high hazard dam based on widespread economic losses that may be caused by dam failure that are beyond the financial ability of the dam owner to repair, or due to impacts that limit or prevent adequate provision of emergency services.

In addition, the Department may assign a higher hazard classification based on loss of life rather than PAR. The evaluation of loss of life from a dam failure requires a significant amount of judgment, assumptions, and detailed analyses. Accordingly, the Department relies on PAR estimates. If it appears readily apparent that one or more lives will be lost from the failure of a dam, the dam is classified as high hazard, regardless of PAR. An example of this condition would be the severe and sudden inundation of a residence immediately downstream of a dam.

An evaluation of the hazard classification of a dam must include a narrative that justifies the classification. The narrative shall include a discussion of the factors which informed the hazard classification.

3. Accepted Methods for Conducting a Dam Breach Analysis

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 Department, in order of increasing complexity, are as follows: 1) Screening Level, 2) Simplified, and 3) Standard Incremental Flood Analysis (Standard). If the Screening Level analysis clearly indicates no hazardous condition exists downstream, then no additional breach analysis is required.

3.1. Screening Level Breach Analysis

The Screening Level Breach Analysis may be used for a dam that is less than 20 feet tall as measured from the upstream toe to the top of the dam. The Screening Level Breach Analysis is appropriate when it seems readily apparent that no hazard exists downstream, and thus the dam hazard level is estimated to be “low”. An acceptable Screening Level Breach Analysis should demonstrate that the lowest point of entry of all inhabitable structures, recreational areas, etc., located between the dam and a downstream major waterway, are at a relative elevation above the adjacent, receiving channel bottom that is equal to or greater than the height of the dam. 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.

Where a roadway or railroad crosses a stream below the dam before joining another significant waterway (e.g. having a drainage area equal to or greater than that which contributes to the dam), a Screening Level Breach Analysis is not typically acceptable.

The Screening Level Breach Analysis must consider full build-out conditions based on current approved zoning.

An acceptable Screening Level Breach Analysis requires a sufficiently detailed justification of the hazard classification. Acceptable documentation of the dam, reservoir, and downstream conditions includes:

- Satellite photos showing the location of the dam and all downstream structures;
- Topographic maps;
- Location of major waterways;
  - FEMA Floodplain, if applicable
  - USGS Streamstats Drainage Area Delineation
- Elevations of structures and roadways;
- Elevation of dam crest and location of dam;
- Stage-storage relationships for the pond, and for a downstream road/rail embankment that may cross the stream;
- Drainage area delineated for all downstream tributaries; and
- Drainage area map of dam.

3.2. Simplified Breach Analysis

Where a Screening Level Breach Analysis is not applicable due to downstream development, the engineer should evaluate whether a Simplified Breach Analysis is appropriate. To qualify to use a Simplified Breach Analysis, the dam must be less than 20 feet tall as measured from the upstream toe to the top of the dam, have a drainage area of less than one square mile, have a storage volume of less than 20 acre-feet, and not be the upstream dam in series with another dam. Where a dam exceeds any of the criteria for a simplified level analysis, a Standard breach analysis shall be performed.

The Simplified Breach Analysis consists of determining the peak breach discharge from the dam using the National Weather Service Simple Dam Break (NWS SMPDBK) equation using the *Dam Breach Worksheet for Earthen Dams* (the Dam Breach Worksheet) available on the Department's website (Wetmore & Fread, 1981). The Brim-Full condition should be evaluated for the Simplified Breach Analysis with both the breach and non-breach conditions evaluated. The breach and non-breach discharge should be routed downstream using hydraulic tools (models, equations) that can produce resultant water surface elevations at critical locations downstream of the dam where the potential for hazardous conditions must be evaluated (roadways, houses, buildings, parks, etc.). Additional details describing the requirements of a Simplified Breach Analysis are provided in the following sections.

Where the results of a Simplified Breach Analysis indicate that the floodwave impacts (touches) a structure, a Standard Breach Analysis shall be performed.

3.3. Standard Breach Analysis

Where a visual reconnaissance indicates that a clear hazard exists, or a Screening Level or Simplified Breach Analysis is not applicable, a Standard Breach Analysis is required. The Standard Breach Analysis evaluates a range of hydrologic loading conditions at the dam and their resultant breach discharges. The engineer may elect to determine the peak breach discharge using the NWS SMPDBK equation from the worksheet, or by parametric relationships available in software such as HEC-RAS, HEC-HMS, or HEC-1. 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, 1D versus 2D HEC-RAS) and the degree of refinement is at the engineer's discretion provided it is within accepted engineering practices. Additional details describing the requirements of a Standard Breach Analysis are provided in subsequent sections.

4. Components of a Breach Analysis

At a basic level, the components of a breach analysis include:

- Determine the discharge from the dam that would result from normal operations (no breach) for various hydrologic conditions;
- Determine the discharge from the dam that would result from an uncontrolled release of the impounded water (dam breach) during those same hydrologic conditions;
- Route/model those discharges downstream of the dam;
- Analyze the change in downstream impacts between breach and non-breach conditions; and
- Determine the Hazard Classification.

4.1. Determine Discharge from the Dam

4.1.1. Hydrologic Conditions to Evaluate

The level of analysis will ultimately determine what specific hydrologic scenarios to analyze; however, the Simplified and Standard breach analyses must include an analysis and comparison of all hydrologic conditions modeled assuming both:

- The dam remains in place; and
- The dam is breached.

The breach discharge is the flow from the dam due to the uncontrolled release of the reservoir. For certain scenarios, the discharge at the dam location should be evaluated assuming no dam is in place (e.g., dam removals, spillway redesign for design storm increase). The appropriate hydrologic conditions to apply for Simplified and Standard breach analyses are discussed in detail in the following sections.

4.1.1.1. Simplified Breach Analysis

A Simplified analysis requires the evaluation of a Brim-Full event, both with and without failure of the dam. The Brim-Full event is defined as an event that would fill the reservoir to the lowest point on the dam crest (excluding the emergency spillway). Where the dam in question has a permanent pool greater than six (6) feet in depth and greater than five (5) acre-feet of volume, the Sunny Day failure condition must also be analyzed.

Analysis of these two conditions can, in most cases, adequately determine the hazard potential for dams that meet the height and storage volume requirements of a Simplified Breach Analysis. Unique cases may exist where analysis of additional hydrologic conditions is warranted and the Department reserves the right to require a Standard Breach Analysis.

4.1.1.2. Standard Breach Analysis

A Standard Breach Analysis consists of modeling the following five (5) hydrologic scenarios:

- Sunny Day;
- 100-Year Storm;
- Brim-Full Storm;

- ½ Probable Maximum Flood (by flow, not precipitation depth); and
- Probable Maximum Flood.

The Standard Breach Analysis must include an analysis of both breach and non-breach scenarios for each of these hydrologic conditions, with the exception of the Sunny Day, which requires only the breach scenario. If the pond is a dry facility, the Sunny Day pond volume and breach height shall be computed assuming the low-flow orifice(s) of the riser structure is plugged, and the pond is filled to the high-stage weir crest.

The Department reserves the right to require the analysis of additional hydrologic conditions for certain unique cases where the results are anticipated to better inform the hazard classification.

4.1.2. Breach Parameter Estimation

There are several critical parameters that contribute to the peak breach discharge associated with the uncontrolled release of the reservoir as a result of a dam breach. These factors include:

- Final breach width;
- Breach height;
- Side slopes of breach;
- Breach Formation Time; and
- Method by which breach develops (overtopping vs. piping).

A number of studies have been performed using dam failure data sets from across the world in an attempt to correlate observations of breach geometry, time to failure, and peak breach discharges with the height of the dam, the depth and volume of water impounded at the time to failure, and in some cases the volume of the dam embankment. The relationships that are generally accepted by the Department include the following:

- National Weather Service (NWS) Simple Dam Break Equation (Wetmore & Fread, 1981)
- Froehlich's Embankment Dam Breach Parameters Revisited (1995) (breach parameters only)
- Froehlich's Embankment Dam Breach Parameters and Their Uncertainties (2008) (breach parameters only)
- MacDonald & Langridge-Monopolis' Breaching Characteristics of Dam Failures (1984) (limited applicability)

Additional breach parameter relationships, such as Xu & Zhang's *Breaching Parameters for Earth and Rockfill Dams* (2009), and Von Thun & Gillette's *Guidance on Breach Parameters* (1990), are included in software such as HEC-RAS. These relationships require additional documentation, and must be approved prior to their use (USACE).

The Dam Safety Division has developed the Dam Breach Worksheet that is available on the Department's website. Engineers completing a dam breach analysis should complete this spreadsheet for all hydrologic conditions modeled, and include them as part of the dam breach report. The worksheet requires the entry of specific information for each hydrologic condition being modeled, such as maximum depth and volume of water impounded by the dam. The worksheet will compute critical breach parameters using the

Froehlich (1995), Froehlich (2008), or MacDonald & Langridge-Monopolis (1984) equations. The user must then enter the selected breach parameters used in the analysis.

Evaluating the failure of a weir wall or gravity dam due to sliding, overturning or structural failure will depend on the details of the structure (e.g., joint spacing) and requires separate evaluation. Breach analysis for such structures generally involves the instantaneous removal (i.e. time of failure 0.01 hrs) of a portion of the structure, or in some cases, the entire structure.

4.1.3. Breach Discharge Estimation

Peak breach discharges may be determined using approved empirical relationships or parametric models as discussed in this document. Empirical relationships provide a single peak discharge value. Parametric models may be used to develop a peak breach discharge or a breach hydrograph by assigning critical breach parameters in a hydraulic model. Some popular models in the public domain that can develop breach flow hydrographs include HEC-1, HEC-HMS, and HEC-RAS. Models not in the public domain may only be used with prior approval from the Department.

Special Considerations for Wide Roadway Embankments

Where a wide roadway embankment forms a dam, the combination of a relatively large crest width, and low storage volume can lead to a condition where a full breach may not develop. If such an embankment has been determined to have adequate freeboard for a PMF storm, or overtopping flows would flow along the roadway rather than over it, the engineer may determine the breach discharge due to a piping failure rather than an overtopping failure. The MacDonald & Langridge-Monopolis (1984) empirical breach parameter relationships (with time to failure determined using the Washington State Methods[1]) can be considered in such a case. If the full breach cannot develop, the increased discharge from an enlarged "pipe" can be used in lieu of the peak breach discharge (Washington State Department of Ecology, 1981). Use of this method requires an understanding of the materials used in the embankment construction and its applicability to a specific project should be confirmed with the Department before use.

A detailed discussion of this method and conditions where its use may be appropriate has been developed by the State of Colorado, Department of Natural Resources, Division of Water Resources, Dam Safety Branch (State of Colorado, 2010). The Colorado Dam Safety Branch webpage also hosts spreadsheets that can be used to calculate the MacDonald & Langridge-Monopolis (1984) breach parameters and peak breach discharge.

4.1.3.1. Simplified Breach Analysis

Empirical Method

When performing a Simplified Breach Analysis, the engineer must complete the Dam Breach Worksheet to determine the peak breach discharge using the NWS Simple Dam Break Equation. The NWS Simple Dam Break equation computes a breach flow for a range of breach widths, from 1*H to 5*H, where "H" represents the peak height of water above the upstream toe of the dam for the particular hydrologic scenario being modeled. The combined discharge from the principal and emergency spillways at the top

[1] The Washington State Methods refers to the work done by the Washington State Department of Ecology, and their consultants, to adjust the MacDonald & Langridge-Monopolis method for time of failure based on whether the dam is made of cohesive or cohesionless materials. This method is described in detail in the Colorado Guidelines for Dam Breach Analysis, Feb. 2010.

of dam must be included as part of the peak breach discharge. The largest peak breach flow value reported from the range of associated final breach widths must be used.

If the final dimensions of the dam and/or pond volume are still subject to future refinement due to the nature of the project (e.g. Design-Build), a Simplified Breach Analysis may be performed based on conservative anticipated embankment height and storage volume. It is recommended that these values be at least ten (10) percent greater than the largest anticipated final design value for the purpose of determining a time of failure and peak breach discharge. Upon completion of design, the peak breach discharge used in the analysis shall be checked against the predicted peak breach discharge based on the final embankment geometry to confirm that the initial analysis was conservative. This method is not acceptable where a Standard Breach Analysis is required due to dam size or storage volume, or where the dam failure creates a hazardous condition downstream.

For wide roadway embankments with small pond volumes, the MacDonald & Langridge-Monopolis (1984) method may be used to compute peak breach discharge with approval from the Department provided the conditions of the "*Special Considerations for Wide Roadway Embankments*" in Section 4.1.3 are satisfied.

Parametric Methods

A hydrologic model, such as HEC-1 or HEC-HMS, or HEC-RAS can be used to model the Brim-Full storm event and to compute the peak breach discharge. Breach parameters associated with the worst case peak flow, calculated using the NWS Simple Dam Break Equation, shall be selected as the breach parameters to be input into the model.

HEC-RAS 2D

A Simplified Breach Analysis may use HEC-RAS 2D, Version 5.0.3 or later, to compute a breach hydrograph. The model shall consist of a storage area connected to a 2D Flow Area by a Storage Area-2D Area Connection. In lieu of entering a peak outflow (Qo) value associated with outflow at the top of the dam, the HEC-RAS model should assume a dam height one-tenth greater than the actual height, and must interpolate a storage volume above the actual storage volume to that height. The model will assume that the principal spillway and emergency spillways are blocked (USACE). The time of failure should be 0.17 hours, and the failure mode shall be "overtopping." Breach bottom elevation shall be assumed to be the bottom of the pond. If the model is to incorporate downstream hydrology and flows from additional tributaries, upstream boundary conditions shall be modeled as unsteady flows, and shall account for timing of the hydrographs, in conjunction with an associated hydrologic model.

HEC-RAS version 5.0.4 was released in May 2018. New capabilities include improvements to culvert modeling, and the ability to model dams using rating curves (USACE). The Department should be consulted when using this model.

4.1.3.2. Standard Breach Analysis

The use of empirical or parametric methods to determine the breach discharge is acceptable for an incremental breach analysis. Regardless of the method used, the Dam Breach Worksheet should be completed for each hydrologic condition and included in the submission for review.

Empirical Methods

The use of empirical methods in a Standard Breach Analysis differs from the Simplified Breach Analysis due to the range of hydrologic conditions that must be evaluated. Accordingly, the worksheet must be completed for each hydrologic condition in conjunction with a hydrologic model that has the ability to route storm events through the reservoir. This is necessary to determine the peak outflows (Qo) and water surface elevations, as input parameters and resultant peak breach discharges will vary with increasing water surface elevations and storage volumes. Examples of hydrologic modeling software in the public domain and acceptable to the Department include the following:

- TR-20 (WinTR-20) (USDA, 1992);
- HEC-1 (USACE, 1998); and
- HEC-HMS (USACE).

Parametric Methods

If the use of parametric model is planned for a Standard Breach Analysis, modeling software that can determine peak breach flows or develop a breach hydrograph must be used. The resulting peak breach discharge may be used to route the flows downstream using a steady flow model or the breach hydrograph may be used to route flows downstream using an unsteady flow model. Hydrologic modeling software that can be used to develop the breach hydrograph, that is acceptable to the Department includes: HEC-1, HEC-HMS, and HEC-RAS. TR-20 is not capable of developing a breach hydrograph. As with the Standard Breach Analysis using empirical methods, the Dam Breach Worksheet should be completed for each hydrologic condition.

Breach Timing Considerations for Parametric Methods

When using a parametric model, the breach trigger shall be specified at both the peak water surface elevation for each scenario, and at time that will result in the maximum peak breach discharge so as to analyze the worst case scenario. Typically, for a worst case scenario, the peak breach discharge should occur at the same time as the peak non-breach discharge. This may require breaching the dam on the rising limb of the outflow hydrograph. If this condition is not accounted for, a discussion of why it is not necessary, or why such a condition is not possible or reasonably likely, shall accompany the analysis.

4.1.4. Hydrologic Considerations

4.1.4.1. Hydrologic Considerations for Simplified Dam Breach Analysis

Generally, it is good engineering practice to consider the downstream hydrology in a dam breach model, including the timing of the hydrographs. Typically, a Simplified Breach Analysis does not need to consider downstream hydrology to determine the hazard classification of a dam. However, in certain scenarios where a significant additional drainage area contributes to the danger reach upstream of buildings, roads, or other critical locations being analyzed for hazardous flow conditions, downstream hydrology shall be considered. In a Simplified Breach Analysis, absent setting up a hydrologic model to account for hydrograph timing, the 100-year peak flow from downstream drainage areas as defined by USGS StreamStats, GISHydro, TR-55, or other approved methods, shall be added to the peak breach and non-breach discharges when analyzing impacts to structures, roadways, and other critical locations of interest. Alternatively, it is preferred to use a hydraulic model to time the peak discharges from the dam with downstream drainage areas. If this method is used, the modeler only needs to consider the hydrologic condition that will fill the dam to the brim.

4.1.4.2. Hydrologic Considerations for Standard Breach Analysis

Hydrologic considerations for breach analyses depend on the size of the drainage area. Hydrologic computations to a dam with a drainage area of more than one-square mile shall be calibrated in accordance with methods described by the Maryland Hydrology Panel's *Application of Hydrologic Methods in Maryland* (MDE, 2016), or latest version.

Storm return intervals up to the 1000-year storm event shall use NOAA Atlas-14 rainfall depths and associated rainfall distributions. Depths associated with the Probable Maximum Flood (PMF) and fractions thereof shall refer to "Hydrometeorological Report No. 51; Probable Maximum Precipitation Estimates, United States East of the 105th Meridian" dated June 1978, for rainfall depths. Alternatively, a site-specific Probable Maximum Precipitation study may be conducted with approval of the Department. Where the time of concentration has been determined to be sufficiently less than six (6) hours, a six (6) hour storm may be used for the PMF, ½ PMF, and Brim-Full storm scenarios. If the computed time of concentration approaches three (3) hours or greater, the Department must be consulted to determine if a longer duration storm is necessary or if multiple storm durations are appropriate. The PMF, ½ PMF, and Brim-Full six (6) hour storms shall use the distribution defined in "Figure 2-4: Dimensionless design storm distribution, auxiliary spillway and freeboard" of the Natural Resources Conservation Service's *Technical Release No. 60: Earth Dams and Reservoirs* (USDA, 2005).

For dams with times of concentration longer than, or sufficiently approaching six (6) hours, a longer storm event shall be considered when modeling the PMF, ½ PMF, and other fractions of the PMF, including the Brim-Full event, shall use the HMR-52 computer program, developed by the United States Army Corps of Engineers, and available on the Department's website. For dams where a storm of longer than 72 hours may be appropriate, consult with the Department.

For dams with a drainage area larger than ten (10) square miles, the HMR-52 program shall be used to determine the probable maximum flood. Using other methods requires approval from the Department. The HMR-52 program has the ability to develop a temporal and spatial storm pattern to maximize the probable maximum precipitation for a given drainage area.

Downstream hydrology shall be considered to the satisfaction of the Department to account for the addition of major tributaries to the danger reach, and to account for additional flow contributions to the danger reach as flows travel downstream. Hydrology shall be computed to all roadway crossings analyzed in order to accurately depict non-breach conditions. If homes or major subdivisions are located downstream of the last roadway modeled, the hydrology to that location shall be incorporated into the model. It is recommended that the modeler agree to a hydrologic model with the Department prior to finalizing hydraulic modeling of dam breach flows downstream of the dam.

4.1.5. Hydraulic Considerations

In general, the level of analysis is commensurate with the complexity of the downstream danger reach. HEC-RAS cross sections may be determined using LiDAR data, or survey information, but the source of the information must be documented. HEC-GeoRAS may be used to set up cross section geometry. Supporting information should be included to support downstream bridge opening and culvert dimensions (e.g. spot shots, as-built drawings, field measurements, etc.). HEC-RAS 2D models shall use a terrain resolution appropriate for the size of the dam being analyzed. The Department should be consulted if HEC-RAS 2D terrain is developed using anything other than LiDAR data obtained from Maryland iMAP. Assumptions for Manning's roughness coefficients associated with land use or land cover data, as well as the source of the data, shall be documented.

Culverts equal to or less than 36 inches in diameter, and less than 1,000 feet downstream of the dam shall be considered fully blocked when modeling a dam breach condition. Culverts greater than 36 inches and less than 1,000 feet downstream of the dam shall be considered ½ blocked. More than 1,000 feet downstream of the dam, culverts less than 36 inches in diameter shall be considered ½ blocked, and culverts greater than 36 inches in diameter may be modeled based on the percent blockage that exists at the time of the analysis. A deviation from the standard shall be accompanied by an engineering analysis to the satisfaction of the Department.

4.2. Modeling Flows Downstream

Once the dam breach discharge and the runoff from the necessary hydrologic conditions have been determined, the maximum breach and no-breach water surface elevations and velocities shall be computed by modeling or routing the discharges downstream. Route the breach flow using hydraulic tools (models, equations) that can produce resultant water surface elevations at critical locations downstream of the dam where the potential for hazardous conditions must be evaluated (roadways, houses, buildings, parks, etc.). Flow may be modeled downstream using a steady flow or unsteady flow analysis.

The location of the breach along the embankment may impact the results of the analysis. All breach analyses should consider a breach location at the principal spillway. Where the dam embankment is long or has a curvilinear shape, it may be necessary to perform additional analyses with the breach location at one (1) or more additional locations. The selection of additional breach locations should consider the terrain and anticipated floodwave path; adjacent vulnerable structures, roads, or recreation areas; low points on the embankment crest; and other conditions that may make a portion of the dam embankment more vulnerable to failure. The downstream impacts must be evaluated for each breach location to determine the hazard classification. The inundation map must be a composite of the maximum extents of both breach conditions.

Flow attenuation is a benefit of using a hydraulic model (e.g., HEC-1, HEC-HMS, and HEC-RAS) to route flows downstream. The peak flow will typically decrease (attenuate) as the floodwave travels downstream. This attenuation can be particularly significant where a relatively small volume of water is released in the dam breach. A steady flow model can be configured to account for flow attenuation, provided the flows are routed using a modeling software such as HEC-1, HEC-HMS, or HEC-RAS. If a hydrologic model is set up in order to account for flow attenuation of a dam breach floodwave, downstream hydrology contributing to the danger reach shall also be considered at critical locations (e.g. culvert and bridge crossings, houses, etc.), regardless of the size of the drainage area. An unsteady model using HEC-RAS can model storage in the floodplain as floodwave travels downstream, and can often more accurately determine the maximum water surface profile and velocity.

4.2.1. Acceptable Modeling Tools

For all dam breach analyses, the complexity of tools and methods used to evaluate the maximum water surface profiles and velocities of dam breach flows should be commensurate with the complexity of the downstream area to be modeled and the anticipated hazard posed by the dam. For all dam breach analyses, HEC-RAS is the preferred tool to compute maximum water surface profiles and velocities of dam breach flows. HEC-RAS must be used for Standard Breach Analysis, but is optional for Simplified Breach Analyses provided the tools and methods used are appropriate.

Proprietary software exists that can perform similar functions as HEC-RAS (e.g., FLO-2D, MIKE-11); however, the Department does not maintain licenses to these software, and thus their use is strongly discouraged. If the use of such software is proposed, consult with the Department prior to beginning work to determine how the results will be presented, reviewed, and accepted.

4.2.1.1. Simplified Breach Analysis Flow Modeling Tools

Simplified Breach Analyses may use simple tools, where appropriate. An example of a simple tool is the Federal Highway Administration HY-8 program to model flows through and over roadway crossings. If the only downstream hazards to be analyzed are roadway crossings, the peak breach and non-breach flows may be modeled using HY-8 (FHWA). Additionally, modeling the entire breach flow overtop a roadway using the weir equation may conclusively demonstrate that a dam is not a hazard to a roadway; situations where this may be appropriate include small pond volumes upstream of a wide, flat roadway. A simple Manning's cross section may also be used to show that flood depths in a stream channel are far outside of being a hazard to structures; however, using a simple Manning's cross-section is not appropriate where stream constrictions may impact the results of the computation by creating a tailwater condition, or where backwater from a culvert or other flow obstruction may impact the results of the computation. This analysis is most applicable to a relatively straight stream valley without significant deviations in valley width and without obstructions. A cross section shall be placed at all critical locations (e.g. houses). Scaled maps showing the cross section locations and associated contours or spot shots shall be included in the report for verification. If this method shows that houses are close to being impacted (i.e., within 6 inches in vertical dimension), a more robust modeling effort shall be used. When used, a Manning's cross-section must assume a conservatively flat channel slope (half the actual), and a conservatively rough manning's roughness coefficient (double). HEC-RAS has the ability to account for backwater from channel constrictions and obstructions, and is therefore always preferable to single, simple cross sections, but the Department recognizes that HEC-RAS may not always be necessary (USACE).

HEC-RAS 2D may be used for a Simplified Breach Analysis. If there are no significant tributaries upstream of critical locations within the danger reach, then a Brim-Full HEC-RAS 2D model is acceptable. Reservoir, dam, and breach parameters associated with such an analysis shall be set up in accordance with requirements of Section 4.1.3.1. All culverts shall be assumed blocked with this method. If there is more than one road crossing in the danger reach, the impact of blocking the upstream culvert on the hazard to the downstream road crossing shall be discussed.

4.2.1.2. Standard Breach Analysis Flow Modeling Tools

Full Incremental Breach Analyses shall use HEC-RAS modeling software. Modeling shall be conducted in accordance with the HEC-RAS User's Manual (USACE). Inflows from additional contributing downstream drainage areas shall be timed in accordance with the hydrologic model.

4.2.2. Model Termination

A dam breach analysis shall extend to a point downstream where the difference in elevation between a breach and non-breach condition is less than one-foot, or where there is clearly no hazard. While approximate methods exist for determining danger reach length based on factors such as valley width, height of dam, and storage volume, the results of such a computation are not acceptable as a justification for terminating a danger reach. If such methods are used, it is recommended that they be used for screening purposes only, in order to determine how far the danger reach should be conducted in the first iteration; results of the actual analysis will determine whether the reach length is sufficient.

In some cases, the danger reach for small dams, located on small tributaries to rivers or other major waterways, can be terminated when the danger reach joins with the major waterway. Although the termination point will be readily apparent to an experienced modeler, justification must be provided in the narrative. Demonstrating that the breach floodwave can be contained within the major floodway's channel banks using a conservatively rough (double manning's roughness value) and conservatively flat (assume slope is half that of the major waterway) manning's equation is an example such a demonstration. Another example of such a demonstration is using FEMA Floodplain information to demonstrate that the 100-year peak flow of the major waterway is greater than that of the dam breach flow as determined by the NWS Simple Dam Breach Equation. Where houses are located in the floodplain shortly downstream of the junction of the danger reach with the major waterway, such a justification is not appropriate absent additional analysis.

5. Determining Population-at-Risk (PAR) and assigning Hazard Classification

The population-at-risk (PAR) includes those people present in the inundation flood zone at the time of failure, including permanent residents and transient individuals such as recreationist or the traveling public. To determine whether an impacted house, road, or unprotected person(s) contributes to the population at risk (PAR), the maximum depth and velocity of the floodwave during a breach and non-breach condition shall be plotted on the appropriate Depth-Velocity Flood Danger relationship charts published on the Department's website. These charts have been converted to Microsoft Excel spreadsheets for easier use, and replicate those found in the ACER Technical Memorandum No. 11 (ACER 11) *Downstream Hazard Classification Guidelines (USBR, 1988)*. The Depth-Velocity Flood Danger Charts have been developed to ascertain the potential hazard that various combinations of flow depth and velocity pose to persons in passenger vehicles, houses, and those who are otherwise unprotected (i.e., a person outdoors).

A structure/vehicle/person shall be considered to contribute to the overall PAR when the depth-velocity relationship changes from a "low danger" to "high danger", due to the breach, for any of the hydrologic conditions modeled. If the relative danger remains within the same zone for the breach and no-breach condition for all hydrologic conditions analyzed (e.g., both plot in the low danger, or both in the high danger zones), then the structure/car/person being investigated is not considered to contribute to the PAR value. If the depth-velocity relationships plot in the "judgment zone", the engineer shall provide justification for their decision to include/exclude the population as PAR. In general, if a slight increase in either depth or velocity results in a "high danger" condition then a scenario that plots in the "judgment zone" should be considered to contribute to PAR.

The Department uses the following guidelines to relate PAR to hazard classification:

- **High Hazard**: PAR equal to or greater than six (6) persons, or obvious loss of life.
- **Significant Hazard**: PAR equal to or greater than one (1), but less than six (6) persons.
- **Low Hazard**: PAR of zero (0) persons.

The engineer must submit the appropriate Depth-Velocity Flood Danger Charts with maximum depth-velocity values plotted for both the breach and non-breach scenarios as part of the hazard classification justification. The USBR ACER 11 (1988) document can be downloaded from the Department's website. The document contains detailed information regarding the hazard classification process, and the Department encourages that engineers become familiar with the guidance before completing a dam breach analysis.

5.1. Determining PAR for Structures

The Depth-Velocity Flood Danger Charts provide relationships for "houses built on foundations" and for mobile homes. If the charts are modified or applied in a different manner the logic behind such reasoning must be sound and documented. The following should be considered when determining PAR associated with flood risks at structures:

- Plot the maximum depth-velocity relationship on the appropriate Depth-Velocity Flood Danger Charts for the breach and non-breach scenarios to determine if an increase in danger exists for a given dam failure.
- The depth of flooding should be the depth above the lowest point of entry, including basement access should one exist. Include in the narrative the source of the first floor or lowest point of entry elevations (e.g., field survey, As-Builts, building permits).
- In general, a single-family home can be considered to contribute a PAR equal to three (3). Census block data can be used to determine average household size, if desired, when greater than ten (10) homes are impacted.
- Where a small portion of a structure is impacted by the floodwave, or where the impact to a structure is at a location where the floodwave would not reasonably cause damage or interior flooding of the structure (e.g., along a concrete wall with no doorways and windows above flood level), the engineer may submit justification to reduce the potential hazard and/or PAR.
- For commercial/retail buildings, schools, hospitals or office buildings, the PAR shall be assigned based on the permitted maximum occupancy rate of the levels that may be inundated. A justification is required to determine if a lesser PAR may be accepted.

5.2. Determining PAR for the Traveling Public

Determining effect of a dam failure for vehicles travelling on an impacted roadway requires the consideration of the flow depth, flow velocity, the duration of roadway overtopping, the volume of vehicular traffic, the road classification, the speed of vehicular traffic, warning time, and a variety of other factors. Accordingly, the Department has developed the following criteria to simplify the assessment of PAR for passenger vehicle occupants when a road is impacted by a dam failure.

- Consider that vehicles have two (2) occupants (i.e., a potential PAR equal to two (2)).
- The Depth-Velocity Flood Danger Charts are based on the danger to stationary vehicles. To determine an approximate number of vehicles that may be impacted by a dam breach and contribute to PAR, the following method shall be used:

    1. Evaluate the depth-velocity flood hazard relationships for all hydrologic conditions assessed. The evaluation shall consider the maximum depth and velocity of the floodwave at the road crossing. If any of the hydrologic conditions indicate an increase in hazard between the breach and no-breach condition, proceed to step 2. If there is no increase in hazard for any of the hydrologic conditions assessed, then zero PAR may be assigned to the road crossing.
    2. Determine the width of each downstream road (parallel to centerline) impacted by 12 inches or greater depth of flooding[2].
    3. Determine the number of passenger vehicles that may be impacted by the floodwave based on the width determined in step 2 and the following criteria:

[2] A depth of 12 inches was selected to account for uncertainty in the dam breach analysis and vehicles entering a flooded roadway.

a. For a section of roadway that has a functional classification of “Local” or “Minor Collector”, consider 0.2 vehicles per lane per 100 linear feet of road impacted by flooding depths equal to or greater than 12 inches.
b. For a section of roadway that has a functional classification of “Major Collector” or higher, consider one (1) vehicle per lane per 100 linear feet of road impacted by flooding depths equal to or greater than 12 inches.

4. The number of vehicles impacted by the floodwave should then be multiplied by two (2) to determine the PAR. The PAR value should be rounded up to the nearest whole person.
5. After completing steps one (1) through four (4), if a roadway is impacted by flood flows and has an Annual Average Daily Traffic (AADT) of less than 400[3] vehicles per day, the road can be assumed to have no vehicles at risk provided traffic count data is submitted to support this determination for the Department’s review and approval.

In cases where the road acts as a dam, it is nearly impossible to determine the risks presented by vehicles falling into a developing breach, or driving into an already formed breach due to constrained sight-lines, poor lighting, or other similar scenarios. In some cases, the potential danger is mitigated by road closures, or can easily be seen on a well lit road surface. Conversely, one can foresee that a person might drive into a previously formed breach channel on a dark, winding road in heavy rain. Accordingly, the engineer should consider assigning vehicles on the road/dam crest as potentially at risk if there are known conditions that may place vehicles in danger due to a breached roadway.

If the dam or impacted road is the sole access route for ten (10) or more homes or businesses, then a classification of significant or greater hazard shall be assessed if the expected damage to the road from a dam breach would prevent safe travel. If the road serves as sole access for 100 or more homes or businesses, then a classification of high hazard shall be assessed.

5.3. Determining PAR for Unprotected Persons

Attractions such as parks, playgrounds, ball fields, camping sites or other similar areas can result in a gathering of persons who are vulnerable to flood flows and are unprotected by vehicles or structures. The Depth-Velocity Flood Danger Charts for Adults and Children should be applied in a similar fashion as described in previous sections if such an attraction exists within the danger reach. If the population at risk is mixed (adults and children) then the “Children” chart should be used for conservativeness. Infants are not treated as children, and instead are assumed to be attended by adults (thus the Adult hazard chart is applicable). The ability to self-evacuate (e.g., run to high ground) should not be considered as the warning time, terrain, and mobility of persons is unknown. A conservative method to estimate the number of persons in the area is by assuming the adjacent parking area (if any) is full, with two (2) persons per vehicle. Other reasonable means to assess the number of persons at risk can be considered if available. Where the hazard classification is driven by additional danger to persons during storm events, the reasonableness of the areas being populated at the time of failure may be considered.

[3] Where recent (less than five (5) years old) traffic count data is not available, or where an existing traffic study cannot be demonstrated to be valid, traffic counts must be conducted in accordance with Maryland Department of Transportation, State Highway Administration, Office of Planning and Preliminary Engineering, Traffic Monitoring System Team guidance titled “Maryland Traffic Monitoring System Handbook, May 2016”. The minimum traffic count duration is six (6) hours. Traffic counts must be adjusted for duration, day of the week, and month of the year based on the roadway classification and the factors published in the most recent MDOT SHA Traffic Trend Report.

5.4. Other PAR Considerations

5.4.1. Railroads

If a railroad is impacted by breach flows, the depths and velocities over or along the impacted railroad should be reported. The engineer shall note whether the rail line is used by passenger rail or freight rail. The engineer shall also describe the frequency of use of the rail line and whether it is a main line or a secondary branch/spur line. A hazardous condition is assumed to exist if the velocity of water flowing against the ballast for a main line is equal to or greater than 7.5 feet/second and for a secondary branch or spur line is equal to or greater than of 5 feet/second. A dam breach that creates a hazardous condition on a rail line carrying passengers or hazardous freight shall, at a minimum, warrant a significant hazard classification.

5.4.2. Downstream Dams

If a dam failure contributes to the failure of one or more downstream dams, then the hazard class of the upstream dam should be at least as high as the classification of the downstream dam(s). This should reflect the likelihood of the threats of interruptions and damage attributable to incremental domino-like cascading failures of the downstream dams.

5.4.3. Environmental Damage

Although the Department may consider the potential for environmental damage caused by a dam failure, this factor typically does not drive the hazard classification. However, the following conditions may warrant an increased hazard classification as determined by the Department:

- The potential for negative impacts to listed endangered species including long term loss of endangered species habitat; or
- The potential for release of contaminated sediment or hazardous materials.

References

FHWA. N.d. *HY-8 Culvert Hydraulics Analysis Program.* Federal Highway Administration, United States Department of Transportation.

Froehlich, D. 1995. Peak Outflow from Breached Embankment Dam. *ASCE Journal of Water Resources Planning and Management, vol. 121*(1), pp. 90-97.

Froehlich, D. 1995. Embankment Dam Breach Parameters Revisited. *First International Conference, Water Resources Engineering, Environmental and Water Resources Institute (EWRI), 14-18 August 1995. ASCE, Water Resources Engineering Proceeding*, pp. 887-891.

Froehlich, D. 2008. Embankment Dam Breach Parameters and Their Uncertainties. *ASCE Journal of Hydraulic Engineering, vol. 134*(12), pp. 1708-1721.

MacDonald, T., & Langridge-Monopolis, J. 1984. Breaching Characteristics of Dam Failures. *ASCE Journal of Hydraulic Engineering, vol. 110*(5), p. 567-586.

MDE. 2016. *Application of Hydrologic Methods in Maryland, Fourth Ed*. Maryland:Maryland Hydrology Panel, Maryland Department of the Environment.

MDOT. 2016. *Maryland Traffic Monitoring System Handbook, May 2016*. Maryland: Maryland Department of Transportation, State Highway Administration, Office of Planning and Preliminary Engineering, Traffic Monitoring System Team.

NOAA.1982. *Application of Probable Maximum Precipitation Estimates - United States East of the 105th Meridian.* Washington, D.C.: U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

NOAA. 2006. *NOAA Atlas 14 Precipitation-Frequency Atlas of the United States Volume 2 Version 3.0: Delaware, District of Columbia, Illinois, Indiana, Kentucky, Maryland, New Jersey, North Carolina, Ohio, Pennsylvania, South Carolina, Tennessee, Virginia, West Virginia, United States East of the l05th Meridian*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, U.S. Department of the Army Corps of Engineers.

State of Colorado. 2010. *Guidelines for Dam Breach Analysis*.Colorado: Department of Natural Resources, Division of Water Resources, Dam Safety Branch.

USACE. 1998. *HEC-1 Flood Hydrograph Package (HEC-1).* United States Army Corps of Engineers, Institute for Water Resources, Hydrology Engineering Center.

USACE. 1982. *HEC-2 Water Surface Profiles (HEC-2).* United States Army Corps of Engineers, Institute for Water Resources, Hydrology Engineering Center.

USACE. N.d. *Hydrologic Engineering Center's River Analysis System (HEC-RAS).* United States Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center.

USACE. N.d. *Hydrologic Engineering Center's River Analysis System 2D version 5.0.3 (HEC-RAS 2D).* United States Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center.

USBR. 1988. *Downstream Hazard Classification Guidelines, ACER Technical Memorandum No. 11*. Denver, Colorado:United States Bureau of Reclamation, Assistant Commissioner-Engineering and Research.

USDA.1992. *Technical Release No. 20: Computer Program for Project Formulation Hydrology (TR-20)*. Natural Resources Conservation Service, United States Department of Agriculture.

USDA. 2005. *Technical Release No. 60: Earth Dams and Reservoirs (TR-60)*. Natural Resources Conservation Service, United States Department of Agriculture.

U.S. Department of Transportation, Federal Highway Administration. 2013. *Highway Functional Classification Concepts, Criteria and Procedures*. Publication No. FHWA-PL-13-026.

Von Thun, J. & Gillette, D. 1990. *Guidance on Breach Parameters*. Denver, Colorado: unpublished internal document, U.S. Bureau of Reclamation.

Washington State Dept. of Ecology. 1992. *Dam Safety Guidelines, Technical Note 1, Dam Break Inundation Analysis and Downstream Hazard Classification*. Olympia, WA: Water Resources Program.

Westmore, J. & Fread, D. 1981. *National Weather Service Simple Dam Break Equation (SMPDBK).* National Oceanic and Atmospheric Administration, National Weather Service, Office of Hydrologic Development.

Xu, Y. & Zhang, L. 2009. Breaching Parameters for Earth and Rockfill Dams. *ASCE Journal of Geotechnical and Geoenvironmental Engineering, Volume 135*(12), pp.1957-1970.

Glossary

100-YEAR FLOOD **-** A flood event having a 1-percent chance of being equaled or exceeded in any given year.

ABUTMENT **-** That part of the valley side against which the dam is constructed. The left and right abutments of dams are defined with the observer viewing the dam looking in the downstream direction, unless otherwise indicated.

ACRE-FOOT **-** A unit of volumetric measure that would cover one acre to a depth of one foot. It is equal to 43,560 cubic feet.

ANNUAL AVERAGE DAILY TRAFFIC (AADT) - A measurement of the number of vehicles which use a highway over a period of a year divided by 365 to obtain the average for a 24-hour period.

BALLAST **-** Gravel or broken stone placed in a railroad bed to bear the load from the railroad ties, to facilitate drainage of water, to keep down vegetation that might interfere with the track structure, and to hold the track in place.

BREACH **-** An opening through a dam that allows the uncontrolled draining of a reservoir. A controlled breach is a constructed opening. An uncontrolled breach is an unintentional opening caused by discharge from the reservoir. A breach is generally associated with the partial or total failure of the dam.

BREACH DISCHARGE HYDROGRAPH **-** A flood hydrograph resulting from a dam breach.

BREACH FORMATION TIME **-** The time taken from initiation of the breach until it has formed by a vertical headcutting process from the dam crest to the breach bottom elevation.

BREACH HEIGHT **-** Height of the dam embankment which is breached.

BREACH WIDTH **-** Bottom width of a breach channel that is formed through a dam embankment at the time of failure (rather than the width after emptying of the reservoir has widened the breach channel).

BRIM FULL **-** The condition that exists when the reservoir is filled to the lowest point on the dam crest (excluding the emergency spillway).

CREST **-** The elevation of the uppermost surface of a dam (typically an earthen embankment), excluding any parapet walls, railings, etc. It does not refer to the spillway crest.

DAM **-** The Code of Maryland Regulations (COMAR) defines a “dam” as any obstruction, wall or embankment together with its abutments and appurtenant works built for the purpose of storing or diverting water. FEMA Model law: Any artificial barrier, including appurtenant works, with the ability to impound water, wastewater, or liquid borne materials and which (a) is 25 feet or more in height from the natural bed of the stream or watercourse measured at the downstream toe of the barrier, or from the lowest elevation of the outside limit of the barrier, if it is not across a stream channel or watercourse, to the maximum water storage elevation; or (b) has an impounding capacity at maximum water storage elevation of 50 acre-feet or more.

DAM FAILURE **-** Catastrophic failure characterized by the sudden, rapid, and uncontrolled release of impounded water or the likelihood of such an uncontrolled release.

DAM HEIGHT **-** The vertical distance between the lowest point on the top of the dam to the lowest point along the upstream toe. If the bottom of the impoundment is excavated below the embankment, then the height shall include the excavation depth if there is potential for the impounded water to be released as a result of dam failure.

DAM TOP WIDTH **-** Average width of the dam crest that is measured perpendicular to the dam axis.

DANGER REACH **-** That area downstream of a dam within which sudden release of waters resulting from failure of the dam during the inflow design flood would cause an artificial flood exceeding the flood that might be expected from the same storm if the dam had not existed.

DEPTH-VELOCITY FLOOD DANGER LEVEL RELATIONSHIP CHARTS **-** Charts used to assess the potential hazard to unprotected persons and persons in structures and passenger vehicles based on the depth and velocity of a floodwave.

DOWNSTREAM TOE **-** The junction of the downstream face of a dam with the natural ground.

EMBANKMENT DAM **-** Any dam constructed of compacted natural materials, such as earthfill and rockfill, or of industrial waste materials, such as a tailings dam.

EMERGENCY SPILLWAY **-** A secondary (upper level) spillway designed to operate only during large floods to divert flows away from the dam. A constructed earthen embankment may not be used as an emergency spillway.

FLOODPLAIN **-** That area along or adjacent to a stream or a body of water within the waters of the State that is capable of storing or conveying floodwaters. The area of the floodplain is generally delineated by a frequency (or size) of flood.

FLOOD ROUTING ANALYSIS **-** A technique used to predict the changes in shape of a hydrograph as water moves through a river **channel** or a **reservoir.**

FREEBOARD **-** Vertical distance between a specified stillwater (or other) reservoir surface elevation and the top of the dam, without camber.

GRAVITY DAM - A dam constructed of concrete and/or masonry, which relies on its weight and internal strength for stability.

HALF PMF - Is one half of the PMF runoff (not half of the rainfall).

HAZARD CLASSIFICATION (HAZARD POTENTIAL CLASSIFICATION) - A system that categorizes dams according to the degree of adverse incremental consequences of a failure or improper operation of a dam. The hazard potential classification does not reflect in any way on the current condition of the dam (i.e., safety, structural integrity, flood routing capacity).

HAZARD CREEP (RISK CREEP) - The increase in hazard classification of a dam due to new development downstream of existing dam. Reclassification of a dam to a higher hazard category requires modification of the existing spillway to increase capacity and/or modification of the existing reservoir to increase storage volume.

HIGH HAZARD DAM - Failure would likely result in loss of human life, extensive property damage to homes and other structures, or cause flooding of major highways such as State roads or interstates. High Hazard dams are referred to as “Category I” dams in the Code of Maryland Regulations (COMAR 26.17.04.05) and “Class C” ponds by the US Natural Resources Conservation Service (NRCS).

HIGH STAGE WEIR CREST - A large weir opening on a riser or control structure that allows flow to pass through the facility.

LOW FLOW ORIFICE - A relatively small opening on a pond control structure that allows for the slow release of flow from the pond by utilizing storage upstream of the orifice.

LOW HAZARD DAM - Failure is unlikely to result in loss of life and only minor increases to existing flood levels at roads and buildings is expected. These structures are referred to as “Category III” dams in COMAR and “Class A” by NRCS.

MANNING’S EQUATION - An empirical formula estimating the average velocity of a liquid flowing in a conduit that does not completely enclose the liquid, i.e., open channel flow by relating the velocity to flow area, roughness coefficient, and slope.

OVERTOPPING FAILURE - The progressive vertical and horizontal erosion of the dam embankment due to flow over the crest. The process continues at a progressively faster rate until failure of the dam.

PEAK FLOW OR PEAK DISCHARGE - The flow from the dam due to the uncontrolled release of the reservoir.

PIPING FAILURE - Progressive erosion and removal of embankment or foundation soil by concentrated seepage flows through a dam, dike, or levee, its foundation, or its abutment. As material is eroded, the area of the "pipe" increases, and the quantity and velocity of flow increase, which in turn erodes more material. The process continues at a progressively faster rate until dam failure occurs.

POOL SURFACE AREA **-** The surface area (in acres) of a pool or reservoir at a specific water potential elevation when viewed from above.

POPULATION AT RISK **-** The number of people in the danger reach area prior to the issuance of any flood or dam failure warnings.

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

NON-BREACH FLOW **-** With regard to the Dam Breach Worksheet for Earthern Dams, the sum of the flow from the principal and auxiliary/emergency spillways at the maximum non-breach water surface elevation associated with a given hydrologic loading condition.

RAINFALL HYTEOGRAPH **-** A graphical representation of rainfall intensity over time.

RISER STRUCTURE **-** A vertical pipe or structure which (typically) extends from the bottom of a pond and houses the control devices (weirs/orifices) to achieve the discharge rates for specified designs.

ROAD EMBANKMENT **-** A roadway with a culvert conduit at its base for the purpose of conveying stream flow underneath the road in which the height of the impounded water at the entrance divided by the culvert diameter is greater than two.

SIGNIFICANT HAZARD DAMS **-** Failure could possibly result in loss of life or increase flood risks to roads and buildings, with no more than 2 houses impacted and less than six lives in jeopardy. These are referred to as “Category II” dams in COMAR and “Class B” by NRCS.

SMALL POND **-** A pond formed by a dam embankment that is less than 20 feet tall (measured from upstream toe), less than 1 square mile drainage area, less than 50 acre-feet storage volume (maximum), and a low hazard classification.

SPILLWAY **-** A structure that passes normal and/or flood flows in a manner that protects the structural integrity of the dam.

STORAGE VOLUME **-** The volume of water (in acre-feet) impounded by the dam at any given water surface level.

STEADY FLOW MODEL **-** A 1-dimensional model that computes water surface elevations using a single flow that does not vary with time.

SUNNY DAY CONDITION - The elevation of the reservoir after a period of dry weather.

TAILWATER - The water in the natural stream immediately downstream from a dam. The elevation of water varies with discharge from the reservoir.

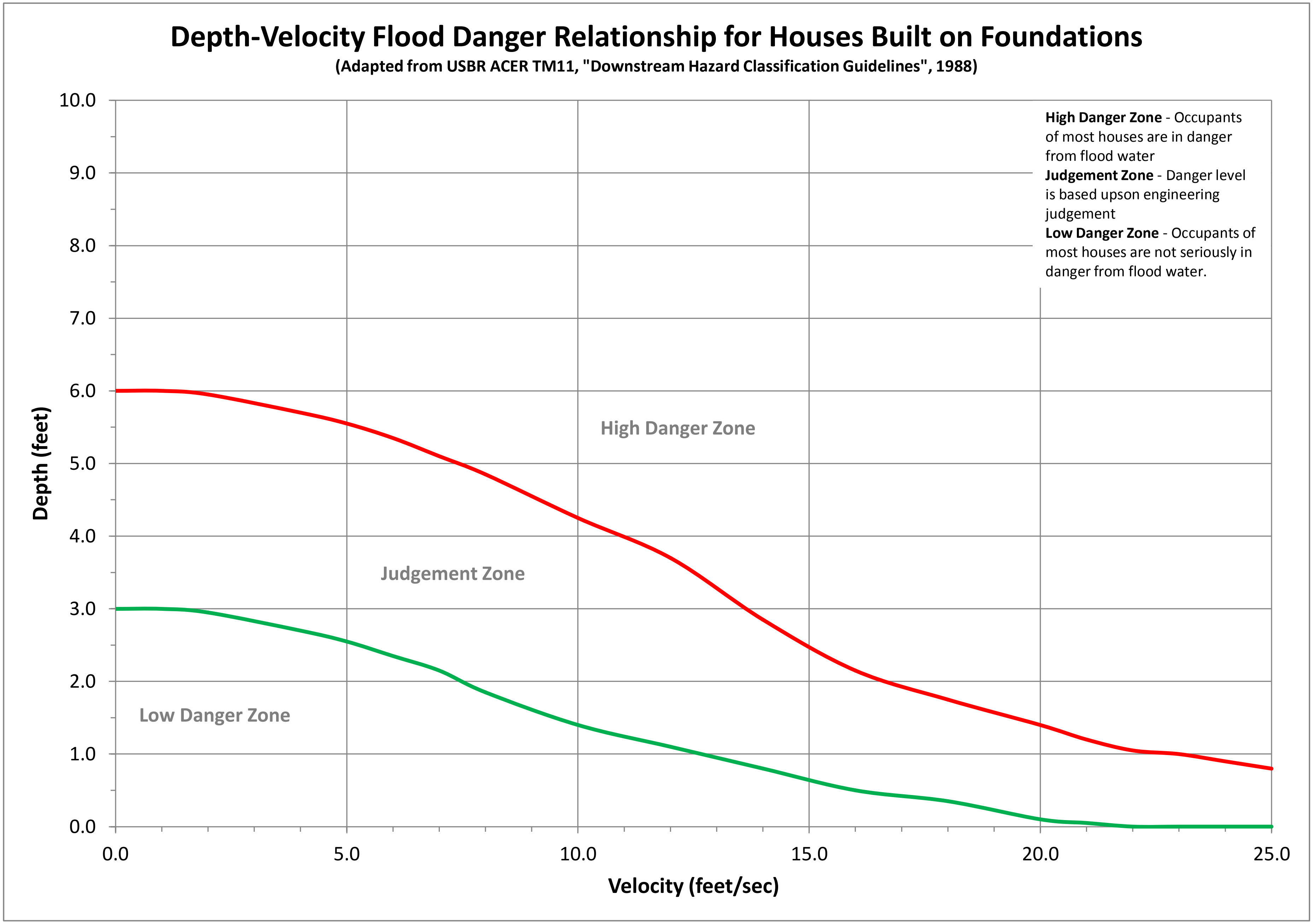
TIME OF CONCENTRATION - The time needed for water to flow from the most remote point in a watershed to the watershed outlet. It is a function of the topography, geology, and land use within the watershed.

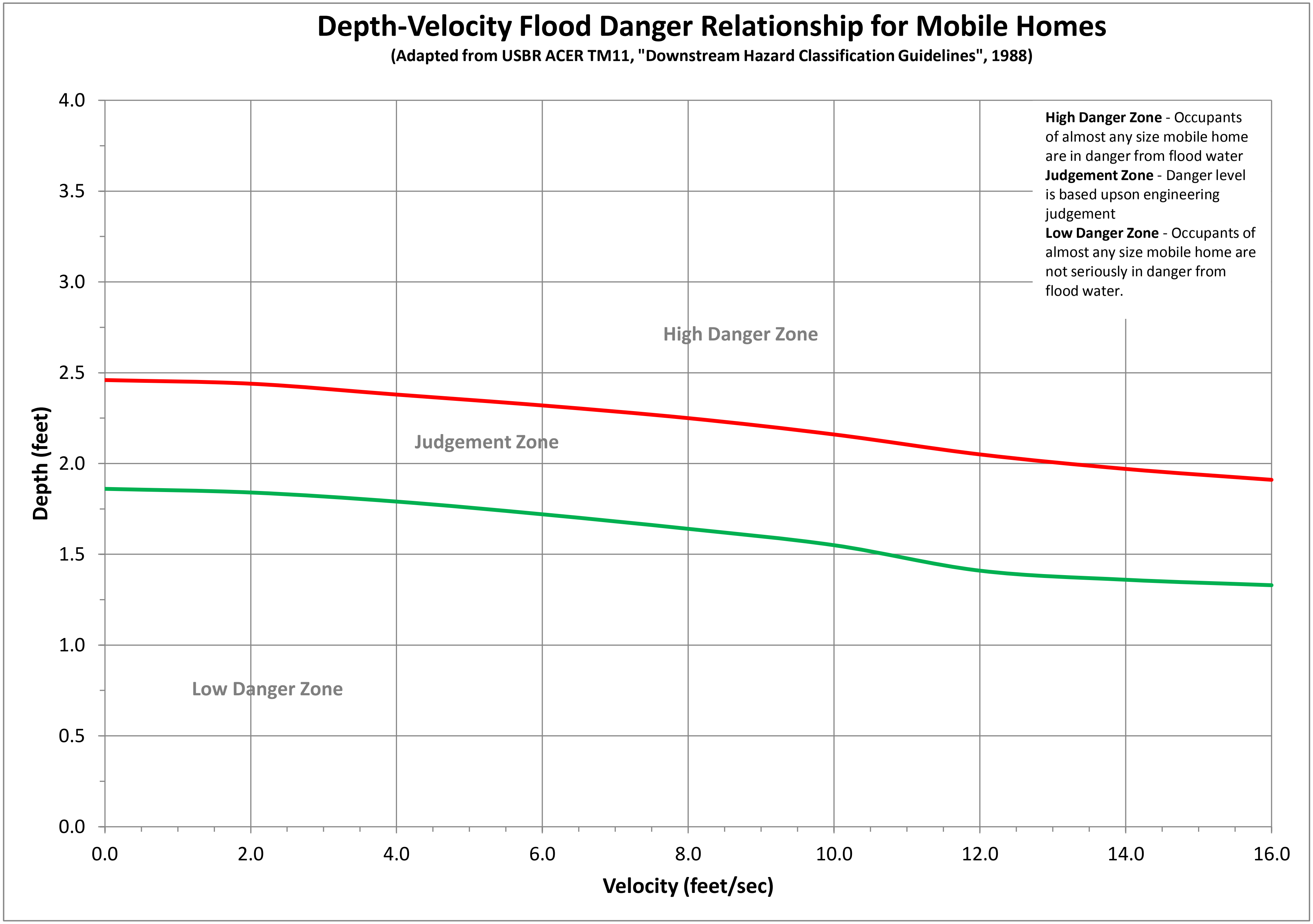
UPSTREAM TOE - The junction of the upstream face with ground surface.

UNSTEADY FLOW MODEL - A 1 or 2-dimensional model that models flow that varies with time, typically a hydrograph.

WEIR WALL - A form of a spillway structure that is built across an open channel, typically in the form of a reinforced concrete wall.

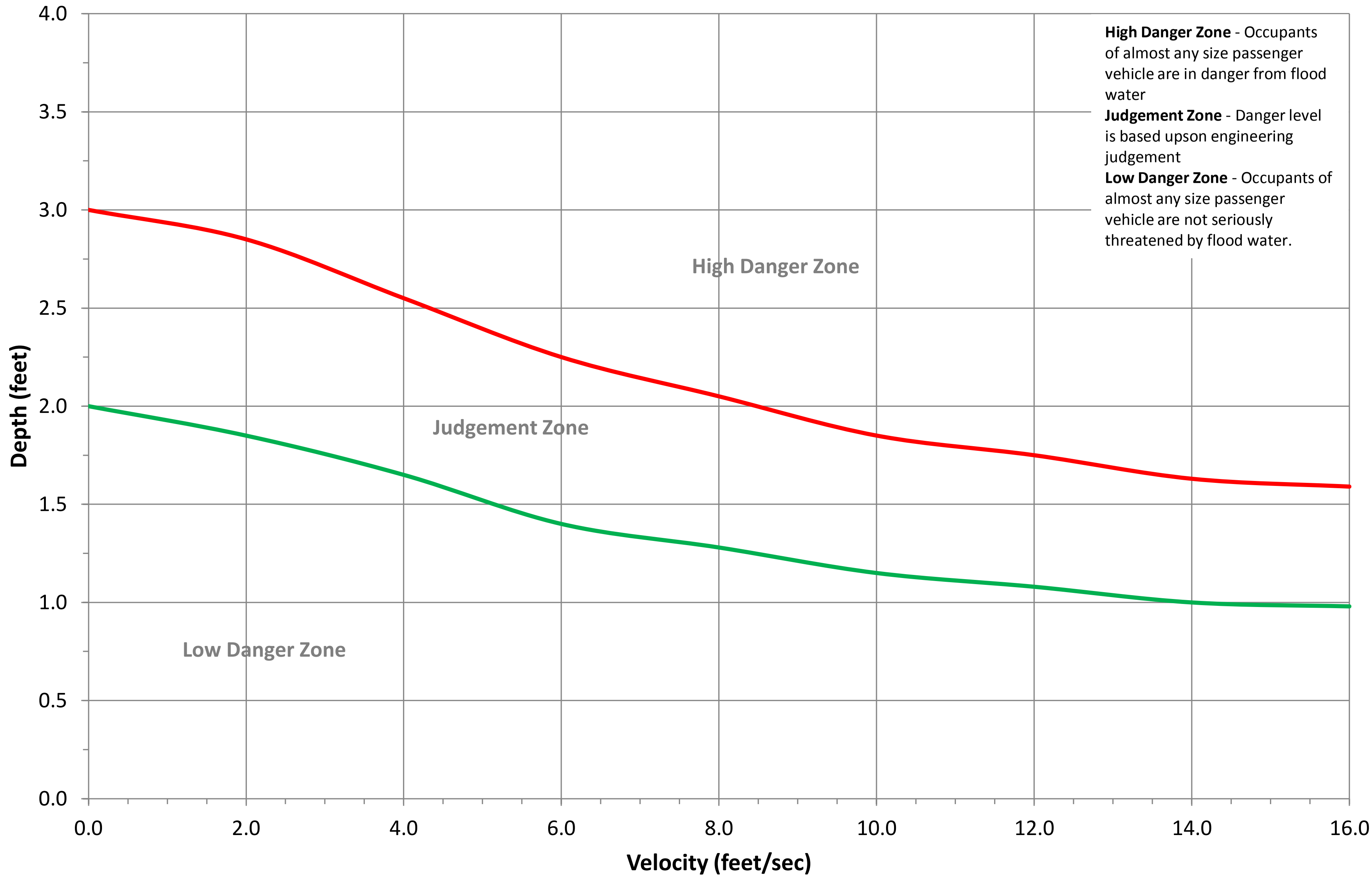
Depth-Velocity Flood Danger Relationship Charts


Depth-Velocity Flood Danger Relationship for Houses Built on Foundations
(Adapted from USBR ACER TM11, "Downstream Hazard Classification Guidelines", 1988)
High Danger Zone - Occupants of most houses are in danger from flood water
Judgement Zone - Danger level is based upson engineering judgement
Low Danger Zone - Occupants of most houses are not seriously in danger from flood water.
High Danger Zone
Judgement Zone
Low Danger Zone
Depth (feet)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
5.0
10.0
15.0
20.0
25.0
Velocity (feet/sec)


Depth-Velocity Flood Danger Relationship for Mobile Homes
(Adapted from USBR ACER TM11, "Downstream Hazard Classification Guidelines", 1988)
High Danger Zone - Occupants of almost any size mobile home are in danger from flood water
Judgement Zone - Danger level is based upson engineering judgement
Low Danger Zone - Occupants of almost any size mobile home are not seriously in danger from flood water.
High Danger Zone
Judgement Zone
Low Danger Zone
Depth (feet)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
Velocity (feet/sec)

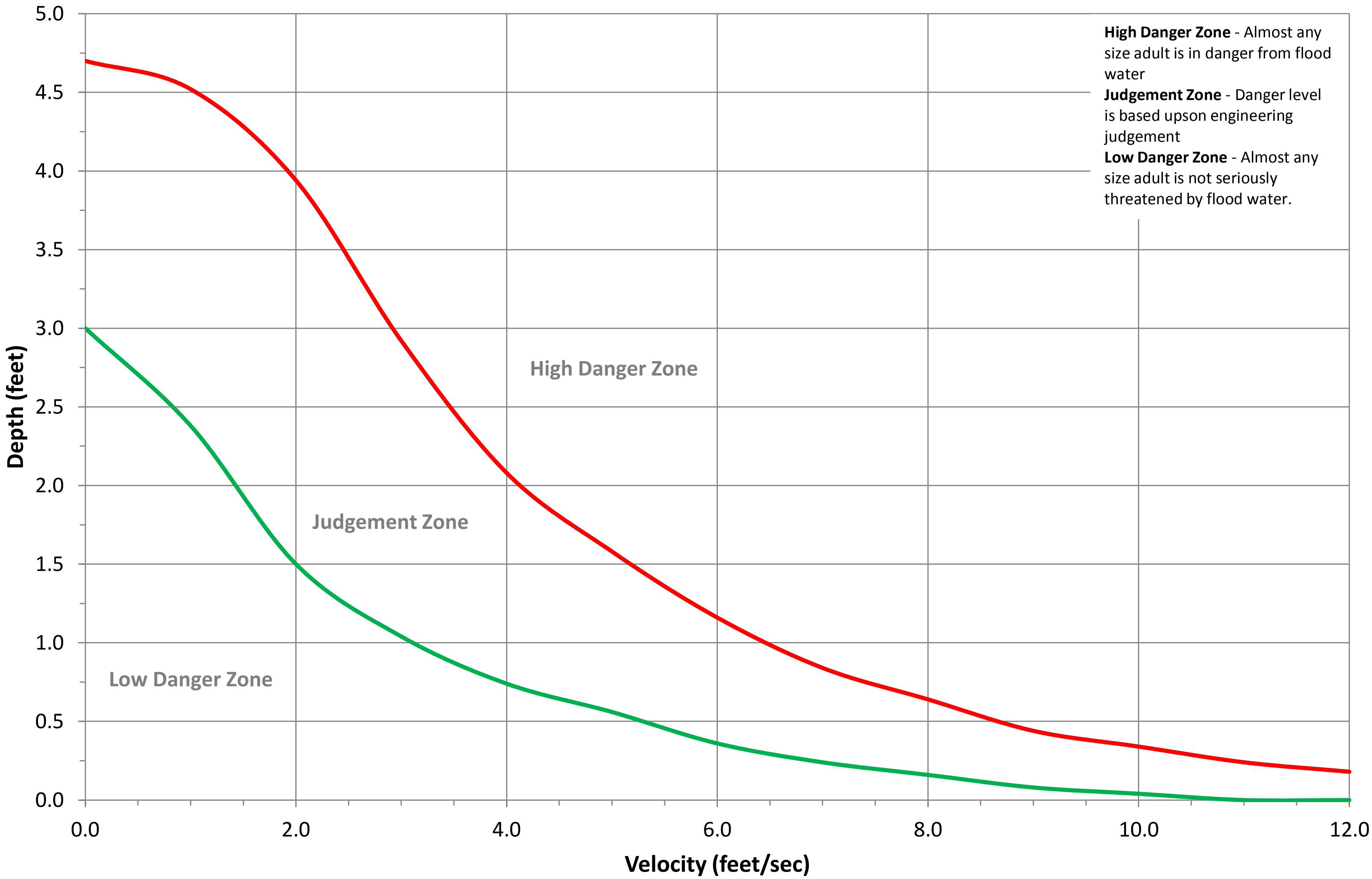
Depth-Velocity Flood Danger Relationship for Passenger Vehicles

(Adapted from USBR ACER TM11, "Downstream Hazard Classification Guidelines", 1988)



Depth-Velocity Flood Danger Relationship for Adults

(Adapted from USBR ACER TM11, "Downstream Hazard Classification Guidelines", 1988)



Depth-Velocity Flood Danger Relationship for Children

(Adapted from USBR ACER TM11, "Downstream Hazard Classification Guidelines", 1988)