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ASSISTANT COMMISSIONER - ENGINEERING AND RESEARCH
DENVER, COLORADO

DOWNSTREAM HAZARD CLASSIFICATION GUIDELINES

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Assistant Commissioner - Engineering and Research

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DOWNSTREAM HAZARD CLASSIFCIATION GUIDELINES

UNITED STATES DEPARTMENT OF THE INTERIOR
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PREFACE

The purpose of this document is:

1. To define the Safety Evaluation of Existing Dams (SEED) method for assigning a dam's hazard classification;

2. To provide guidance and present methods, for the purpose of downstream hazard classification, for estimating the downstream area susceptible to flooding due to a dam failure;

3. To provide guidance and criteria for identification of downstream hazards; and

4. To bring objectivity and consistency into downstream hazard classification.

Although these guidelines are intended to be used for all dams, they are especially useful for small dams, and/or dams whose failure flood would affect only a small population. For larger dams, downstream hazard classification is usually obvious.

This ACER Technical Memorandum was written by Douglas J. Trieste of the Dam Safety Inspection Section at the Denver Office. Deep appreciation goes out to all of those who have offered valuable review, information, and suggestions which greatly helped in preparing this document.

This document replaces in entirety the previous hazard classification guidelines, "Dam Safety Hazard Classification Guidelines," United States Department of the Interior, Bureau of Reclamation, Division of Dam Safety, October 1983. Questions or comments regarding the materials presented herein should be directed to the Chief, Dam Safety Office (D-3300) at the Denver Office.

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DOWNSTREAM HAZARD CLASSIFICATION GUIDELINES

I. INTRODUCTION

A. Definition of Downstream Hazard

A downstream hazard is defined as the potential loss of life or property damage downstream from a dam and/or associated facility (e.g., dike) due to floodwaters released at the structure or waters released by partial or complete failure of the structure [1].[1]

Downstream hazard classification is not associated with the existing condition of a dam and its appurtenant structures or the anticipated performance or operation of a dam. Rather, hazard classification is a statement of potential adverse impact on human life and downstream developments if a designated dam failed.

The cost of the dam, related facilities (e.g., pump stations, canals, pipelines, etc.), and project losses are not considered in downstream hazard classification. Also, the consequences of a rapid reservoir drawdown; due to a dam failure, on persons upstream from the dam are not considered in downstream hazard classification. Only the direct effects of a dam-break flood on persons, property, or outstanding natural resources at officially designated parks, recreation areas, or preserves downstream from the dam are considered.

B. Purpose of Downstream Hazard Classification

Dams are given a hazard classification for two reasons:

1. The Department of the Interior (DOI) Departmental Manual, Part 753 [2], establishes that a hazard classification is to be assigned to every DOI dam.

2. Hazard classification serves as a management tool for determining which dams are to undergo the full SEED (Safety Evaluation of Existing Dams) process. Dams having a low downstream hazard classification are excluded, whereas those having a significant or high downstream hazard classification are included.

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[1] Numbers in brackets identify references listed in section VI.

For large dams, hazard classification guidelines may seem superfluous; almost all large dams are obvious high-hazard facilities. Although it is with the smaller structures that these guidelines become most useful, all dams are given the same depth of analysis if needed. The hazard classification of small dams is often uncertain and requires detailed technical analysis, good engineering judgment, and a good "feel" for the impacts of dam failure floods (app. A).

For any dam, a situation can always be imagined that would result in loss of life regardless how remote the location of a dam and/or how little the chance of persons being affected by its failure flood. Thus, guidelines can be very useful in these situations to avoid being unduly conservative and to provide consistency to hazard classification as much as possible.

C. Purpose of the Downstream Hazard Classification Guidelines

The purpose of this document is:

1. To define the SEED method for assigning a dam's hazard classification (secs. I and II);

2. To provide guidance and present methods, for the purpose of downstream hazard classification, for estimating the downstream area susceptible to flooding due to a dam failure (sec. III and app. A);

3. To provide guidance and criteria for identification of downstream hazards (sec. IV); and,

4. To bring objectivity and consistency into downstream hazard classification.

Section III on estimating inundated area is included to present state-of-the-art methodology and a systematic approach that can be used by analysts not familiar with dam-break/inundation study techniques. A discussion of other accepted methods is included in appendix A.

Identifying downstream hazards is often controversial and/or nebulous. Due to this, section IV on identification of hazards is presented in order to bring objectivity and consistency, as much as can be reasonably expected, into the identification of downstream hazards. New concepts that equate flood depth and velocity relationships to hazard identification have been developed and are presented in section IV.

It is very important to note that these guidelines are intended for hazard classification purposes, but **not** for preparation of inundation maps for Emergency Preparedness Plans (EEPs) or hazard assessments.

Dam-break/inundation studies are not an exact science, and guidelines and criteria for performing these studies will vary depending upon the intent. Although studies for hazard classification and EPPs have some similarities, there are still major differences; these differences are explained in subsection III.A.

Dam-break/inundation studies performed for hazard assessments (as opposed to hazard classification) pose still another set of criteria. Such studies focus upon risk analysis which uses expected values. Thus, guidelines and criteria for these studies are based upon the highest probability of what is expected to occur [3].

II. DOWNSTREAM HAZARD CLASSIFICATION SCHEME

The system presented in table 1 is used by the SEED Program for classifying Bureau of Reclamation (Reclamation) and other DOI dams.

Table 1. - Downstream hazard classification system

Classification	Lives-in-jeopardy	Economic loss
Low	0	Minimal (undeveloped agriculture, occasional uninhabited structures, or minimal outstanding natural resources)
Significant	1-6	Appreciable (rural area with notable agriculture, industry, or worksites, or outstanding natural resources)
High	More than 6	Excessive (urban area including extensive community, industry, agriculture, or outstanding natural resources)

A. Lives-in-Jeopardy

Lives-in-jeopardy is defined as all individuals within the inundation boundaries who, if they took no action to evacuate, would be subject to danger commensurate with the criteria in section IV.

Lives-in-jeopardy is limited to direct downstream impacts resulting from the dam failure flood. Thus, lives-in-jeopardy does not consider situations such as persons in the reservoir or vehicle accidents due to a washed out highway crossing (after the flood wave has passed).

Lives-in-jeopardy is divided into permanent and temporary use. Permanent use includes:

- Permanently inhabited dwellings (structures that are currently used for housing people and are permanently connected to utilities, including mobile homes; three residents per dwelling are assumed based on 1980 National Census)
- Worksite areas that contain workers on a daily (workweek) basis. Commonly affected worksites include:
  - Public utilities and vital public facilities (powerplants, water and sewage treatment plants, etc.)
  - Private industrial plants or operations including materials production (sand, gravel, etc.)
  - Farm operations
  - Fish hatcheries

Temporary use includes:

- Primary roads along the channel, on the crest of the dam, or crossing the channel
- Established campgrounds and backpacker campsites
- Other recreational areas

The values in table 1 ("1-6" and "more than 6" for significant and high, respectively) are purely arbitrary. Previous downstream hazard classification criteria used lives-in-jeopardy of "few" and "more than few" for the significant- and high-hazard categories, respectively. The values in the table are presented for the intent of quantifying "few" and "more than few." It seemed reasonable to consider all occupants of two average households as "few." According to the 1980 census, the average U.S. household has three occupants; thus, "few" was quantified as six persons, and "more than few" was considered "more than 6." The lives-in-jeopardy for low-hazard classification, which had been "none expected," was quantified as "zero."

It is important to note that hazard classification deals only with lives in jeopardy, as opposed to "estimated loss of life". Estimated loss of life is the likely number of fatalities that would result from a dam failure flood event and is a forecast based on warning time that the population at risk would receive of dangerous flooding, and also on the use of historical relationships between warning time and loss of life. Details of the "estimated loss of life" are included in ACER Technical Memorandum No. 7 [3].

Determining the estimated loss of life involves many uncertainties and good judgment by the analyst. Analyses may indicate catastrophic flooding of a permanently occupied area, thus, indicating obvious loss of life to any occupants, or indicate as little as only shallow flooding (e.g., 1 to 2 feet (0.3-0.6 m)) with low velocities in areas of temporary use. In the latter case, it is difficult to determine the extent of loss of life, if any, that will occur to occupants affected by the flood. People may be safe if they remain in buildings, automobiles, move to high ground, etc. Flooding may be little more than just wetting of an area such that a person is safe to wade, but it is conceivable that a small child could fall into a ditch or depression or be drowned by locally fast moving water. Persons commuting to work may be unaware of a current dam failure, residents may not receive warning or may ignore warnings, residents may not be able to safely evacuate, etc.

Other factors to consider regarding estimating loss of life are proximity of the hazard and time of day. A community may be susceptible to catastrophic flooding but be located far enough downstream to allow ample warning and evacuation of its occupants. A dam could fail during the most inopportune time of day (11:00 p.m. to 6:00 a.m.), thus, allowing for little or no warning to downstream residents.

Due to these many uncertainties and unknowns with regard to estimated loss of life, a conservative approach of using lives-in-jeopardy (versus estimated loss of life) in the hazard classification system (table 1) is adopted by the SEED Program.

B. Economic Loss

Economic loss is that loss resulting from damage to residences, commercial buildings, industries, croplands, pasturelands, utilities, roads and highways, railroads, etc. Consideration should also be given to economic loss resulting from damage to outstanding natural resources within officially declared parks, preserves, wilderness areas, etc. Also, if a toxic or harmful substance is known to be present in significant quantities in the impoundment, the effect of its dispersion on downstream areas (with respect to economic loss only) should be considered in the downstream hazard classification. Because the dollar value of real property changes over time and varies according to the uses of the property, no attempt is made to assign dollar values as guidelines.

Economic loss does not include the loss of the dam and associated project facilities.

Hazard classification due to economic loss is based on the judgment of the analyst. However, judging economic value is, in most cases, not a problem because it is rarely addressed. The reason for this is that if economic loss is involved, then usually lives-in-jeopardy is a factor and the downstream hazard classification will be based solely on that. Thus, if a dam is classified as low or significant hazard based on lives-in-jeopardy, only then is economic loss evaluated to determine if a higher hazard classification is justified.

C. Multiple Dams

If failure of an upstream dam could contribute to failure of a downstream dam(s), the minimum hazard classification of the upstream dam should be the same as the highest classification of the downstream dam(s).

III. ESTIMATING INUNDATED AREA

A. Introduction

Determining hazard classification based on the downstream hazard classification scheme presented in table 1 is straightforward providing the lives-in-jeopardy and/or economic loss that would result from a dam failure is known. Lives-in-jeopardy and/or economic loss can be determined if the potential inundation downstream from a dam is known.

This section presents methods used to estimate the downstream inundation should a dam fail. These methods include:

- Use of an existing inundation study,
- Engineering judgment, or
- Performing a dam-break/inundation analysis.

The methods presented here are recommended for hazard classification purposes only, as opposed to preparation of inundation maps for publication (e.g., EPPs). Several reasons for this are:

1. Flood routing for a downstream hazard classification study is terminated at the downstream channel location such that the hazard classification can accurately be defined, or the downstream terminal point is reached. Thus, the study may involve only a small channel reach downstream from a dam if a high hazard classification is justified. Studies used for preparation of inundation maps almost always consider the full channel reach to the downstream terminal point.

2. The analytical procedure for hazard classification can vary from simply engineering judgment to the most detailed, state-of-the-art analytical methods. Studies performed for published inundation maps follow more strict procedures.

3. Hazard classification has no relevance to flood wave travel times, whereas EPPs do. Analyses for hazard classification purposes are not concerned with accurate traveltimes. Rather, the focus is on maximum depths and velocities at specific channel cross sections.

B. Existing Inundation Study

Many dams have comprehensive dam-break/inundation studies prepared for the downstream area. If these studies exist, they should be used as the basis for hazard classification. Frequently, these inundation studies have been performed by hydrologists/hydraulic engineers using state-of-the-art analytical techniques, and consequently can be used with confidence for determining hazard classification.

A dam-break/inundation study normally contains a map depicting the predicted extent of flooding downstream from a dam. If a map does not exist, sufficient data and information will likely be included so that an accurate assessment of flooding can be made.

Dam-break/inundation studies may be obtained from (but not limited to) Bureau Regional Offices, the U.S. Army Corps of Engineers, Federal Emergency Management Agency (FEMA), State and local governments, and private engineering and consulting firms.

C. Engineering Judgment

In some situations, the downstream hazard classification may be obvious; thus, the downstream hazard classification is based solely on engineering judgment using information from a field survey and/or current topographic maps. For example,

1. A community located in the flood plain immediately downstream from a dam, or

2. A flood plain completely unoccupied and undeveloped downstream to a point where the failure flood would obviously attenuate and be contained within the main channel banks, or reach a large body of water (e.g., large reservoir or ocean) without threat to human life, or economic loss.

In the first case, the dam would be an obvious high-hazard facility, and in the second case, the dam would be an obvious low-hazard facility. No computational analysis is necessary in either case.

D. Performing a Dam Break/Inundation Study for Downstream Hazard Classification

If a comprehensive dam-break/inundation study does not exist, or the hazard classification is not obvious, then an analysis should be performed to define the inundated area. Many methods with differing levels of sophistication are available for performing such an analysis. A specific method is presented in subsection III.D.3. Also, the subject is discussed in general terms with reference to state-of-the-art methods in appendix A. A bibliography (app. B) referencing other useful literature is included if additional information is desired.

There are three main phases to a dam-break/inundation study:

- Assume a dam failure scenerio,
- Determine downstream terminal point of flood routing, and
- Perform the recommended analytical procedure.

1. Assuming a Dam Failure Scenario. - The results of a dam-break/inundation study would be the most accurate if we knew the failure scenario a priori. However, for dam-break/inundation studies, this is uncertain and can only be assumed.

The failure scenario possibilities are nearly infinite. A dam failure may be earthquake induced, result from piping on a clear day, from a sudden structural breakdown on a clear day, from structural damage due to a large flood, from erosion due to overtopping, etc. Discharges and downstream flooding due to different dam failure scenarios could result in different downstream hazard classifications being assigned to the same dam.

Because the dam failure scenario is not known a priori, and for dam safety conservativeness, a procedure for selecting a dam failure scenario which seeks the highest hazard classification that is reasonable is suggested. This approach could be lengthy and labor intensive. Fortunately, it is rarely used. Usually, if the dam has the potential for a high-hazard classification, an assumed "sunny-day"[2] failure scenario results in sufficient downstream flooding to classify the dam as high hazard, as is the case for most large Bureau dams. But, for smaller dams where the hazard classification may be borderline between categories (table 1), the following procedure should be applied (fig. 1).

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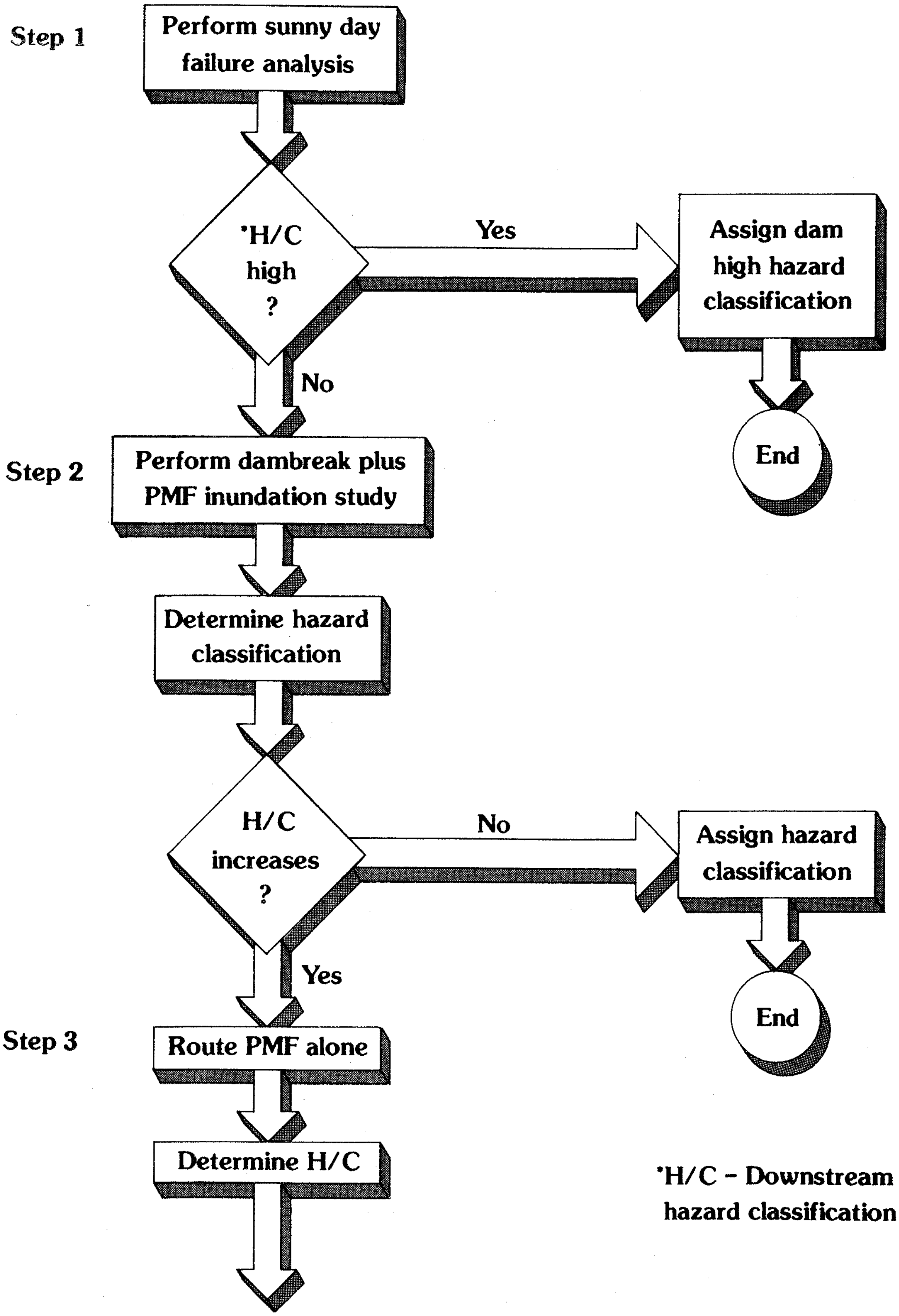
[2] A sunny day failure is a failure other than from a large flood. The reservoir is assumed at NWS and inflows are average. The mode of failure may be earthquake induced, structural weakness, piping, etc.

Figure 1 - Downstream hazard classification procedure flow chart



*H/C - Downstream hazard classification

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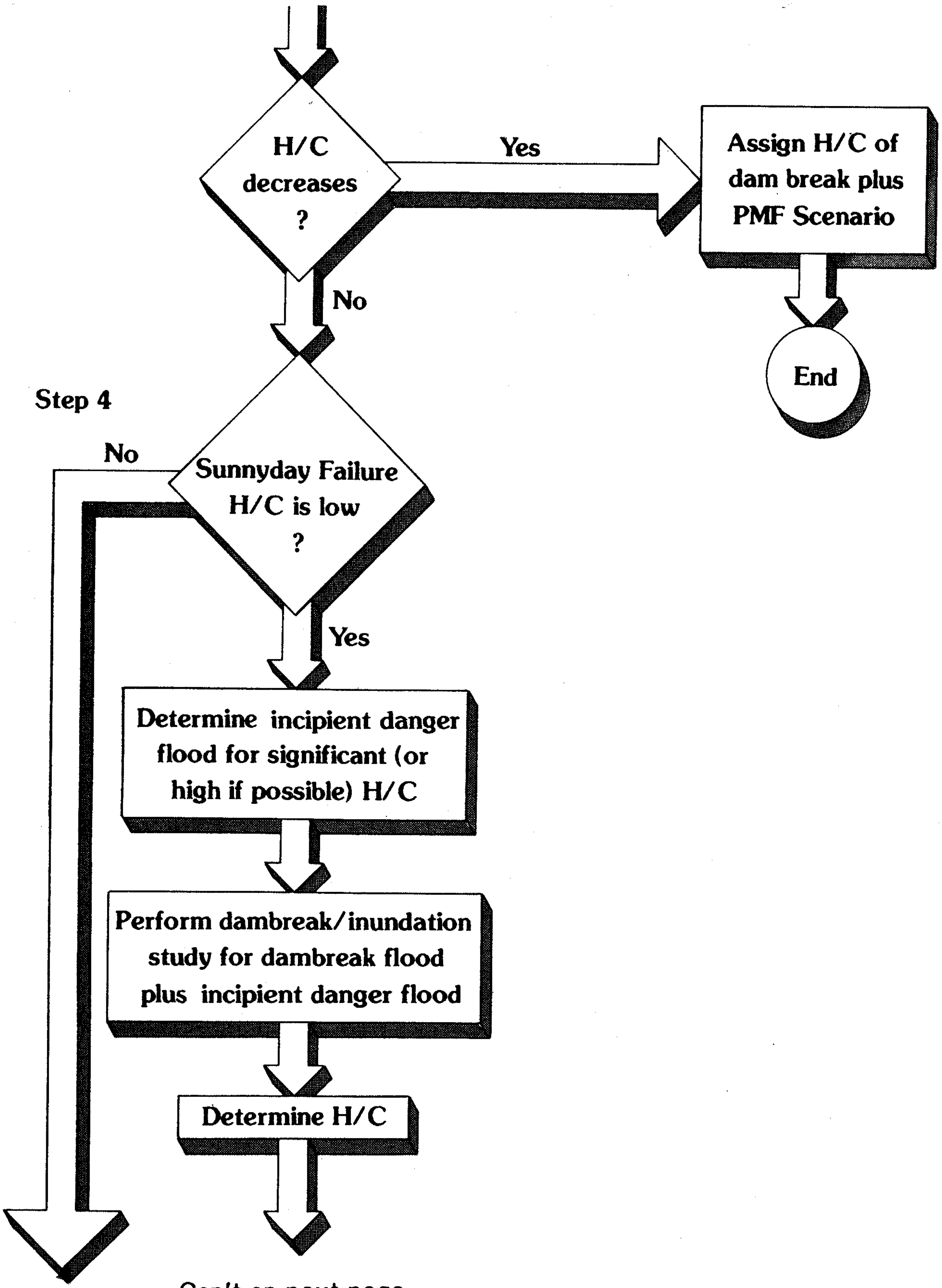

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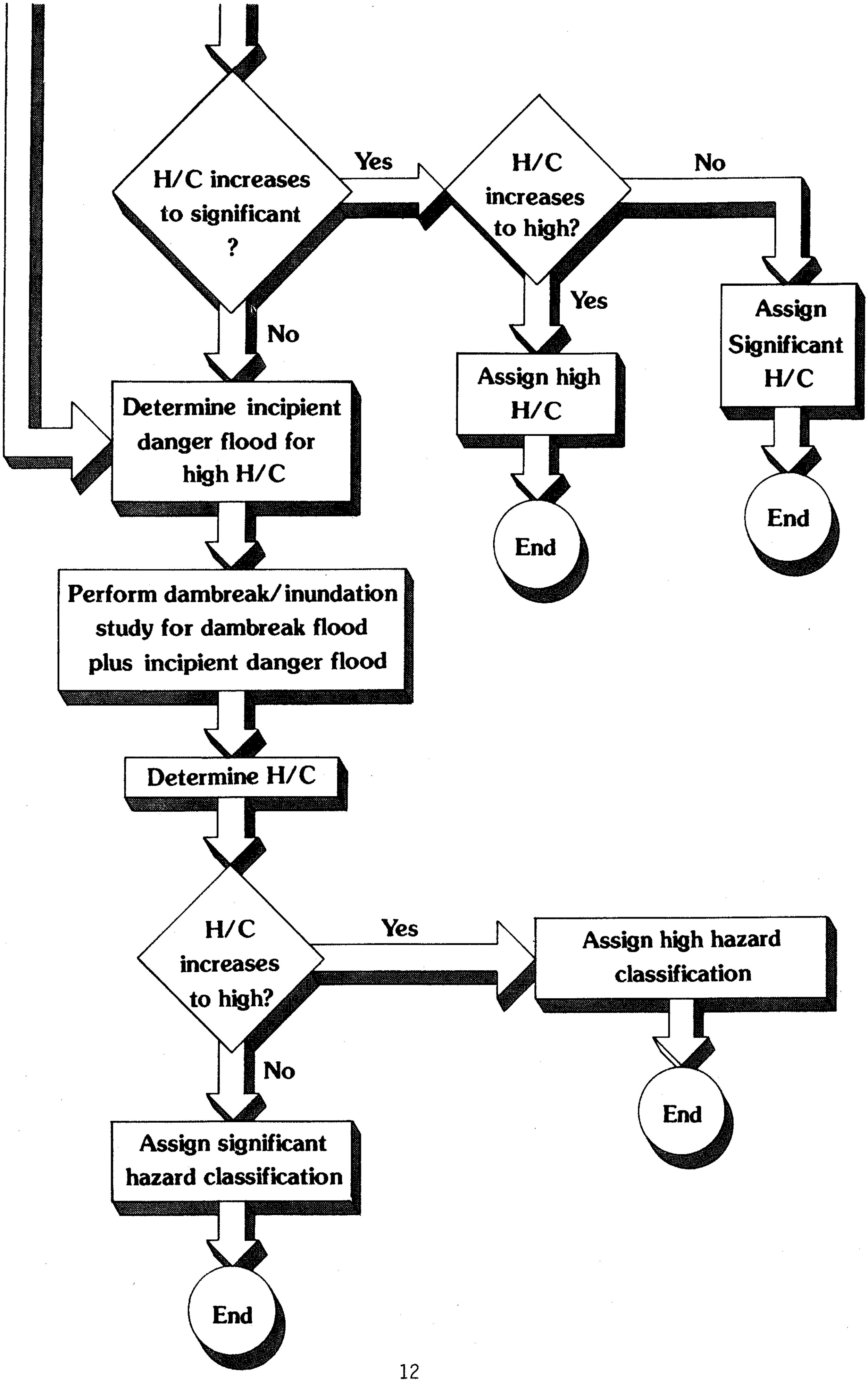

H/C increases to significant ?
Yes
H/C increases to high?
No
Assign Significant H/C
End
Yes
Assign high H/C
End
No
Determine incipient danger flood for high H/C
Perform dambreak/inundation study for dambreak flood plus incipient danger flood
Determine H/C
H/C increases to high?
Yes
Assign high hazard classification
End
No
Assign significant hazard classification
End

Step 1. Assume a "sunny day" failure and perform a dam-break/inundation study (subsec. III.D.3). If a high-hazard classification is valid for this assumption, then this dam failure scenario is sufficient. Increasing the loading conditions (that is, inflow flood) for the dam-break/inundation study would not change the hazard classification.

Step 2. If the hazard classification obtained from the first step is less than high, then it is necessary to increase the loading conditions; that is, determine if a dam-break discharge combined with a large inflow flood would result in an increase in the hazard classification.

The easiest method in making this determination is to create a scenario that combines the dam-break discharge with the probable maximum flood (PMF). The PMF is used, rather than the inflow design flood (IDF) because the IDF may be a less severe flood than the PMF. The intent is to evaluate a worst case scenario which has to account for the PMF. If the hazard classification does not increase under these assumptions, then the hazard classification obtained from the "sunny day" failure scenario does not change with an increase in loading conditions and can be assigned with confidence. But, if the hazard classification is raised, then some specific size inflow flood can occur, such that when combined with the dam-break discharge, it will raise the hazard classification. This inflow flood, referred to as the "threshold inflow flood," is some fraction of the PMF.

Thus, when the dam-break plus PMF flood results in a hazard classification higher than that for a "sunny day" failure assumption, it becomes necessary to determine the incremental effects of a dam-break flood combined with an inflow flood on the downstream flooding. The reason for this is to separate the flooding due to a dam failure from that due to a natural flood. That is, if a natural runoff flood can occur such that a situation is a borderline hazard, then would the additional (incremental) flooding resulting from a dam failure cause the "borderline hazard" to become a hazard?

A dam can actually have a higher hazard classification under a "sunny day" failure assumption than under PMF failure assumptions. For example, a dam is rated as significant hazard due to potential inundation of one dwelling downstream. But, if the hazard classification is evaluated under PMF assumptions (that is, the dam fails during the PMF event and the dam-break discharge is combined with the PMF discharge), the dam is rated low hazard because the incremental impact of flooding is negligible (that is, the dwelling is inundated by the PMF whether or not the dam fails).

Increasing the loading conditions does not always raise the hazard classification. For example, consider a small dam and reservoir located in a channel that drains a basin capable of producing very large floods. The dam is rated low hazard under "sunny day" failure conditions. However, downstream flooding from a runoff flood (not including a dam failure discharge) would result in large loss of life and severe economic loss. The effects of the dam failure combined with such a flood would be negligible and probably imperceptible. Thus, the dam would still be rated low hazard.

Because situations similar to those illustrated in the preceding examples actually exist, an incremental loading condition approach is important.

Step 3. Route the PMF alone (without considering the dam in place) and determine the "hazard classification" in the same manner as if done for a dam. If a hazard classification less than that obtained from the dam failure discharge plus PMF scenario is obtained, then the hazard classification obtained from the dam break plus PMF scenario is assigned to the dam. The reasoning here is that the incremental effects of a dam failure raise the hazard classification above that for a PMF alone; hence, the effects of a dam-break flood on downstream inundation should not be ignored.

Step 4. If, when routing the PMF alone, the hazard classification raises above that obtained from a "sunny day" failure, then the incremental effects of a dam-break flood on the hazard classification are evaluated. To make this evaluation, the "incipient danger flood" is sized. This is accomplished by determining the flood discharge that results in the hazard in question ("possible hazard", see subsec. IV.A.) to experience incipient flooding. For example, the discharge that results in a house having floodwater reaching its foundation; or the discharge that results in a roadway just getting wet. Next, the incipient danger flood is combined with a dam-break flood, and the downstream hazard classification reevaluated. This can be done by modeling the incipient danger flood as "initial conditions" prior to the dam-break; or by determining an inflow flood hydrograph such that when routed to the downstream hazard site, its peak will equal the incipient danger flood peak.

The incremental downstream hazard classification is determined by applying figures 2 through 6, per the criteria in section IV. If the incremental differences in depths and velocities are within the low-danger zone, then the incremental lives-in-jeopardy is zero. If the incremental differences in depths and velocities are above the low-danger zone, then a dangerous situation is possible. More information on the use of figures 2 through 6 is explained in section IV.

If the hazard classification raises, then it is the result of increased flooding from the dam failure combined with a specific-size natural flood. Thus, the flood from a dam failure is capable of inundation significantly greater than that by the runoff flood alone.

The full results of an incremental hazard classification should be discussed when presenting the results.

2. Determining Downstream Terminal Point of Flood Routing. - A dam-break flood routing needs only to be performed for a distance downstream from the dam until the hazard classification can be ascertained, or until "adequate floodwater disposal" is reached. For example, if a community located 1 mile (1.6 km) downstream from a dam would be inundated by a dam failure flood and hence the dam would be assigned a high-hazard classification, then additional downstream analysis is not necessary, because additional analysis would not change the hazard classification from "high."

Adequate flood water disposal is defined as: that point below which potential for loss of life and significant property damage caused by routed floodflows appear limited [4]. This includes such situations as:

- No human occupancy
- No anticipated future development
- Floodflows being contained in a large downstream reservoir

- Floodflows entering a bay, ocean, or large channel
- Floodflows being contained within the channel banks

3. Recommended Analytical Procedure. -

a. General. - The procedure presented in this subsection is a compromise between simplistic and complex analytical methods for performing dam-break/inundation studies. This procedure will result in consistency among analysts, does not require an extensive hydraulics background, and will produce reasonably accurate results.

The procedure is simply application of the National Weather Service Simplified Dam-Break Model (SMPDBK) [5], with guidelines and criteria given for determination of all model input parameters. Tests of SMPDBK versus the National Weather Service DAMBRK model [6], a very sophisticated state-of-the-art dam-break flood forecasting model, have indicated accuracy of SMPDBK in computing peak flood depths and velocities to be less than 20 percent of those computed from using DAMBRK, as long as model assumptions are not violated. This particularly applies to backwater conditions where SMPDBK results are usually in large error.

Model input parameters can vary considerably for a single dam and still be "correct." Due to this, SMPDBK results can also vary considerably while being "correct." These "correct" output values can range from liberal to conservative; that is, depths and velocities ranging from minimum to maximum, respectively.

It is very important to note that the recommended parameter values presented in this section are not intended to predict peak breach discharge. Rather, they are intended to bring consistency among analysts while resulting in reasonable upper-limit peak breach discharges and downstream depths and velocities. Such reasonable maximum values add a margin of safety to flood inundation predictions, and are consistent with the downstream hazard classification philosophy of considering worse-case dam-break scenarios and downstream flooding.

The breach parameters TFM (time for breach to develop) and BW (width of rectangular breach) need special attention. Many different methods are available for "predicting" these values as well as peak breach discharge (app. A). When different methods are applied to a specific dam, a very wide range of values typically results. Also, different TFMs and BWs can result from different analysts using the same method. Thus, the study results, and consequently the downstream hazard classification, can be dependent on the method used for predicting breach parameters and/or peak breach discharge. Because of this, the recommended prediction equations presented in the following section for determining TFM and BW are a combination of policy and the consideration of historical failure data, intended to satisfy one of the overall purposes of these guidelines, that of bringing consistency and objectivity into downstream hazard classification. Also, the parameter equations are very helpful for the inexperienced analyst and/or those without the proper technical background. These equations will yield values that are within the range determined by application of all other methods.

In the majority of downstream hazard classification studies, SMPDBK will yield adequate results. However, sometimes situations may have to be analyzed that violate the assumptions of SMPDBK, and/or may require sophisticated modeling that is beyond the scope of SMPDBK. In such cases, DAMBRK should be used (app. A). To the contrary, simplistic calculations may be adequate, or computer facilities may not be available. Should this be the case, the simpler methods explained in appendix A may be used.

Appendix A is included to provide information on various state-of-the-art methods of performing dam-break/inundation studies. The analyst should become familiar with these methods so that they can be applied when a situation requires their use. However, a method other than the "recommended procedure" should not be used unless it can be justified. Such justification should be explained in the hazard classification report.

b. Guidelines for Determining SMPDBK Input Data Values. - SMPDBK requires user specified values of the following input parameters:

DAMN - Name of the dam
RIVN - Name of the river
IDAM - Code for type of dam
HDE - Elevation of crest of dam, or elevation of water surface when dam breaches
BME - Final bottom elevation of breach bottom
VOL - Volume (acre-ft) of reservoir

SA - Surface area (acres) of reservoir at HDE
BW - Width (ft) of rectangular breach
TFM - Time (min) for breach to develop
QO - Nonbreach flow (spillway, outlet, overtopping) which occurs with maximum breach flow
NS - Number of cross sections
NCS - Number of top widths for each cross section
CMS - Manning's "n" associated with off-channel storage
D(I) - Distance (mi) from dam to Ith cross section
FLD(I) - Depth (ft) in cross section at which flooding and deflooding times will be computed
HS(K,I) - Elevation (m.s.l.) associated with Kth top width (BS) of Ith cross section; first elevation is the invert elevation
BS(K,I) - Kth top width (ft) of Ith cross section
BSS(K,I) - Kth inactive top width (ft) of Ith cross section
CM(K,I) - Kth Manning's "n" associated with Kth top width of Ith cross section

Criteria for determining input values follow. Should an experienced analyst have sound reason to vary from these criteria, this may be done, but should be documented in the hazard classification report.

DAMN. - Name of dam.

RIVN. - Name of river.

IDAM. - Type of dam.

HDE. - Use a value commensurate with the dam-break scenario. For a sunny day failure where the dam is assumed to fail at normal pool, enter normal pool elevation. For an overtopping failure where dam is assumed to fail when overtopped by 1.0 foot (for example), enter dam crest elevation plus 1.0 foot.

BME. -

Earthen dam: Use the streambed elevation at the downstream toe of the dam.

Concrete and stone-masonry dam: Same as for earthen dam except add 0.20(HDE - BME) to BME.

VOL. - Use the reservoir volume associated with HDE - BME.

SA. - Use the reservoir surface area associated the HDE.

BW. -

Earthen dam: BW = 3 (HDE - BME).

Concrete arch dam: BW = 0.45 (CL + BL).

Concrete gravity dam: BW = 0.375 (CL + BL).

Stone-masonry dam: BW = 0.3 (CL + BL).

Rock-placed dam: BW = 2.5 (HDE - BME).

TFM. -

Earthen dam: TFM = 0.20 BW.

Concrete arch dam: TFM < (HDE - BME)/1,000; i.e., instantaneous failure.

> Note: If TFM < (HDE - BME)/1,000, then the SMPDBK assumption of gradually varied breach flow is violated and SMPDBK defaults to computing peak breach discharge via an instantaneous failure equation. Thus, TFM will not be used in peak breach discharge calculations.

Concrete gravity dam: TFM equals the lesser of:

(1) 1 minute per toppled monolith (if applicable), or
(2) 0.050 BW.

Stone-masonry dam: TFM = 0.075 BW

Rock-placed dam: TFM = 0.125 BW

QO. - Use maximum spillway, outlet, and overtopping (when applicable) discharge commensurate with HDE.

NS. - Use sufficient cross sections to adequately represent the routing reach. Fewer cross sections are needed for uniform channels than for channels that vary significantly in cross section geometry.

NCS. - Use at least 3.

CMS. - Use SMPDBK default of 0.3 if in doubt.

D(I). - Note that the slope used in breach discharge submergence calculations is computed as [D(2) - D(1)] / [Elev(2) - Elev(1)]. Thus, it is important to select these two cross sections so that the true slope immediately downstream from the dam can be calculated as accurately as possible by the model.

FLD(I). - Enter 0. Not needed for hazard classification.

HS(K,I), BS(K,I), and BSS(K,I). - These values can usually be determined from USGS 7-1/2-minute topographic quadrangle maps. However, when contour intervals are large (i.e., 40 ft, or 10 or 15 m), and/or sufficient detail is lacking, a field survey may be necessary.

CM(K,I). - Use values commensurate with large floods rather than typical in-bank flows [7]. When in doubt, select values on the high side of the possible range of values.

4. Peak Flood Depths and Velocities. - Both peak depths and velocities are needed for the criteria specified in section IV. The March 1988 version of SMPDBK outputs peak depths at each cross section, but not peak velocity. To determine peak velocity, compute cross-sectional area of flow at the cross section of interest and divide the peak discharge by this area ($V = Q/A$).

If many hazard classifications are to be performed using SMPDBK, SMPDBK could be modified to output peak velocity; a few lines of code are all that is necessary.

IV. IDENTIFICATION OF HAZARDS

A. Introduction

A dam-break/inundation study is performed for the purpose of determining the impact of a dam failure flood on "possible hazards." A possible hazard is one that has been identified as having the possibility to constitute a hazard, but field work and/or analysis needs to be performed for confirmation.

Possible hazards are identified from topographic maps, photographs, field surveys, and information from "locals." They include any situation that is suspicious of having potential for lives-in-jeopardy or economic loss due to a dam failure. Some examples are listed in section II.

Sometimes, downstream hazard classification is obvious. That is, an analysis is not necessary because lives would be in jeopardy, and/or property damage would occur, with little doubt, due to a dam failure.

Analysis does not always prove a possible hazard to be a confirmed hazard; many "gray areas" exist in hazard classification. Analysis may indicate that a residence could be flooded by 1 foot (0.3 m) of water, but will this result in loss of life? If a failure flood overtops a highway bridge, will the bridge be destroyed? If not, will a vehicle be carried by floodwater or go out of control due to hydroplaning? Or, will a vehicle crash due to a damaged road or bridge after the flood has passed? Questions and gray areas such as these are the underlying reasons for guidelines regarding identification of downstream hazards. Such guidelines are presented in subsections B. through G.

Subsections B. through E. contain curves of depth versus velocity (figs. 2 through 6) that are indicative of dangerous floodflows for various possible hazards. Figure 2 is a modification by the author of a study performed by Black [8]. The curves in figures 3 through 6 were derived theoretically by the author. Figure 4 is in reasonable agreement with a theoretical analysis performed by Simons, Li and Associates [9]. The lower curve in figure 5 is in reasonable agreement with a theoretical analysis performed by David J. Love and Associates, Inc. [10], and a laboratory flume study performed at Colorado State University by Abt and Wittler using monoliths [11]. Very little research has been done on this topic; however, even if this were the case, there would be discrepancies which cannot be avoided due to the many initial assumptions that have to be made, very large number of variables that have to be considered, and philosophy. This was emphasized by Abt and Wittler [11] who conclude, "Physical tests of human subjects, even in a controlled laboratory environment, indicated that the ability of the subject to adapt to flood flow conditions is difficult to quantify." The relationships presented in figures 2 through 6 are very reasonable for estimating lives-in-jeopardy for downstream hazard classification purposes, and satisfy one of the purposes of these guidelines - to bring consistency and objectivity into downstream hazard classification. In addition, they are logical and easy to use.

The depth-velocity flood danger level relationships are divided into three zones: low danger, judgment, and high danger. An explanation of these zones follows:

Low-danger zone. - If a possible hazard is subject to a depth-velocity combination plotting within this zone, then the number of lives-in-jeopardy associated with possible downstream hazards is assumed to be zero.

High-danger zone. - If a possible hazard is subject to a depth-velocity combination plotting within this zone, then it is assumed that lives are in jeopardy at all possible downstream hazards.

Judgment zone. - The low-danger and high-danger zones represent the two extremes of reasonable certainty regarding the occurrence of no lives-in-jeopardy and some lives-in-jeopardy, respectively. Between these two extremes exists a zone of uncertainty with respect to assessing lives-in-jeopardy. Because every flood situation is unique, it is impossible to account for all of the variables that may result in lives to be in jeopardy if the flood magnitude (depth and velocity) plots in this zone. Thus, in this case, it is left up to the analyst to use engineering judgment for determining lives-in-jeopardy. Whenever possible, several opinions, and a common agreement among analysts should be reached in making this determination. There are many possible factors to consider; examples include:

- A designated campground, attraction, monument, etc. may receive very little visitor use. Such facilities may be visited for a very small total time during a year (e.g., 100 person-hours). Thus, the chance for lives to be in jeopardy due to flood depths and velocity combinations being in the judgment zone of figure 5 or 6, is very small and lives-in-jeopardy can be considered zero.

- The total time that the flood depths and velocities reach magnitudes within the judgment zone. An example is a dam-break flood from a small reservoir that rapidly reaches a peak discharge, then rapidly decreases. If the only possible hazard is a highway receiving little use, then the chance of a vehicle being exposed to a dam-break flood is very small. On the other hand, vehicles on a heavily traveled highway that could receive flooding from a large reservoir having sustained high flows are likely to be "caught" in a flood situation. Although the effect of the flood on loss of life is uncertain in this zone, the fact that there is a large population involved cannot be ignored, and conservative judgment should be used such that loss of life is considered possible.

- A residence subject to a flood depth-velocity in the judgment zone may be a three-story, well-built, brick home. In such a case, the assumption could be made that the occupants are not in serious danger - especially if the flooding is of fairly short duration. However, occupants of a single-story, poorly constructed home subject to floods of a long duration should be assumed to be in danger.

- Multiple-story frame houses may provide safety to occupants above the first floor. However, it has to be assumed that the occupants will be aware of the flood (e.g., not sleeping) and will move to a higher level.

It is very important to understand that the zones (low-danger, judgment, high-danger) represented in figures 2 through 6 are not "cast in stone." Predicting lives-in-jeopardy is far from being an exact science. If the analyst has sound reason to believe that lives are in jeopardy for conditions in the low-danger zone, or no lives are in jeopardy for conditions in the high-danger zone, then such reasoning can override figures 2 through 6. However, the reasons have to be documented in the hazard classification report.

In many hazard classifications, especially where large dams and catastrophic flooding are involved, reference to figures 2 through 6 is superfluous because of the obvious flood danger. But, for situations where the hazard classification of a dam is solely dependent upon an isolated flood situation where occupants of a dwelling or vehicle may be in danger, or a person having no protective environment (e.g. house, vehicle) may be in danger, these figures should be used. In such situations, the analyst will have predicted a reasonable maximum depth and velocity, "with confidence" (refer to the following paragraph), at the possible hazard site and needs to make a decision as to the floods effect on the possible hazard so that lives in jeopardy can be assessed. If depths and velocities cannot be predicted with confidence, then a conservative approach should be used that assumes any possible hazard in the path of a dam-break flood is in danger and is considered a downstream hazard. But, for situations where the analyst is confident about the predicted depths and velocities, figures 2 through 6 can be used for estimating the susceptibility of a possible hazard to impacts from the predicted floodwaters. Then, the analysts can decide if the possible downstream hazard should be confirmed as a downstream hazard, and assess lives-in-jeopardy.

The adequacy of predicted depths and velocities can be ascertained by performing sensitivity analyses on critical breach outflow and channel routing parameters. If predicted depths and velocities at a specific channel site do not change significantly with significant changes in the critical parameters, then the predicted depth and velocity can be used "with confidence." More information regarding sensitivity analysis is contained in appendix A, subsection D.

Extent of economic loss is the decision of the analyst, as previously stated. Thus, depth-velocity-damage relationship curves are not presented in the following sections.

B. Permanent Residences, Commercial and Public Buildings, and Worksite Areas

Permanent residences are considered dwellings attached to foundations, and hooked to utilities. Some mobile homes are not attached to foundations; these are discussed separately in subsection IV.C.

Worksite areas include facilities that contain workers on a daily (work week) basis. This includes farm operations, oil and gas operations, sand and gravel operations, and fish hatcheries.

The lives-in-jeopardy includes all occupants of dwellings located within the inundation boundaries, subject to a combination of flood depth and velocity plotting above the low-danger zone of figure 2. However, but

HIGH DANGER ZONE - Occupants of most houses are in danger from floodwater.
JUDGEMENT ZONE - Danger level is based upon engineering judgement.
LOW DANGER ZONE - Occupants of most houses are not seriously in danger from flood water.

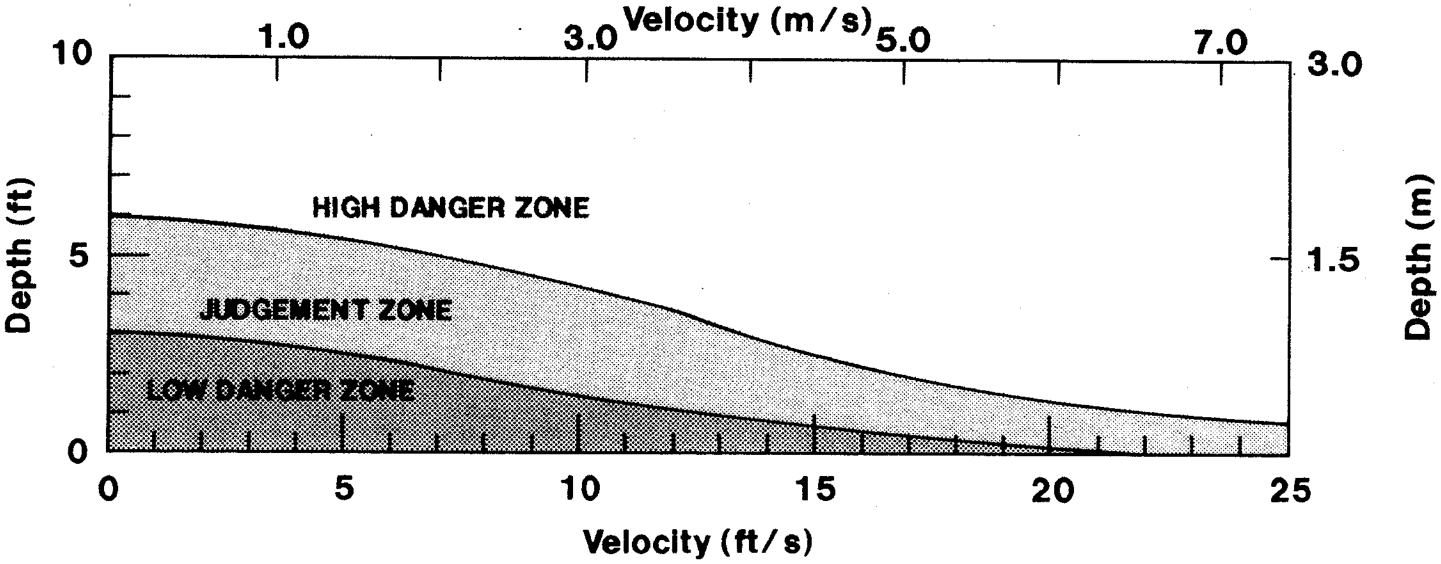


Figure 2. – Depth–velocity flood danger level relationship for houses built on foundations.

only if justifiable, no lives-in-jeopardy has to be associated with occupants of dwellings subject to a flood depth and velocity plotting within the judgment zone. Lives-in-jeopardy is always associated with occupants of dwellings subject to a combination of flood depth and velocity plotting within the high-danger zone except very special cases where the analyst can present strong justification.

If flood depth and velocity cannot be predicted with reasonable confidence, then the lives-in-jeopardy includes all occupants of residences within the inundation boundaries with no reference to depth or velocity, and the downstream hazard classification can be assigned accordingly.

For situations where pedestrians may be a factor in the downstream hazard classification, refer to subsection IV.E.

C. Mobile Homes

Mobile home parks are typically located in flood plains due to zoning requirements in many areas. This creates a very dangerous situation for occupants of mobile homes, as they are very susceptible to movement from relatively small floods. Thus, depth-velocity-flood danger level relationships (fig. 3), other than those for houses on foundations, are used for mobile homes.

The lives-in-jeopardy includes all occupants of mobile homes located within the inundation boundaries, subject to a combination of flood depth and velocity plotting above the low-danger zone of figure 3. However, but only if justifiable, no lives-in-jeopardy has to be associated with occupants of mobile homes subject to a combination of flood depth and velocity plotting within the judgment zone. Lives-in-jeopardy is always associated with occupants of mobile homes subject to a combination of flood depth and velocity plotting within the high-danger zone except very special cases where the analyst can present strong justification.

If flood depth and velocity cannot be predicted with reasonable confidence, then the lives-in-jeopardy includes all persons likely to be in the inundated area with no reference to depth and velocity, and the downstream hazard classification can be assigned accordingly.

HIGH DANGER ZONE – Occupants of almost any size mobile home are in danger from flood water.
JUDGEMENT ZONE – Danger level is based upon engineering judgement.
LOW DANGER ZONE – Occupants of almost any size mobile home are not seriously in danger from flood water.

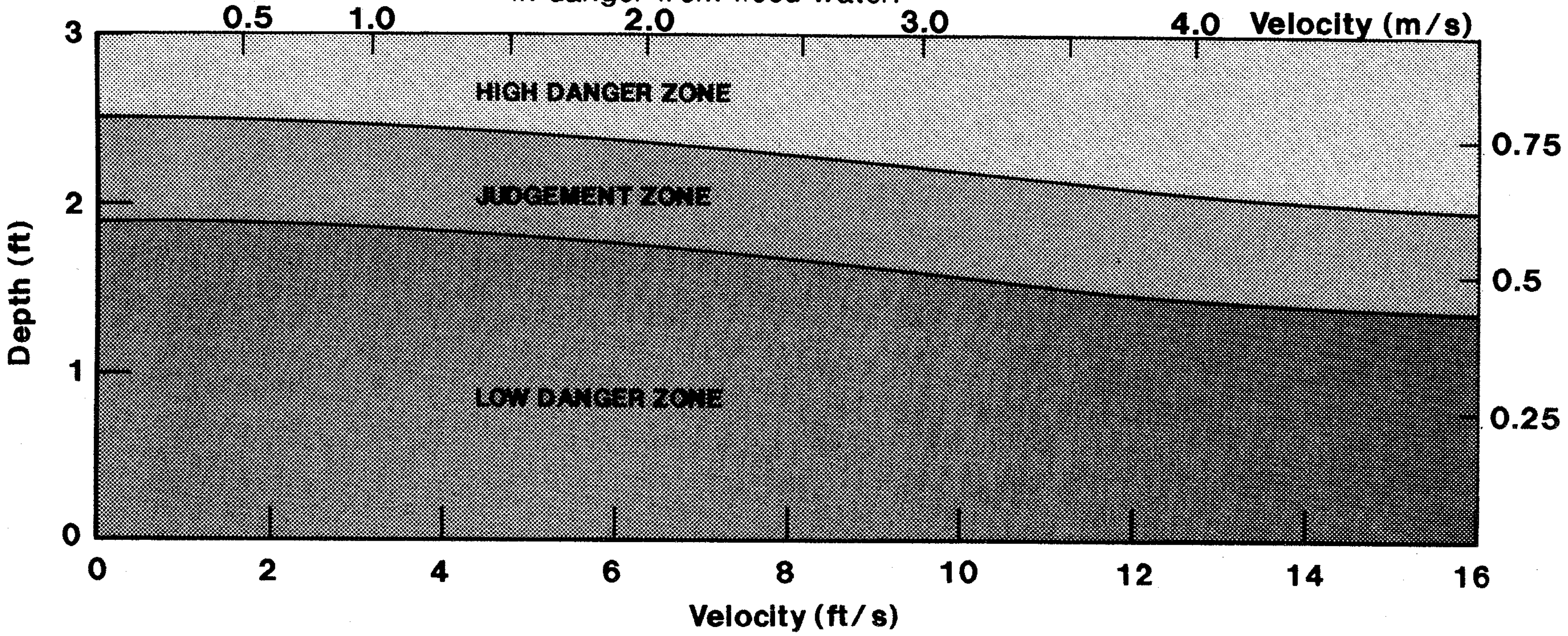


Figure 3. – Depth–velocity flood danger level relationship for mobile homes.

D. Roadways

If a dam-break flood wave inundates a roadway, the possibility for loss of life to motorists and pedestrians (guidance for pedestrians is covered in subsec. IV.E.) should be evaluated. In most cases, a roadway is inundated due to its crossing the channel via a bridge or culvert, or due to its running parallel to the channel such as in a canyon.

Loss of life is possible on a roadway as a result of a dam failure due to several causes. These include:

- A vehicle being carried downstream by floodwater,
- Loss of control and subsequent crash of a vehicle due to its impact with the floodwater, and,
- A vehicle crash resulting from road damage after the flood has passed.

However, because downstream hazard classification is based on the direct impacts from a dam-break flood (subsec. I.A.), situations such as a vehicle crash resulting from road damage after the flood wave has passed are not considered when estimating lives-in-jeopardy. It is assumed that vehicles are already on, or attempting to enter a roadway when it is inundated.

The lives-in-jeopardy includes all occupants of vehicles within the inundation boundaries subject to a combination of depth and velocity plotting above the low-danger zone of figure 4. However, but only if justifiable, no lives-in-jeopardy has to be associated with occupants of vehicles subject to a combination of flood depth and velocity plotting within the judgment zone. Lives-in-jeopardy is always associated with occupants of vehicles subject to a combination of flood depth and velocity plotting within the high-danger zone except very special cases where the analyst can present strong justification.

If flood depth and velocity cannot be predicted with reasonable confidence, then the number of lives-in-jeopardy includes all persons likely to be in the inundated area with no reference to depth and velocity and the downstream hazard classification can be assigned accordingly.

A roadway will be a factor in determining the downstream hazard classification of a dam, only when it is paved. This criteria provides a simplified way of accounting for the amount, frequency, and speed of traffic on that particular roadway.

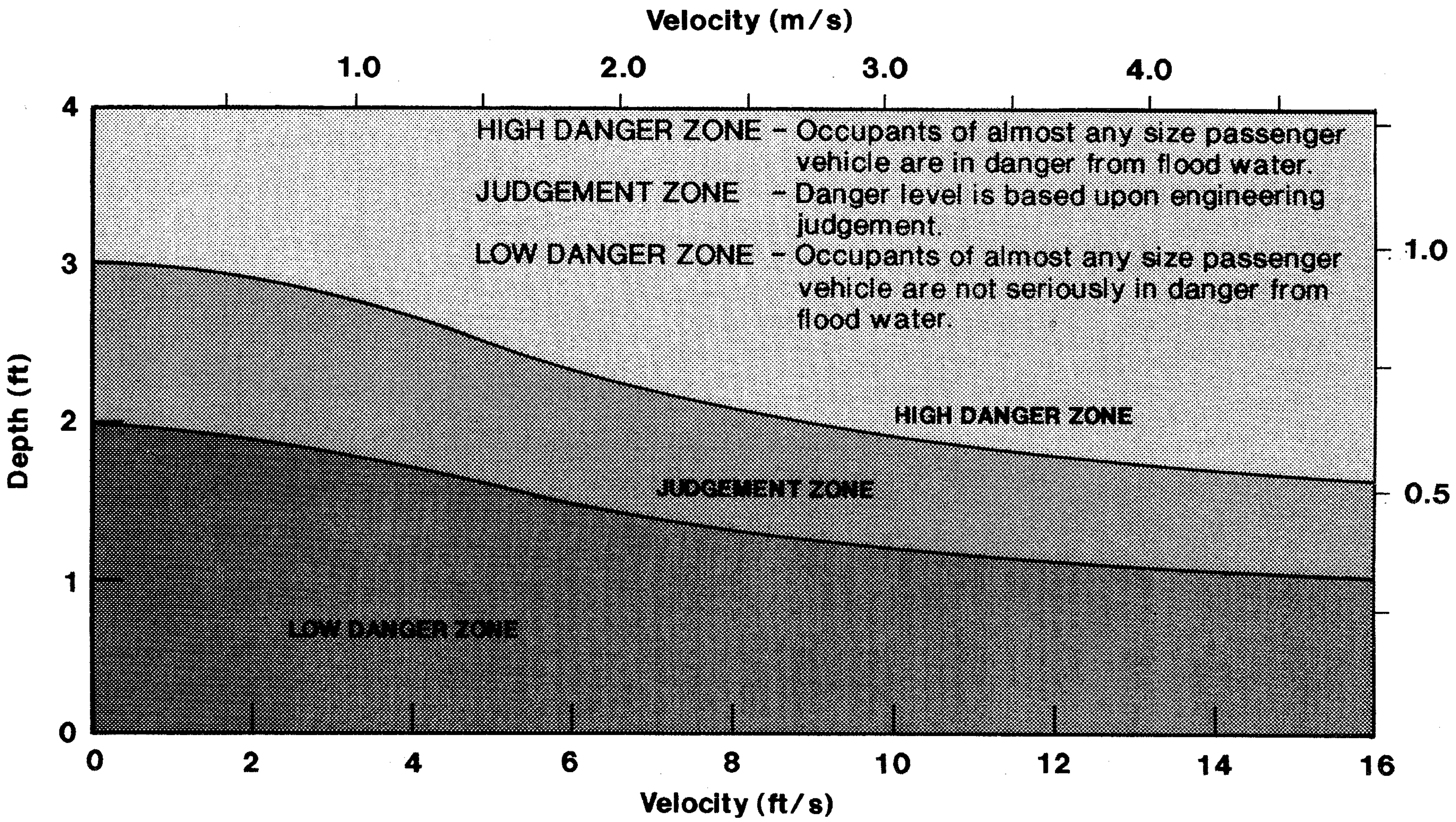


Figure 4. – Depth–velocity flood danger level relationship for passenger vehicles.

The paved road criteria apply unless the analyst can provide reason to the contrary. For example, a paved roadway may be located in a very remote location and rarely traveled. Or a roadway may be closed during the time of year that the dam failure is assumed to occur. Such a case is when a dam failure flood can only endanger a roadway if the failure occurs in combination with a large flood, but, the large flood can only occur in late spring (rain-on-snow flood) when a roadway located in an alpine area is closed.

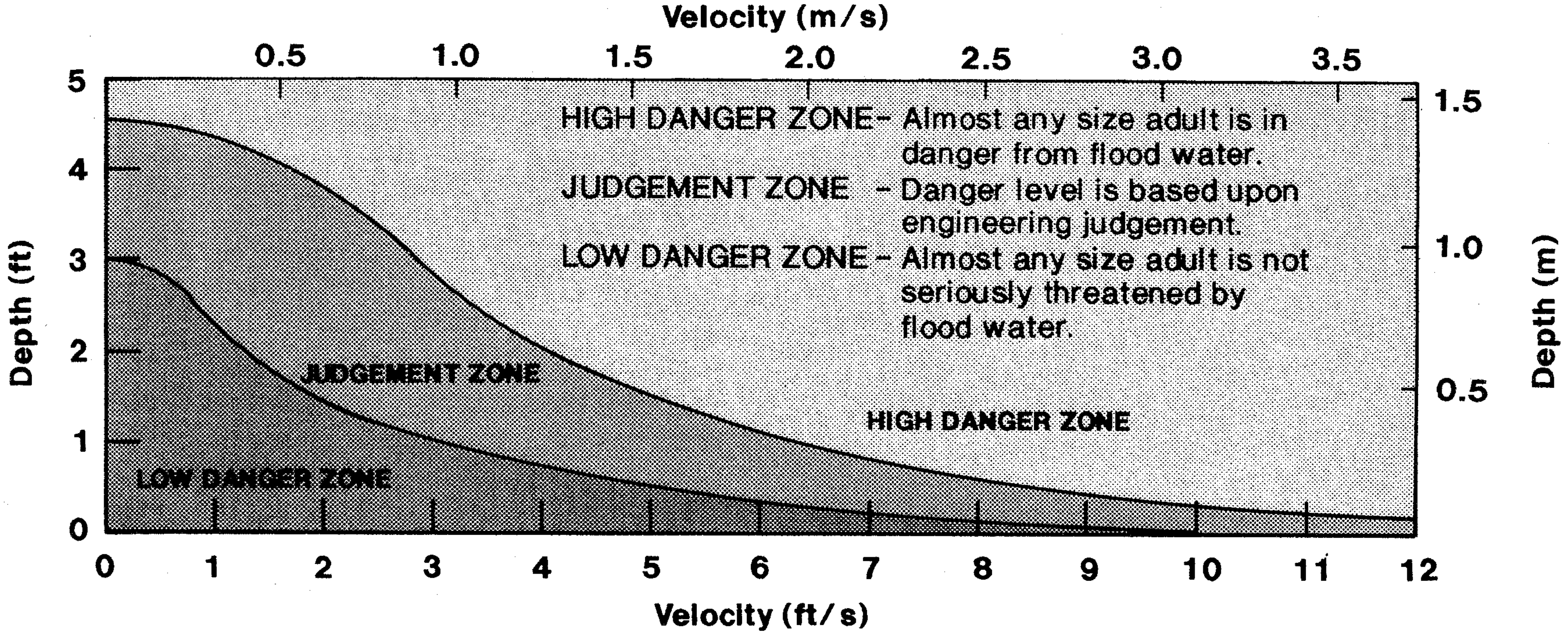
Conversely, unpaved roads can also present a lives-in-jeopardy situation, thereby resulting in a significant- or high-hazard classification if proper justification can be made. An example is a gravel road in a long narrow canyon with a dam located upstream. This road receives moderate traffic because it is an access to an established recreational area, scenic attraction, residential housing division, etc. However, because the road passes through a long narrow canyon, a dam failure flood could very likely result in loss of life to motorists in the canyon due to the difficulty in escaping the flood.

Economic loss includes replacement costs of the highway and crossings only.

E. Pedestrian Routes

Pedestrian routes include sidewalks, bicycle paths, and walking/hiking trails. For situations where pedestrian routes are isolated, and/or may influence the hazard classification, the lives-in-jeopardy can be estimated using figures 5 and 6. Figures 5 and 6 are depth-velocity-flood danger level relationships for adults and children, respectively. Separate figures for adults and children (versus one figure for all humans) are included so possible hazards that may not include children can be evaluated differently than mixed populations of both adults and children. Examples of "adult only" populations are worksites and adult-only residential areas. An adult is considered (for the use of figures 5 and 6) any human over 5 feet (150 cm) tall and weighing over 120 pounds (54 kg). The choice of using either figure 5 or 6 is the decision of the analyst based on knowledge and understanding of the population. However, when populations are mixed (i.e., adults and children), figure 6 should be used for conservativeness.

Infants are not treated separately; instead, they are assumed to be safely attended by adults.



HIGH DANGER ZONE - Almost any size adult is in danger from flood water.

JUDGEMENT ZONE - Danger level is based upon engineering judgement.

LOW DANGER ZONE - Almost any size adult is not seriously threatened by flood water.

Figure 5. – Depth–velocity flood danger level relationship for adults.

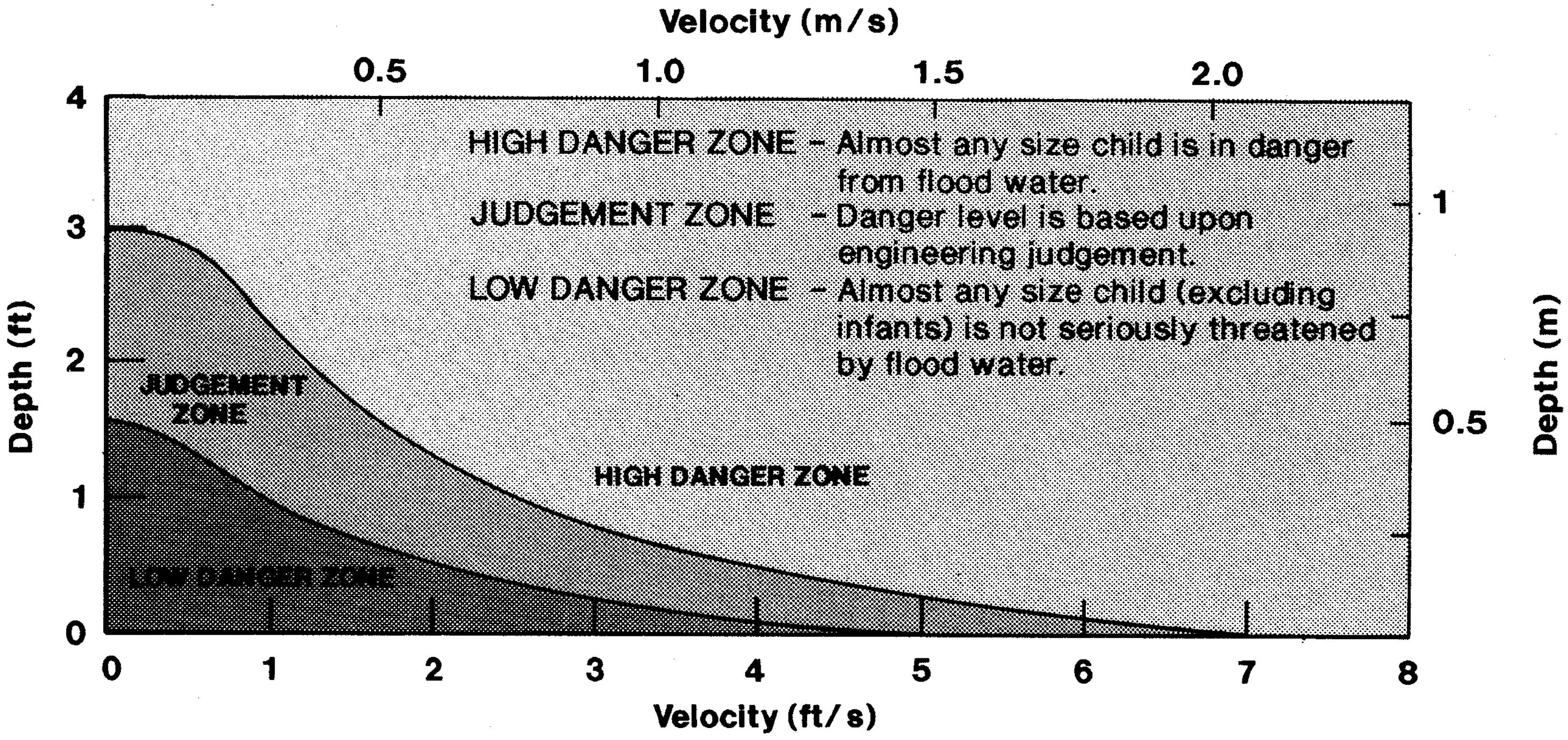


Figure 6. – Depth–velocity flood danger level relationship for children.

The lives-in-jeopardy includes all pedestrians, located within the inundation boundaries, subject to a combination of flood depth and velocity plotting above the low-danger zone of figure 5 or 6. However, but only if justifiable, no lives-in-jeopardy has to be associated with pedestrians subject to depths and velocities plotting within the judgment zone. Lives-in-jeopardy is always associated with pedestrians subject to a combination of flood depth and velocity plotting within the high-danger zone except very special cases where the analyst can present strong justification.

If flood depth and velocity cannot be predicted with reasonable confidence, then the lives-in-jeopardy includes all persons likely to be in the inundated area with no reference to depth and velocity and the downstream hazard classification can be assigned accordingly.

F. Designated Campgrounds and Recreation Areas

A designated campground and/or recreational area downstream from a dam is treated the same as pedestrian routes. Such a facility can be one that is owned, operated, and maintained by a Government agency or by private interests, and is advertised via signs, brochures, maps, etc. Campgrounds may include facilities intended for recreational vehicle hookups, to facilities intended for primitive camping. Recreational areas include scenic attractions, hiking trails, fishing and hunting areas, golf courses, boating areas and launching facilities, etc. For hazard classification purposes, it is assumed that such a facility will be occupied during a dam failure flood (unless the failure scenario takes place out of season) and lives may be in jeopardy. For estimating lives in jeopardy, the number of people likely to use the facility during a heavy use period (e.g., Fourth of July) should be considered.

The failure scenario may be such that persons are in danger only when the dam failure is combined with a large runoff flood occurring during a certain time period (e.g., spring runoff). In such a case, the use of the facility during this time period should be considered in estimating lives-in-jeopardy. For example, if the dam can threaten lives in the facility only for the case when failure occurs during the spring runoff, then anticipated use during the spring should be considered when estimating lives-in-jeopardy.

G. Mixed Possible Hazard Sites

A typical community usually contains all of the possible hazards identified in subsections IV.B. through F. Estimating lives-in-jeopardy for this situation may require the use of all, or some of the criteria in subsections IV.B. through F. For example, if a small community is comprised of permanent residences on foundations, mobile homes, and a small park, then all of the criteria in subsections IV.B. through F. are needed to accurately estimate lives-in-jeopardy.

H. Economic Loss

As stated in subsection II.C., no dollar value is used for determining economic loss. However, hazard classification is rarely based on economic loss alone, so judging economic loss usually is not required. This is because in most situations where economic loss is involved, lives-in-jeopardy is a consideration also. Rarely does a situation exist where the lives-in-jeopardy is zero, but appreciable or excessive economic loss will occur resulting in a significant- or high-hazard classification based on economic loss alone (table 1).

Thus, it is best to assign the dam a hazard classification based on lives-in-jeopardy before economic loss is considered. Then, if the lives-in-jeopardy is greater than 6, resulting in a high-hazard classification, estimation of economic loss is not necessary because it will have no influence on the hazard classification. However, if the hazard classification is less than high, economic loss should be evaluated to determine if the hazard classification could increase.

V. CONCLUDING REMARKS

Downstream hazard classification is important as a management tool because it could be the deciding factor that determines whether or not a formal safety evaluation and possible modification are performed on a dam.

Determining hazard classification could vary simply from a "windshield survey" or glancing at a topographic map to analyses requiring detailed field data, sophisticated analytical models needing a high-speed digital computer, and extensive user training and experience.

While hazard classification may be obvious for many large dams, it often requires detailed analysis combined with good judgment for small dams. However, detailed analysis does not always result in a firm hazard classification. Many unknowns exist with regard to structural damage to buildings, roads, occupancy, behavior of persons threatened by flooding, etc. Due to these unknowns, agency policy is important to give objectivity and consistency in assigning hazard classifications. These guidelines are intended to provide such assistance.

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APPENDIXES

APPENDIX A - METHODS FOR PERFORMING A DAM-BREAK/INUNDATION STUDY

A. Estimating Breach Hydrograph or Peak Discharge
    1. Physically based
    2. Parametric
    3. Empirical
    4. Comparison

B. Routing Breach Discharge Downstream
C. Determining Flood Depths and Inundation Boundaries
D. Errors Associated With Dam-Break Flood Routing Models

APPENDIX B - BIBLIOGRAPHY

APPENDIX A

METHODS FOR PERFORMING A DAM-BREAK/INUNDATION STUDY

Dam-break/inundation studies are both an art and a science. Although many advances in computer models and analytical methods have been made in recent years, much knowledge and judgment by the analyst are still necessary for meaningful results.

The purpose for this appendix is to present an overview of state-of-the-art dam-break/inundation study methods of varying complexities, for persons not familiar with or wanting more information on such methods. From this, an individual can choose a method best suited for his/her specific needs, resources (time, money), and computing facilities (or lack of). As stated in subsection III.D.3., other analytical methods can be used if the analyst has good reason to do so; this appendix presents such "other methods."

A. Estimating Breach Hydrograph or Peak Discharge

If the breach size, slope, and time to develop are known, the breach outflow can be determined using hydraulic principles. However, unless a major structural weakness and obvious failure condition are known, estimating the breach parameters is based on previous experience and engineering judgment.

Many assumptions can be made and scenarios envisioned regarding a dam failure. For example, a dam could fail from overtopping by a large inflow flood or by piping on a clear day. A thin arch dam may burst almost in its entirety, or just a section of it may fail. The complete breaching of an embankment dam may take as little as 30 minutes to form, or 2 hours or longer; it can vary widely in size and shape. The reservoir may be half full or at its maximum capacity. These factors can only be speculated prior to a dam failure.

The type of failure (assumed) and dam should be considered when estimating a peak breach discharge. Two basic categories of failure are possible. The first is an "overtopping failure." This failure of a dam by erosion and/or structural damage is due to the reservoir overtopping the dam. The reservoir storage and discharge capability of the appurtenances are insufficient during the occurrence of a large flood of significant magnitude and duration to prevent overtopping of the dam for a significant time period.

The other failure category is a "sunny day" or "normal pool" failure. Basic assumptions are that the reservoir's water surface elevation is at the normal pool level and the reservoir is receiving average inflow (usually insignificant) when dam failure occurs. Failure mechanisms in this case include seepage, piping, embankment slope instability, structural weakness, reservoir rim landslide induced, and earthquake induced.

The type of dam has a significant effect on breach configuration and peak breach discharge. The dam may be either a well constructed or poorly constructed embankment dam, a concrete gravity, arch or buttress dam, slag pile (mine waste), or other type.

In general, breach discharge increases with dam height, reservoir surface area, and a small time for full breach development. The reverse is true regarding small breach discharges.

A reasonable maximum breach discharge can be estimated based on four principal methods:

- Physically based,
- Parametric,
- Predictor, and
- Comparison.

A discussion of each follows:

1. Physically based. - Physically based methods are those such as BREACH [12] which computes a breach size and shape using principles of hydraulics, sediment transport, soil mechanics, and material properties of the dam.

2. Parametric. - Parametric models use observations of previous dam failures to estimate the size, shape, and time to failure of a breach. The breach is developed by time-dependent linear geometric increments to its assumed final dimensions, and the discharge is computed at each increment using hydraulic principles. DAMBRK [6] and SMPDBK [5] are examples of models that use this approach.

3. Predictor. - Many models exist that are of the form:

$$Q_{bmax} = C \cdot X^m$$

where Q_{bmax} is peak breach discharge and C and m are constants determined from historical data. The parameter X is usually dam height, reservoir volume, or the product of the two. The parameter m has no physical reference. The values of C and m are determined using several different approaches. These approaches, as explained in SCS National Bulletin No. 210-6-19 [13], are:

a. The formal approach would determine the undefined constants C and m using linear regression on the logarithmic transforms of paired data sets of reported Q_{bmax} and X.

b. The semiformal approach might determine m by a regression or other analysis but then evaluate C visually (using plots of Q_{bmax} vs. height, storage, or their product) on the basis of intuition and judgment.

c. The purely empirical approach has no constraints. C and m are arbitrarily selected.

Many different C and m values have been published by different researchers [4, 14, 15, 16, and 17] because the researchers used available historical dam failure data in various ways to arrive at the C and m values. For instance, a data set may have included only embankment dams, or embankment dams within a certain range of height and storage, or only concrete dams, etc. Due to this, much confusion exists as to which predictor models are "best." It is very important to note that no one model is best. Different predictor models are applicable to different situations.

If the analyst chooses to use a predictor model, then he can select the most suitable one for a specific dam by reviewing the data used in its development and determining if the historical data are similar to the situation being analyzed. Also, conservative or liberal estimates can be obtained, depending on the purpose of the evaluation, by choosing predictor models that estimate high- or low-peak breach discharges. For hazard classification purposes, conservative (high) estimates are recommended to be consistent with dam safety philosophy.

Another approach is for the analyst to "customize" the C and m values for the particular dam-breach scenario being analyzed. This is done by using historical failure data (subsec. I.D.) of similar failure scenarios (dam height, reservoir volume, similar construction, etc.) and fitting C and m by applying the approaches explained in this subsection.

3. Comparison. - If the subject dam is very similar in size, construction, and materials to a failed dam with known data, the breach characteristics and peak outflow of the failed dam could be used in estimating the same for the subject dam. Some data on such failures are contained in references [4], [14], and [15].

Determining a peak breach discharge for use in hazard classification is very subjective. There is no "cook-book" method or single procedure that is applicable for all situations. Consequently, it is best to use several different methods for one analysis, compare the results, and choose a peak breach discharge that is most reasonable and/or is similiar among several different methods.

Predicted peak breach discharge can range considerably depending on the method of evaluation. Due to this, one has the choice of being liberal, conservative, or somewhere in between. For hazard classification purposes, conservative estimates should be favored. It is best to "err" and predict more severe inundation and greater lives-in-jeopardy so, should a dam failure occur, the chances of underestimating lives-in-jeopardy and hazard classification will be lessened. That is, the chances of classifying a dam as low- or significant-hazard, when it should have been significant or high, will be less. However, it is not unusual for predicted peak breach discharges to vary greatly among different methods - as much as one order of magnitude. In cases where such a large difference exists, the highest value may not be a good choice for a conservative peak breach discharge; instead, it could be considered an outlier. The engineer performing the analysis must have a strong knowledge of dam failure mechanics and hydraulics and be very familiar with historical dam failures. Only then can the engineer use good judgment in determining a reasonable peak breach discharge.

Fortunately, estimates of peak breach discharge can usually vary considerably without affecting the final results (hazard classification). The difference in flood depths computed from routing different breach discharges downstream diminishes with distance downstream from the dam (fig. A-1) and eventually becomes negligible. This distance is dependent on the difference in discharge at the dam, reservoir storage, and channel configuration, slope, and roughness. This topic is treated quantitatively by Fread [18].

B. Routing Dam-Break Discharge Downstream

The dam-break hydrograph will disperse as it travels downstream resulting in attenuation of the peak discharge. This is illustrated on figure A-2. To determine the amount of attenuation so that the discharge can be computed at selected points of interest (such as possible hazards), the dam-break flood is routed downstream. Normally, for the purpose of hazard classification, only the peak discharge is routed.

Many factors affect attentuation of the dam-break hydrograph; the primary ones are listed below, and their effect is illustrated on figure A-3.

Small attenuation	Large attenuation
Large reservoir volume	Small reservoir
Small channel and overbank storage	Large channel and overbank storage
Steep channel slope	Gentle channel slope
Little frictional resistance to flow	Large frictional resistance to flow
Supercritical flow	Subcritical flow

Many methods and models are available for predicting the flow characteristics of a flood wave resulting from a breached dam. Some of the more popular, state-of-the-art methods are discussed and compared in a recent study by Wurbs [19]. Wurbs concludes "The National Weather Service (NWS) Dam-Break Flood Forecasting Model (DAMBRK) is the optimal choice of model for most practical applications. The computer program

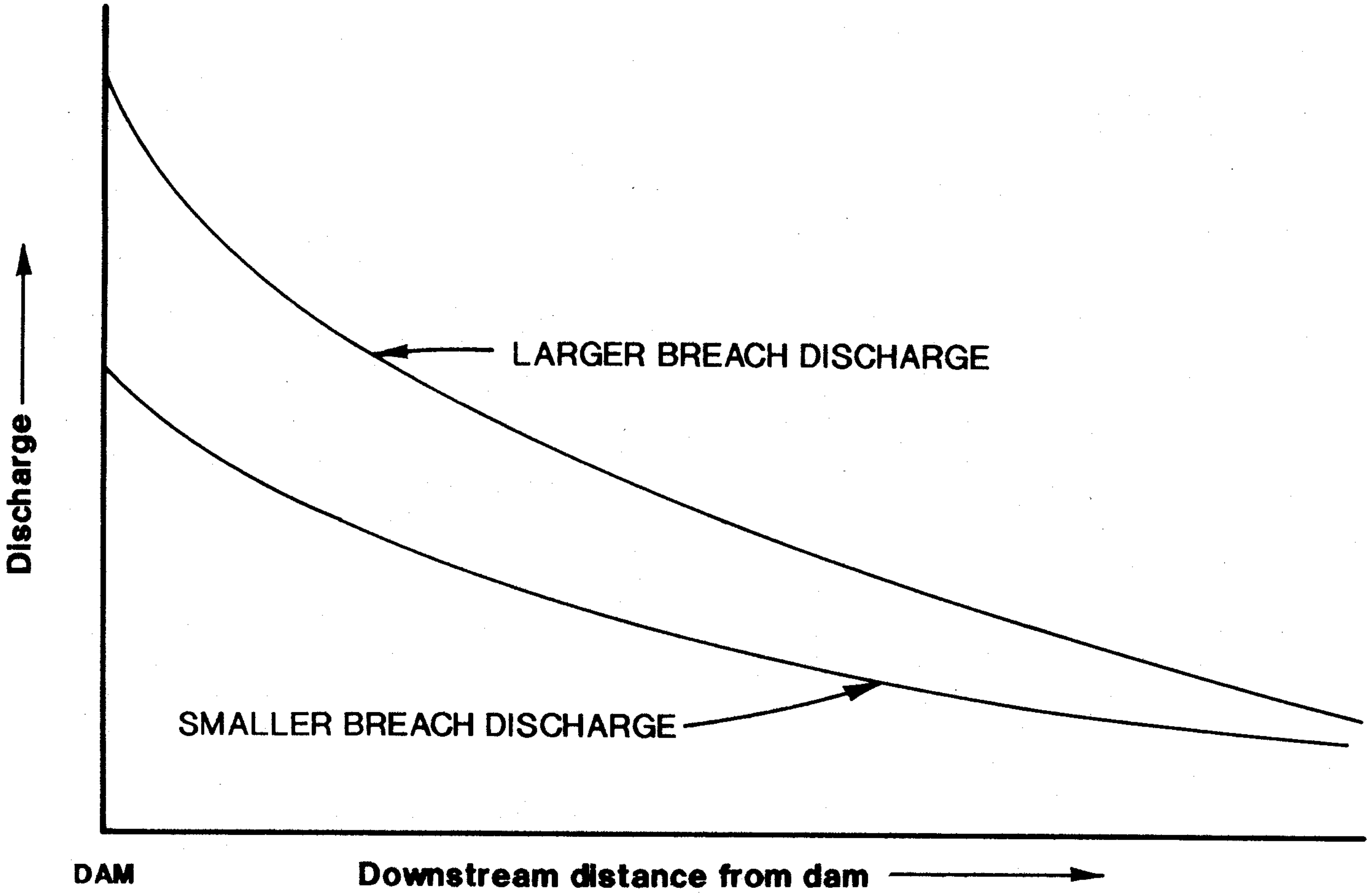

Figure A-1. – Convergence of depths of different size breach discharges routed down same channel.

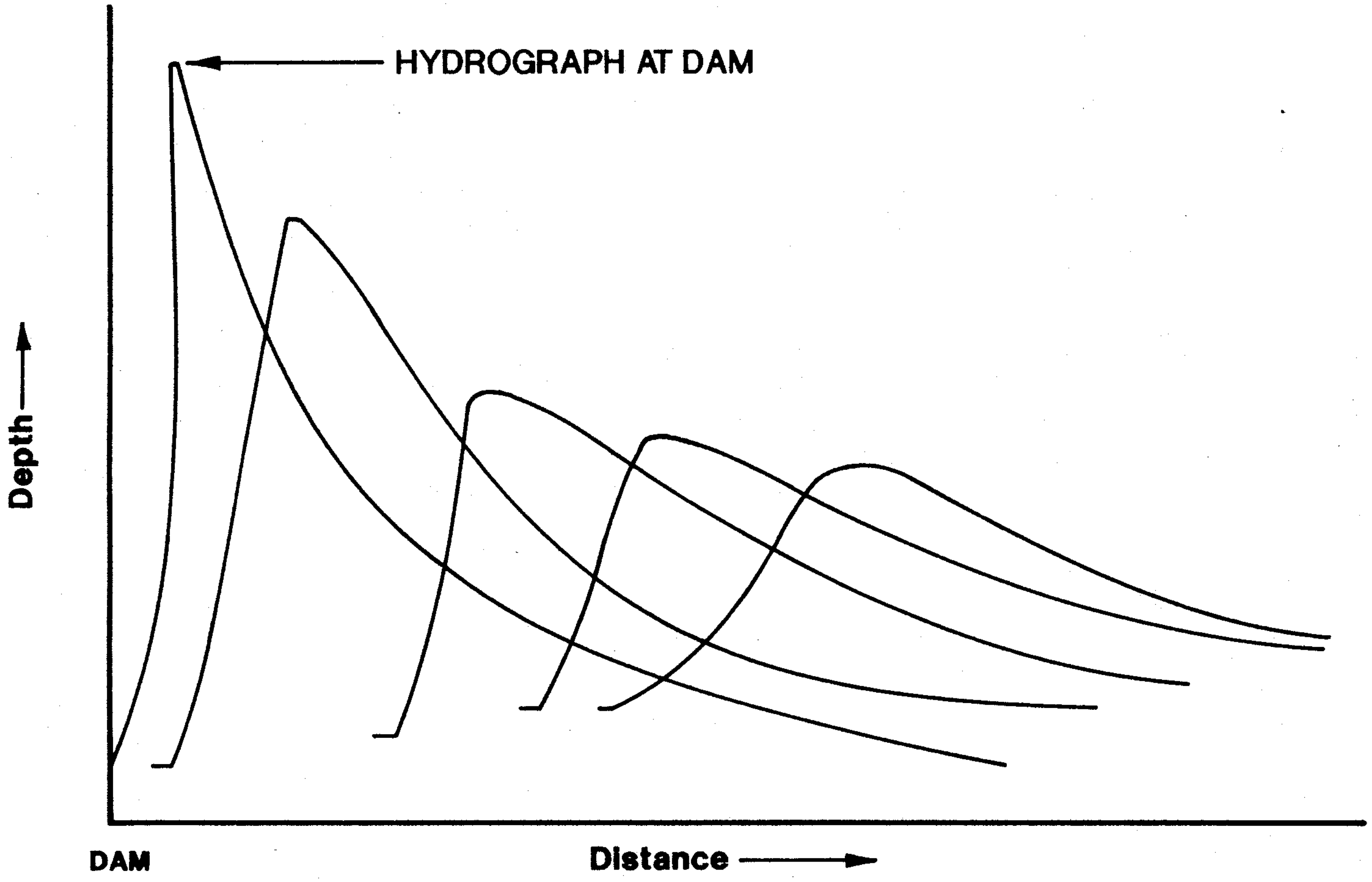

Figure A–2. – Dam–break discharge hydrograph dispersion and attenuation.

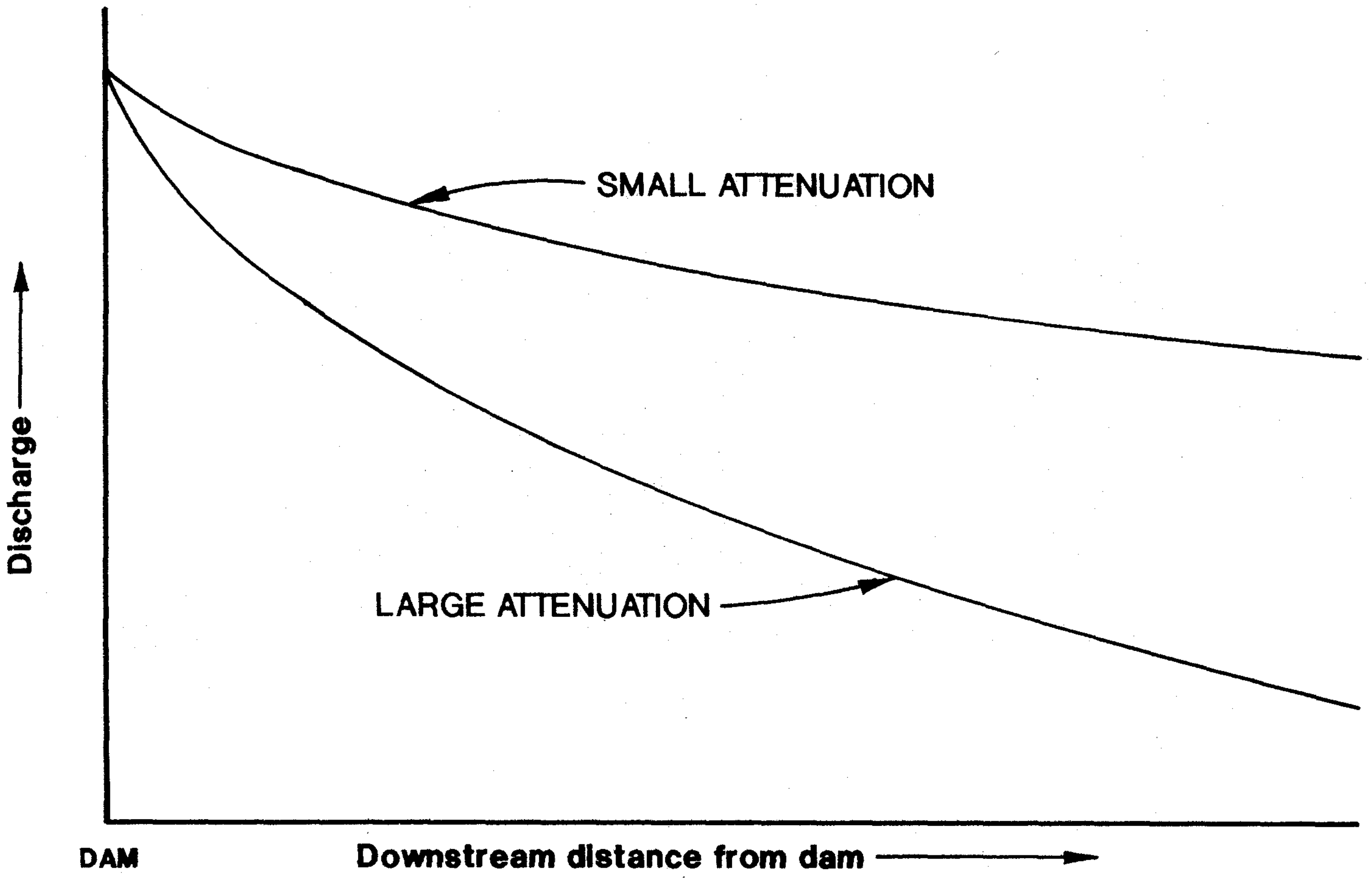

Figure A–3. – Dam–break hydrograph attenuation.

is widely used, well documented, and readily available from the NWS. Some civilian as well as military applications require the capability to perform an analysis as expeditiously as possible. The Simplified Dam-Break Flood Forecasting Model (SMPDBK) is the optimal choice of model for most of these types of applications." After using both models in numerous dam-break/flood routing studies, the author concurs with this conclusion. In addition, both DAMBRK and SMPDBK have microcomputer versions available from NWS.

SMPDBK [5] routes and attenuates the dam-break flood peak by a channel storage technique that uses channel geometry data and attenuation curves developed from DAMBRK [6]. This method is physically based, accurate, relatively easy to use, and not very labor and time intensive. It is an excellent model for hazard classification purposes when complicated channel hydraulics are not involved and the highest degree of accuracy is not needed.

If more accuracy is needed, and/or more hydraulic detail should be accounted for, DAMBRK is a recommended model. This model employs the dynamic wave method of flood routing. Only the dynamic wave method accounts for the acceleration effects associated with the dam-break flood waves and the influence of downstream unsteady backwater effects produced by channel constrictions, dams, bridge-road embankments, and tributary inflows. DAMBRK routes the complete hydrograph, rather than only the peak flow, downstream. The DAMBRK manual states:

> "The hydrograph is modified (attenuated, lagged, and distorted) as it is routed through the valley due to the effects of valley storage, frictional resistance to flow, flood wave acceleration components, and downstream obstructions and/or flow control structures. Modifications to the dambreak flood wave are manifested as attenuation of the flood peak elevations, spreading-out or dispersion of the flood wave volume, and changes in the celerity (translation speed) or travel time of the flood wave. If the downstream valley contains significant storage volume such as a wide flood plain, the flood wave can be extensively attenuated and its time of travel greatly increased."

Most dam-break models (such as DAMBRK and SMPDBK) use some form of the Manning equation for open-channel hydraulic calculations. The Manning equation is discussed in most open-channel flow hydraulics textbooks. One of the input variables that requires special attention due to characteristics of dam-break floods is the Manning roughness coefficient, n. To account for energy losses other than boundary friction, a much higher n-value for dam-break floods is used (or any other large flood) than for typical within-bank flows. The use of traditional values of n will result in significant error because computed discharge is inversely proportioned to n. Trieste and Jarrett [16] discuss this problem and make recommendations for selecting n-values used for open-channel computations of large floods.

A simple flood routing procedure using a regression equation determined from historical dam failure data is discussed in ACER Technical Memorandum No. 7 [3]. The independent variables are peak breach discharge, distance from the dam to the forecast point, and an attenuation parameter. This method is useful if time, computer facilities, and persons having knowledge of open-channel hydraulics are not available.

C. Determining Flood Depths and Inundation Boundaries

The end product in a dam-break/inundation study performed for hazard classification purposes is to determine flood depths at possible hazard sites so that the possible hazards can be confirmed. In some cases, where possible hazards are scattered along a channel reach, inundation boundaries are determined on topographic maps so that the total extent of flooding can be assessed. Inundation boundaries are delineated by plotting the maximum water surface elevation on both sides of the channel using topographic maps as a base.

Maximum water surface is dependent upon many factors. Some of these include peak discharge, channel roughness, channel obstructions and constrictions, and channel slope.

Peak flood depths are standard output data in DAMBRK and SMPDBK and in most other flood routing computer models. If such a computer model is not used but an estimate of peak discharge at the site has been determined, then depths can be readily calculated using Manning's equation, which is widely used and accepted. It is described in hydraulics textbooks such as Chow [20], Henderson [21], and Brater and King [22].

One must use good judgment in interpreting the flood damage and lives-in-jeopardy within the inundation boundaries. Due to small size map scale (e.g., 7-1/2 minute or 15 minute) and large contour intervals (e.g., 40 feet), it is difficult (or impossible) to draw accurate inundation boundaries. The impact of flooding in the vicinity of these boundaries is subject to interpretation and a conservative "benefit-of the-doubt" philosophy is recommended.

D. Errors Associated with Dam-Break Flood Routing Models

Many improvements have evolved in dam-break flood models in the last decade. State-of-the-art methods can simulate dam-break flood discharges and depths within 5 to 10 percent if the key parameters are known. That is, using data from historic dam failures that have been extensively studied (such as Teton Dam), modern state-of-the-art models can very accurately simulate the actual failure flood. Unfortunately, most parameters are not known before a dam-break flood study, and these unknowns result in large error in performing such studies. Some of these unknowns are described by Fread [18]:

- When will a dam fail?
- When and to what extent will a dam be overtopped?

- What is the size, shape, and time of formation of the breach?
- What is the storage volume and hydraulic resistance of the downstream channel valley?
- Will debris and sediment transported by the flood wave significantly affect its propagation?
- Can the flood wave be approximated adequately by the one-dimensional flow equations?

It is very important that the analyst have an understanding of these sources of error so that the results of a dam-break flood study are interpreted properly.

These errors and limitations are presented to emphasize that dam-break/ inundation studies are not exact. The engineer must be very cautious when important decisions regarding hazard classification are based on the results of an analysis. For instance, if the results of a study indicate that water levels from a dam failure will flood a community by 1 foot (for example), a low hazard classification should not be concluded. Sensitivity of various parameters and different dam failure scenarios should be evaluated to determine that if given the right combination of circumstances and model variable values, the flood depths at the community could be significantly greater.

Sensitivity analyses on important and questionable parameters are highly suggested. This is done by varying parameter values within reasonable limits and plotting critical model results (such as breach discharge, downstream discharge, and depths) against the variable. In this way, the analyst can decide if a variable value that initially may be a rough estimate at best requires more care in its selection, and/or if field data are necessary. Also, parameters that are determined to be insensitive can be used with confidence, thus eliminating concern and possible future justification.

APPENDIX B

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