Dams Sector

Estimating Loss of Life for Dam Failure Scenarios

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Contents

Executive Summary

Homeland Security Presidential Directive 7 (HSPD-7), *Critical Infrastructure Identification, Prioritization, and Protection*, directs the U.S. Department of Homeland Security (DHS) to develop a National Infrastructure Protection Plan (NIPP) in order to identify, prioritize, and coordinate the protection of the Nation's critical infrastructure. The NIPP provides the unifying structure for the integration of a wide range of efforts for the enhanced protection and resilience of the Nation's critical infrastructure into a single national program.

As one of the 18 critical infrastructure sectors, the Dams Sector comprises a wide range of assets, including dam projects, navigation locks, levees, hurricane barriers, mine tailings impoundments, and other similar water retention and/or control facilities. The potential risks associated with the failure or disruption of Dams Sector assets could be considerable and potentially result in significant destruction, including loss of life, massive property damage, and severe long-term consequences. Therefore, consistent consequence estimation approaches must be incorporated as part of a sector-wide risk assessment framework to preliminarily identify those assets within the sector whose failure or disruption could potentially lead to the most severe impacts. Guidelines for consequence estimation are needed to directly facilitate the comparison of results and support the development and implementation of sector-wide risk management strategies. As indicated by the NIPP, consequences are divided into four main categories: public health and safety; economic (direct and indirect); psychological; and governance/mission impacts.

This report provides guidelines and recommendations for estimating loss of life resulting from dam failure or disruption. The objective of this report is to assist in the development of consequence assessments that are consistent and can be systematically compared across multiple owners and different jurisdictions. The general approaches presented in this report can be applied to both safety and security scenarios; therefore, this report provides the necessary consistent framework for an all-hazards perspective, as required by the NIPP. This report does not address the probability of the triggering event or the probability of unsatisfactory performance leading to the failure or disruption consequences. Of course, consistent estimation of these probabilities constitutes a critical step in the development and implementation of a sector-wide risk assessment framework.

This report is the result of a sector-wide collaborative effort involving public and private partners. The initial version of this document was developed by the U.S. Bureau of Reclamation (Reclamation) under Interagency Agreement HSHQDC-07-X-00612 with DHS. This version incorporates the technical review and contributions provided by multiple public and private Dams Sector stakeholders.

1. Introduction

HSPD-7, *Critical Infrastructure Identification, Prioritization, and Protection*, directs DHS to develop a NIPP in order to identify, prioritize, and coordinate the protection of the Nation's critical infrastructure. The NIPP provides the unifying structure for the integration and coordination of protection and resilience efforts for all 18 critical infrastructure sectors. The goal of the NIPP is to build a safer, more secure, and more resilient America by preventing, deterring, neutralizing, or mitigating the effects of deliberate efforts by terrorists to destroy, incapacitate, or exploit elements of the Nation's critical infrastructure; and to strengthen national preparedness, timely response, and rapid recovery of critical infrastructure in the event of an attack, natural disaster, or other emergency. The NIPP and corresponding Dams Sector-Specific Plan provide a strong foundation for identifying and implementing programs that help enhance protection and resilience across the Dams Sector from an all-hazards perspective.

The Dams Sector comprises a wide range of assets, including dam projects, navigation locks, levees, hurricane barriers, mine tailings impoundments, and other similar water retention and/or control facilities. As such, this sector is not conducive to a "one size fits all" approach to risk management. Therefore, development of a consistent framework that allows a direct comparison of risk variables (i.e., consequence, vulnerability, and threat) among different assets across the sector is needed to better identify sector critical assets, define the sector risk profile, facilitate the prioritization of sector-wide programs, and justify implementation of sector-wide protective programs and resilience strategies.

Potential risks associated with the failure or disruption of Dams Sector assets could be considerable and potentially result in significant destruction, including loss of life, massive property damage, and severe long-term consequences. Therefore, consistent consequence estimation approaches must be incorporated as part of a sector-wide risk assessment framework to preliminarily identify those assets within the sector whose failure or disruption could potentially lead to the most severe impacts. Guidelines for consequence estimation are thus needed to directly facilitate the comparison of results and support the development and implementation of sector-wide risk management strategies.

As indicated by the NIPP, consequences are divided into four main categories:

- Public Health and Safety: Effect on human life and physical wellbeing (e.g., fatalities, injuries/illness).
- Economic: Direct and indirect economic losses (e.g., cost to rebuild asset, cost to respond and recover, cost of downstream damages, long-term costs due to environmental damage).
- Psychological: Effect on public morale and confidence in national economic and political institutions. This encompasses those changes in perceptions emerging after a significant incident that affects the public's sense of safety and wellbeing and can manifest into aberrant behavior.
- Governance/Mission Impacts: Effect on government or industry's ability to maintain order, deliver minimum essential public services, ensure public health and safety, and carry out national security-related missions. Under the general rubric of governance/mission impacts are several federally-mandated missions that may be disrupted. Although many of these missions are directly fulfilled by government agencies, some are fulfilled or supported by the private sector. These include the responsibility to ensure national security, ensure public health, maintain order, enable the provision of essential public services, and ensure an orderly economy.

In general, indirect and cascading impacts are difficult to understand and may be even more difficult to quantify. Some indirect and cascading impacts may be accounted for in estimates of economic losses, while others may require further development efforts to be considered in a more comprehensive risk assessment. A full consequence assessment should take into consideration all four consequence categories; however, estimating potential indirect impacts may be beyond the capabilities commonly available (or the analytical sophistication needed) for a given risk assessment. At a minimum, consequence assessments should focus on the two most fundamental impacts; those corresponding to human consequences, and those associated with the most relevant direct economic consequences.

Consistent estimation of consequence variables constitutes a problem of paramount importance. Common definitions, scenarios, assumptions, and metrics are needed to ensure risk assessment efforts can effectively contribute to a shared understanding of the sector risk profile among sector partners. This report provides information on methodologies for estimating loss of life resulting from dam failure or disruption. The objective of this report is to assist in the development of consequence assessments that are consistent and can be systematically compared across multiple owners and different jurisdictions. The general approaches presented in this report can be applied to both safety and security scenarios. A companion DHS Dams Sector report with the same objective, "*Estimating Economic Consequences for Dam Failure Scenarios*," provides information on methodologies for consistently estimating economic consequence assessments.

1.1 Dam Failures in the United States

As a preview to the description of methods used to estimate loss of life resulting from dam failure, U.S. dam failure data is presented below. It is helpful for anyone attempting to estimate loss of life from dam failure to become familiar with this information.

A dam size categorization strategy was developed by the U.S. Army Corps of Engineers (USACE) for implementing Public Law 92-367 (National Dam Inspection Act) and provides a useful measure for describing the size of the dams that have failed. Size classification may be determined by either storage or height, whichever gives the larger size category. The size classification guideline is shown in table 1. In general, as a dam increases in size, the peak dam failure outflow, flood depths, and river distance experiencing dangerous flooding increase.

Table 1. Size Classification for Impoundments (Source: USACE)

	Impoundment	
Category	**Height (feet)**	**Storage (acre-feet)**
Small	25 to <40	50 to <1,000
Intermediate	40 to 100	1,000 to 50,000
Large	More than 100	More than 50,000

Data from all U.S. dam failures causing 25 or more fatalities and all dam failures from 1960 through 2009 causing one or more fatalities, is listed in table 2. Note that with the exception of Ka Loko Dam, which failed in 2006, and Mike Olson Dam, which failed in 2000; all of the failures shown in table 2 occurred before 1999, the year in which Reclamation issued "A Procedure for Estimating Loss of Life Caused by Dam Failure," (DSO-99-06). Dams too small to meet the definition of a 'dam' (less than 25 feet in height and less than 50 acre-feet; or less than 6 feet in height, regardless of storage; or less than 15 acre-feet, regardless of height; and if failure does not pose a significant threat to human life or property; as provided in the National Dam Safety Program Act (National Dam Safety Program Act, 2000)), are shown in table 2 as having a size category of 'non-jurisdictional size.' Between 1960 and 2009, there were approximately 317 lives lost as a result of dam failures in the U.S. (derived from table 2, plus 3 fatalities from Georgia dam failures in 1994). Most of the deaths occurred during the 1970s.

As shown in table 2, the majority of dam failure fatalities have been caused by dams having a size category of intermediate or large. The failure of four dams in the late 1800s and early 1900s: Mill River Dam, South Fork Dam, Walnut Grove Dam, and St. Francis Dam; all having a size category of intermediate or large, caused more than 2,800 fatalities. The failure of dams with a size category of small has caused comparatively few fatalities. The data in table 2 shows that loss of life resulting from small dams is most prevalent in close proximity to the dam. For the failure of several small dams, all of the loss of life occurred in the first 3 miles downstream. As an example, the Laurel Run Dam failure resulted in 40 fatalities all occurring in the first 3 miles downstream from the dam. The failure of intermediate sized Buffalo Creek Coal Waste Dam caused flooding along a 15-mile stretch from the communities of Saunders to Man in southwestern West Virginia. Communities were scattered throughout the 15 miles. Eighty-five percent of the fatalities from this dam failure occurred within the first 7 miles downstream from the dam and only 15 percent beyond. With large dams, loss of life has extended more than 15 miles from the failed dam. For example, approximately 20 percent of the fatalities from the Swift Dam failure occurred more than 15 miles downstream from the dam.

Loss of life resulting from dam failure, as measured by fatality rates or total number of fatalities, has generally been higher for populations near the dam than for those located further downstream. This is due to the following reasons:

- Peak dam failure discharges and stages are largest immediately downstream from the dam and attenuate with increasing distance from the dam.
- Stream flow capacity usually increases with increasing distance downstream from a dam. The same flow will cause more out of channel flow in upstream areas compared to downstream areas.
- There is usually a more pronounced 'wall-of-water' (rapid rise in flood levels) phenomenon in areas in close proximity to the dam.
- Steeper river gradients in close proximity to the dam result in higher flood velocities.
- Warnings are inadequate in close proximity to the dam because they are:
    - Often not issued in time for people to take action.
    - Unclear about the dam failure, extent of possible flooding, or the need to evacuate.

During the 9-year period from late 1985 to late 1994, there were more than 400 dam failures in the United States. Many of these dams were unregulated and either non-jurisdictional or small size. There was no loss of life associated with more than 98 percent of the dams that failed during this time period.

Appendix A provides a synopsis of notable U.S. dam failures. It provides a description of the dam, failure sequence, warning scenario, and the factors that influenced loss of life resulting from the failure.

Table 2. U.S. Dam Failure Data (listed in ascending order of volume released) (Source: Bureau of Reclamation)

Dam	State	Date of Failure	Failure Cause	Dam Height (Feet)	Volume Released (Ac-Ft)	Size Category	Warning Time (Hours) (1)	People at Risk (2)	Loss of Life	Percentage of Total Loss of Life in Listed Distance Downstream		
										First 3 miles	First 7 miles	First 15 miles
Lakeside Dam	SC	Sept 18, 1975	Overtopping	n/a	n/a	n/a	n/a	n/a	1	100		
Electric Light Pond Dam	NY	1960	n/a	26	n/a	Small	n/a	n/a	1	n/a	n/a	n/a
Bear Wallow Dam	NC	2:30 am, Feb 22, 1976	Rainfall; probable overtopping	36	40	Small	0	8	4	100		
Lake “O” Hills	AK	April 1972	n/a	15	48	NJS	n/a	n/a	1	n/a	n/a	n/a
Evans Dam	NC	9:30 pm, Sept 15, 1989	Overtopping	18	72	Small	n/a	n/a	Included on next line	n/a	n/a	n/a
Lockwood Dam	NC	10:00 pm, Sept 15, 1989	Overtopping resulting from Evans failure	14	32	NJS	n/a	n/a	2	100		
Eastover Mining Co. Dam	KY	4:00 am, Dec 18, 1981	n/a	n/a	77	Small	n/a	100	1	100		
Mohegan Park Dam	CT	9:30 pm, Mar 6, 1963	Piping during elevated level from rainfall	20	138	Small	0	500	6	100		
Bergeron Pond Dam	NH	6:50 pm, Mar 13, 1996	Dam not overtopped	36	193	Small	0	50	1	100		
Mike Olson Dam (Grand Forks County Comm. No. 1 Dam)	ND	June 12, 2000	Undermining of downstream end of spillway conduit	29	263	Small	0	n/a	2	100		
Lee Lake Dam	MA	1:25 pm, Mar 24, 1968	Piping during normal weather	25	300	Small	0	80	2	0	100	
Mill River Dam	MA	7:20 am, May 16, 1874	Embankment slide	43	307	Intermediate	0	888	138	41	100	
Buffalo Creek Coal Waste Dam	WV	8:00 am, Feb 26, 1972	Slumping of dam face during 2-year rainfall	46	404	Intermediate	0	4,000	125	28	85	100
Laurel Run Dam	PA	2:35 am, July 20, 1977	Overtopping	42	450	Intermediate	0	150	40	100		
Kelly Barnes Dam	GA	1:30 am, Nov 6, 1977	Embankment slope failure during 10-year flood	40	630	Intermediate	0	250	39	100		
Cripple Creek Dam No. 3 and domino failure of Dam No. 2	CO	Evening, June 17, 1965	Rainfall caused failure of No. 3, then overtopping failure of No. 2	n/a	640 (total from both dams)	Small	0	10	1	0	100	
Lawn Lake Dam	CO	5:30 am, July 15, 1982	Piping during normal weather	26	674	Small	0	25	1	0	100	
Cascade Lake Dam	CO	7:42 am, July 15, 1982	Overtopping resulting from Lawn Lake Dam failure	17	25	NJS	some	4,275	2	100		
Kendall Lake Dam	SC	7:00 pm, Oct 10, 1990	Overtopping	18	690	Small	0	n/a	4	100		
Baldwin Hills Dam	CA	3:38 pm, Dec 14, 1963	Piping during normal weather	66	700	Intermediate	1.3	16,500	5	100		
Canyon Lake Dam	SD	10:45 pm, June 9, 1972	Overtopping; 245 total deaths from area-wide flood	30	700 (10,100 flood total)	Small	n/a	100	165	n/a	n/a	100
Nix Lake Dam	TX	Mar 29, 1989	Overtopping	23	837	Small	0	6	1	100		
Austin Dam	PA	2:00 pm, Sept 30, 1911	Foundation weakness	43	850	Intermediate	0	900	78	100		

Table 2. U.S. Dam Failure Data (listed in ascending order of volume released) (Source: Bureau of Reclamation)

Dam	State	Date of Failure	Failure Cause	Dam Height (Feet)	Volume Released (Ac-Ft)	Size Category	Warning Time (Hours) ([1])	People at Risk ([2])	Loss of Life	Percentage of Total Loss of Life in Listed Distance Downstream		
										First 3 miles	First 7 miles	First 15 miles
Virden Creek Dam	IA	8:00 am, July 17, 1968	Overtopping	20	1,100	Intermediate	n/a	5,400	1	100		
Little Deer Creek Dam	UT	6:13 am, June 16, 1963	Piping during normal weather	86	1,150	Intermediate	0	50	1	0	100	
Ka Loko Dam	HI	5:30 am, Mar 14, 2006	Overtopping	44	1,400	Intermediate	0	7	7	100		
Timberlake Dam	VA	11:00 pm, June 22, 1995	Overtopping	33	1,449	Intermediate	0	A 2-lane and 4-lane road	2	100		
South Fork Dam	PA	3:10 pm, May 31, 1889	Overtopping	72	11,500	Intermediate	0 (for most areas)	20,000	2,209	n/a	n/a	~100
D.M.A.D. Dam	UT	1:00 pm, June 23, 1983	Backcutting from collapse of downstream diversion dam	29	16,000	Intermediate	1+	500	1	0	0	100
Swift Dam	MT	10:00 am, June 8, 1964	Overtopping	157	34,300	Large	Probably 0	n/a	19	0	0	79
St. Francis Dam	CA	12:00 am, Mar 12-13, 1928	Sliding on weak foliation with the schist comprising left abutment.	188	38,000	Large	0	n/a	420	Fatalities occurred throughout the 54-mile reach from the dam to the Pacific Ocean		
Lower Otay Dam	CA	1916		136	40,000	Large	?	?	30	n/a	n/a	n/a
Walnut Grove Dam	AZ	2:00 am, Feb 22, 1890	Overtopping	110	60,000	Large	0	n/a	70 to 100	Precise location not available. Many deaths at construction camp, 15 miles from dam.		
Teton Dam	ID	11:57 am June 5, 1976	Piping during initial reservoir filling	305	250,000	Large	1.2	25,000	11	9	9	73
										Six people drowned, all in first 8 or 9 miles. Five died from stress or gunshots, all beyond 7 miles.		

Includes all dam failures from 1960 to 2009 causing one or more fatalities plus dam failures prior to 1960 causing 25 or more fatalities. Listed in order of volume released. Note: "n/a" indicates that the data is not available or unknown.

Lower Two Medicine Dam does not appear in this table because the flood related deaths downstream from Lower Two Medicine Dam occurred several hours before the dam failed. The deaths were the result of flooding that preceded dam failure.

[1] "Warning Time" is defined as the interval between the first issuance of dam failure warnings and the initiation of dam failure. This definition of warning time may differ from that used elsewhere in this document. Most of the entries in this column are zero, indicating that dam failure warnings were not issued prior to dam failure. In some cases in which no warnings preceded dam failure, none of the people at risk were warned. In other cases, people living close to the dam were not warned, but warnings were issued for areas farther downstream as the dam failure was discovered or the flooding was observed. In some cases, warnings were issued for areas downstream from a dam due to natural flooding not associated with the dam failure; this was not considered a dam failure warning and was therefore assigned a zero in the table.

[2] "People at Risk" is defined as the number of people in the dam failure floodplain immediately prior to the issuance of any flood or dam failure warning.

2. Methods for Estimating Loss of Life Resulting from Dam Failure

Dam failures and associated flash floods can result in high fatality rates, especially when flooding overwhelms an unsuspecting group of people (fatality rates used in this document represent the number of fatalities divided by the number of people exposed to the flooding). Dam failures that produce slowly rising floods tend to result in lower fatality rates.

2.1 Key Concepts and Considerations in Estimating Loss of Life from Dam Failure

Loss of life resulting from a dam failure, whether due to a major natural event (e.g., flood, earthquake), design or construction defect, or successful adversarial attack, is influenced by the following three groups of factors:

Dam failure flood event:

- Cause and type of dam failure;
- Dam breach location;
- Breach geometry and rate of development;
- Reservoir pool at the initiation of failure;
- Time of day, day of week, and time of year;
- Weather and pre-failure flood conditions throughout the downstream inundation area;
- Extent, velocity, depth, rate of rise, and arrival times throughout the downstream inundation area; and
- Detection time of the dam failure event relative to failure initiation.

Number and location of people exposed to the dam failure flood event:

- Initial spatial distribution of people throughout the downstream inundation area;
- General health of people threatened by floodwater;
- Quantity, quality, accuracy, forcefulness and effectiveness of warnings;
- Availability of sensory cues (sight or sounds of floodwater) to people at risk;
- Propensity to evacuate for those at risk;
- Response of people to warnings;
- The opportunity for, and effectiveness of, evacuation;
- Impediments to evacuation (washed-out bridges, traffic jams, etc.); and
- The degree of shelter provided by the setting where people are located (structure, vehicle, on foot, etc.) at the time of arrival of the dam failure flood wave.

Loss of life amongst the threatened population:

- The number of people who remain in the inundation area at the time of arrival of the dam failure flood wave;
- Flood severity (physical characteristics of the flood event); and
- Degree of shelter provided by the setting where people are located at the time of arrival and after the flood wave has passed for those who survive it.

2.2 Model Limitations and Uncertainty of Results

Several methods are available for estimating loss of life resulting from dam failure. These methods are described later in this report. Either directly or indirectly, these methods incorporate some or most of the loss of life influencing factors described in the preceding section. Although it is the intent of each method to provide accurate and consistent estimates of loss of life, this goal is difficult to achieve. Inherent in any loss of life estimating methodology is uncertainty associated with natural variability, dependent on chance or luck, and arises because of natural and unpredictable variations in the performance of the dam under study. The other type of uncertainty is associated with the lack of, or error in, knowledge about the behavior of the system under study.

Examples of natural variability uncertainty:

- Depth of dam overtopping that causes failure;
- Does failure occur when impacted area is crowded with people due to special event?;
- Are warnings issued before dam failure?;
- Does the failure occur during the light of day or dark of night?;
- Is the warning process effective?; and
- Are roadways impassible due to flooding that precedes the arrival of dam failure flooding?

Examples of knowledge uncertainty:

- Breach shape, ultimate size, and rate of breach development;
- Speed at which the flood travels downstream;
- Effects of floating debris on flood depths;
- The factors that will motivate a particular individual to mobilize (begin evacuating);
- The amount of time from the issuance of a warning to when a particular individual mobilizes;
- The percentage of people who do not evacuate; and
- Flood depths and velocities that will destroy structures.

It is difficult to categorize some of these factors. For instance, 'breach shape, ultimate size, and rate of breach development' are listed in the knowledge uncertainty section. There are various methods available for estimating breach characteristics, and various peak dam failure outflow estimating equations each of which will provide a different estimate of the peak breach outflow. There may also be natural variability associated with the breaching process – overtopping and the formation of a breach at one end of a dam would likely result in a different peak breach outflow than if the breach forms at a different location along the dam crest.

Natural variability and knowledge uncertainty, combined with poorly calibrated or inappropriately applied loss of life estimating methods can result in a range of uncertainty in loss of life estimates produced by the various methods.

2.3 Data Requirements and Sources

Each method for estimating loss of life requires significant data inputs. The type and format of data required is model specific. In general, information is needed to describe the dam failure and resultant flooding, the number of people at risk and the type of shelter that provides protection, as well as warning issuance and evacuation. The following is a summary of data requirements and potential data sources that may be required for the method being used.

Dam Failure Modeling and Resultant Flood Inundation:

- Existing dam failure inundation studies and inundation maps;
- Peer reviewed technical journal articles providing breach characteristics or dam-break peak flow estimating equations;
- National Elevation Dataset;
- Various Geographic Information System (GIS) datasets;
- Dam failure modeling software and tools:
  - National Weather Service (NWS) Dam Break Flood Forecasting Model (DAMBRK);
  - NWS Flood Wave Dynamic Model;
  - Hydrologic Engineering Center-River Analysis System (HEC-RAS);
  - MIKE 11; and
  - MIKE 21.

Number and Location of People at Risk and shelter provided:

- Hazard-United States-Multi-Hazard (HAZUS-MH) and supporting databases;
- Various GIS datasets and software tools;
- Google® Earth aerial photography;
- Landscan USA;
- United States Department of Agriculture, Farm Service Agency's National Agriculture Imagery Program;
- Census data, including block data;
- Day/Night population grids developed by McPherson et.al at Los Alamos National Lab;
- Parcel data bases;
- Structure inventory;
- Road networks;
- Information provided by local officials or facility operators; and
- Site visit.

Warning Issuance and Evacuation:

- Based on analysis of historical dam failure data for similarly situated dams;
- Contents of Emergency Action Plan (EAP) and outcomes from previous EAP testing;
- Consultation with dam tender, local public safety officials, and managers of public or private facilities or buildings;
- Warning diffusion (spreading) curves or relationships; and
- Mobilization (people begin evacuating) curves or relationships.

Several methods are available for estimating loss of life that could result from a dam failure. This section provides information on five methods for estimating loss of life, two developed by Reclamation, two by USACE/Utah State University, and one by BC Hydro. The Reclamation methods are discussed in detail and overviews are provided for the USACE/Utah State University and BC Hydro methods.

2.4 Bureau of Reclamation DSO-99-06 Procedure

The failure of Reclamation's Teton Dam in 1976 during its initial filling and other dam failures in the 1970s brought about a renewed awareness of risks posed by dams. Following the failure of Lawn Lake Dam in 1982, Reclamation developed dam failure loss of life estimating procedures for internal agency use. These efforts were described in the December 1988 paper, "Assessing the Threat to Life From Dam Failure," published in the Water Resources Bulletin of the American Water Resources Association. Efforts to enhance Reclamation's dam failure loss of life estimating procedures continued through the 1990s, culminating with the publication of "A Procedure for Estimating Loss of Life Caused by Dam Failure," DSO-99-06, prepared by Reclamation's Dam Safety Office in September 1999.

The DSO-99-06 procedure is currently widely used for estimating loss of life resulting from dam failure. The procedure is based on an analysis of dam failures, flash floods, and floods located primarily in the U.S. Dam failures used to develop the model included every dam failure in the country that caused more than 50 fatalities, dam failures in the U.S. from 1960 through 1998 that resulted in 1 or more fatalities, and a cursory analysis of more than 400 dam failures that occurred in the U.S. from 1985 to 1994. The procedure should be well calibrated for dams in the size range represented by most of the entries in table 2, such as dams ranging up to 100 feet in height and storing as much as 10,000 to 50,000 acre-feet. However, there are many dams in the United States that greatly exceed these values, and the procedure may produce less accurate results for failure of these large structures.

The dam failure data provided insights into factors that influence when warnings are initiated for dam failure. These factors included the type of dam, cause of failure, drainage area at the dam, time of day when failure occurs, and if observers were at or near the dam when the failure occurred. The dam failure data also provided insight into how fatality rates (i.e., percentage of pre-evacuation population at risk who die) are a function of the amount of warning people in various areas have, the degree to which those issuing and receiving the warning fully comprehended the magnitude of the flood danger, and the flood severity (largely a measure of the ability of the flood to wash buildings off their foundation). Flood severity was assigned using flood depths and an average flood depth multiplied by velocity value.

The procedure contains general guidance for estimating when a dam failure warning would be initiated; although factors that would influence this for a particular dam, including failure mode scenario, should be given greater weight whenever available. This time will vary depending upon the type of dam, failure cause or mechanism, size of drainage area, time of day, and whether a dam tender or lay people are usually near the dam. Warning initiation time can vary from the guidance provided in the procedure based on dam surveillance and monitoring, specifics related to failure development and progression, dam specific emergency action plans, or other factors. Evacuation is not specifically evaluated but is incorporated into fatality rates that use the pre-evacuation population at risk (PAR). Fatality rates are based on flood severity, warning time, and warning quality. Typically, fatality rates are lower in downstream areas due to increased warning time, improved warning quality, and reduced flood severity; however, this trend would be influenced by how long before or after the time of dam failure warnings are issued.

2.4.1 Advantages of the DSO-99-06 Procedure

The DSO-99-06 procedure has been described as being useful, robust, easy to understand, and easy to apply while producing plausible results. Specific strengths include:

- Three variables that have played dominant roles in dam failure outcomes—flood severity, warning time, and warning urgency—are used in the model. Flood severity factors an order of magnitude more important than the warning time, and the warning time factors an order of magnitude more than the degree of understanding of the warning.

- Loss of life relationships (fatality rates) are based on judgment. The suggested ranges have credible orders of magnitude and progress in a logical sequence. Fatality rates are more than 1,000 times greater for areas that receive no warning and high severity flooding than for areas that receive hours of accurate and forceful warning and low severity (benign) flooding.

- The area downstream from the dam can be divided into as many different reaches (evaluation units at various distances downstream from the dam) as are necessary to accurately portray differences in warning time, warning quality, flood depths, flood velocities, wall-of-water or rate-of-rise characteristics, typical housing or shelter characteristics, etc.

- The procedure provides results that are generally consistent, which is important when risks at various dams are compared and prioritized across an inventory.

- The cost to conduct a study using the procedure is relatively low provided that inundation maps and PAR information are available.

- The procedure and key factors that lead to fatality rates are easy to understand and it is easy to explain what drives a given loss of life estimate.

- The procedure can be used with varying levels of information, from inundation boundaries overlaid on a quad sheet to digitally produced, one-and two-dimensional hydraulic modeling results, which can be overlaid on GIS maps along with census data and other key information.

- This dam failure data provides insights into factors that influence when warnings are initiated for dam failure. These factors include type of dam, failure cause, drainage area at the dam, time of day when failure occurs, and if observers are at or near the dam when the failure occurs.

- The warning concepts of 'none,' 'some,' and 'adequate' (associated in DSO-99-06 with <15 minutes, 15 to 60 minutes, and greater than 60 minutes) are very useful conceptual categories. Associating them with precise time ranges can be inappropriate in some instances, so it might be better to consider them in terms of verbal descriptors rather than actual number ranges.

2.4.2 Limitations of the DSO-99-06 Procedure

The DSO-99-06 procedure has several limitations. It has been stated that the model is an empirical, generalized model that does not use detailed or localized data in its calculations. Some of the specific weaknesses include:

- Many factors that change with the type of dam break or natural flooding event are not separately distinguished.
- Travel times, depths, and velocities that affect the fate of people, vehicles, and buildings are based on large-scale averages.
- PAR is considered for the entire area of inundation or for large sub-groupings of the PAR, which does not distinguish the many attributes that are important determinants of life loss. This may be acceptable if most of the people are exposed to the same flood depths and velocities and if they are in similar structures. However, if some people are in mobile homes and some are in a 10-story building, the population grouping may cause significant error.
- Warning time is considered as a single variable without taking into account the chain of events that must occur before a message can be disseminated, the rate of warning propagation, extent to which the warning reaches a community, efficacy of the warning message, and rate of mobilization.
- Evacuation is not considered as a separate process, and the benefits of relocation to safer shelters of those who do not evacuate are not explicitly included. Evacuation is not specifically evaluated, but is incorporated into fatality rates that use the pre-evacuation PAR.
- Since the procedure is easy to use and is outlined in a step by step approach, users may apply it inappropriately, without thinking about their specific situation and how it may differ from the case histories that form the basis for the fatality rates.
- Case histories that involve large population centers were not available for the development of fatality rates.
- For large population centers with limited warning time, evacuation will become a major issue and restrictions on individuals' ability to evacuate will greatly increase fatality rates.
- A number of the end branch categories (combinations of flood severity, warning time, and flood severity understanding) defined by the procedure have limited or no case histories on which to base the fatality rates. Although the database in DSO-99-06 may have been larger than previous studies, it is still small. Of the 15 end branch categories in DSO-99-06, five have zero case histories to back them up, and four have only one case supporting the suggested fatality rates.
- Communication options and vehicles are significantly different now than they were at the time of many of the case histories.
- Although a numerical method for distinguishing between low and medium severity is provided, there is no similar guidance on choosing between medium and high severity, other than the descriptions that are provided for the two cases.
- Dam failures used in developing the model included every dam failure in the U.S. that caused more than 50 fatalities, dam failures in the country from 1960 through 1998 that resulted in 1 or more fatalities, and a cursory analysis of more than 400 dam failures in the U.S. that occurred from 1985 to 1994. Many cases where a dam failure did not lead to loss of life have not been incorporated into the fatality rates. The dam heights, reservoir storage, and dam break discharge are all small for the large majority of the zero-life-loss scenarios, but since there are a large number of these failures every year, there should have been a significant number of times when DSO-99-06 would have predicted very conservative results.
- The fatality rates in DSO-99-06 are intended to apply across the entire PAR within a reach. There was an arbitrary designation when the various reaches in case histories were categorized and there is an arbitrary designation when a new reach is considered. Given that census data, topographic data, and inundation boundaries can easily be overlain, it is not that difficult to separate out the medium from low severity areas in any given PAR.
- A table is used to estimate the time (relative to dam failure) for a warning to be initiated. This table is based on very general considerations and does not consider the specific conditions at a given dam and the characteristics of the failure mode.

2.4.3 Application of the DSO-99-06 Procedure

As originally published, the DSO-99-06 procedure contained seven steps. In practice, it is easier to consider the procedure as having 11 steps, as shown below. Steps 1 through 5 have been re-sequenced from the original procedure. Steps 6 through 10 were embedded in just one original step titled "Apply empirically-based equations or method for estimating the number of fatalities." Step 11 involves evaluating uncertainty. The 11-step process for estimating loss of life from dam failure using DSO-99-06 is as follows:

Step 1 – Choose dam failure scenario;

Step 2 – Choose time categories;

Step 3 – Evaluate areas flooded for each dam failure scenario;

Step 4 – Estimate the number of people at risk for each failure scenario and time category;

Step 5 – Estimate when dam failure warnings would be initiated (based on discussions with personnel involved in developing dam-specific emergency action plans);

Step 6 – Estimate how often the warning time in downstream areas might fall in the *none*, *some*, and *adequate* categories;

Step 7 – Evaluate how well the flood severity is understood;

Step 8 – Estimate the proportion of PAR exposed to each of the three flood severity categories posed by the flood;

Step 9 – Select an appropriate fatality rate based on the flood characteristics in each reach;

Step 10 – Present life loss estimates; and

Step 11 – Evaluate how uncertainties in various parameters affect overall uncertainties in life loss estimates.

Each of the 11 steps is described below, along with suggestions or comments associated with its application.

Step 1 – Choose dam failure scenarios

Historical data indicates that most dam failures have occurred during the first few years of dam operation, or at any time during a dam's existence from rainfall and flood conditions that exceed reservoir storage and/or spillway/outlet discharge capacity. The loss of life from dam failure may be highly dependent on the failure mechanism.

The dam failure scenarios chosen for evaluation may include, but not be limited to:

- Failure caused by piping during normal weather conditions;
- Failure caused by an earthquake during normal weather conditions;
- Failure caused by a flood which results in high reservoir levels or dam overtopping; and
- Failure caused by intentional human actions under highest reasonable reservoir levels (worst reasonable conditions).

Step 2 – Choose time categories

The time of day, day of week, and month or season during which the dam failure takes place may strongly influence the resulting loss of life. Dam failures at night are less likely to be detected; therefore, dam failure flood warnings may not be issued to people in close proximity to the dam. When warnings are issued, nighttime presents difficulties in quickly and efficiently spreading warning. If people are not aware of the situation, evacuations may be delayed or not take place at all. The day of week during which a failure occurs should be random (unless caused by malicious acts). A failure on a weekend, depending on the season, may impact full campgrounds. At other times, these campgrounds may be empty. The month during which the failure occurs may have an influence on the number of people at risk. 'Piping' dam failures are more likely to occur when the reservoir is at or near historic levels and flood induced failures are more likely during months that typically produce extreme rainfall and/or floods for watersheds in the vicinity of the dam.

The time categories chosen for evaluation may include, but not be limited to:

- Time of day when the failure occurs:
  - Sunrise to sunset;
  - Sunset to 11 pm (dark, but most people awake); and
  - 11 pm to sunrise (dark, and most people asleep).
- Day of the week when failure occurs:
  - Monday through Friday;
  - Saturday and Sunday; and
  - Coincidence with special events.
- Time of year when the failure occurs:
  - Summer;
  - Fall;
  - Winter; and
  - Spring.

Step 3 – Evaluate areas flooded for each dam failure scenario

The downstream flooding caused by dam failure is influenced by reservoir and dam characteristics (high dams or dams storing vast quantities of water will produce larger peak outflows than dams not exhibiting these characteristics). Dam failures that form rapidly and/or have very large breach widths will produce larger peak outflows than those that do not. Downstream channel and valley geometry will influence flood depths, flood water velocity, and flood arrival times at downstream locations.

Dam failure inundation mapping is needed for each dam failure scenario identified in step 1. If existing dam failure inundation maps are available, their adequacy to represent the flooding for the scenarios identified in step 1 will need to be assessed. For instance, a dam failure inundation map based on the overtopping failure of a 120-foot high embankment dam may be an adequate representation of the flooding that would occur if the dam failed with the reservoir level three feet below the dam crest, whereas it probably would not adequately represent the flooding if the dam failed with the reservoir level 25 feet below the dam crest. In the latter example, some adjustment to the existing flood boundaries may be warranted or a new analysis would need to be conducted. New dam failure studies and/or inundation mapping may need to be developed if no failure mapping exists. Approximations in dam failure analysis and mapping methodology may sometimes be sufficient for the purpose of estimating consequences.

Step 4 – Estimate the number of people at risk for each failure scenario and time category

For each failure scenario identified in step 1, and for each time category identified in step 2, the number of people at risk needs to be estimated. PAR is defined as the number of people occupying the dam failure flood path prior to the issuance of any warning or evacuation.

Flooded areas downstream from the dam should be divided into several different locations or river reaches based on anticipated differences in:

- Occupancy type (e.g., tent in a campground versus one-story dwelling);
- Varying occupancy considering season, time of day, or other factors (e.g., manufacturing facilities, summer resort areas, campgrounds, picnic areas);
- Population density (e.g., scattered residences, small town, large city);
- Flood characteristics (i.e., flood depths, velocities, rate-of-rise); and
- Warning characteristics (i.e., timing, amount, and quality).

PAR can be obtained using the inundation data overlaid with census data within GIS, HAZUS data, aerial photographs from Google® Maps or elsewhere, parcel databases, structure inventories, onsite field trips, phone interviews, and other sources. Adjustments may need to be made to published information to account for the daily movement of people from home, school, workplace, etc. For each scenario considered, most-likely high and low estimates and a best estimate should be reported (see discussion on uncertainty in step 11 below).

Step 5 – Estimate when dam failure warnings would be initiated

The time at which dam failure warnings are initiated is defined as the time at which public safety officials, using assistance from the media (as applicable), begin informing the public of the imminent dam failure danger and prompting people at risk to take protective action.

Estimating when a dam failure warning is initiated is an important part in estimating loss of life from dam failure. Dams have failed with and without the downstream population being warned. If warnings do not precede dam failure, people immediately downstream of the dam will receive no official warning. If the stream length flooded is short (such as the 4-mile reach of Wailapa Stream flooded on March 14, 2006, when Ka Loko Dam failed on the Island of Kauai in Hawaii), it is possible that no one at risk is warned of the dam failure. By the time people downstream from the remote Ka Loko Dam recognized what was happening, the flood was in the process of passing through the impacted area and would soon enter the Pacific Ocean.

In other cases, warning provided by emergency management or public communications personnel may not precede dam failure and people near the dam receive no official warning, but observations of the flooding downstream from the dam begin a process that results in warnings being issued in those areas. This occurred on July 15, 1982, when Lawn Lake Dam failed in Rocky Mountain National Park (RMNP) in Colorado. Campers at the back-country RMNP-managed campsites along the 4.5 mile reach of the Roaring River received no formal or informal warning (although the flood itself, and the tossing of trees and boulders, provided visual and auditory indicators of danger). Near the mouth of the Roaring River, an individual observed the flooding caused by the dam failure and used an emergency telephone at a nearby trailhead to contact the RMNP dispatch center, which eventually led to the issuance of dam failure warnings for people located further downstream.

Early warning systems typically address the following components:

- Detection (people, processes, and equipment for collecting and verifying real-time event information and dam response);
- Decision making (processes to translate data into decisions regarding the need for alerts and warnings);
- Notification (communicating information about the emergency condition to local officials);
- Warning (processes, including using the media, for informing the public of the imminent danger and prompting people at risk to take protective action); and
- Evacuation (people at risk moving to safety).

A dam owner is usually responsible for the first three components and the downstream public safety officials (e.g., State, county, cities, tribal) are responsible for the last two. The first three system components should be described in detail within an emergency action plan. The last two components should be detailed within an all-hazards local emergency operations plan.

In predicting warning associated with future failures, it is necessary to surmise the chain of events leading to the decision to warn the downstream population to evacuate.

The following factors will influence whether events leading to a dam failure are detected:

- The mechanics of the failure mode and how fast it is likely to progress;
- Frequency and extent of dam monitoring activities:
    - Monitored continuously with an onsite dam tender or caretaker;
    - Visually observed daily;
    - Visually observed weekly;
    - Visually observed infrequently (monthly or longer); and
    - Monitored remotely only.
- Is the dam remotely operated?
- Do cell phones (or other communication methods) function at the dam site during inclement weather?
- How long will it take for dam officials to get to the dam to verify the emergency condition?
- Will access be cut off due to the same event that is threatening the dam?
- Are alternate routes and means of accessing the dam during inclement weather available?
- Weather forecasts:
    - Do National Weather Service (or private) weather forecasts accurately pinpoint areas where dams may be threatened by excessive rainfall?
    - Do dam officials send people to the site for monitoring?

- The awareness of the precursors or visible “triggers” or conditions that would indicate a potential failure mode is manifesting or in progress (e.g. trained observer vs. local official or public observer);
- The availability and robustness of automated monitoring equipment:
    - Does it exist?
    - Designed for all potential failure modes?
    - Are the gages properly distributed geographically and functionally?
    - Will gages function during dam failure?
    - Are gages properly calibrated?
    - Is equipment properly tested and maintained?
    - Will gages operate properly during hazardous events?
    - Will data transmission (e.g., satellite, phone, microwave, radio) take place?
    - Will the receiving station be powered on and working properly?
    - Will people be monitoring the received data?
    - Will dam officials be contacted in a timely manner?

The following factors will influence the decision making associated with the developing situation:

- Does an EAP exist for the dam?
    - Is emergency contact information up to date?
    - Has it been exercised? Recently?
    - Are the decision criteria clear and succinct for each corresponding response level?
    - Is there a person of authority available for reaching the final step calling for widespread warning and evacuation? Is there a written delegation of authority provided in the plan? Is there hesitation to issue evacuation warnings?
    - What is the quality of judgment and decisiveness of the authority orchestrating the response levels defined in the EAP?
    - Are areas that would be impacted by dam failure accurately described using inundation maps or some other tool?
- When an EAP does not exist for the dam:
    - Is a person of authority available to make decisions?
    - Does this person (or ad hoc group) know who to contact?
    - Does the person of authority or ad hoc group have the judgment and decisiveness to make proper decisions regarding warning and evacuation?
- Can the decision to warn the public be made without dam officials reaching the dam to provide visual confirmation of the dam deterioration/failure?

The following factors will influence notifications made to local officials:

- Is there a clear understanding of protocol/procedures to be used to notify downstream public safety officials?
- Are systems available for making the notifications?
- Will primary and alternative sources of communication work?
- Are personnel (high-ranking, authoritative, knowledgeable, believable, well-spoken) available for making the notifications?
- Is there enough time to make the notifications?
- Does the notification accurately describe the situation and what the local officials should do?
- Will the message prompt public safety officials to take action – do they understand who needs to be warned and evacuated?
- Do members of the public take the initiative to call 911 (or other officials) when they observe abnormalities at the dam or flooding that has occurred after the dam has failed?

The actual warning provided to the public is described in steps 6 and 7 below. These steps account for warning time at the various impacted areas and the accuracy and other characteristics of the warning message provided to people at risk. Evacuation, or the lack thereof, is accounted for in the fatality rates (using the pre-evacuation PAR) described in step 9.

Assumptions regarding when dam failure warnings for a particular dam would be initiated can be based on an analysis of the detection, decision making, and notification systems or procedures for the dam. Single value best estimates can be used or best-case and worst-case values can be used. Another method is to use table 3, which provides guidance for estimating when dam failure warnings would be initiated for earthfill dams. The times given under the heading "When Would Dam Failure Warning be Initiated" represents the time at which a concerted effort begins to get people out of harm's way. The guidance provided in table 3 was derived based on the following considerations and assumptions:

- Make use of (and calibrate to) available dam failure data. Note that most of the data is for dams having small drainage areas that failed from overtopping at night or for dams that failed during normal weather conditions during the day.
- Warnings will be issued earlier if there are many observers at the dam (i.e., if a dam tender lives on high ground and within site of the dam, dam is visible from the homes of many people, or the dam crest serves as a heavily used roadway). With many people casually observing the dam, there is a greater likelihood that someone will recognize an abnormal situation that might lead to failure and notify officials/authorities.
- Warnings will be issued earlier if the dam fails during daylight. Visual cues of impending failure can be observed with the benefit of light brought about by daytime when most people are awake, allowing for consultation, coordination, and minimal delay.
- When warnings do not precede dam failure, people who are in downstream areas observe or are exposed to the flooding may recognize the cause of the flooding, and provide notifications that ultimately result in dam failure warnings being initiated.
- For overtopping failures of embankment dams, small drainage areas may be capable of producing large floods that quickly overwhelm reservoirs that have small flood storage space. Weather conditions may prevent people from reaching the dam site to monitor the situation. Warnings may not precede dam failure for dams having little flood storage space located on small drainage basins. It was assumed that as the drainage area exceeds 100 square miles, more time will be involved in filling and overtopping the reservoir, thus increasing the chance that timely warnings are issued.

Although empirical data is limited, it appears that timely warning is not likely for the sudden and complete failure of a concrete dam. No warnings were initiated prior to the 1911 failure of Austin Dam in Pennsylvania or the 1928 failure of St. Francis Dam in California.

The original procedure does not provide any guidance on dam failures caused by intentional human actions affecting embankment or concrete dams. The closest example for this type of event shown in table 3 would be a dam failure caused by a seismic event with an immediate dam failure. Each is likely to occur suddenly without any prior awareness or warning.

Table 3. Guidance for Estimating When Dam Failure Warnings Would be Initiated (Earthfill Dam)
(Source: Bureau of Reclamation)

Dam Type	Cause of Failure	Special Considerations	Time of Failure	When Would Dam Failure Warning be Initiated?	
				Many Observers at Dam	No Observers at Dam
Earthfill	Overtopping	Drainage area at dam less than 100 mi² (260 km²)	Day	0.25 hrs before dam failure	0.25 hrs after floodwater reaches populated area
			Night	0.25 hrs after dam failure	1.0 hrs after floodwater reaches populated area
		Drainage area at dam more than 100 mi² (260 km²)	Day	2 hrs before dam failure	1 hr before dam failure
			Night	1 to 2 hrs before dam failure	0 to 1 hr before dam failure
	Piping (full reservoir, normal weather)		Day	1 hr before dam failure	0.25 hrs after floodwater reaches populated area
			Night	0.5 hrs after dam failure	1.0 hr after floodwater reaches populated area
	Seismic	Immediate Failure	Day	0.25 hrs after dam failure	0.25 hrs after floodwater reaches populated area
			Night	0.50 hrs after dam failure	1.0 hr after floodwater reaches populated area
		Delayed Failure	Day	2 hrs before dam failure	0.5 hrs before floodwater reaches populated area
			Night	2 hrs before dam failure	0.5 hrs before floodwater reaches populated area

"Many Observers at Dam" means that a dam tender lives on high ground and within sight of the dam, the dam is visible from the homes of many people, or the dam crest serves as a heavily used roadway. These dams are typically in urban areas.

"No Observers at Dam" means that there is no dam tender at the dam, the dam is out of sight of nearly all homes, and there is no roadway on the dam crest. These dams are usually in remote areas.

Step 6 – Estimate how often the warning time in downstream areas might fall in the none, some, and adequate categories

The warning time for any particular location downstream from a dam would depend not only on when a dam failure warning is initiated, but also on how long it takes floodwater to travel from the dam to the location of interest. For instance, if a dam is located in an urban area, with many observers nearby, the assumption might be made that a warning would be initiated one hour before dam failure. If it takes two hours for the leading edge of the flood wave to travel from the dam to a particular location downstream from the dam, warning is assumed to be initiated three hours before the flooding arrives at this location and starts to impact the most at-risk portion of the area.

Step 7 – Evaluate how well the flood severity is understood

Flood or dam failure warnings are less likely to bring about the desired response of evacuation if the message is less accurate or tentative (e.g., “the dam may fail”), timidly worded (e.g., “officials are recommending that people near the river evacuate”), or casually issued. These types of warnings are more likely when dam failure is possible, but has not yet occurred.

Flood or dam failure warnings are more likely to bring about the desired response of evacuation if the message is accurate, strong, forcefully worded, and forcefully issued. Warnings of this type are more likely when dam failure has occurred or is certain to occur in the immediate future.

As stated in step 6, there may be some dam failure scenarios (identified in step 1), time categories (identified in step 2), and locations (identified in step 4) that receive no formal warning because the warning is initiated after dam failure. Even without the issuance of formal warnings, environmental cues such as the noise made by the flood or the sight of approaching floodwater may prompt people to evacuate.

DSO-99-06 uses the term “Flood Severity Understanding” to describe the degree to which the events that are about to unfold are understood. This level or degree of understanding affects notifications made from dam officials to emergency management agencies and media, warnings issued to people at risk, and responses by people receiving the warning.

The flood severity understanding categories are as follows:

- Vague Understanding of Flood Severity: Warning issuers have not yet seen the dam fail or do not comprehend the true magnitude of the flood that is about to ensue. Dam failure is a possibility, but not certain to occur. Less forceful warnings are anticipated.
- Precise Understanding of Flood Severity: Warning issuers have an excellent understanding of the flooding due to observations of the flooding. Dam failure is in progress, or has occurred. Strong and forceful warnings are anticipated with this type of warning.

A sliding scale exists between the two categories shown above. As dam failure becomes more likely (perhaps associated with the highest response level in an emergency action plan), notifications from dam owner representatives to local officials and the media would convey increased likelihood of failure and greater danger. As an event progresses, the understanding of flood severity may go from vague to precise.

Flood severity understanding may also change based on a function of the distance or time from the dam failure, or the source and origin of flooding. Warnings issued before a dam has failed, or during a flash flood in which the true flood magnitude is often not known until the event concludes, are likely to be advisory rather than mandatory and would be weak, timid, and possibly inaccurate. Recipients of this type of warning are therefore not likely to get an accurate depiction of the magnitude of the event, and may not evacuate at all or as quickly as they should. Further downstream, the warning will likely be precise and accurate. This is a result of people seeing the flooding in upstream areas, the understanding of the damage potential of the flooding, and warnings being subsequently adjusted to reflect the actual danger. Similarly, the people receiving the warning should obtain a better understanding of the danger to which they are exposed.

For each dam failure scenario (identified in step 1), time category (identified in step 2), and location (identified in step 4) expected to receive warning, one of the two flood severity understanding categories should be chosen.

Step 8 – Estimate the proportion of the PAR exposed to each of the three flood severity categories posed by the flood

DSO-99-06 contains a detailed history and discussion of flood lethality and flood severity, and provides guidance for selecting the flood severity category based on written descriptors of building damage, flood depth, and the parameter DV (i.e., an indicator of the averaged depth multiplied by the velocity for a particular site).

The following is a summary of guidance from DSO-99-06 on selecting the flood severity category:

- Low flood severity occurs when no buildings are washed off their foundation. Most structures are exposed to flood depths of less than 10 feet (3 meters). The parameter DV, described below, is less than 50 ft2/s (4.6 m2/s).
- Medium flood severity occurs when homes are destroyed but trees or mangled homes remain for people to seek refuge in or on. Most structures are exposed to flood depths of greater than 10 feet (3 meters). The parameter DV is greater than 50 ft2/s (4.6 m2/s).
- High flood severity occurs when the flood sweeps the area clean and nothing remains. The event will result in very deep floodwater reaching its ultimate height in just a few minutes. This type of flooding occurred downstream from St. Francis Dam and Vajont Dam.
- Parameter DV has units of depth multiplied by velocity. Although the parameter DV is not representative of the depth and velocity at any particular structure, it is representative of the general level of destructiveness that would be caused by the flooding. DV increases with increases in peak discharge from dam failure or decreases in the flood width. The formula for computing DV is as follows:
    - DV= (Qdf – Q2.33)/ Wdf; where:
        - Qdf is the discharge at a particular site caused by dam failure.
        - Q2.33 is the mean annual discharge at the same site. This discharge is an indicator of the safe channel capacity.
        - Wdf is the maximum width of flooding caused by dam failure at the same site.

Another factor, rate of rise, not contained in DSO-99-06, could be considered when selecting the appropriate flood severity category. The rate at which flood levels increase is another indicator of flood severity. Research involving two-dimensional modeling of flooding case histories combined with assessments of life loss situations from the same case histories may eventually result in more specific guidance. In the meantime, the following guidance is provided:

- The estimation process should gather and describe evidence that would put a given reach into one of three categories:
    - Low flood severity: Flood levels rise very slowly, generally less than one inch (2.5 cm) every 5 minutes.
    - Medium flood severity: Flood levels rise several feet every 5 minutes and could ultimately reach great depth and velocity, but the rate of rise would generally be slow enough that people would have a chance to escape should they choose to make the correct responses.

    - High flood severity: Flood levels rise more than 10 feet (3 m) every 5 minutes – too rapidly to allow people a reasonable chance to escape.

- For a given population center downstream of the dam, populations experiencing low severity, medium severity, and high severity should be distinguished and the appropriate fatality rates applied to each subset.
- The flood severity categories apply in general to people living in and seeking shelter in single family homes as typically found and constructed in the U.S. In selecting the appropriate flood severity category, consideration should be given to the type of shelter that most people would call "home" at each location identified in step 4. Will the home or shelter provide a safe refuge from the flood? People in structures such as tents, recreation vehicles, tent trailers, mobile homes, etc. would be at much greater risk than someone in a high rise building. As an example, a flash flood on August 7, 1996, in the Arás drainage basin in the Central Pyrenees in Spain caused a sudden great torrent of water and sediment more than 1 meter (3.3 feet) deep to rush into a camping area. Most people did not have time to take refuge in any of the existing buildings. The flood, which lasted 10 minutes, violently swept away people, cars, and camping vehicles. Of the 150 people present in the camping area when the flood occurred, there were 87 fatalities producing a fatality rate of nearly 60 percent. Medium or High flood severity best characterizes the flooding for this site with its shelter type. Had this same flood, or even one much greater, occurred with people located in a multi-story office or apartment building, then low severity flooding might have best characterized the flooding in that particular incident.

Step 9 – Select an appropriate fatality rate based on the flood characteristics in each reach

Fatality rates were developed based on an analysis of approximately 40 flood events, many of which were caused by dam failure. Appendix C describes how the fatality rates were derived. Recommended fatality rates for estimating loss of life from dam failure are shown in table 4. Except where noted for high severity flooding, the fatality rates in table 4 should be used with the pre-evacuation PAR identified in step 4.

Most of the loss of life associated with dam failure has resulted from the direct impact of the floodwater. Deaths indirectly linked to dam failure, such as those caused by injury or illness associated with evacuation, clean up, repair, or loss of electricity have been inconsistently recorded in past dam failures.

Estimates of dam failure loss of life should include both direct impact and indirect impact deaths. For low severity flooding accompanied by excellent warning, table 4 suggests using a fatality rate of 0.0002, that represents 1 death for every 5,000 people at risk. This fatality rate should reflect both direct and indirect deaths.

As stated in DSO-99-06, the fatality rate in areas with medium severity flooding should drop below that recommended in table 4 as the warning time increases well beyond one hour. No specific guidance is provided on how to do this. Repeated dam failure warnings, confirmed by visual images on television and modern electronic media showing massive destruction in upstream areas, should provide convincing evidence to people potentially at risk that a truly dangerous situation exists and there is a need to evacuate. This should result in higher evacuation rates in downstream areas, resulting in a lower fatality rate. However, with more severe flooding, there will still be direct impact deaths from people who fail to evacuate and more indirect deaths (compared to low severity flooding) due to the more extensive flooding and subsequently rebuilding efforts. Even with several hours of effective warning, the fatality rate should remain well above 0.0002.

Table 4. Recommended Fatality Rates for Estimating Loss of Life Resulting from Dam Failure

(Source: Bureau of Reclamation, DSO-99-06)

Flood Severity	Warning Time (minutes)	Flood Severity Understanding	Fatality Rate (Fraction of people at risk projected to die) Suggested	Suggested Range
HIGH	No warning	Not applicable	0.75	0.30 – 1.00
	15 to 60	Vague	Use the values shown above and apply to the number of people who remain in the dam failure floodplain after warnings are issued. No guidance is provided on how many people will remain in the floodplain.	
		Precise		
	More than 60	Vague		
		Precise		
MEDIUM	No warning	Not applicable	0.15	0.03 – 0.35
	15 to 60	Vague	0.04	0.01 – 0.08
		Precise	0.02	0.005 – 0.04
	More than 60	Vague	0.03	0.005 – 0.06
		Precise	0.01	0.002 – 0.02
LOW	No warning	Not applicable	0.01	0.0 – 0.02
	15 to 60	Vague	0.007	0.0 – 0.015
		Precise	0.002	0.0 – 0.004
	More than 60	Vague	0.0003	0.0 – 0.0006
		Precise	0.0002	0.0 – 0.0004

When dam failure results in significant destruction in areas more than 15 miles downstream from the dam, loss of life is possible from both direct impacts of floodwater and indirect causes. After the flood recedes, there may be fatalities associated with the clean-up and repair of damaged facilities. Natural deaths (heart attacks, etc.) may also occur and could be related to the added stress caused by the losses that people experience during a crisis. Based on information derived from the second most destructive U.S. hurricane (Hurricane Andrew) that hit south Florida in 1992, indirect loss of life in severely flood-damaged downstream areas can be estimated using a fatality rate ranging from 0.001 to 0.0001.

Highway congestion may present a special problem and fatality rates shown in table 4 will have to be used with caution or with modification. None of the dam failures in the U.S. after 1960 have impacted a community with a road network insufficient to meet the evacuation traffic demand. Some people may have died from the 1963 Baldwin Hills Dam failure when they drove toward the danger, rather than away from it. For the Baldwin Hills dam failure, even though it occurred in an urban area, and all other dam failures contained within the limited body of case history data used to develop DSO-99-06, no one is known to have died due to being held up in a traffic queue. Roads blocked by flooding impacted the ability of people to escape in Johnstown from the 1889 South Fork Dam failure, 1972 Canyon Lake Dam failure in Rapid City, and the 1976 Big Thompson Canyon flash flood. Flooding that occurs prior to dam failure may make it difficult for people to evacuate as some part of their escape route may be impassible. In a similar way, an earthquake that causes dam failure may cause highway bridges to collapse, debris to fall on roadways, and incapacitation of traffic signals resulting in the reduction of roadway capacity.

None of the dam failures used to develop fatality rates in DSO-99-06 have occurred in situations with very large populations. The failure of some dams, storing in the millions of acre-feet, could flood areas with populations in the hundreds of thousands. Roadway networks may not provide the capacity for all to evacuate from the impacted area prior to the arrival of the flood from the dam failure. It is interesting to note that Teton Dam, the largest dam (both in height and reservoir volume released) that ever failed in the U.S., caused near complete destruction of homes in a 24 square mile sparsely populated area with an average of only six residences per square mile in and near the community of Wilford, Idaho. In east Denver, a typical suburban type area, there are approximately 1,500 residences per square mile. Had the area downstream from Teton Dam been as densely populated as a typical urban area, the roadway network may not have been sufficient to allow all to escape before flooding arrived.

When evaluating a dam, the failure of which will impact a densely populated area, the study should judge whether pre-failure flooding will close exit routes, earthquakes will impact the road network, or vehicles being driven out of harm's way will be caught in traffic (and perhaps still be in harm's way) due to limited roadway capacity.

When evaluating larger towns or cities with limited warning time, a more detailed evaluation of the population center should be made, including an examination of evacuation routes, to determine how likely it would be that everyone would be able to escape. An estimate of the number of people that remain when the flood wave arrives should be made, and a range of fatality rates should be applied to those that remain, with flood severity being the key consideration. The following paragraphs (not in the original DSO-99-06) provide some guidance to judge whether the evacuation routes are sufficient.

Post-disaster hurricane surveys indicate a wide variation in the number of evacuating vehicles per residential household. The number of evacuating vehicles per residential household ranged from 1.1 to 2.15 for five counties evacuated as a result of Hurricane Lili; this range bounded the range reported from other researchers for other hurricanes (Lindell and Prater). To evaluate whether exit lane supply will meet demand, 1.1 to 2.15 evacuating vehicles per residential household can be assumed for dam failures (there is little or no data available on the number of evacuating vehicles per household for evacuations necessitated by dam failure). Some people might leave immediately after notification, while others might depart some time after notification.

The network of roads leading out of a particular area flooded from dam failure can be identified after superimposing the dam failure flood boundary on a road/street map. The supply or capacity (vehicles per lane per hour) of roads and highways leading out of the dam failure flood area needs to be identified and compared to the demand identified above. The capacity of a road or highway lane will be a function of road design, number of traffic signals, green time at signalized intersections, number of stop signs (2-way or 4-way), turn lanes, and other factors.

The fate of people attempting to evacuate but becoming trapped within the dam failure flooded area due to limited exit lane capacity is highly uncertain. Vehicle drivers and/or their passengers may obtain some guidance on what to do by listening to commercial radio broadcasts or by using their cell phone to communicate with others who may know the procedures for effective evacuating. Some people may abandon their vehicle and walk or run to safety (depending upon distance), while others may abandon their vehicle and gain entry into a more substantial structure providing greater safety.

Although it is important to judge whether the evacuation demand exceeds the roadway capacity in the time available for evacuation, no specific guidance is provided in this document on how to estimate loss of life in such situations. Limits on evacuation based on roadway capacity would identify the maximum evacuation that could occur and would provide a minimum number of people that would not be evacuated.

Step 10 – Determine life loss estimates

A best estimate for the potential loss of life and a range for the estimate can be computed for each failure scenario (identified in step 1), time category (identified in step 2), and location (identified in step 4). For each location (identified in step 4), the potential life loss is based on assumptions regarding when dam failure warnings are issued (identified in step 5), the warning time and quality (identified in steps 6 and 7, respectively), and the flood danger and associated fatality rate (identified in steps 8 and 9, respectively).

Step 11 – Evaluate how uncertainties in various parameters affect overall uncertainties in life loss estimates

Uncertainty should be addressed in loss of life estimates. Estimates should be developed for various scenarios to capture the variability that is possible at a given site. Consideration should be given to: varying the time of day and day of the week if there are potential differences in PAR; varying the reservoir elevation at the time of breach; varying the breach characteristics; varying the breach development time; varying the time when warnings are issued; and varying the fatality rates. Loss of life estimates should include a range that reflects the uncertainty.

Since the key factors that affect loss of life are intrinsically uncertain, decision makers should be provided information regarding the nature and degree of the uncertainty in order to help decide whether to gather more information or conduct additional analyses. There are many kinds of uncertainty; typically, however, they are placed into three main categories: natural variability, knowledge uncertainty, and decision model uncertainty.

Natural variability uncertainty is associated with chance and can arise as a result of natural variations in the materials and processes affecting performance of the dam under study. In principle, this uncertainty is irreducible. Examples include the time of year when an earthquake might strike, number of hours of cloudy seepage that precedes breach formation, depth of overtopping during a major flood that causes failure, number of people who ignore a warning (if issued) and remain at their residence; or the time of day, week, or year during which the breaching process begins. Natural variability uncertainty can be partially addressed by estimating loss of life for various dam failure scenarios, time of day, day of week, warning assumptions, etc. Uncertainty due to natural variability can also be addressed by using a range of estimates rather than point-value estimates for system behavior. For example, rather than assuming that the fatality rate is a point value, a range may be used. Similarly, rather than assuming that single story houses are destroyed by 10 feet of water, a range of 6 to 14 feet could be used.

Knowledge uncertainty is attributed to lack of data or little understanding regarding the behavior of the system under study, and can be further subdivided into two main categories: model uncertainty and parameter uncertainty. Examples include the rate at which the leading edge of the flood moves downstream, the number of people who live or work within dam break inundation boundaries, effects of floating debris on flood depths, fatality rates associated with various depths and velocities of flowing water, and depths and velocities of flooding that cause various types of structures to be washed away. Knowledge uncertainty can be reduced by acquiring more information, either by gathering more data or by working to validate predictive models. Varying dam-break scenarios and assumptions for the various parameters in the aforementioned steps to produce a range of potential life loss estimates can inform the decision. Recording the sensitivity of the life loss estimates to changes in various parameters can inform a decision to gather more data or to perform additional analyses; and therefore, would make sense to spend additional money only on those aspects which most affect the outcome.

An extremely important variety of knowledge uncertainty is associated with the inability to precisely determine fatality rates. There was uncertainty associated with categorizing some the flood events used in deriving the fatality rates presented in DSO-99-06. Similarly, some of the factors that contribute to loss of life are not captured in the categories shown in table 4. This type of uncertainty can introduce significant, but unknown, errors into the loss-of-life estimates. Some possible ways of handling this uncertainty include:

- Use the range of fatality rates shown in table 4.
- When the flooding at a particular area falls between two categories (e.g., when it is unclear if the flood severity would be medium or low), the loss-of-life estimates can be developed using the fatality rate and range of rates from both categories.
- Events cataloged in DSO-99-06 can be evaluated or researched to judge whether there are any that closely match the situation for the dam and downstream impacted locations under study.

The third category of uncertainty is associated with the inability to clarify decision objectives. Should the best estimate for potential life loss be used to prioritize work on specific dams in a portfolio? Should the maximum estimate for a range be used to declare an individual dam "safe?" Should risk-reduction strategies be based solely on reducing potential life loss rather than performing structural modifications to a dam? Should present PAR or future PAR influence a decision? These are only a few of the questions affected by decision model uncertainty. The influence of decision model uncertainty is usually ignored when considering potential life loss estimation.

2.5. Flood Comparison Method

In 2007, URS Corporation, Inc., under contract with the Federal Emergency Management Agency (FEMA), developed a risk prioritization tool to assist State dam safety offices in determining relative risk values corresponding to dams in their inventories. In March 2008, FEMA issued the corresponding user manual for this risk prioritization tool. Appendix B of the FEMA document ("Risk-Based Dam Safety Prioritization – A Method for Easily Estimating the Loss of Life from Dam Failure") contains a proposed loss of life estimation procedure developed by Reclamation in support of this risk prioritization tool. This alternative loss of life estimation procedure is referred to as the "Flood Comparison Method."

The Flood Comparison Method was developed to provide an easy-to-use tool for a dam safety manager or regulator to compare the likely loss of life for a portfolio of dams. Although not explicitly stated in the method, it should not be used with dams storing more than 5,000 acre-feet of water. Table 2 (U.S. Dam Failure Data) indicates that only dam failures that have released more than 34,000 acre-feet are known to have caused loss of life beyond 15 miles. It may therefore be reasonable to assume that loss of life from dam failure will not occur in large numbers more than 15 miles downstream from failed dams that release less than 5,000 acre-feet of water. The method is most applicable to nighttime failures for which no warnings are issued. It assumes that people do not evacuate before dam failure floodwaters arrive. Effective warning and evacuation would result in loss of life estimates less than those derived using this method.

The method is based on empirical data showing that fatality rates are higher near the dam than farther downstream, and higher when the peak dam failure discharge is unusually large compared to normal flows. The method projects fatality rates for three different reaches: from the dam to 3 miles downstream, from mile 3 to mile 7, and from mile 7 to mile 15. Fatality rates are based on the ratio of peak discharge from dam failure to the 10-year flood discharge. The rates are applied to the pre-evacuation PAR to reflect a worst-case event where warnings are not issued. This method does not use the flood severity descriptors of low, medium, and high that are used in the DSO-99-06 procedure.

For a given ratio of peak discharge resulting from dam failure divided by the 10 year flood discharge, fatality rates decrease with increasing distance from a dam because the model incorporates an assumption that flood levels will rise more gradually farther downstream, allowing more successful escape. The 10-year flood is not meant to be a measure of risk perception, but rather the 10-year flood magnitude is an indicator of the stream size and associated capacity. It was selected to provide some indication of the flow that can be conveyed without significant overbank flooding. For example, a sudden increase in flow of 10,000 ft3/s may cause minimal increases in flood levels on a large river such as the Missouri, where the 10-year flood may be 400,000 ft3/s. This same sudden increase of 10,000 ft3/s would likely cause massive and unprecedented flooding on a small stream where the 10-year flood is 400 ft3/s.

Fatality rates are as high as 0.75 for areas in the first few miles downstream from the dam when the ratio of dam failure flood discharge to 10-year flood is more than 100. The fatality rate drops to 0.001 for the same area when the flood ratio is less than one, meaning that the dam failure discharge is less than the 10-year flood discharge.

As it is meant to be a simple model, loss of life obtained using this method represents what might happen if the dam failed between 11 pm and 5 am, with no warning issued to people at risk and with no evacuation. This could be particularly relevant for security scenarios, where the failure is considered to occur under the worst reasonable conditions as the result of intentional human actions.

The results obtained using this method should be considered as an index value rather than an actual estimate of the loss of life anticipated from dam failure. As the index value increases, loss of life would increase.

2.5.1 Advantages and Strengths of the Flood Comparison Method

The Flood Comparison Method has several strengths, including the following:

- Uses fatality rates that vary from as low as zero to as much as 0.75, rates that have been observed from actual dam failures. It is important to distinguish that the fatality rates apply to the entire PAR within a reach, whereas other approaches have the capability of subdividing the PAR into much smaller evaluation units.
- Fatality rates are very high when the dam failure discharge is significantly larger than typical and normal flows. Previous dam failures having very high fatality rates had very large peak discharges compared to normal flood discharges.
- With increasing distance from a dam, the ratio of peak dam failure discharge to 10-year flood discharge decreases. As the dam failure flooding progresses downstream, the rate at which flood levels rise at a particular location typically lessens. Both of these phenomena result in a lower fatality rate, as reflected in the fatality rate table contained in the method.

2.5.2 Limitations of the Flood Comparison Method

The Flood Comparison Method contains some limitations, including the following:

- Requires further calibration to determine the range of fatality rates to use for various ratios of dam failure flood discharge to 10-year flood discharge.
- Needs additional work to allow for the effects of warning and evacuation. As currently configured, it should only be used for dam failures with no warning issued to people at risk and not for situations when it is anticipated that evacuation will take place in response to dam failure warnings. Such warnings would leave fewer people in harm's way.
- Should not be used for dams that function as flood control structures and typically store very little water. The dam failures used in developing the method did not include any dams of this type.
- Does not account for site specific information. The distance based fatality rates are arbitrary. Dams may fail with the reservoir elevation below the crest, so failure under normal operations may be ignored or misrepresented using this method.
- Should not be used for dams storing more than 5,000 acre-feet.

2.5.3 Application of the Flood Comparison Method

The steps involved in using this method are as follows:

Step 1 – Choose a dam failure scenario to evaluate;

Step 2 – Evaluate the area flooded by the dam failure;

Step 3 – Estimate the number of people at risk from the dam failure;

Step 4 – Evaluate the danger posed by the flood: Compare the peak discharge from the dam failure to a more common flood;

Step 5 – Select a fatality rate based on the flood ratio and the distance from the dam; and

Step 6 – Present life-loss estimates.

These steps are further described below.

Step 1 – Choose a dam failure scenario to evaluate

Assume that the dam fails with the reservoir water surface at the crest of the dam or at the top of the active storage (worst reasonable scenario). Although dams may fail from piping or other causes with the water below the crest, this simplifying assumption is reasonable to use for many dams.

Step 2 – Evaluate the area flooded by the dam failure

If dam failure inundation maps are not available, it will be necessary to develop some approximation of the flooding that would result from the dam failure. This necessitates the estimation of the peak dam failure outflow at the dam and in downstream areas, and subsequent determination of the extent of flooding that would result from these discharges. Dam failure modeling can be used for this; or, more simplified procedures, as described below, can be used.

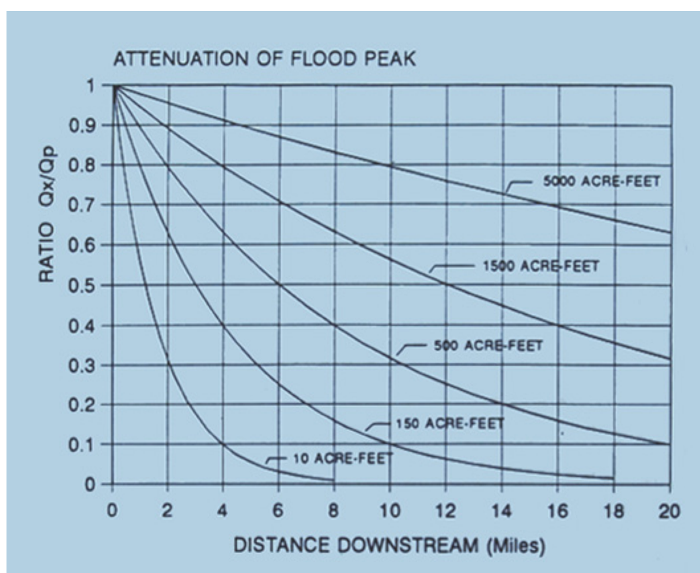

Figure 1. Generalized Flood Attenuation Curves
(Source: Dam Safety Guidelines)

The peak dam failure discharge for embankment dams can be estimated using an equation contained in the paper, "Peak Outflow from Breached Embankment Dam," by David C. Froelich. The equation, in English units, is Qp = 40.1V 0.295H 1.24, where Qp is the peak outflow in cubic feet per second from the breached embankment dam; V is the reservoir storage volume in acre-feet at the time of failure; and H is the height of the embankment in feet from the bottom of the final breach to the top of the embankment.

The peak discharge from a dam failure decreases, sometimes rapidly, as the flood travels downstream from the dam. Plots of peak discharge (as a percentage of the discharge immediately downstream from the dam) versus distance downstream from the dam are available for estimating flows in downstream areas. One such plot, reproduced in figure 1, appears in "Dam Safety Guidelines, Technical Note 1: Dam Break Inundation Analysis and Downstream Hazard Classification," issued by the State of Washington in July 1992. Flood depths at various locations along the river can subsequently be determined by applying Manning's equation, using cross-section geometry obtained from the best available topographic maps. Flood boundaries can then be approximated on available mapping.

Step 3 – Estimate the population at risk

Using the results from step 2, the PAR can be estimated for various locations downstream from the dam. It is suggested that the PAR be estimated for three different reaches: the dam to mile 3, mile 3 to mile 7, and mile 7 to mile 15. PAR can be estimated using the population of communities and the percentage of the community that is flooded, or by obtaining the number of houses from maps, or from a site visit, and then multiplying the number of houses or residences by three. Seasonally occupied locations or sites that have significant differences in population between weekdays and weekends (e.g., campgrounds) may need special consideration.

Step 4 – Evaluate the danger posed by the flood: Compare the peak discharge from the dam failure to a more common flood

A dam failure can potentially cause large loss of life when the associated discharge is much greater than typical and usual flows on the stream or river that the flood wave follows. Comparing the discharge from dam failure to commonly occurring flows can provide some measure of the potential danger caused by the dam failure flood. The 10-year flood (i.e., flooding that has a 10 percent chance of occurring in any given year) can be used as a basis for comparison. The 10-year flood is used because it can generally be accurately estimated for a site. Estimates of the 10-year flood can be obtained from various sources, including the U.S. Geological Survey's "National Streamflow Statistics Program." At various locations downstream from the dam, compute the ratio of the dam failure flood (attenuated as the flood moves downstream) to the 10-year flood, which often increases downstream due to an increase in the drainage area. Ignore any flood reduction afforded by the dam and reservoir in computing the 10-year flood discharge.

Step 5 – Select a fatality rate based on the flood ratio and the distance from the dam

Loss of life from dam failure can be estimated by using a fatality rate that is appropriate for each area impacted by the dam failure. Table 5 provides fatality rates that can be used in this estimation. The table separates the area downstream from a dam into three reaches (measured by distance from the dam) and provides fatality rates based on the ratio of the peak dam failure discharge divided by the 10-year flood for each of the three reaches. The flood discharge ratio should be calculated at the upstream end of each reach (i.e., at the dam [mile 0], mile 3, and mile 7).

Table 5. Fatality Rates for Estimating Life Loss from Dam Failure

(Source: Derived from an analysis of U.S. dam failures. Subject to revision)

Ratio of Peak Discharge from Dam Failure to 10-year Flood Peak Discharge	Fatality Rate (Percentage of people [prior to any evacuation] within the dam failure floodplain who would likely die as a result of dam failure)		
	From mile 0.0 to mile 3.0	From mile 3.0 to mile 7.0	From mile 7.0 to mile 15.0
More than 100	0.75	0.50	0.37
50 to 100	0.50	0.33	0.25
30 to 50	0.25	0.20	0.13
20 to 30	0.20	0.15	0.10
10 to 20	0.10	0.08	0.05
5 to 10	0.02	0.015	0.01
3 to 5	0.01	0.007	0.005
1 to 3	0.005	0.003	0.002
Less than 1	0.001	0.0001	0.0000

Step 6 – Determine loss-of-life estimates

Table 6 is an example showing how results using this method might be displayed.

Table 6. Loss of Life Resulting from Dam Failure at Example Dam

Reach (distance from dam, in miles)	Number of People within Dam Failure Flood Boundary	Ratio of Peak Discharge from Dam Failure to 10-year Flood Peak Discharge	Fatality Rate	Loss of Life
0.0 to 3.0	60	35	0.250	15
3.0 to 7.0	400	6	0.015	6
7.0 to 15.0	500	2	0.002	1
Total (mile 0.0 - 15.0)	960	Not applicable	Not applicable	22

2.6 USACE/Utah State University LIFESim and Simplified LIFESim Models

"LIFESim – A Model for Estimating Dam Failure Life Loss" (LIFESim) is a modular, spatially-distributed, dynamic simulation system developed to estimate potential loss of life from natural and/or dam and levee failure floods. LIFESim can be used for dam safety risk assessments and by dam owners and local authority emergency managers to explore options for improving the effectiveness of emergency planning and response. The LIFESim methodology was originally developed for USACE and is based on research conducted over several years at Utah State University and sponsored by USACE and the Australian Committee on Large Dams and several of its member organizations. The development work for LIFESim by Utah State University was conducted in two phases. The first phase consisted of a detailed characterization of almost 60 flooding case histories (both with and without life loss), and included the development of scale-independent empirical fatality-rate probability distributions for three flood (lethality) zones, described below. The second phase consisted of the actual development and implementation of the methodology.

Depending on the requirements of the consequence assessment, there are two methodologies available that implement the base LIFESim theory and can be applied to estimate flood related loss of life. These methodologies are applied through two separate tools – *the LIFESim Modeling System* which uses the LIFESim methodology for determining loss of life estimations and the *Hydrologic Engineering Center Flood Impact Analysis (HEC-FIA)* program that uses the Simplified LIFESim methodology for estimation of loss of life. The LIFESim and Simplified LIFESim procedures described herein are based on the foundation of knowledge gained from an in-depth analysis of case histories conducted by McClelland and Bowles (McClelland and Bowles, 2002).

2.6.1 LIFESim Model

LIFESim is a spatially-distributed dynamic simulation modeling system developed to estimate potential loss of life. It has been formulated to overcome the limitations of the purely empirical life-loss estimation approaches; these are detailed by McClelland and Bowles [2002] and summarized by Aboelata et al [2003]. LIFESim considers evacuation, detailed flood dynamics, loss of shelter, and historically-based life loss. LIFESim can be used to provide inputs for dam safety risk assessment and to explore options for improving the effectiveness of a dam owner's emergency plans or a local authority's response plans.

LIFESim has been formulated using an underlying development philosophy that emphasizes including the important processes that can affect life loss, while depending on only readily-available data sources and requiring only a reasonable level of effort to implement. Estimated flooding conditions are obtained from an external dam break flood routing model. LIFESim can operate in Deterministic or Uncertainty Modes. The Uncertainty Mode provides estimates of life loss and other variables relating to warning and evacuation effectiveness, as probability distributions.

LIFESim is structured as a modular modeling system built around a database. Each module exchanges data with other modules through the database. Data required to conduct a LIFESim analysis includes hydraulic modeling output data, population and building structural inventory data (locations and building types) obtained from Census and HAZUS-MH data, and road network data. Default relationships and values are provided for many other inputs. One-dimensional (1D) hydraulic modeling has typically been used, but LIFESim can accommodate two-dimensional (2D) hydraulic modeling outputs as well.

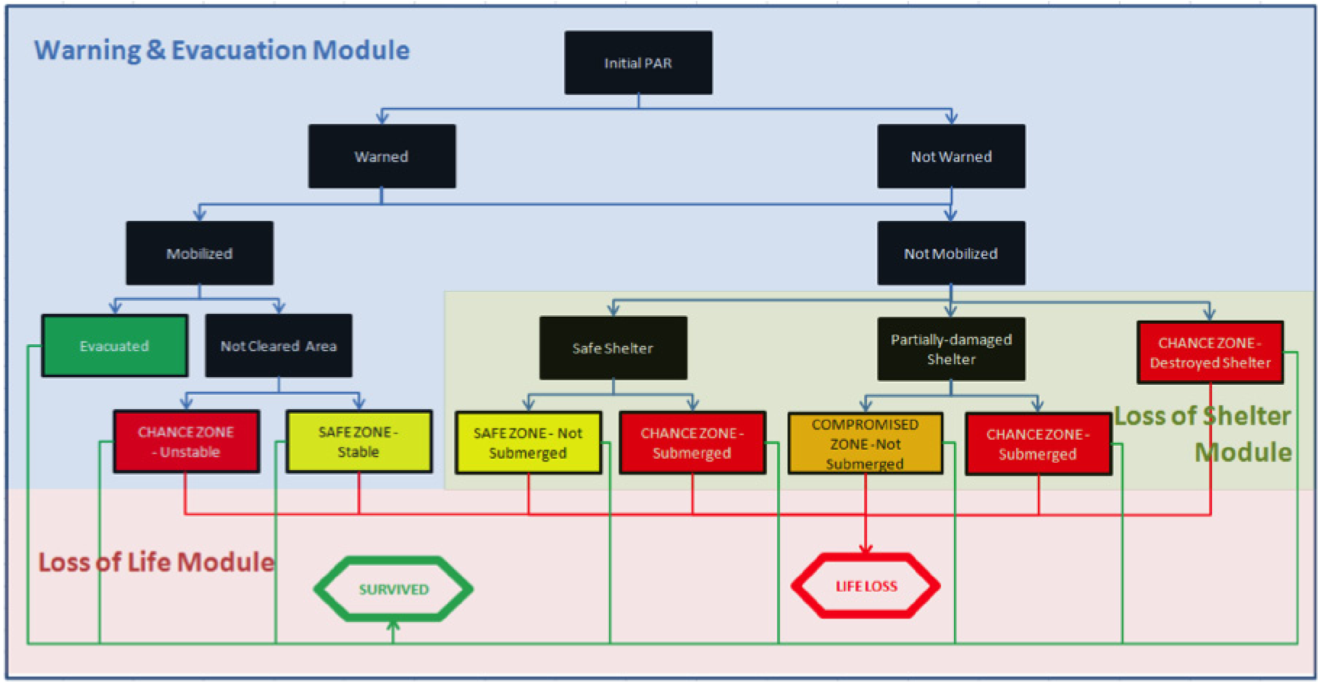

Figure 2. Schematic of the LIFESim Approach to Life-Loss Estimation (Source: Bowles 2007)

Figure 2 is a schematic of the LIFESim approach to life-loss estimation. The four major modules that comprise LIFESim are as follows:

- **Dam Break Flood Routing Module** – Interfaces with an existing dam-break flood routing model, such as DAMBRK [BOSS 1999] or HEC-RAS [HEC 2002], to provide a set of grids representing water depth and flow velocities over the entire study area and throughout the duration of the flood event.
- **Warning and Evacuation Module** – Simulates the spatial redistribution of the PAR following initiation of a warning.
- **Loss-of-Shelter Module** – Simulates the exposure of people in buildings during each flood event as a result of structural damage, building submergence and toppling of people in partially damaged buildings.
- **Loss-of-Life Module** – Estimates life-loss using life-loss probability distributions developed by McClelland and Bowles [2000 and 2002], modified in Aboelata et al [2004a] and presented later in this paper in the Loss-of-Life Module subsection.

LIFESim is designed to be applied to a set of event-exposure scenarios. Events include different dam failure modes and breach locations, no-failure flooding, and different flood severities. Exposure cases can include different seasons, day/night and weekend/weekday conditions affecting the size and distribution of the PAR and various aspects of the warning and evacuation system performance. The simulation period for each LIFESim model run should commence with the initiation of the first evacuation warning and continue to the time of occurrence of the maximum peak of the hydrograph of the flood event at the most downstream consequence center that is considered. The Uncertainty Mode of LIFESim propagates input uncertainties through the model to provide probability distributions of the uncertainties in life-loss estimates.

Loss-of-Shelter Module

The Loss-of-Shelter Module simulates the exposure of people in buildings during each flood event as a result of structural damage, building submergence, and toppling of people in partially damaged buildings. Loss-of-Shelter categories are assigned to each level in several types of buildings throughout the flooding area for which historical fatality-rate probability distributions were estimated by McClelland and Bowles [2000 and 2002]. Flood (lethality) zones distinguish physical flood environments in which historical rates of life loss have distinctly differed. Three flood zones are physically defined by McClelland and Bowles [2000 and 2002] by the interplay between available shelter and local flood depths and velocities, summarized as follows:

- *Chance zones*: Flood victims are typically swept downstream or trapped underwater and survival depends largely on chance; that is, the apparently random occurrence of floating debris that can be clung to, getting washed to shore, or otherwise finding refuge safely. Historical fatality rates range from 50 percent to 100 percent, with an average rate of approximately 90 percent.
- *Compromised zones*: Available shelter has been severely damaged by the flood, increasing the exposure of flood victims to violent floodwaters. An example might be when the rooms inside a building experience rapidly-moving shoulder-height flood water. Historical fatality rates range from zero to 50 percent, with an average rate of approximately 10 percent.
- *Safe zones*: Typically dry, exposed to relatively quiescent floodwaters, or exposed to shallow flooding unlikely to sweep people off their feet. Examples might include the second floor of residences and sheltered backwater regions. Historical fatality rates are virtually zero.

Use of homogeneous flood zones by McClelland and Bowles [2000 and 2002] lead to a scale-independent approach to estimating fatality rates for use in LIFESim, that in turn, extracts more information from available case studies.

Warning and Evacuation Module

The Warning and Evacuation Module spatially redistributes the PAR from its initial distribution by PAR type at the time that a warning is issued, to a new distribution with assigned flood zone categories at the time of arrival of the flood. It does this through simulation of the warning dissemination, mobilization, and evacuation-transportation processes. Figure 3 is a schematic of an example of event sequences and their associated time lines for the three types of organizational entities for a typical warning and evacuation process as represented in LIFESim. It is summarized below:

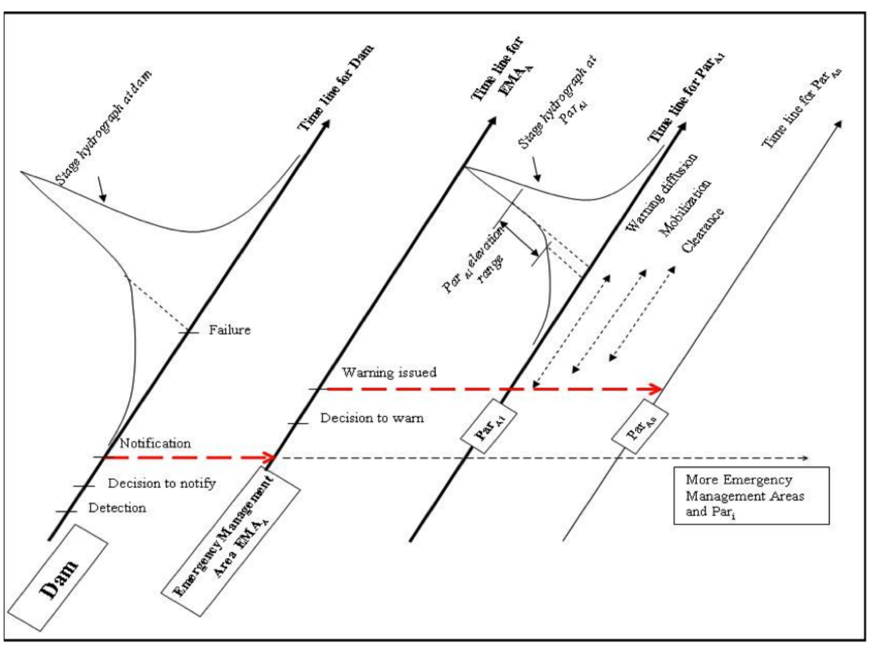

Figure 3. Time lines for events in warning and evacuation processes (Source: Aboelata and Bowles)

- *Dam and dam owner/operator events*: detection of a failure or potential failure; decision to notify the authorities in each emergency management area; notification; and dam failure [1].

- *Emergency management area (EMA) events*: receiving a notification from the dam owner; decision to warn the public; and initiation of formal warnings.

- *subPAR (PARi) events:* receiving a warning; mobilizing; traveling across and clearing the flooding area; and flood arrival shown by a stage hydrograph. More than one EMA may exist below a dam and numerous subPAR are located within each EMA.

The three major components in the Warning and Evacuation Module are summarized in the following subsections.

Warning: The warning initiation time is the time at which an evacuation warning is first issued to the PAR. It is defined to be positive if the warning is issued after dam failure occurs, or to be negative if the warning is issued before failure occurs. Proper consideration of staged warnings using LIFESim [Aboelata et al 2003] as spillway discharges increase for both no-failure floods and the pre-failure phase of flood-induced failure floods, is important for estimation of life loss for these cases and for the estimation of incremental life loss for flood-induced failures.

The rate at which the warning is received throughout an EMA is represented in LIFESim using a warning diffusion curve, that is the cumulative percentage of the Par that receives the warning message versus time, starting at the warning initiation time. The overall area to be warned may be divided into several emergency planning zones (EPZs), possibly with different warning initiation times. Empirical warning diffusion curves are available in LIFESim for a range of different types of warning systems and different time-of-day activities. The use of LIFESim to compare the effectiveness of an existing warning and evacuation system and an improved system was demonstrated by Aboelata et al [2004b].

Mobilization: After receiving the warning message, people who are willing and able to leave will prepare to leave. The rate of mobilization is represented in LIFESim using a mobilization curve, that is a cumulative percentage of the warned Par that starts moving away from the area of potential flooding towards emergency shelters or other safe destinations.

At the time of arrival of the flood at a particular location, some people may remain in buildings. This would include people who choose to evacuate vertically in buildings, those who did not receive the warning, and those who received the warning but decided not to mobilize; did not have the physical capability to evacuate, or did not have enough time to mobilize before outside conditions became unsafe.

Evacuation-Transportation: This process commences with mobilization and ends with either clearance of the flooding area or entrapment if the evacuation route becomes blocked by flooding. People who clear the flooding area are assigned to a "safe" flood zone and people who are trapped on the road are assigned to a flood zone that depends on their mode of evacuation and the most severe flooding conditions for the event. Three modes of evacuation are included in LIFESim: cars, sports utility vehicles, and pedestrians.

The Greenshield [1935] transportation model is used to represent the effects of traffic density and road capacity on vehicle speed. The original model was modified to represent congestion and traffic jams, as described in Aboelata [2005], by introducing a minimum "stop-and-go" speed (Vjam) if the jam density (Djam) for a road class is exceeded.

1 The order of these events may vary. For example, detection may not take place until after failure. In some circumstances, the detection, decision, and notification steps may be performed by someone other than the dam owner's representative.

Census data is used to assign each road segment to a road class and to specify its length and interconnectivity with other road segments. Each road class is assigned default values of the number of lanes, free flow speed (ffs), Djam, and Vjam based on the Highway Capacity Manual (HCM) [TRB 2000], although these can be overridden if more detailed information is available for the road system. Contraflow can be represented by doubling the number of lanes assigned to road classes.

People who reach a safe destination at the boundary of the area that becomes flooded are considered as the "cleared" group. The locations of safe destinations can include "islands" of higher ground or buildings, that is considered to be capable of withstanding the anticipated flooding, inside the flooding area. Therefore, safe destination locations must be carefully defined by the user to represent the expected evacuation situation. Designated routes in evacuation traffic management plans should be used to the degree that it is expected that these would be used; that might be expected to depend on factors such as the effectiveness of community information campaigns, the credibility of emergency planners in the community, the inclusion of clear evacuation route instructions in warning messages, and the existence of sufficient warning time to allow the police to direct traffic during an evacuation. As illustrated by Aboelata et al [2004a], alternative safe destination locations can be considered to evaluate alternative evacuation strategies.

Loss-of-Life Module

Based on the assigned flood zone categories, as defined in the "Loss-of-Shelter Module", life-loss estimates are made using life-loss probability distributions developed by McClelland and Bowles [2000], updated by Aboelata et al [2003].

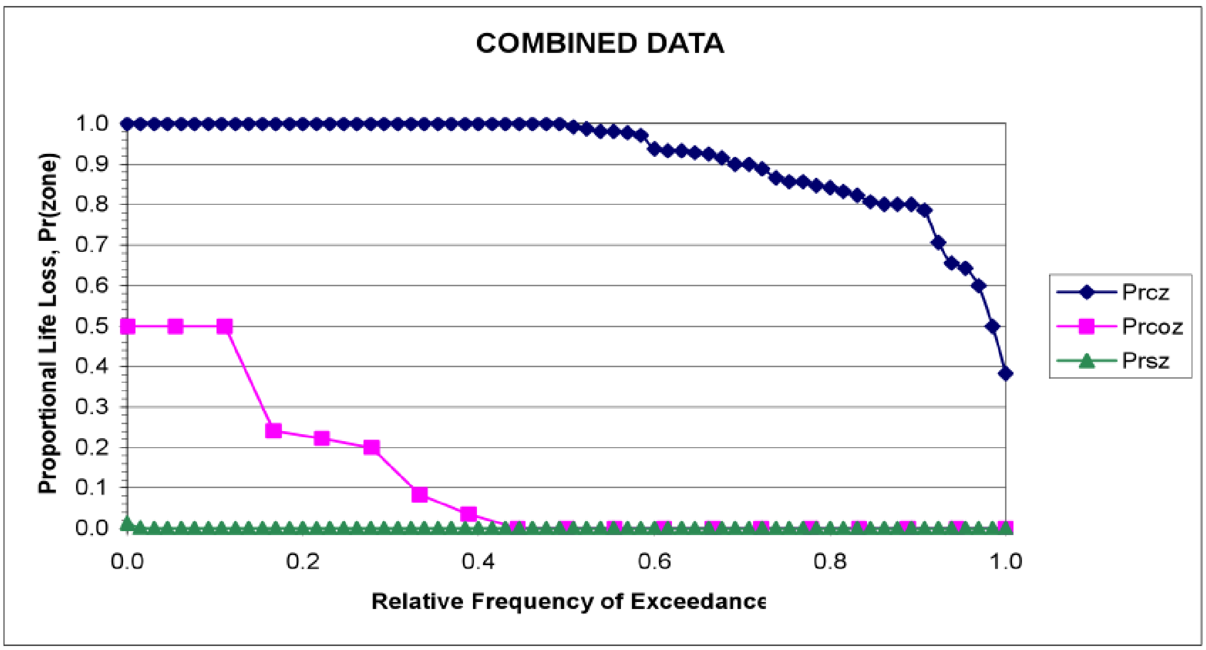

Figure 4. Probability distributions for fatality rates for each flood zone (Source: Aboelata et al, 2003)

Uncertainty Mode

The Uncertainty Mode of LIFESim propagates model parameter and input uncertainties through the model to provide probability distributions of the uncertainties in life-loss estimates. These are epistemic or knowledge uncertainties. Aleatory uncertainties or natural variabilities due to factors such as the time-of-the day and season of the year are handled by making a set of runs to represent these speared exposure conditions. The resulting distributions of life loss can be combined with estimates of the uncertainties in other risk assessment inputs to obtain estimates of uncertainties in risk assessment results, and subsequently evaluate against tolerable risk guidelines. This approach has been illustrated by Chauhan and Bowles [2001 and 2004].

2.6.2 Simplified LIFESim Model

The Simplified LIFESim methodology is a scaled down approach to consequence estimation that attempts to capture some of the features contained in the full LIFESim model. The applicability depends on the goals of the assessment as well as the characteristics of the study area.

Model Inputs

Simplified LIFESim is applied within the HEC-FIA economic and life loss consequence estimation model. A description of the inputs required by HEC-FIA to compute life loss and direct property damage are provided below.

Digital Elevation Grid: A digital elevation grid is required to compute consequences in HEC-FIA. The digital elevation model is used to assign elevations to structures as well as in the evacuation effectiveness computation. The digital elevation model used in HEC-FIA should be the same as that used to develop the hydraulic model of the dam break.

Structure Inventory with Population: All consequence estimates in HEC-FIA are done on an individual structure basis. Therefore, an inventory that represents all the structures within the flooded area is required. Each structure must have a ground elevation and population assigned to it at a minimum, but the height of the structure is also important (1-story, 2-story, etc). If a detailed structure inventory does not exist for the study area, capabilities available in HEC-FIA allow the user to generate a structure inventory for an area using an existing parcel database (shapefile) or the database that comes with the FEMA HAZUS-MH tool. A detailed structure inventory is preferable for all levels of analysis and recommended for analysis in support of dam safety modification studies. A parcel database can be used in place of a detailed structure inventory, if available. The detailed structure inventory must be supplied in the form of a point shapefile with supporting database (.dbf). Likewise, the parcel database must be supplied in the form of a polygon shapefile with supporting database (.dbf). When a structure inventory is generated using the HAZUS data, it should be checked against aerial imagery to ensure that it is representative of the study area.

The number of people in a structure often fluctuates between day and night and weekday and weekends in residential, commercial, and industrial areas. In addition, population in a structure or area can also vary significantly on a seasonal basis for campgrounds and other types of recreational facilities. Therefore, it is desirable to consider a range of different exposure cases to capture the temporal variations in the numbers of people in a structure. The number of people estimated in each structure should apply to the time that an official public warning to evacuate would be issued for a dam failure for each failure event that is considered. It is important to consider the fact that certain flood-initiated failure events occur only during a specific season of the year, and that the range of reservoir pool elevations is highly correlated with the season of the year.

Capabilities available in HEC-FIA allow the user to generate day and night populations for an existing structure inventory using the most recent census data. Day and night populations estimated by HEC-FIA take into account the shift of population in an area due to working in or out of the area during the day and returning home during the evening and other similar considerations.

Seasonal considerations and development that has occurred since the most recent census are not included in the default population distribution provided by HEC-FIA. For areas with high seasonal variability, the population in HEC-FIA will be based on the "permanent" population of the area that is representative of the number of people that identified that location as their primary residence in the most recent census. An approximate way to adjust the population in HEC-FIA to account for seasonal variations or increases/decreases since the most recent census is to take the final life loss and economic results computed by HEC-FIA and factor them up or down as appropriate.

Inundation Data for Each Flood Scenario: The Simplified LIFESim methodology requires an estimate of the time of arrival of the flood wave for each structure. The arrival time represents the end of the opportunity to evacuate a structure, and by default, is defined in HEC-FIA when the depth initially becomes greater than 2 feet and it is assumed that people will choose to evacuate vertically in a structure instead of trying to move horizontally to a safer location.
There are two methods for estimating and entering flood wave arrival times in HEC-FIA. Currently, for dam breaks modeled with HEC-RAS, the most efficient procedure for estimating flood wave arrival time is to use hydrograph output at each cross-section and storage area. HEC-FIA contains capabilities to load cross-section and storage area geospatial information used in the HEC-RAS model, and access the corresponding HEC-DSS (Data Storage System) files to determine the time at which the flooding depth first reaches 2 feet at each cross-section. It linearly interpolates the arrival time at the structure using the station information of the structure and the upstream and downstream cross-sections. For structures that fall within a storage area, arrival times are computed by using the stage hydrograph for that specific storage area (no interpolation is necessary). Since the flood wave progression is highly dependent on the failure/no-failure scenario and the specific failure mode, a different set of hydrographs must be developed and provided for each scenario to properly estimate arrival times.

The other method available for entering flood wave arrival times in HEC-FIA is with an arrival time grid. Arrival time grids are the most efficient approach for using 2-dimensional dam failure hydraulic results to estimate life loss in HEC-FIA. Each cell in the arrival time grid must contain the date and time at which the depth in that cell initially becomes larger than 2 feet for the specific failure or non-failure scenario being studied.

Warning issuance times: The Warning Issuance Time is defined as the time at which an official evacuation order is released from the responsible emergency management agency to the PAR. The actual process of breach initiation, detection, evacuation warning, and dam failure is illustrated in Figure 5 for a dam failure scenario where the breach is detected prior to actual dam failure, although other sequences can be handled in LIFESim and Simplified LIFESim. Life-loss estimates are highly sensitive to warning issuance time and other relationships that affect the effectiveness of warning and evacuation processes for the PAR. There is significant uncertainty in the model parameters that represent these processes. Sensitivity studies can also be used to provide some information on the effects of uncertainties on life-loss estimates. LIFESim also provides an uncertainty analysis capability that provides for explicit consideration of the uncertainties and provides confidence intervals for life-loss estimates as illustrated in Aboelata et al (2005).

For the purpose of this discussion, the parameters illustrated in Figure 5 are defined as follows:

- **Major Problem Acknowledged:** Time when seepage (or evidence related to other failure mode) is determined to be significant enough that dam failure is likely. Successful intervention is no longer considered probable. Leads to notifying public of impending dam failure.
- **Evacuation Notification from dam owner to EMAs:** Time when observed increase in seepage or other failure mode has been determined to be significant enough to notify EMAs to start the warning and evacuation process.
- **Failure:** Time when rising limb of flow hydrograph through breach begins to increase rapidly. Represents time corresponding to "Trigger Failure" parameter in HEC-RAS dam breach input.

- **Warning Opportunity Time Window:** Amount of time between when the dam owner discovers significant seepage progression that could lead to impending dam failure and actual failure. Positive value if significant evidence related to failure mode is discovered prior to failure initiation, negative if after failure.
- **Breach formation time:** Amount of time between failure and when breach reaches full width and depth. Corresponds to 'Full Formation Time' parameter in HEC-RAS dam breach data.

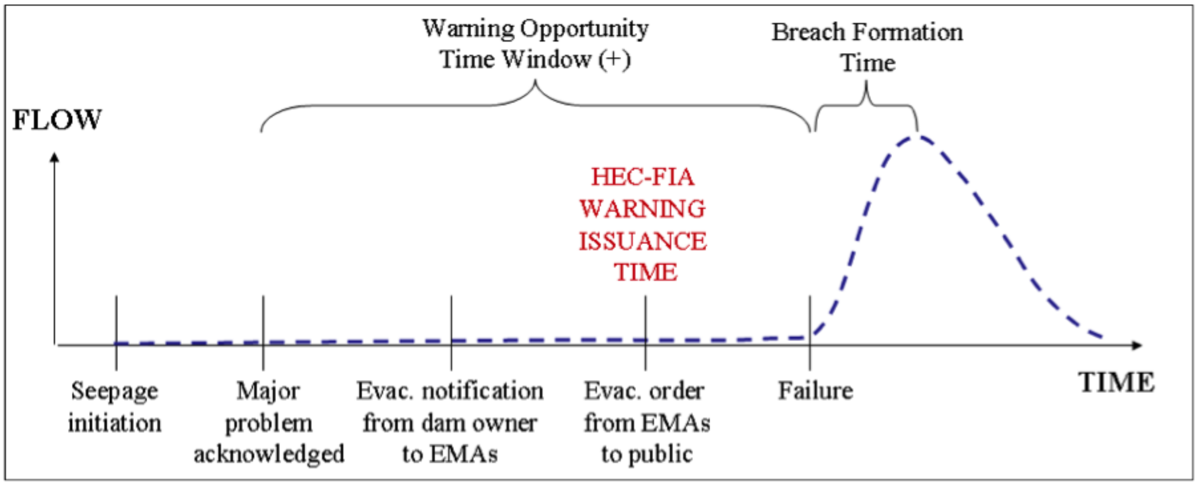

Figure 5. Detection and warning timeline for observed seepage failure scenario (Source: Aboelata and Bowles)

For most failure modes where the failure progress is observable prior to a catastrophic dam failure, warning issuance times should be determined by first estimating the time when a major problem would be acknowledged relative to the time of dam failure. The major problem acknowledgment time for these failure modes is the time at which a dam owner would determine that a failure is likely imminent, and they would decide that the dam breach warning and evacuation process should be initiated by notifying the responsible authorities. The time lag between major problem acknowledgement and when an evacuation order would pass from the dam owner to the responsible EMA and then from the EMA to the public (Warning Issuance Time) should be estimated based on the judgment of dam operations personnel and emergency management personnel who have jurisdiction in the areas of each downstream community. In obtaining input from operations personnel and emergency management personnel, it is important to carefully describe the dam failure scenario, including key assumptions that define the development and detection of the failure mode that is considered in each failure event-exposure scenario for which life loss is being estimated in order to consider all associated factors in estimating warning issuance times for structures. It is useful to have more than one responsible person involved in this expert elicitation process, since different individuals will often think of different important factors and their judgments may vary resulting in a range of estimates of warning issuance times. The process will often result in new ideas for reducing warning issuance times. If a Potential Failure Mode Analysis is being performed, the warning issuance times should be estimated by the group during discussion relevant to each failure mode.

Warning System Information: The amount of time between the evacuation warning issued by the responsible agency (warning issuance time) and the PAR receiving that warning is dependent on the warning system or process. A typical warning would be received by the population through various means. For example, the first group of people would typically receive warning through the primary warning process (e.g. Emergency Broadcast System), but then a secondary warning process would begin that includes emergency responders and the general population spreading that warning via word of mouth. The warning dissemination process is provided to HEC-FIA in the form of warning diffusion curves. A warning diffusion curve defines the relationship between time from warning issuance and the percentage of the PAR that has received that warning. Default warning diffusion curve relationships are provided in HEC-FIA for common types of warning systems. For large studies, it is likely that communities within the inundated area will have different types of warning systems with varying levels of efficiency. HEC-FIA has capabilities to define separate impact areas that can each be assigned different warning issuance times as well as different types of warning systems.

Mobilization Information: Mobilization time is defined as the amount of time between when a warning is received and when that warned person mobilizes (i.e., they leave their structure). The mobilization time is defined in HEC-FIA by a mobilization curve. The mobilization curve contains two important pieces of information for determining the number of people that have evacuated their structures when the flood arrives: (1) the percentage of warned people that mobilize over time; and (2) the maximum mobilization percentage. The maximum mobilization percentage defines the highest percentage of people that are estimated to mobilize, given the characteristics of the nature of the potential dam failure, warning message, and many other factors including cultural considerations; and in some cases, the effects of past evacuation experiences. One hundred percent minus the maximum mobilization percentage yields the percentage of people that are either unable or choose not to mobilize after receiving the warning. HEC-FIA contains multiple predefined mobilization relationships. It is recognized that the life loss estimate is highly dependent on the mobilization information provided to HEC-FIA, and that the actual mobilization decision process contains many contributing factors and is highly uncertain. Research is currently underway to refine and improve the process and guidance for developing and applying mobilization curves in HEC-FIA.

Evacuation Timing Information: The time required to evacuate depends on many factors, including mobility, location of shelters, and capacity of the evacuation route. The full LIFESim model includes detailed dynamic transportation simulation modeling capabilities to obtain estimates of the evacuation process throughout the inundation area (Aboelata and Bowles 2005; Aboelata et al 2005). This capability represents the effects of traffic density on vehicle speed, the effects of traffic jams, and blockage of road segments by flooding and also contraflow. It provides this capability using road network data readily available in the HAZUS GIS database and default parameter values based on the Highway Capacity Manual (TRB 2000), without requiring additional inputs of the details of road geometry and traffic signal operations. For the Simplified LIFESim procedure, it is necessary to either reduce the evacuation process to a straight-line shortest distance process or rely on the judgment of first responders who have jurisdiction in the areas of each downstream community. It may also be useful to consult with managers of facilities such as schools, hospitals, large public gathering places, recreational areas, etc, to obtain their judgments on how rapidly they could complete an evacuation and the extent to which vertical or in-place evacuation would be utilized. As in estimating other inputs, it is important to carefully describe the dam failure scenario to those first responders and others who are involved in this expert elicitation process to estimate evacuation effectiveness.

For a typical dam failure consequence analysis in HEC-FIA, the following steps can be used to estimate a time required to evacuate for each structure:

1) Assume the safe location is anywhere that the maximum inundated depth for a given flood scenario is less than 2 feet. Create a polygon representing this hazard boundary.
2) Load the hazard boundary into HEC-FIA and provide a nominal speed at which evacuating people could travel along the assumed straight-line distance. This nominal speed is less than the actual speed along the road network because the distance is greater through the road network than along a straight-line path as represented in Simplified LIFESim.
3) HEC-FIA will compute the time required to evacuate by determining the distance from each structure to the safe boundary and then dividing that distance by the nominal speed.

Lethality Zone Parameters and Fatality Rates: Flood (lethality) zones distinguish physical flood environments where historical rates of life loss have distinctly differed. McClelland and Bowles (2002) defined three flood zones for which historical rates of life loss have been estimated and these fatality rates are used in HEC-FIA to estimate life loss. Each flood zone is physically defined by the interplay between available shelter and local flood depths and velocities, as summarized below:

- *Chance Zones*: Flood victims are typically swept downstream or trapped underwater, and survival depends largely on chance; that is, the apparently random occurrence of floating debris that can be clung to, getting washed to shore, or otherwise finding refuge safely. The historical fatality rate in Chance Zones ranges from 38 percent to 100 percent, with an average rate of more than 91 percent.
- *Compromised Zones*: Available shelter has been severely damaged by the flood, increasing the exposure of flood victims to violent floodwaters. An example might be when the front of a house is torn away, exposing the rooms inside to flooding. The historical fatality rate in Compromised Zones ranges from zero to 50 percent, with an average rate near 12 percent.
- *Safe Zones*: Typically dry, exposed to relatively quiescent floodwaters, or exposed to shallow flooding unlikely to sweep people off their feet. Depending on the nature of the flood, examples might include the second floor of residences and sheltered backwater regions. Fatality rate in Safe Zones is virtually zero and averages 0.02 percent.

As previously mentioned, the Simplified LIFESim approach in HEC-FIA removes the velocity parameter from the lethality zone relationship. Therefore, assignment to a specific lethality zone for a given structure is based solely on the final depth of flooding at that structure and the height of that structure. By including the height of the structure, the very significant impact of vertical evacuation is accounted for in the Simplified LIFESim methodology.

HEC-FIA assigns lethality zones based on the evacuation outcome for people starting in each structure and the height of the structure. The logic followed by HEC-FIA for assignment of evacuation outcome categories is described below. After the determination of evacuation outcome is made, then lethality zones are determined. Certain parameters in the lethality zone assignment process are set by default in HEC-FIA, but should be reviewed during the application process to ensure that they are representative of the study area region:

1) Cleared: People who evacuate safely do not receive a flood lethality zone assignment.
2) Caught: People who get caught evacuating are assigned to the Chance Zone.
3) Not mobilized: People who stay in structures are assigned to flood lethality zones based on maximum depth of flooding over the entire flood event and the height of the structure (the full version of LIFESim also accounts for water velocity when categorizing structures into flood lethality zones). The assumption in Simplified LIFESim is that people evacuate to the level above the highest habitable level in the structure (e.g., the roof or an attic).
    a) For any structure: If event maximum depth < 2 feet or less than the first floor height (fh) of structure, no flood lethality zone assignment is made and the people are grouped with the Cleared evacuation category;
    b) If 1-story structure:
        i) If event maximum depth < fh + 13 feet, assign to Safe Zone;
        ii) If event maximum depth ≥ fh + 13 feet and < fh + 15 feet, assign to a Compromised Zone;
        iii) Other event maximum depth ≥ fh + 15 feet then assign to a Chance Zone.
    c) For each additional story, add 9 feet to the depth criteria in b) to determine flood lethality zone.

In the Simplified LIFESim Procedure, the following average fatality rates are used based on the probability distributions of fatality rates for each Flood Lethality Zone described by McClelland and Bowles (2002):

- Safe Flood Zone: 0.0002;
- Compromised Flood Zone: 0.12; and
- Chance Flood Zone: 0.91.

Application Methodology

The Simplified LIFESim methodology applied within the HEC-FIA program includes the following steps for a selected Event-Exposure Scenario and given structure inventory with population.

1) Obtain the **dam failure flood wave arrival times** for each structure. The arrival time is the time at which the depth of flooding at the location of the structure is estimated to be large enough that the inhabitants of that structure will choose to stay in the structure and evacuate vertically instead of risk leaving the structure. The default value in HEC-FIA is 2 feet. HEC-FIA estimates arrival times for each structure by interpolating them off of the hydrograph data provided at the nearest upstream and downstream location to each structure, or by selecting it from the arrival time grid in the specific cell where the structure is located.
2) Calculate the **warning time** for each structure by finding the difference between their respective dam failure flood wave arrival times (from step 1) and the public warning issuance time. Warning time indicates the amount of time that the population of each structure has to receive a warning and mobilize.
3) Compute the **time required to evacuate** for each structure, which is an estimate of the amount of time it would take for the people in a structure to evacuate to a safe location after they have mobilized.
4) Combine the user defined **warning and mobilization curves** into one relationship that represents the number of people who have both received a warning and mobilized.
5) Compute the percentage of people in each **Evacuation Outcome Category.** For each structure, estimate the percentage of its occupants that fall into each of three possible evacuation categories at the time of arrival of the dam failure flood wave. This estimate computes fractions of people in individual structures. When the results are summed for the inundated area, it will provide an estimate of the total life risk for the specific scenario (see figure 6).
6) For each structure, assign a **lethality zone** to the people in each evacuation outcome category as described in the previous section.
7) Calculate the **overall fatality rate for the occupants initially assigned to each structure** by summing the following fatality rates for each evacuation outcome category:
   a) The fatality rate for evacuation outcome category 1 (Cleared) is 0.
   b) The fatality rate for evacuation outcome category 2 (Caught) equals the percentage of people caught evacuating multiplied by 0.91.
   c) The fatality rate for evacuation outcome category 3 (Not mobilized) equals the percentage of people that stayed in the structure multiplied by fatality rate for the flood zone (depends on maximum inundation depth at the structure).
8) Calculate the **life-loss estimate for each structure** by multiplying the initial population of each structure (from step 2) by its respective overall fatality rate (from step 7).
9) Calculate the **total life-loss estimate** by summing the life-loss estimates for all structures (from step 8).

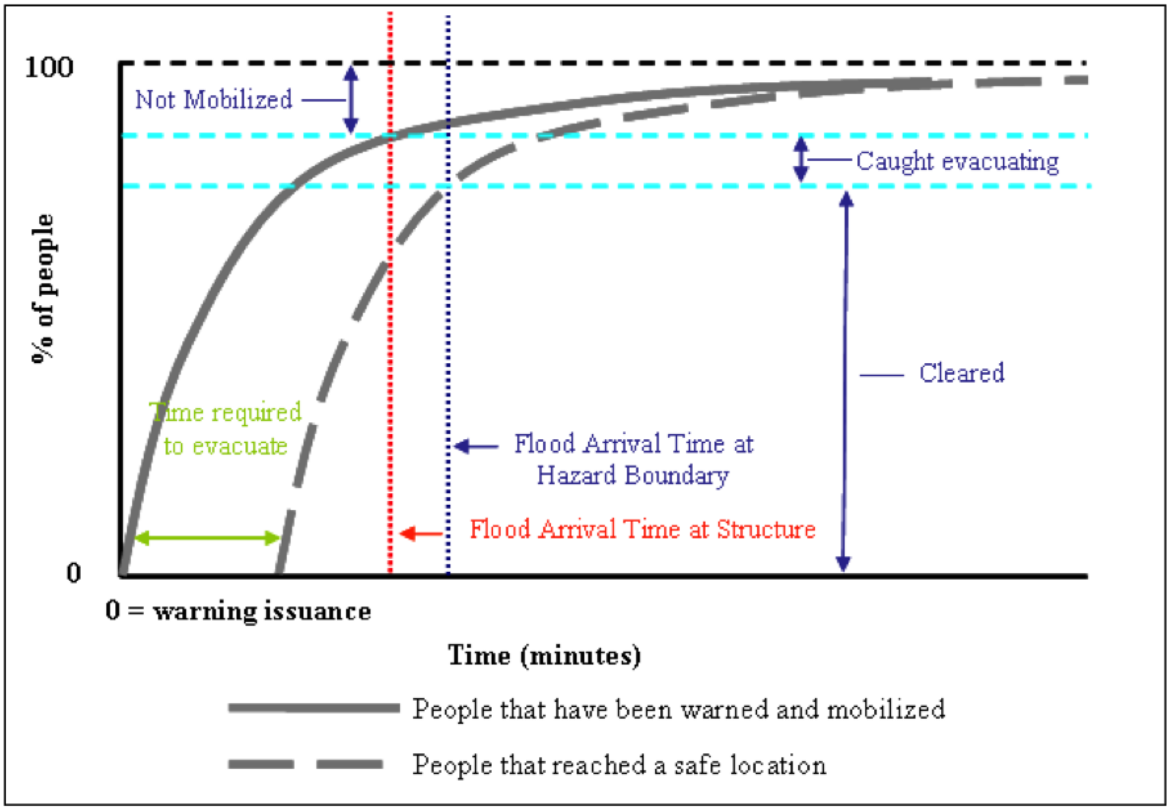

Figure 6. Assignment of Evacuation Outcome Categories (Source: Aboelata and Bowles)

The methodology described above provides a single value or 'point' estimate of life loss. Range estimates can be made in recognition of the uncertainty associated with these point estimates. Range estimates can be based on conducting a sensitivity analysis by varying key inputs to the Simplified LIFESim procedure in a sensitivity analysis. The full LIFESim Model provides the preferred approach to obtaining probabilistic estimates using uncertainty analysis if time and resources are justified (Aboelata and Bowles 2005, Aboelata et al 2005).

2.6.3 Comparison of LIFESim and Simplified LIFESim

The most significant differences between Simplified LIFESim and LIFESim are as follows:

Evacuation Simulation - Simplified LIFESim uses a basic evacuation model where the user either provides the amount of time required for inhabitants of each structure to evacuate to safety or provides a hazard boundary in the form of a polygon shapefile. If a hazard boundary is provided, HEC-FIA determines the shortest straight-line distance from a structure to the hazard boundary and applies a nominal evacuation speed along that line to estimate the amount of time required to evacuate. The effect of traffic jam potential must be accounted for implicitly by the choice of the nominal evacuation speed. If the loss of life for a study is highly dependent on evacuation efficiency, including the effects of traffic congestion, application of the full version of LIFESim should be considered.

LIFESim uses a transportation network based on the modified Greenshield transportation model. The Greenshield model is used to route the flow of evacuating motor vehicles. This transportation model represents the effects of traffic density and road capacity on vehicle speed. The original model was modified to consider congestion and traffic jams, including a minimum 'stop-and-go' speed (Vjam) if the jam density (Djam) for a road class is exceeded. Djam and Vjam parameters are based on the Highway Capacity Manual [TRB 2000], although these can be overridden if more detailed information is available for the road system. The evacuation transportation process begins with mobilization and ends with either clearance of the flooded area or entrapment if the evacuation route becomes blocked by flooding.

Velocity - Simplified LIFESim does not account for the impact of water velocity on structure stability, and therefore water velocity does not influence the loss of life estimate. The full version of LIFESim accounts for the effects of water velocity on the stability of structures, vehicles and people. In many cases, locations that experience water velocities high enough to sweep a structure away will also experience depths large enough to inundate that structure, making the ultimate fatality rate for the inhabitants of that structure the same. If flooding characteristics in the study area show many areas with high water velocities and relatively low depths, application of the full version of LIFESim should be considered.

Arrival Times - In Simplified LIFESim, flood arrival time at a structure is computed by interpolating cross-section hydrograph output from a 1D hydraulic model or from a grid that contains arrival time values. The full version of LIFESim computes flood wave arrival time by accessing a time-series of depth and velocity grids for the entire flood event throughout the inundated area. Both models can utilize output from a two-dimensional model. Importantly, the Simplified LIFESim methodology contained in HEC-FIA still draws on the foundation of knowledge gained from an in-depth analysis of case histories conducted by McClelland and Bowles (2002). In addition, since the Simplified LIFESim methodology is derived from the LIFESim approach, a specific application Simplified LIFESim can be scaled up to the full version by developing and gathering the necessary supplemental data.

Typically, 1D hydraulic modeling results are used as input to the Simplified LIFESim. Life loss estimates in HEC-FIA require either a cross-section shapefile with associated hydrograph data in HEC-DSS format or by generating arrival time grids from 2D model output. Output from any 1-D model can be converted into the cross-section shapefile/HEC-DSS format.

2.7 BC Hydro Life Safety Model

BC Hydro of Vancouver, Canada, developed a "Life Safety Model" (LSM) with the assistance of the Canadian Hydraulics Centre, a division of the National Research Council, Canada. Current development of the LSM is now facilitated by HR Wallingford of the United Kingdom. The LSM is a simulation based numeric model developed to predict fatalities resulting from flooding events such as dam failures or flash floods. Although originally developed to determine loss of life risks associated with dam failure, the model has also proven to be valuable in determining evacuation potential for flood situations.

LSM combines existing technologies, including GIS, artificial intelligence, two-dimensional hydrodynamic modeling, structural reliability analysis, and human behavior characterization. The model is based on the belief that simplistic, empirically derived formulae are largely inadequate for estimating loss of life from dam failure. Loss of life is estimated using synthetic data from simulations that are based on realistic models of the situation that might evolve (Johnstone, et al., 2005).

The key system inputs to the LSM include representations of the natural environment (ground surface), the socioeconomic environment (location of people, buildings, and roads), and flood wave models. The core of the model is the LSM Simulator, that requires a description of the initial state of objects that are modeled (e.g., individuals, groups, buildings, vehicles, roads) and the flood wave.

In the LSM model, the movement of each individual person or group of people and the movement of water are simulated. The general logic for this model is described as follows: People, or groups of people, are initially located either indoors in a building or outdoors and are unaware of the impending flood event. People become aware of the flood either from a warning center, warning from others, or direct observation; and subsequently decide whether to remain in place or attempt to evacuate. Loss of life is assumed to have occurred if people are in a building that is destroyed or if they are overwhelmed by the flood when attempting to escape by foot or vehicle.

The following input data is required in a digital format: two dimensional (2D) hydraulic modeling output data, road network data, building location data, and initial locations of PAR (expressed as either individuals or groups). Each of the input data requirements is briefly described below.

2D Modeling Output: The LSM requires hydraulic modeling input data be based on 2D modeling. Outputs from the 2D modeling should be generated at a frequent enough time interval to get a reasonable representation of the flood wave progression, considering the potential interaction between a population attempting to evacuate and an advancing flood wave. The hydraulic input data is required to be in a time series format, and include information on depths, water surface elevation, and resultant velocity (magnitude and direction). Digital terrain bathymetry is also required.

Road and Footpath Network Data: The LSM requires a detailed road and footpath network. Each roadway or footpath segment must be assigned attributes. Road and footpath attributes include road type, speed limit (also applied to footpath travel), number of lanes, status (open or closed), and elevation. Input road network data should be sufficiently dense in order to get a reasonable representation of traffic flow when evaluating evacuation attempts.

Buildings Data: The building data serves two purposes in the LSM. First, the building data is used to define an initial location for people at the start of a simulation. Second, for situations where people do not attempt to evacuate during a flood, persons located within a building can potentially become fatalities if the structural stability threshold values for the building are exceeded.

The creation of building data input can be tedious and time consuming. Data can often be obtained from local community GIS offices. The data can be found in the form of building footprint outline polygons, or geo-addressing data.

Building DV (depth multiplied by velocity) criteria is set for each building. These criteria determine at what DV value a building may be assumed collapsed. If a building collapses during an LSM simulation, all inhabitants are assumed to become fatalities. The LSM Users' Guide (BC Hydro Engineering Report No. E310) suggests the following building stability DV criteria values for use in LSM:

- 54 ft2/s (5 m2/s) for poorly constructed buildings;
- 108 ft2/s (10 m2/s) for well built timber buildings;
- 162 ft2/s (15 m2/s) for well built masonry buildings;
- 215 ft2/s (20 m2/s) for concrete buildings; and
- 377 ft2/s (35 m2/s) for large concrete buildings.

It should be noted that buildings can be preset to act as safe haven locations. These designated safe haven buildings cannot be destroyed, regardless of DV or depth values at the structure.

Population at Risk Groups and Population at Risk Units: In an LSM simulation, PAR can be evaluated as groups or individuals. Groups can be defined as families, class rooms of students, bus loads of people, groups of people located in a single building or an apartment, etc. These groups can be subdivided into individual PAR units. Population at Risk Groups

(PARG) can be declared "separable" or "inseparable". If assumed "inseparable" the PARG would stay together during the evacuation, meaning that they would travel in the same vehicle or together on foot. When traveling by foot, a group is defined to move only as fast as its weakest member. PARG and Population at Risk Units (PARU) attributes include the following inputs:

- **Travel mode** – Designates whether the PAR will attempt to evacuate by vehicle or foot. There is also a "stationary" selection which means an evacuation from a building will not be attempted.
- **Time to first awareness** – Establishes sequencing for planned or informed evacuation.
- **Vehicle floating/stalling/toppling parameters** – Defines when a vehicle may become non-functioning.
- **Parameters related to persons attempting evacuation on foot** – Critical DV for toppling or drowning, highest safe depth, parameters related to physical condition/exhaustion.

LSM Outputs: The LSM produces numerous output files. The most basic output file is the summary file. This includes such determinations as the number of people aware of the flooding and attempting evacuation, the number of people successfully reaching a safe haven, and the number of fatalities subdivided into those killed in buildings that collapsed, those killed in vehicles, and those killed on foot. Information is also available in the summary file on the final status of buildings and vehicles.

Use of the LSM may lend insight into the limitations of transportation networks during the evacuation of large urban areas. These results may help answer questions related to evacuation that are currently unanswerable using other methods such as the DSO-99-06 procedure.

3. Current and Future Developments Related to Life-Loss Estimation

This section provides information pertaining to future efforts that will further the knowledge and understanding of methods utilized to predict life loss due to dam failure. The Dams Sector will benefit from the refinements produced by these efforts and, as an end result, greater confidence will be gained in the overall process of consequence estimation.

3.1 Determination of Flood Severity Zones Using 2D Modeling Results

1D models are used extensively for flood inundation studies. These models are particularly applicable to long, well defined river reaches. However, sector partners recognize the value of using 2D inundation modeling when warranted by topographic conditions. Many flood inundation studies that involve relatively flat terrain have split flow and/or located in areas where the differentiation of flooding depths and durations are critical (such as in high population areas), have been performed using a 2D model or integrated 1D-2D model. In cases where 2D modeling is used exclusively or in combination with 1D modeling, the techniques described in this section can be applied.

Customized outputs from 2D hydraulic models can be used to develop and map maximum flood inundation boundaries that incorporate ranges of flood severity. These detailed modeling results can be used to obtain better estimates of flood severity zones. Mapping of 2D maximum inundation boundaries categorized by flood severity allows for a rapid and consistent method of assigning fatality rates to PAR. Outputs generated from the Danish Hydraulic Institute MIKE21 model, for example, can include maximum depth and maximum velocity values for every inundated grid cell in the study area. Using the Environmental Systems Research Institute software program ArcGIS, depth grids can be multiplied by velocity grids for each output interval to obtain maximum DV values. These DV values are then categorized into ranges of values which define low, medium, and high severity zones. The digital polygon developed from this analysis can be overlaid with census block data to obtain a flood severity specific PAR determination.

DSO-99-06 does not contain specific guidance on how to classify the transition point between medium and high flood severity. Reclamation has recently focused on efforts to attempt to establish an interim estimate for a medium to high severity transition in terms of a DV value combined with rate of rise. Interim DV criteria for the medium/high transition point is based on approximate building structural stability criteria that were compiled by BC Hydro and are contained in the LSM Users Guide (BC Hydro Engineering Report No. E310). These criteria are listed in table 7.

Table 7. BC Hydro LSM Building Stability Criteria
(Source: LSM Users Guide)

Building Type	DV [1,2]
Poorly Constructed	54 ft^2/s (5 m^2/s)
Well Built Timber	108 ft^2/s (10 m^2/s)
Well Built Masonry	162 ft^2/s (15 m^2/s)
Concrete	215 ft^2/s (20 m^2/s)
Large Concrete	377 ft^2/s (35 m^2/s)

1. Original calculations used m2/s units
2. Assumed to result in partial failure or total collapse of the structure.

Based on what is known from historic dam failure events that are thought to fit into the high severity range, decision was made to assume an interim DV value for the medium/high transition point at the BC Hydro value that corresponds to the partial failure or collapse of a well built masonry building. This value, which is approximately 160 ft2/s, would be combined with a rate of rise equal to or greater than 10 feet in 5 minutes. Table 8 describes flood severity rating criteria that are currently being applied to PAR using 2D modeling output.

Table 8. Flood Severity Rating Criteria for Use with 2D Modeling Output (Source: LSM Users Guide)

Flood Severity Rating	Rating Criteria
Low	DV less than 50 ft^2/s
Medium	DV equal to or greater than 50 ft^2/s and less than 160 ft2/s
High	DV equal to or greater than 160 ft^2/s combined with rate of rise of at least 10 feet in 5 minutes

Further research on building structural stability criteria may be conducted by BC Hydro and their affiliates in the future. Refinement of the values presented in tables 7 and 8 is possible. In addition, future research into dam failure case histories may help establish a more precise estimate of what quantifies as low, medium, and high flood severity.

Another possibility is the development of flood severity criteria that varies according to downstream conditions. For example, flooding in an area where PAR is located in sturdy multistory structures could have a different categorization of flood severity than flooding through a recreational area where PAR is camping in tents and trailers.

3.2 Analysis-Based Efforts to Refine Flood Severity Categorization in Relation to Fatality Rates

Flood severity and its relation to fatality rates is variable and highly subjective. A number of dam failure and other major flood event case histories exist where the location of fatalities could possibly be determined. This information, combined with a 2D hydraulic recreation of the flooding, could be used to refine fatality rates used for the various categorizations of flood severity contained in DSO-99-06.

Hydraulic recreation of historical dam failure case histories can be used to evaluate fatalities in relation to DV and rate of rise values. In some cases, there may be general information available on whether PAR fatality was located in a structure, and there may possibly be some assessment of the type of structure.

Recognizing the limitations inherent in the flood inundation modeling (modeling parameter assumptions, limited terrain data resolution, limitations of currently available computer hardware which places limits on the modeling), the goal would be to develop some generalized findings. However, these findings could provide some significant refinement to currently used fatality rates in relation to flood severity used by DSO-99-06.

3.3 Benchmark Studies and Model Enhancements

The Life Safety Model is sophisticated and will be continuously refined and further developed based on user requirements. Since 2007, a multi-agency, international effort has been underway to beta-test, refine and further develop this model. This consortium of LSM users/developers includes BC Hydro, Canada; TU Delft University, Netherlands; H.R. Wallingford, UK; University of British Columbia, Canada; University of New South Wales, Australia; and Reclamation. To date, two LSM models have been constructed by Reclamation, and a third is underway. BC Hydro has used the LSM extensively. H.R. Wallingford and TU Delft have both completed projects using the LSM.

The experience gained from conducting LSM simulations will assist Dams Sector partners in improving their understanding of the model, its advantages and strengths, as well as its weaknesses and limitations. By completing pilot studies, the participating entities also hope to develop ways to streamline the data preparation and model setup process.

There are ongoing efforts focused on the development of an ArcGIS interface to the LSM (referred to as LSMi). This project will result in the creation of a powerful toolset for conducting pre- and post-processing within a GIS environment. Also included in this effort is the development of a conversion tool that will enable the import of MIKE21 2D hydraulic modeling output to the LSM. Currently, the LSM will only read input from the Telemac 2D hydraulic model. The LSMi preprocessing module will allow rapid development and editing of complex road networks and building layouts. Some highlights of LSMi pre-processing features are as follows:

- A semi-automated routine can be used to distribute households within their respective census blocks in an effort to approximate residential building layouts. This data can be used in lieu of actual building location data for cases where this data does not exist.
- The ability to utilize spatial attributes to characterize PAR data parameters.
- Road network node linking and delinking tool will allow for more flexibility in designing realistic LSM evacuation scenarios.
- Creation of LSM input file attributes within a GIS environment allows the user to easily distinguish input parameter characteristics by geographic regions.

LSMi post-processing features will include the ability to spatially query output data attributes and to develop high quality ArcGIS-based animations.

In addition, USACE has been collaborating with Reclamation to develop a joint 'toolbox' for dam safety consequence estimation. The toolbox would include the life loss estimating methods currently in use by both agencies such as LIFESim, Simplified LIFESim, DSO-99-06, and the LSM. This toolbox will contain recommendations for their appropriate application resulting from comparison analyses. The intended purpose of this comparison is to identify the strengths and weaknesses of each model. Findings and conclusions of these studies will help determine which models are most appropriate for specific applications.

4. Application Example

In this section, two of the methods previously presented (DSO-99-06 procedure and Flood Comparison Method), are applied to a case study. This will provide additional insights regarding how to apply the models and how to deal with uncertainty.

The dam used for the case study, Sailfish Dam, is a hypothetical site. The earthen dam is located on Sailfish Creek. The dam was completed in 1926 with financing obtained from a group of real estate developers. The reservoir formed by Sailfish Dam is known as Sailfish Lake. The lake and dam are owned and managed by Sailfish Lake Homeowner's Association. The association's main source of income is from dues paid by property owners.

Sailfish Dam has a height (streambed at dam axis to dam crest) of approximately 44 feet. A 10-foot-wide free-overflow spillway with a crest 6 feet below the dam crest exists near the right abutment of the dam. The dam is operated to keep the lake level at the spillway crest elevation. During drought conditions, the water level has fallen several feet below the spillway crest. Sailfish Lake has a surface area of 160 acres and a shoreline of approximately 2.5 miles. The dam stores approximately 2,000 acre-feet of water with the lake at the spillway crest and 3,000 acre-feet with the lake at the dam crest. The drainage area upstream from the dam is approximately 25 square miles.

There are approximately 66 year-round lakefront residences at Sailfish Lake. Several hundred additional residences are located on streets that are parallel to the lake's shoreline. There is a narrow valley downstream from the dam; there is no development in the narrowest sections. Table 9 provides a summary of the areas that would be impacted by failure of Sailfish Dam. Note that Sailfish Creek empties into the Hammerhead River, 18 miles downstream from Sailfish Dam.

Table 9. Summary of Facilities Potentially Impacted by Failure of Sailfish Dam

Location	Description
Embankment to mile 1.9	No residences or other facilities
Mile 2.0	Sailfish Creek Campground
Mile 2.1 to mile 8.4	No residences or other facilities
Mile 8.5 to mile 9.5	Humpback Village
Mile 9.6 to mile 16.1	No residences or other facilities
Mile 16.2 to mile 17.9	Flounder City
Mile 18.0	Sailfish Creek empties into the massive Hammerhead River

4.1 DSO-99-06 Procedure

DSO-99-06 is used to estimate the loss of life resulting from the failure of Sailfish Dam for a range of situations. The following is a step-by-step evaluation:

Step 1 – Choose dam failure scenarios

In this example, three different failure scenarios are assumed – they are:

- Failure caused by piping during normal weather.
- Failure caused by intentional human actions under highest reasonable reservoir level.
- Failure caused by high reservoir levels or dam overtopping during a major flood.

For the first two failure scenarios, it is assumed that Sailfish Lake is at the level of the spillway crest. For the last failure scenario, it is assumed that the lake level is at or up to a few feet above the dam crest.

Step 2 – Choose time categories

The time when a dam fails has a major impact on the resultant losses. For any given level of occupancy, a nighttime failure will generally result in the worst outcome. Some downstream locations experience fluctuations in occupancy. The time categories chosen for evaluation are:

- Dam fails during the day;
- Dam fails during the night;
- Dam fails during summer vacation/travel season; and
- Dam fails during non-summer vacation season.

Step 3 – Evaluate areas flooded for each dam failure scenario

This step requires some type of analysis to determine the area flooded from dam failure. This dam failure flood information is used to estimate the number of people at risk, flood severity category, and fatality rates.

To satisfy State dam safety laws, a dam failure inundation study for Sailfish Dam was completed in 2002. The study evaluated the dam for two different failure scenarios. The first was for a failure with the lake level at the spillway crest elevation during normal weather conditions, and the second was for a failure with the dam overtopping by one foot during a major flood. Inundation maps were prepared for both of these scenarios, and covered the entire reach between the dam and Hammerhead River. The study and flood inundation maps show that failure of the dam with the lake level at the spillway crest elevation would result in a flooded area approximately 20 percent smaller and flood depths approximately 4 feet below those resulting from a flood-induced overtopping failure.

Step 4 – Estimate the number of people at risk for each failure scenario and time category

The inundation data obtained in step 3 is used in estimating PAR, which is defined as the number of people occupying the dam failure floodplain prior to the issuance of any warning.

Information for Sailfish Creek Campground was obtained by telephone interview with the onsite campground host. Campsites are close to Sailfish Creek and all would be flooded by a dam failure to a depth of at least 10 feet, regardless of whether the dam fails with the lake at the spillway crest elevation or dam crest elevation. The campground is closed from the day after Labor Day to the day before Memorial Day. From Memorial Day to Labor Day an average of 40 people over-night at the campground. This varies from approximately 20 people on weeknights to 90 people on weekend nights. During the day many people travel to a nearby flood-free recreation facility leaving only about 25 percent of the people at the campground. Large floods in the vicinity of Sailfish Creek Dam are caused by slow-moving thunderstorms that develop rapidly, usually in the late afternoon or evening. It is not anticipated that the appearance of cloud buildup would influence people's decisions to use the campground.

Information for Humpback Village, an incorporated community, was obtained using satellite view from Google® Maps in combination with the available dam failure inundation map. The population of Humpback Village is 842 people. Based on visually superimposing the inundation map (for an overtopping failure) on the aerial imagery, it was estimated that 60 percent of the community would be flooded (more precise estimates could have been developed using GIS). This equates to 505 people, rounded to 500 people. As stated in step 3, a failure of the dam with the lake at the spillway crest would result in a flood footprint 20 percent smaller than that from an overtopping failure. The PAR for failure with the reservoir at the spillway crest was assumed to be 400 people. Based on discussions with the Humpback Village Clerk, these estimates are reduced for a daytime failure because many people travel outside of the community for employment on weekdays and for recreation opportunities on weekends.

Information for Flounder City was obtained similarly to that for Humpback Village. Flounder City is much larger than Humpback Village. As people leave their residences, they are likely to remain in the community; therefore day and night PAR estimates are the same. The PAR downstream from Sailfish Dam is summarized in table 10.

Table 10. Number of People at Risk

	Dam Failure Cause							
	Piping During Normal Weather, or Intentional Human Action				High Reservoir Levels or Dam Overtopping During Flood			
	Summer Season		Non-Summer Season		Summer Season		Non-Summer Season	
Location	**Day**	**Night**	**Day**	**Night**	**Day**	**Night**	**Day**	**Night**
Sailfish Creek Campground (Mile 1.0)	10 (5 to 23)	40 (20 to 90)	0	0	10 (5 to 23)	40 (20 to 90)	0	0
Humpback Village (Mile 8.5 to 9.5)	200	400	200	400	250	500	250	500
Flounder City (Mile 16.2 to 17.9)	2,500	2,500	2,500	2,500	4,000	4,000	4,000	4,000
Total	**2,710**	**2,940**	**2,700**	**2,900**	**4,260**	**4,540**	**4,250**	**4,500**

Step 5 – Estimate when dam failure warnings would be initiated (based on discussions with personnel involved in creating dam-specific emergency action plans)

The volunteer-position public works coordinator (ad hoc dam tender) for the Sailfish Lake Homeowner's Association was contacted by telephone. She indicated that an emergency action plan was prepared in 2003 to meet State dam safety requirements. The plan was prepared by a local engineering firm. She indicated that the plan has not been reviewed or updated since it was developed. She further indicated that telephone numbers in the plan are probably outdated, especially since so many people have switched to cell phones in the last several years. She did remember that the dam is supposed to be monitored every few hours whenever a large rain storm occurs in the area and the lake is at least one foot above the spillway crest. It appears that the emergency procedures for this dam have several inadequacies and may not provide much benefit.

Sailfish Dam can be seen (during clear weather) from a few homes in the vicinity of the dam. No one lives in a location where they can observe the downstream face of the dam. The dam tender lives approximately two miles from the dam, outside immediate visibility of the dam. There is no road on the dam; moreover, only one road leads to the dam, and is generally impassible during heavy rains. Access to the dam would thus be one-quarter mile by a footpath.

It was judged that the emergency action plan for the dam would not significantly increase the chances of a timely warning being issued. It was concluded that the dam would likely be monitored (attended) during extreme flooding that could lead to an overtopping failure. Guidance for when dam failure warnings would be initiated was obtained from table 3. Table 11 summarizes the assumptions made regarding when dam failure warnings would be initiated.

Table 11. Sailfish Dam — Assumptions Regarding When Dam Failure Warnings Would Be Initiated

Failure Caused by Either Piping During Normal Weather or Intentional Human Action		Failure Caused by High Reservoir Levels or Dam Overtopping During Flood	
Day	Night	Day	Night
0.25 hrs after dam failure	1.0 hr after dam failure	0.25 hrs before dam failure	0.25 hrs after dam failure

The basis for the entries in table 11 is as follows: (1) for a failure caused by either piping or intentional human action, it was assumed that no one would be positioned to see the breach develop; (2) recognition of dam failure would come either from observations made by lakefront homeowners of an unexplained drop in the lake level, from observations of the breach once it becomes large enough for people to see, or from reports of flooding as the dam failure flood wave progresses downstream.

For a failure caused by high reservoir levels or dam overtopping during a major flood, it was assumed that the existence of the emergency action plan and the requirement for onsite dam monitoring would make this case fit the category "Many observers at dam" shown in table 3.

Step 6 – Estimate how often the warning time in downstream areas might fall in the none, some, and adequate categories

The amount of warning that is issued in any particular location depends on when a dam failure warning is initiated and how long it takes floodwater to travel from the dam to the location of interest. The dam failure inundation study for Sailfish Dam provided a table indicating that the leading edge of the dam failure flooding would reach Sailfish Creek Campground in 0.2 hours, Humpback Village in 1.8 hours, and Flounder City in 3.4 hours.

Table 12 summarizes the amount of warning time (in hours) for each failure scenario, time, and location.

As shown in table 12, no formal warning would be issued in Sailfish Creek Campground for nearly all failure scenarios and time periods. Some or adequate warning would be issued at Humpback Village. Due to the distance between the dam and Flounder City, and the several hours of flood wave travel time, adequate warning would be issued for all failure scenarios and time periods .

Table 12. Warning Time Available for Each Location (hours)

	Dam Failure Cause							
	Piping During Normal Weather, or Intentional Human Action				High Reservoir Levels or Dam Overtopping During Flood			
	Summer Season		Non-Summer Season		Summer Season		Non-Summer Season	
Location	**Day**	**Night**	**Day**	**Night**	**Day**	**Night**	**Day**	**Night**
Sailfish Creek Campground (Mile 1.0)	None	None	None	None	0.05	None	0.05	None
Humpback Village (Mile 8.5 to 9.5)	1.55	0.8	1.55	0.8	2.05	1.55	2.05	1.55
Flounder City (Mile 16.2 to 17.9)	3.15	2.4	3.15	2.4	3.65	3.15	3.65	3.15

Step 7 – Evaluate how well the flood severity is understood

"Flood Severity Understanding" is a factor that has an impact on fatality rates. The terms 'vague' and 'precise' are used to gauge the quality of the warning issued in areas downstream of the dam. Vague understanding means that warning issuers have not seen the actual dam failure or do not comprehend the true magnitude of the flooding. Precise understanding means that the warning issuers have an excellent understanding of the flood magnitude due to observations of the flooding made by themselves or others. Table 13 summarizes the assumptions regarding flood severity understanding for all failure scenarios and time periods.

Table 13. Flood Severity Understanding

	Dam Failure Cause							
	Piping During Normal Weather, or Intentional Human Action				High Reservoir Levels or Dam Overtopping During Flood			
	Summer Season		Non-Summer Season		Summer Season		Non-Summer Season	
Location	Day	Night	Day	Night	Day	Night	Day	Night
Sailfish Creek Campground (Mile 1.0)	N/A	N/A	N/A	N/A	Vague	N/A	Vague	N/A
Humpback Village (Mile 8.5 to 9.5)	Precise	Vague	Precise	Vague	Precise	Vague	Precise	Vague
Flounder City (Mile 16.2 to 17.9)	Precise	Precise	Precise	Precise	Precise	Precise	Precise	Precise

N/A: Not Applicable

Step 8 – Estimate the proportion of the PAR exposed to each of the three flood severity categories posed by the flood

The three inhabited areas located downstream from Sailfish Dam would receive distinctly different flooding. Rapidly rising floodwater would occur at Sailfish Creek Campground, and flood levels would quickly reach depths of 10 feet or higher in locations where campsites exist. Tents, tent trailers, and recreational vehicles would be extremely vulnerable to this flooding. The flood severity at the campground would likely be either medium or high. Under some circumstances, people may be able to find a safe temporary refuge in trees or by climbing onto floating debris.

The dam failure inundation map and supplemental hydraulic analyses provides insight into the flood levels at Humpback Village. For failures with the reservoir level at the spillway crest elevation, approximately 80 percent of PAR would be exposed to low flood severity and 20 percent to medium flood severity. For dam failure from overtopping, 50 percent of the PAR would be exposed to low flood severity and 50 percent to medium flood severity. At Flounder City, the inundation map and supplemental hydraulic analyses indicate that the flooding would reach a maximum depth in the community of up to 3 to 7 feet, depending upon failure scenario and location within the community. Low flood severity is assumed for the entire PAR for all flood scenarios. Table 14 provides a summary of the number of people at risk according to each flood severity category for each failure scenario, location, and time period.

Table 14. Number of People at Risk Exposed to Specific Flood Severity Categories

	Dam Failure Cause							
	Piping During Normal Weather, or Intentional Human Action				High Reservoir Levels or Dam Overtopping During Flood			
	Summer Season		Non-Summer Season		Summer Season		Non-Summer Season	
Location	Day	Night	Day	Night	Day	Night	Day	Night
Sailfish Creek Campground (Mile 1.0)	10 (5 to 23) M to H	40 (20 to 90) M to H	0	0	10 (5 to 23) M to H	40 (20 to 90) M to H	0	0
Humpback Village (Mile 8.5 to 9.5)	L: 160 M: 40	L: 320 M: 80	L: 160 M: 40	L: 320 M: 80	L: 125 M: 125	L: 250 M: 250	L: 125 M: 125	L: 250 M: 250
Flounder City (Mile 16.2 to 17.9)	L: 2,500	L: 2,500	L: 2,500	L: 2,500	L: 4,000	L: 4,000	L: 4,000	L: 4,000

Flood categories are Low (L), Medium (M), and High (H)

Step 9 – Select appropriate fatality rate based on the flood characteristics in each reach

Table 15 provides fatality rates based on the warning time described in step 6, flood severity understanding from step 7, and flood severity from step 8. The fatality rates were obtained from table 4.

Table 15. Fatality Rates

<table>
<tr><th rowspan="4">Location</th><th colspan="8">Dam Failure Cause</th></tr>
<tr><th colspan="4">Piping During Normal Weather, or Intentional Human Action</th><th colspan="4">High Reservoir Levels or Dam Overtopping During Flood</th></tr>
<tr><th colspan="2">Summer Season</th><th colspan="2">Non-Summer Season</th><th colspan="2">Summer Season</th><th colspan="2">Non-Summer Season</th></tr>
<tr><th>Day</th><th>Night</th><th>Day</th><th>Night</th><th>Day</th><th>Night</th><th>Day</th><th>Night</th></tr>
<tr><td>Sailfish Creek Campground (Mile 1.0)</td><td>0.15 to 0.75</td><td>0.15 to 0.75</td><td colspan="2">Not occupied.</td><td>0.15 to 0.75</td><td>0.15 to 0.75</td><td colspan="2">Not occupied.</td></tr>
<tr><td>Humpback Village (Mile 8.5 to 9.5):</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Low Severity Flooding ....</td><td>0.0002</td><td>0.007</td><td>0.0002</td><td>0.007</td><td>0.0002</td><td>0.0003</td><td>0.0002</td><td>0.0003</td></tr>
<tr><td>Medium Severity Flooding ....</td><td>0.01</td><td>0.04</td><td>0.01</td><td>0.04</td><td>0.01</td><td>0.03</td><td>0.01</td><td>0.03</td></tr>
<tr><td>Flounder City (Mile 16.2 to 17.9)</td><td>0.0002</td><td>0.0002</td><td>0.0002</td><td>0.0002</td><td>0.0002</td><td>0.0002</td><td>0.0002</td><td>0.0002</td></tr>
</table>

Step 10 – Present life loss estimates

Loss of life estimates are determined using the pre-evacuation PAR shown in steps 4 and 8, and the fatality rates shown in step 9. Table 16 provides loss-of-life estimates.

Table 16. Estimated Loss of Life

	Dam Failure Cause							
	Piping During Normal Weather, or Intentional Human Action				High Reservoir Levels or Dam Overtopping During Flood			
	Summer Season		Non-Summer Season		Summer Season		Non-Summer Season	
Location	**Day**	**Night**	**Day**	**Night**	**Day**	**Night**	**Day**	**Night**
Sailfish Creek Campground (Mile 1.0)	1.5 to 7.5 (0.75 to 17.25)	6 to 30 (3 to 67.5)	Not occupied.		1.5 to 7.5 (0.75 to 17.25)	6 to 30 (3 to 67.5)	Not occupied.	
Humpback Village (Mile 8.5 to 9.5):								
Low Severity-Flooding	0.03	2.24	0.03	2.24	0.025	0.075	0.025	0.075
Medium Severity Flooding	0.4	3.2	0.4	3.2	1.25	7.5	1.25	7.5
Flounder City (Mile 16.2 to 17.9)	0.5	0.5	0.5	0.5	0.8	0.8	0.8	0.8
Total (with fractional values)	2.4 to 8.4 (1.7 to 18.2)	11.9 to 35.9 (8.9 to 73.4)	0.9	5.9	3.6 to 9.6 (2.8 to 19.3)	14.4 to 38.4 (11.4 to 75.9)	2.1	8.4
Total (rounded)	2 to 8 (2 to 18)	12 to 36 (9 to 73)	1	6	4 to 10 (3 to 19)	14 to 38 (11 to 76)	2	8

Table 16 shows the loss of life calculated with fractional values and with rounded numbers. During the non-summer season, loss of life ranges from 1 for daytime piping during normal weather or intentional human actions up to 8 for overtopping during a major flood at night. Much higher values occur during the summer season when the Sailfish Creek Campground is in use. The loss of life estimated for Sailfish Creek Campground represents the average summer occupancy multiplied by fatality rates ranging from 0.15 to 0.75, and the value in parentheses represents a range based on a low estimate calculated by multiplying the weekday occupancy by a fatality rate of 0.15 and a high estimate calculated by multiplying the weekend occupancy by a fatality rate of 0.75. A failure of Sailfish Dam on a summer weekend could result in as many as 68 fatalities in Sailfish Creek Campground.

Step 11 – Evaluate how uncertainties in various parameters affect overall uncertainties in life loss estimates

The loss of life estimates, summarized in table 14, ranging from 1 to 76 are based on many assumptions. There are many different ways in which a failure at Sailfish Dam would actually unfold. The following are some factors that could influence the event scenario and corresponding loss of life:

- Dam is (or is not) able to withstand several feet of overtopping before the breach begins to form.
- Breach initiation time or breach development time is much different than that upon which the inundation study is based.
- Flooding in downstream areas rises much faster (or slower) than anticipated.
- Breach width is much larger (or smaller) than that used in developing the dam failure inundation maps.
- Flood travel times are faster (or slower) than shown in the inundation study or on the inundation maps.
- Through chance, people fishing near the dam find a large sinkhole and alert officials several hours before the breach begins to form.
- Dam tender provides excellent (or poor) decision making regarding the need to warn/evacuate people in downstream areas.
- Campers at Sailfish Creek Campground observe rapidly rising water and hastily warn others. People do / do not respond to the information they receive.
- Campers at Sailfish Creek Campground are young and fit (or are not), with some campers capable of surviving after being swept into the rushing Sailfish Creek.

The organization preparing a dam failure loss of life analysis must decide how to evaluate uncertainty. DSO-99-06 contains additional information on uncertainty as well as a range of fatality rates that can be used with each combination of flood severity, warning time, and flood severity understanding. The largest contributors to uncertainty are related to flood severity and warning time. Variations thereof significantly alter the loss of life estimates.

4.2 Flood Comparison Method

In this section, the Flood Comparison Method is applied using the same case study, Sailfish Dam. This method can be used for Sailfish Dam because the reservoir, when full, stores less than 5,000 acre-feet of water. The following is a step by step evaluation:

Step 1 – Choose dam failure scenario to evaluate

It is assumed that the dam fails with the reservoir water surface at the crest of the dam.

Step 2 – Determine area flooded from dam failure

Froehlich's equation of Qp = 40.1V 0.295H 1.24 is used to estimate the peak outflow from dam failure. With an H of 44 feet and a V of 3,000 acre-feet, the peak outflow from dam failure is 46,400 ft3/s. The peak discharge at downstream locations can be estimated using figure 1. If inundation maps are not available, these discharges can be used with Manning's equation to approximate a flood depth or elevation from which flood boundaries can be determined.

Step 3 – Estimate the number of people at risk from dam failure

The number of people at risk can be derived from existing inundation mapping or from the simplified analysis described in step 2. In this example, PAR will be the same as that used in demonstrating the use of DSO-99-06. The Flood Comparison Method is most appropriate for use during a nighttime failure with no warning. For that reason, only nighttime PAR is considered. The PAR is summarized in table 17.

Table 17. Number of People at Risk (at Night) from the Failure of Sailfish Dam with the Reservoir Water Surface at Dam Crest

Location	Season	
	Summer	Non-summer
Sailfish Creek Campground (Mile 1.0)	40 average (20 on weekdays and 90 on weekends)	0
Humpback Village (Mile 8.5 to 9.5)	500	500
Flounder City (Mile 16.2 to 17.9)	Not included because community is more than 15 miles downstream from dam	Not included because community is more than 15 miles downstream from dam
Total	**540**	**500**

Step 4 – Evaluate the danger posed by the flood

Compare the peak discharge from dam failure to a more common flood. At mile 3, the peak discharge would be approximately 90 percent of that at the dam and at mile 7, the peak discharge would be approximately 80 percent of that at the dam. The peak discharges from dam failure are 46,400 ft3/s, 41,800 ft3/s, and 37,100 ft3/s at the dam, at mile 3, and at mile 7, respectively. The 10-year flood discharge can be obtained from the U.S. Geological Survey's "National Streamflow Statistics Program." The 10-year flood is 1,400 ft3/s, 2,300 ft3/s, and 4,500 ft3/s at the dam; at mile 3, and at mile 7, respectively. The ratio of peak discharge from dam failure to the 10-year flood at the same locations is 33, 18, and 8, respectively.

Step 5 – Select fatality rate based on flood ratio and distance from dam

Using the flood ratios from step 4, fatality rates for estimating loss of life from dam failure were obtained from table 5. Table 18 displays the fatality rates applicable to the failure of Sailfish Dam.

Table 18. Fatality Rates for Estimating Loss of Life Resulting from the Failure of Sailfish Dam

Reach (distance from dam, in miles)	Ratio of peak discharge from dam failure to 10-year flood peak discharge	Fatality Rate
0.0 to 3.0 (This reach includes Sailfish Creek Campground at mile 1.0)	33	.25
3.0 to 7.0 (There are no people at risk in this reach)	18	.08
7.0 to 15.0 (This reach includes Humpback Village between miles 8.5 and 9.5)	8	.01

Step 6 – Loss-of-Life Estimates

The loss of life resulting from failure of Sailfish Dam is determined using the number of people at risk shown in table 17 combined with the fatality rates shown in table 18. Estimated loss of life is shown in table 19.

Table 19. Loss of Life Resulting from the Failure of Sailfish Dam

Reach	Season	
	Summer	Non-Summer
0.0 to 3.0 (This reach includes Sailfish Creek Campground at mile 1.0)	10 average (5 on weekdays and 23 on weekends)	0
3.0 to 7.0 (There are no people at risk in this reach)	0	0
7.0 to 15.0 (This reach includes Humpback Village between miles 8.5 and 9.5)	5	5
More than 15 miles downstream	Not included using this method	Not included using this method
Total	**15 (10 to 28)**	**5**

Acronym List

ArcGIS	Environmental Systems Research Institute Geographical Information System software program
1D	One dimensional
2D	Two dimensional
DAMBRK	National Weather Service Dam Break Flood Forecasting Model
DHI	Danish Hydraulic Institute
DHS	Department of Homeland Security
Djam	Traffic jam density of a given road class
DV	Flood depth multiplied by velocity
EAP	Emergency Action Plan
EMA	Emergency Management Area
EPZ	Emergency Planning Zone
FEMA	Federal Emergency Management Agency
fh	Floor Height
GIS	Geographic Information System
HAZUS-MH	Hazard-United States-Multi-hazard
HEC-DSS	Hydrologic Engineering Center-Data Storage System
HEC-FIA	Hydrologic Engineering Center-Flood Impact Analysis
HEC-RAS	Hydrologic Engineering Center-River Analysis System
HSPD	Homeland Security Presidential Directive
LIFESim	A model for estimating Dam Failure Life Loss
LSM	Life Safety Model
LSMi	Life Safety Model with ArcGIS interface
MIKE	Suite of DHI Models (MIKE11, MIKE21, MIKEFlood)
NIPP	National Infrastructure Protection Plan
NJS	Non-Jurisdictional Size
NWS	National Weather Service
PAR	Population At Risk
PARG	Population At Risk Groups
PARU	Population At Risk Units
Reclamation	Bureau of Reclamation
RMNP	Rocky Mountain National Park
USACE	U.S. Army Corps of Engineers
Vjam	Minimum stop-and-go speed when Djam is exceeded

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Appendix A: Synopsis of Notable United States Dam Failures

Most dam failures, especially those that caused large loss of life, have been extensively studied to determine the cause of failure. Investigators focused very little on why fatalities did or did not occur and the factors that influenced the resultant loss of life. This section provides a summary of notable U.S. dam failures including factors that influenced loss of life. The following dams are summarized:

- Dam failures listed in table 2 that caused 25 or more fatalities (with the exception of Lower Otay Dam):
  - Mill River Dam, 1874;
  - South Fork Dam, 1889;
  - Walnut Grove Dam, 1890;
  - Austin Dam, 1911;
  - St. Francis Dam, 1928;
  - Buffalo Creek Coal Waste Dam, 1972;
  - Canyon Lake Dam, 1972;
  - Laurel Run Dam, 1977; and
  - Kelly Barnes Dam, 1977.
- Additional relevant cases:
  - Baldwin Hills Dam, 1963 (flooding within an urbanized area near Los Angeles);
  - Teton Dam, 1976 (failure of a large dam); and
  - Ka Loko Dam, 2006 (recent U.S. dam failure causing fatalities).

The dams are described chronologically based on the failure date. The summary for each dam provides information on dam characteristics, dam history, failure cause, dam failure detection, decision to warn, issue of warnings, flooding, and losses from the flooding. Factors affecting the outcome of each event are described. Some factors promoted chances for a successful (no loss of life) outcome, while others hindered success. Some factors were related to chance or were beyond the control of, or not quickly influenced by, dam operators (dam tenders) and public safety officials. It is important to appreciate the contribution of these factors to dam failure outcome. For example, dams that failed during daylight hours could have just as easily failed at night, and vice versa. Other factors were, to a greater or lesser degree, within the immediate control of, or could be influenced by, these officials.

Mill River Dam, Massachusetts – Failed in 1874

Mill River Dam (also known as Williamsburg Dam) was located in western Massachusetts, north of Northampton. The dam was of earthfill construction with a masonry core wall. Mill River Dam failed at 7:20 am on Saturday, May 16, 1874. The 9-year-old dam failed as seepage carried away fill, causing embankment sliding and ultimately resulted in the collapse of the masonry core wall.

Factors Affecting the Loss of Life Resulting from the Failure of Mill River Dam

Positive Factors	Negative Factors
Not Controllable	
• Dam failed in daytime (7:20 am). Daylight provided the opportunity to see. • No flooding downstream prior to arrival of dam failure flooding – allowed warning to be issued and for people to escape. • Flood path was narrow, so only a few minutes would be needed to walk to safety. • No people at risk in first 3 miles downstream from the dam.	• Steep narrow valley caused high-velocity flow, which swept away many houses. Flood reached depth of 20 to 40 feet. • With technology of the era, no way to communicate between dam and downstream areas. • Several mill-based communities located between 3 and 7 miles downstream from the dam. Structures were placed in valley areas – prone to flooding.
Controllable	
• Gatekeeper (dam tender) lived at dam and observed dam deterioration the morning of the failure. • Gatekeeper traveled by horseback to the community downstream and conferred with reservoir officials. • Another person ran downstream from near dam to alert people.	• Gatekeeper reached Williamsburg, on tired horse, and then discussed situation with reservoir official – warnings delayed. • No consideration for how to quickly notify people using existing social and horse-based transportation systems. • Many people received either no warning or only a few minutes of warning. • Some of the people issuing or spreading the warning had not seen the flood and hence did not know the authenticity of the event or the size of the ensuing flood. • It may be that people could not envision a large flood with the normal weather that existed.

The dam had a height of 43 feet, and at the time of failure, the water was 4 feet below the dam crest. The dam had a crest length of 600 feet. The reservoir volume at the time of failure was 307 acre-feet. The drainage area upstream from the dam was approximately 3 square miles.

The gatekeeper (dam tender) rode 3 miles on horseback to warn the town of Williamsburg (the nearest town and the first settlement in the path of the flood) after observing the large slide. Another person living near the dam ran 2 miles in 15 minutes after seeing the top of the dam break away.

The gatekeeper, who had not seen the large reservoir outflow, got to Williamsburg at about the time the dam failed. Many people received either no warning or only a few minutes of warning.

A flood from 20 to 40 feet in height destroyed brass, silk, and button mills. Boarding houses, houses, and barns were also crushed or swept away. There were approximately 750 people left homeless and 138 fatalities. The total PAR was 888. The fatality rate was approximately 0.16. The dam was never rebuilt.

South Fork Dam (Johnstown Flood), Pennsylvania – Failed in 1889

The South Fork Dam (also known as Johnstown Dam) caused the famous "Johnstown Flood," one of the worst natural disasters in United States history. The dam was located in western Pennsylvania, approximately 70 miles east of Pittsburgh. The dam was of earthfill construction and was originally built for supplying water to a canal system. At the time of failure, it was owned by a recreation club (The dam was never rebuilt; a portion of the area near the dam is a National Memorial, operated by the U.S. National Park Service).

The South Fork Dam pm was completed in 1853. In 1862 a serious break in the dam occurred with a partially full reservoir. The breach caused little downstream damage. The dam was soon abandoned and remained so for 16 years. The site was then acquired by the South Fork Hunting and Fishing Club of Pittsburgh that repaired the dam and put it back into service in 1881. The dam failed at 3:10 pm on Friday, May 31, 1889 from overtopping during an approximate 25-year precipitation event. Prior to the failure, the spillway had been partially blocked using a screen to prevent fish from escaping from the lake.

The dam had a height of 72 feet and the reservoir volume at the time of failure was 11,500 acre-feet. The drainage area upstream of the dam was 48.6 square miles (ASCE Transactions, June 1891).

In the hours prior to the failure, people were at the dam trying to prevent the dam from failing. Between 11:30 am and noon, the resident engineer reached the town of South Fork, 2 miles from the dam, with a warning. A message was telegraphed to Johnstown indicating that the dam was in danger. Five people in South Fork ultimately died as a result of the dam failure.

In Johnstown, (located 14 stream miles downstream from the dam) warnings were not widely disseminated. Little attention was paid to the warnings that were issued due to false alarms that had occurred in previous years. Prior to the arrival of dam failure flooding, Johnstown was already flooded with depths of up to 10 feet in some locations. This pre-failure flooding hindered warning and evacuation and was one of the reasons for the large life loss.

Factors Affecting the Loss of Life Resulting from the Failure of South Fork Dam

Positive Factors	Negative Factors
Not Controllable	
• Dam failed in daytime (3:10 pm). Daylight provided the opportunity to see. • Largest number of people at risk were located far from dam (beginning at mile 11).	• Water backed up behind a 78-foot high railroad viaduct, 5 miles downstream from South Fork Dam, which then collapsed, likely causing a surge of water downstream. • Many houses were swept away. For example, in Woodvale, mile 12.5, nearly every structure was destroyed. • Flooding in Johnstown that preceded dam failure (up to 10 feet) made exit routes impassible and prevented last minute escape. • Whistles on train and some mills sounded, but people may not have understood the intent or meaning. Some thought it meant fire. • Some people thought dam failure would increase water levels only a few feet. • Foul weather – rain may have reduced visibility or muffled sounds.
Controllable	
• Workers at dam tried to prevent dam failure. • Three separate warnings were relayed downstream to alert people to danger.	• Warning did not reach all communities. No warning issued in Woodvale (314 dead) or Johnstown (1,114 dead). • First warning given by someone without a reputation, people did not know him, and he was young. Other warnings seemed to be issued by less than authoritative sources. Warning considered by some officials as rumor rather than fact. • Warning messages sent downstream were not forceful "South Fork Dam is liable to break: notify the people of Johnstown to prepare for the worst," and "The dam is becoming dangerous and may fail." • False (dam failure) warnings had been issued on prior occasions. • No standard method to warn the public.

Floodwaters reached Johnstown approximately one hour after dam failure. There were a large number of buildings destroyed. Some people survived by climbing out of second story windows and then jumping from rooftop to rooftop of moving buildings. There were approximately 20,000 people at risk and 2,209 fatalities. Most of the fatalities occurred within a few miles of Johnstown. The overall fatality rate was approximately 0.11.

Walnut Grove Dam, Arizona – Failed in 1890

Walnut Grove Dam was located on the Hassayampa River approximately 30 river miles upstream from Wickenburg, Arizona. Most of the area between the dam and Wickenburg was sparsely populated in 1890, just as it is now (2009). The rockfill dam was constructed to provide water for irrigation and gold placer mining.

The dam failed at approximately 2:00 am on Saturday, February 22, 1890. The dam was completed in October 1887, and thus only 2 years old when it failed. The dam withstood 3 feet of overtopping for 6 hours before failing.
Walnut Grove Dam had a height of 110 feet and the reservoir volume at the time of failure was approximately 60,000 acre-feet, which is large in comparison to most other dams that have failed in the United States. The drainage area upstream of the dam was approximately 262 square miles.

Factors Affecting the Loss of Life Resulting from the Failure of Walnut Grove Dam

Positive Factors	Negative Factors
Not Controllable	
• Few people at risk in first 14 miles downstream from dam. • Some people were awakened by the roar caused by the flood and were able to climb to high ground before the flood arrived.	• Failed at night (2 am). –Flood swept through populated area in the dark. • Telegraph not available for people at risk. • Floodwaters deep – 60 to 80 feet. • People in structures that would not withstand flooding: tents and small cabins. • A dam, under construction 14 miles downstream, failed due to the flood. People at risk were at a construction camp and headquarters camp downstream.
Controllable	
• Likelihood of failure recognized early – Employee sent on horseback to warn people 11 hours before failure. • Efforts were made to prevent dam from failing – battle lost.	• Warning did not reach downstream area because messenger(s) drowned and/or stopped in saloon and did not continue.

Approximately 11 hours before dam failure, the superintendent of the water storage company directed an employee to ride by horseback to warn people at a construction camp for another dam that was located approximately 15 miles downstream. The rider on horseback never reached the construction camp. This was partially due to flooding on his route to the camp. The majority of people in the construction camp were asleep when the flood arrived. Some heard the roar of the approaching flood and scrambled up the hillside through rocks and cactus. Floodwaters reached depths of 50 to 90 feet in the canyon downstream of the dam. The number of people at risk is not known. There were approximately 70 to 100 fatalities; however, record keeping was not precise. The dam was not rebuilt.

Austin Dam, Pennsylvania - Failed in 1911

Austin Dam was located in north-central Pennsylvania approximately 60 air miles north of State College, Pennsylvania. It was 1.5 miles upstream from the town of Austin, a community of around 2,300 in 1911. The concrete gravity dam was constructed to provide a water supply for a pulp and paper company.

The dam failed at 2:00 pm on Saturday, September 30, 1911. The dam was completed in November 1909, thus less than 2 years old when it failed. The dam failed due to weakness in the foundation or in the bond between the foundation and concrete.

Austin Dam had a height of between 43 and 50 feet (conflicting data available), and the reservoir volume at the time of failure was between 550 and 850 acre-feet.

Factors Affecting the Loss of Life Resulting from the Failure of Austin Dam

Positive Factors	Negative Factors
Not Controllable	
• Dam failed in the daytime (2 pm). Daylight provided the opportunity to see the danger. • No adverse weather; no rain at the time of dam failure. • Dam was visible from nearby homes; person in one of these homes used telephone to convey dam failure observation.	• Narrow valley, high velocities, lots of debris in flood water. • Failure of a concrete dam results in a very rapid increase in peak outflow compared to the failure of an embankment dam. • There were people at risk a short distance downstream from the dam. Austin, where most deaths occurred, was about 1.5 miles downstream. • The topography of the area (steep hillsides) precluded building in areas that would have been safe from the type of flooding that the dam failure caused. • Obstructions (fences) hampered evacuation.
Controllable	
• Mill whistle blown to alert/warn people after dam failure discovered. • Warning disseminated by telephone operator/ switchboard after call came in from dam failure observer.	• No dam failure warnings issued prior to dam failure. • No plans or procedures for warning people in the event of a dam failure. • No dam failure inundation maps available. • Mill whistle had blown twice earlier in day, causing some people to ignore the whistle when it blew again to warn of dam failure.

A person living in a house on the mountain slope near the dam phoned an Austin telephone operator moments after the dam failed. The phone operators warned others, and the paper mill whistle sounded. Many people ignored the warnings. The mill whistle had blown twice earlier in the day as false signals had been received from telephone employees who were repairing telephone lines. A person on a bicycle rode from Austin to Costello, 2 miles downstream, to warn people.

The floodwater traveled from the dam to the town of Austin in either 11, 20, or 30 minutes (conflicting data available). Some of Austin's 2,300 people may have resided in areas untouched by the floodwater. There were 78 fatalities, all within the first 2 miles downstream of Austin Dam. The dam was never rebuilt. It is currently under the jurisdiction of the Austin Dam Memorial Association.

St. Francis Dam, California – Failed in 1928

St. Francis Dam was located approximately 37 air miles north-northwest of downtown Los Angeles. The arched concrete gravity dam was constructed to augment the Los Angeles water supply.

St. Francis failed at approximately midnight, March 12-13, 1928. The flood traveled from the dam, 54 miles to the Pacific Ocean, in a five and one-half hour period during the early morning hours of Tuesday, March 13. The dam was completed in 1926, so the dam was 2 years old when it failed. Failure of this recently constructed dam was caused by sliding on weak foliation within the schist comprising the left abutment, suspected of being part of an old landslide.

St. Francis Dam had a height of 188 feet, and the reservoir volume at the time of failure was about 38,000 acre-feet. The reservoir was approximately 3 feet below the crest of the parapet at the initiation of dam failure.

The failure sequence for this dam can be considered a worst case scenario. The failure occurred in the middle of the night when many people were asleep and darkness prevented people from observing the events that were occurring. The dam failed suddenly with no warning being issued before failure, and the entire contents of the reservoir drained in less than 72 minutes. The dam tender was unable to alert anyone of the danger. He and his family lived in the valley downstream of the dam and perished in the flood.

The Ventura County Sheriff's Office was informed at 1:20 am Telephone operators called local police, highway patrol, and phone company customers. Warning was spread by word of mouth, phone, siren, and law enforcement in motor vehicles.

Flooding was severe through a 54-mile reach from the dam to the ocean. The leading edge of the flooding moved at about 18 miles per hour near the dam and 6 miles per hour nearer the ocean. There were approximately 3,000 people at risk and approximately 420 fatalities, although the number of fatalities reported varies significantly. The fatality rate for the entire reach was approximately 0.14. It was much higher than this near the dam and much lower as the flood neared the Pacific Ocean. The dam was not rebuilt.

Factors Affecting the Loss of Life Resulting from the Failure of St. Francis Dam

Positive Factors	Negative Factors
Not Controllable	
• California had far fewer people in 1928 than today. • No major towns or cities in areas where flooding was most severe. • At the major communities, Fillmore and Santa Paula, only a small portion was flooded.	• Dam failed at midnight. Flood swept through populated area in the dark and when people would normally be asleep. • This concrete dam failed suddenly and completely, resulting in a wall-of-water varying in depth from 100 to 140 feet for the first few miles downstream. • Massive damage: 909 buildings or structures totally destroyed and 331 damaged.
Controllable	
• Although upstream areas received no warning, warnings were issued farther downstream starting around 1:20 am, when flood front had already traveled approximately 17 miles. • Upon learning of and verifying the failure, telephone operators called local police, highway patrol, and phone company customers. Warning spread by word of mouth, phone, siren, and vehicle.	• No warnings issued before dam failure. No warnings issued for at least the first 17 miles downstream from the dam. • No plans or procedures had been established for warning and evacuating people. • California Edison Construction Camp at mile 17 could have been established in a more secure location. About 60% of people at this temporary facility died.

Baldwin Hills Dam, California – Failed in 1963

Baldwin Hills Dam was located in a hilltop area approximately 8 miles southwest of the Los Angeles City Hall. The dam was operated by the Los Angeles Department of Water and Power. Many people living downstream of the dam were unaware of its existence. The earthfill dam stored municipal water.

The 12-year-old Baldwin Hills Dam failed at 3:38 pm on Saturday, December 14, 1963. Failure of the dam, on a bright and sunny day, was attributed to subsidence leading to a piping breach.

Baldwin Hills Dam was 65.5 feet high and the water depth was 59 feet at the time of failure. The reservoir contained 660 acre-feet when the break started.

Factors Affecting the Loss of Life Resulting from the Failure of Baldwin Hills Dam

Positive Factors	Negative Factors
Not Controllable	
• Dam failed in the daytime (3:38 pm). Daylight provided the opportunity to see the danger. Resources for warning were ready. • Failed on Saturday, when many families were together. • Clear, pleasant weather; high temperature in Los Angeles was 67°F. • Easy access to dam by vehicle for confirmation of danger. • Dam located in a major city with a wealth of community resources. • Key city officials were already meeting at the mayor's office when police received official notification of dam's critical condition. This allowed for rapid inter-organizational decision making. • Slowness of breach initiation provided time for decision making and warning.	• Dense urban area impacted. • The hilltop dam was not visible to the downstream residents. Many people receiving the warning had no idea that a dam existed upstream. • Significant flood impacts – 1,400 residential units affected by the flood and 3,000 automobiles damaged.
Controllable	
• Early detection of dam deterioration – reservoir caretaker observed abnormalities approximately 4.5 hours before dam failure. • Warning issued before dam failure. • Los Angeles Dept. of Water and Power's Chief Engineer spoke by phone with L.A. Police Chief about 2 hours before failure and provided a description of the area (bounded by major roadways) within which the worst flooding would probably be confined. • Excellent warning issued – Signal alerts issued through commercial radio and television, helicopters with bullhorns, police officers going door to door, and police cruising through area in police cars and motorcycles. • Attempts were made to lower reservoir after abnormal seepage was discovered.	• No dam failure inundation map was available. • No emergency action plan (specific to dam failure) was available. • At least 1,000 people (out of 16,500 people at risk) remained in the flood zone when the flood passed through.

Shortly after 11 am, on regular rounds, the reservoir caretaker, noting an increase in the sound of running water in the drain system, drove to the base of the dam and entered an inspection tunnel. This led to a series of telephone calls to department personnel and several converged at the dam in the ensuing hours. Efforts were made to repair the leaking dam. At 1:45 pm, 1 hour 53 minutes before failure, the decision was made to evacuate the area downstream of the dam. Warnings to people in the area commenced at 2:20 pm by radio and television sigalerts (messages sent by special radio frequency to commercial broadcasters from the Los Angeles Police Department), by police going from door-to-door, and by a police helicopter equipped with a bull horn flying over the area. Dam failure inundation maps were not available. In a conversation with police officials, approximately 2 hours before dam failure, the Los Angeles Chief Engineer of Water Works described the area expected to receive heavy damage using major well known thoroughfares as boundaries.

The Disaster Research Center at the Ohio State University reported:

> "Several hundred people in the area either did not become aware of the warning or chose not to evacuate. These included both shoppers and residents of the areas. Many were swept along in the flood as they tried to escape on foot and some were trapped in their automobiles. These people, other persons in the process of evacuation, and others in more outlying neighborhoods who were not alerted, climbed rooftops and were rescued by helicopters operated by the Los Angeles Police Department, the Los Angeles County Fire Department, the Coast Guard, and private citizens. Helicopter pilots, many of whom operated in the dark, evacuated 1,000 residents during the disaster."

Approximately 1,400 residential units were affected by the flood. Of those, 41 (32 houses and 9 apartments) were completely destroyed and approximately 986 were damaged. Damage to the other units was mostly to yards and lawns. Damage also occurred at 43 businesses, 13 industrial properties, and to 3,000 motor vehicles. There were 5 fatalities and 27 people required hospitalization. The total PAR was 16,500. The fatality rate was 0.0003. The dam was not rebuilt.

Buffalo Creek Coal Waste Dam, West Virginia – Failed in February 1972

Buffalo Creek Coal Waste Dam No. 3 (commonly shortened to Buffalo Creek Coal Waste Dam) was located in the southwestern part of West Virginia, approximately 38 air miles south of Charleston. The non-engineered dam had been built by dumping waste rock and coal in the narrow valley. The purpose of the dam was to reduce stream pollution by impounding wastewater from a coal washing plant, thus allowing most of the sediment to settle.

The dam failed at about 8:00 am on Saturday, February 26, 1972. The dam was in a constant state of construction and reconfiguration before the failure, so in a sense the dam was brand new. The dam failed during a 2-year storm event from the slumping of the dam face.

Buffalo Creek Coal Waste Dam had a height of 46 feet and a reservoir volume of approximately 404 acre-feet when it failed. The drainage area upstream of the dam was only 1.1 square miles. Dam owner representatives were at the site monitoring conditions prior to dam failure. "At least two dam owner officials urged the Logan County Sheriff's force to refrain from a massive alert and exodus" (Charleston Gazette, 1972). Company officials issued no warnings. At 6:30 am, the senior dam safety official at the dam dismissed two sheriff deputies who were called to the scene to aid evacuation. Residents' reactions to the meager warnings issued were dampened due to at least four previous false alarms.

The flood traveled downstream through the 15-mile-long valley at approximately 5 miles per hour. Over 1,000 homes were either damaged or destroyed. There were approximately 4,000 people left homeless. There were 125 fatalities in the 15-mile reach, thus the fatality rate was about 0.03. Approximately 82 percent of the fatalities occurred in the first 6 miles downstream of the dam.

Factors Affecting the Loss of Life Resulting from the Failure of Buffalo Creek Coal Waste Dam

Positive Factors	Negative Factors
Not Controllable	
• Dam failed in the daytime (8 am). Daylight provided the opportunity to see the danger. • Some people in the upper part of the valley moved to a safer location before failure based on rumors that were circulating throughout the valley (Erikson: 27). • Safe areas could be reached by walking in just a few minutes.	• Dam failed by liquefaction (very suddenly); reservoir emptied in 15 minutes, creating sudden and rapid increase in flood discharges and water levels. • Steep stream gradient (2.2 feet per 100 feet in the vicinity of Saunders) resulted in high flood velocities. Lesser gradient downstream. • Steep and narrow downstream valley; nearly 100% of floodplain used for buildings. • High velocities in the canyon destroyed many homes and made survival difficult for people caught in the flood. • Frame houses on concrete slabs were easily swept away. • Many of the people living in the flooded valley were beholden to the company that owned the dam; perhaps this dampened their interest in getting the dam owner to improve the dam before it failed.
Controllable	
• The dam owner (by way of company employees) recognized that the dam was threatened and the dam was being closely monitored. • Dam owner officials were at or near the dam when it failed. • Some family members of coal company employees evacuated early. • The wife of one coal company employee drove down the canyon warning others.	• False alarms had occurred on at least four occasions (from citizen's report). • No emergency action plan available. • No dam failure inundation map available. • Company employee did not recognize (or admit that he recognized) the dangerous failure possibility: "I didn't think the dam would burst, I thought it might fill up and cut its way out." (Gazette-Mail, April 30, 1972). • Dam owner issued no dam failure warnings; "The senior official on the site dismissed two deputy sheriffs who had been called to the scene to aid evacuation in the event of trouble." (Erikson: 27). • No effective dam failure warnings issued. • Dam had no spillway; there was no way to lower reservoir level when conditions worsened. • The "dam" was not an engineered structure; poorly constructed and maintained.

The peak discharge resulting from dam failure is available for three locations. Less than 1 mile downstream of the dam, at Buffalo Creek below Saunders, the peak discharge resulting from dam failure was 50,000 ft3/s, and the 10-year flood at this site is 805 ft3/s, resulting in a ratio of dam failure discharge to 10-year discharge of approximately 62. About 7 miles downstream of the dam, at Buffalo Creek below Stowe, the peak discharge from dam failure was 13,000 ft3/s and the 10-year flood at this site is 2,100 ft3/s resulting in a ratio of dam failure discharge to 10-year discharge of approximately 6. About 12 miles downstream of the dam, at Buffalo Creek above Accoville, the peak discharge from dam failure was 8,800 ft3/s and the 10-year flood at this site is 2,820 ft3/s resulting in a ratio of dam failure discharge to 10-year discharge of approximately 3.

Canyon Lake Dam, South Dakota – Failed in June 1972

Canyon Lake Dam was located in the western part of Rapid City, in the Black Hills. The earthfill dam was located in a city park and was used for recreational purposes.

Canyon Lake Dam, located on Rapid Creek near Rapid City, failed between 10:45 pm and 11:30 pm on Friday, June 9, 1972. The 39-year-old dam failed from overtopping. The peak inflow to the reservoir was approximately 34,500 ft3/s and the peak dam failure outflow was approximately 60,000 ft3/s. The inflow greatly exceeded the 3,200 ft3/s spillway capacity at the dam.

The dam had a height of about 20 feet and a total volume of about 700 acre-feet was released during the failure. About 10,000 acre-feet passed the dam site during the entire flood sequence. The total drainage area upstream from the dam was 371 square miles; however, only about 51 square miles, located downstream of Reclamation's Pactola Dam, contributed to the inflow at Canyon Lake.

The extreme flooding on June 9 covered an area approximately 40 miles long and 20 miles wide along the eastern slopes of the Black Hills, from Sturgis on the north to Hermosa on the south, with Rapid City near the center. A flash flood warning was issued by the National Weather Service at 8 pm The warning did not carry with it a sense of urgency because of the complete lack of knowledge concerning the incredible amount of rain that was falling west of Rapid City. The 10 pm television news wrap-up indicated that the magnitude and seriousness of the flood was not realized at that time. At 10:30 pm., in a simultaneous television and radio broadcast, the mayor of Rapid City urged people in low-lying areas to evacuate. Dam failure warnings were not issued.

Water started flowing over Canyon Lake Dam at 10 pm (or earlier). Conflicting information is available on when the dam failed, with times ranging from 10:45 pm to 11:30 pm The flood in Rapid City covered an area up to one-half mile wide.

Factors Affecting the Loss of Life Resulting from the Failure of Canyon Lake Dam

Positive Factors	Negative Factors
Not Controllable	
• Dam could be seen from nearby homes. • Easy access to dam by vehicle for confirmation of danger. • Dam located on edge of Rapid City, with its wealth of community resources.	• Dam failed at night. Flood swept through populated area in the dark. • Foul weather – rain may have reduced visibility or muffled sounds. • Many residences impacted. Including those upstream from dam and on other drainages, 1,335 homes or mobile homes destroyed, and 2,820 suffered major damage. • Heavy rainfall was occurring throughout a large area. Extreme flooding occurred in a belt 40 by 20 miles. This made it difficult to focus resources in any one area, including Canyon Lake Dam. • Flooding that preceded dam failure may have made it difficult or impossible for some people to evacuate. • Power and telephone systems became inoperative during the flood limiting communication channels to warn of severe weather and imminent flooding.
Controllable	
• Large contingent of National Guard Reserves stationed nearby were called into action to block roads and to conduct search and rescue.	• Flash flood warnings issued by National Weather Service early in the evening did not carry a sense of urgency. • No emergency action plan was available. • No dam failure inundation map was available. • The magnitude and seriousness of the flood was not recognized during the 10 pm television news broadcast. • In simultaneous TV and radio broadcast at 10:30 pm, Rapid City mayor urged people in "low-lying areas to evacuate." (This message likely failed to convey the severity of the situation.) • Dam failure warnings were not issued prior to dam failure.

The Black Hills Flood (including flooding in areas not impacted by dam failure) caused approximately 238 fatalities and 3,000 injuries. There were approximately 35 fatalities in the 3 miles upstream of Canyon Lake Dam and 36 fatalities on streams other than Rapid Creek. There were approximately 165 fatalities on Rapid Creek downstream of Canyon Lake Dam. A major flood would have occurred on Rapid Creek through Rapid City even if Canyon Lake Dam had not failed. No one will ever know with certainty how many additional lives were lost as a result of the dam failure. The dam was rebuilt and the lake and surrounding area is a Rapid City municipal park.

Teton Dam, Idaho – Failed in 1976

Teton Dam was located in southeastern Idaho, approximately 39 air miles northeast of Idaho Falls. The earthfill dam, undergoing initial filling, was constructed to provide water for irrigation purposes.

The dam failed at 11:57 am on Saturday, June 5, 1976. At the time of failure, the sky was sunny or partly cloudy and the air temperature was 81° F. The dam was being filled for the first time when failure occurred as a result of piping of the dam core in the foundation key trench.

Teton Dam had a height of 305 feet, although at the time of failure the water level in the reservoir was 30 feet below the dam crest. The reservoir volume at the time of failure was approximately 250,000 acre-feet. The drainage area upstream of the dam was 840 square miles.

Teton Dam was unattended from 12:30 am until 7:00 am on the day of the failure. Between 7:00 am and 8:00 am, survey crew members discovered turbid leakage. At 9:30 am, the Project Construction Engineer considered alerting residents but did not issue an alert. He determined that an emergency situation was not imminent and he was concerned about causing undue panic. At 10 am, a larger leak was discovered with flowing turbid water. Between 10:30 am and 10:45 am the Project Construction Engineer notified the sheriff's offices and advised them to alert citizens.

Warnings were initiated a little more than an hour before dam failure. Warnings were issued by police and further spread by commercial radio and television as well as neighborly word of mouth and telephone. Live radio broadcasts had reporters at the dam and in fixed wing aircraft flying above the dam and above downstream communities. The daytime failure combined with clear weather resulted in many people obtaining an important visual cue – the sight of the dust cloud and debris near the leading edge of the flood wave. Most people were able to evacuate before the house-destroying flood water arrived.

The flood varied in intensity as it traveled 156 miles from Teton Dam to American Falls Reservoir. The flooding was much more severe near Teton Dam than it was farther downstream of the dam. Water depths ranged from approximately 75 feet near the dam to 50 feet near the mouth of the five-mile-long Teton River canyon, with velocities possibly exceeding 40 feet per second. The communities of Wilford and Sugar City (12.3 miles from the dam) were flooded by a 15-foot "wall of water" at approximately 1:00 pm The leading edge of the flood wave struck Rexburg (mile 15.3) about 1:40 pm and within minutes approximately 80 percent of the city was inundated to depths of 6 to 8 feet. Flooding began in Roberts (mile 43) approximately 9 hours after the initial failure and reached depths of 5 to 6 feet. Floodwaters reached Idaho Falls (mile 63) 13 hours after failure, but only minor flooding occurred because sandbag levees were erected. Flooding began at the Snake River near the Shelley U.S. Geological Survey (USGS) gauging station (mile 71) approximately 14 hours after failure. River levels then rose from 0.5 to 1.5 feet per hour for the next 21 hours until the peak discharge of 67,300 cubic feet per second was recorded.

Factors Affecting the Loss of Life Resulting from the Failure of Teton Dam

Positive Factors	Negative Factors
Not Controllable	
• Dam failed in the daytime (11:57 am). Daylight provided the opportunity to see the danger. Resources for warning were ready. • Failed on a Saturday, so families were together. • Clear, warm, weather; many people outside working on yards. • Area downstream from dam sparsely populated for many miles. • Few radio stations in area; dominant station from Rexburg covered event well. • Strong, tight-knit communities based on religion. • Easy access to dam by vehicle or air for confirmation of danger. • Roads from major communities to dam passable allowing travel to dam. • Airport 2 miles from Rexburg city center allowed officials to get airborne to see flood. • Telephones remained functioning, allowing spread of warnings. • Citizens Band Radio allowed spread of information. • Comfortable and safe evacuation destination – Ricks College.	• Some people expected the flood to be like a smaller flood that had occurred in 1962. • Massive damage: 771 homes destroyed and 3,002 damaged.
Controllable	
• Early detection of dam deterioration – approximately 7:00 am • Warning issued before dam failure. • On-site broadcast from a Rexburg radio station; with clarity and urgency, described crumbling dam. • People received multiple warnings – radio, friends, neighbors, etc. • Frequent inspections of the dam were required during initial filling. • Basic emergency notification strategy outlined in document titled: "Teton Emergency Notifications." • Many aircraft in the air to observe and report to ground personnel.	• Dam site unattended from 12:30 am to 7:00 am (Fortunately the dam didn't fail then.) • Reservoir in first filling – some people were unaware of large quantity of water behind dam. • Reservoir could not be lowered when leak discovered. • Fear of causing panic caused delay in initiating warning. • No staged evacuation (from upstream to downstream). • Inadequate warning in Teton Canyon. • No dam failure inundation map available. • No emergency action plan for dam and no emergency operations plans in downstream communities.

Floodwaters reached American Falls Reservoir (mile 156) at 12:30 am on June 7, approximately 36 hours after the failure of Teton Dam. The flood eventually covered between 150 and 200 square miles; flooding was several miles wide in some places.

The flooding destroyed or damaged more than 3,700 houses. There were approximately 25,000 people at risk. There were 11 fatalities and 800 injuries (including those from after-flood cleanup). There were six deaths from drowning, three from heart failure, one from accidental gunshot, and one from a self-inflicted gunshot. Ten of the eleven people who died had been warned of the impending flooding. The unwarned person who died was fishing off a small island in the Teton River when water began to rise. He and a fishing partner tried to swim to safety, but only his partner survived. The fatality rate was 0.00044. The dam has not been rebuilt.

Laurel Run Dam, Pennsylvania – Failed in July 1977

Laurel Run Dam was located on Laurel Run approximately 4 miles north of Johnstown (Laurel Run Dam should not be confused with the South Fork Dam which failed in 1889. Laurel Run Dam was located approximately 8 air miles from the South Fork Dam). After flowing out of Laurel Run Dam, water traveled approximately 2.5 miles before entering the Conemaugh River at a point that is approximately 3 river miles downstream from Johnstown. The earthfill dam was constructed to provide a water supply.

The dam failed at 2:35 am on Wednesday, July 20, 1977. The 63-year-old dam failed from overtopping during an area-wide storm (flood damage occurred throughout the Johnstown area).

Laurel Run Dam had a height of 42 feet. The reservoir had a storage capacity of 310 acre-feet with the reservoir at the spillway crest. The amount of water in the reservoir when it failed is not known, but perhaps was approximately 450 acre-feet.

The National Weather Service did not issue any flash flood watches or warnings for the Johnstown area until 2:40 am. The flashflood warning issued at that time was generic and did not name any specific area or stream within the two counties for which the warning applied.

There was no one at the site to observe the dam and no one decided to warn or evacuate. No warnings were issued in the 2.5-mile-long reach where the greatest devastation occurred. In addition, cues of the approaching dam failure floodwave, which might have allowed for a last-minute escape, may have gone unnoticed. Any last-minute escape/evacuation that did occur was surely hampered by the rain and darkness that accompanied the arrival of dam failure flooding. About 30 houses suffered major damage in the 2.5-mile-long reach. A memorial and plaque at the mouth of Laurel Run listed 40 different names when viewed in 1981 and it is presumed that all of the fatalities occurred in the first 2.5 miles downstream of the dam. The fatality rate was approximately 0.27. The dam was not rebuilt.

Factors Affecting the Loss of Life Resulting from the Failure of Laurel Run Dam

Positive Factors	Negative Factors
Not Controllable	
• Only 2.5-mile reach flooded; beyond mile 2.5, flood entered Conemaugh River with much larger capacity. • Only about 30 homes suffered major damage. • Although environmental cues (heavy rain, lightning) may have alerted people to danger, remaining in a home may have felt more comfortable or secure.	• Dam failed at night (2:35 am). Flood swept through populated area in the dark. • Media and public safety agencies not in operation at the time of failure. • Steep stream gradient (1.8 feet per 100 feet) resulted in high flood velocities. • Area-wide storm prevented attention from being focused on Laurel Run Dam area. • Area-wide storm caused power and telephone outages (uncertain if outages occurred in Laurel Run area).
Controllable	
	• No warnings of any kind by NWS until flash flood warning issued at 2:40 am for large area. "Neither the NWS component of the Flash Flood Warning System nor that part involving local communities and Civil Defense did much good for anyone in the Johnstown area." [NOAA, NDSR 77-1, page 59] • No one was at the dam to observe and initiate warnings. • No plans or procedures were established, and no consideration had been given to how to warn and evacuate people. • No dam failure warnings issued before dam failure. • No dam failure warnings issued after dam failure.

The drainage area at Laurel Run Dam was 7.9 square miles. The peak dam failure discharge was 37,000 ft3/s. The 10-year flood at this location is 920 ft3/s. The ratio of the dam failure peak discharge to the 10-year flood peak discharge is approximately 40.

Kelly Barnes Dam, Georgia – Failed in November 1977

Kelly Barnes Dam was located in northeast Georgia, approximately 0.5 stream miles upstream from Toccoa Falls and 2.5 air miles northwest of the City of Toccoa. The dam was earthfill over a rock crib. It was originally built for power generation, but in the years before failure was being used for recreational purposes.

Kelly Barnes Dam failed at approximately 1:20 am on Sunday, November 6, 1977. The dam was completed in 1899 with subsequent modifications. Parts of the dam were 78 years old when it failed. Failure of the dam was caused by heavy rains resulting in saturation of the embankment which led to downstream slope failure.
The dam had a height of 40 feet and the reservoir volume at the time of failure was approximately 630 acre-feet. The drainage area upstream of the dam was 4.6 square miles (Atlas HA-613).

"Two volunteer firemen, associated with the [Toccoa Falls Bible] college, were sufficiently concerned to examine the dam shortly after midnight, November 6. They could see nothing. However, continued rain caused them to become alarmed.

They were warning the residents in the flood plain below the dam of the potential for trouble when the dam broke" (USCOLD, 1977: 14). Other information indicates that the observation was made about 10:30 pm and the volunteer fire chief reportedly told a fellow fireman, "It's as normal as ever. I've seen it much higher many times" (Foster: 36). Dam failure warnings were not issued to the people at risk. Some environmental cues existed, but these did not give most people time to get out of harm's way during the dark of night. Two volunteer firemen died in the flooding and immediate family members of two other volunteer firemen also died.

A peak discharge of 24,000 ft3/s occurred near Forrest Hall college dorm, where the 10-year peak is approximately 1,175 ft3/s. Flooding was approximately 25 feet deep immediately downstream of the dam and 8 to 10 feet deep 1 mile downstream of the dam.

Factors Affecting the Loss of Life Resulting from the Failure of Kelly Barnes Dam

Positive Factors	Negative Factors
Not Controllable	
• No development in the first 0.5 miles between Kelly Barnes Dam and Toccoa Falls. • Beyond Georgia Highway 17 (1.8 miles from dam) flood dissipated and only 2 houses were damaged.	• Dam failed at night (1:20 am). Flood swept through populated area in the dark. • No one lived within sight of dam. • Dam failure flooding caused power outage, making it even more difficult for people to see. • Homes, dormitory and mobile homes (trailers) were very close to river. Some were threatened by the flooding that preceded dam failure. • Residential structures near stream channel, from Toccoa Falls to "Trailer Village" (from mile 0.5 to 1.3).
Controllable	
• As dam failure flooding swept through the narrow valley, a few people recognized the danger, including firemen, and made last minute attempts to warn people by word-of-mouth.	• No one remained at the dam to observe as rainfall continued and dam deteriorated. • Likelihood of dam failure was not recognized until water swept through populated area. • Dam failure warnings were not issued prior to dam failure. • Some people were being alerted to high water, but not to dam failure flooding.

Physical damage was confined to an area below Toccoa Falls to a path approximately 200 to 500 feet wide and 1.5 miles long. Nine houses, 18 trailer homes, and two college buildings were demolished. Four houses and five college buildings were damaged (Sanders, 1979: 2). The number of people at risk was approximately 250. There were 39 fatalities, all of which occurred in the first 1.5 miles downstream of the dam. Three of the deceased had been in Forrest Hall, 18 in permanent residences, 17 in trailer homes, and a volunteer fireman who did not live in the flooded area (Foster, 1978: 157 and Toccoa Record, 1977). The overall fatality rate was approximately 0.16.

Although only three people died in Forrest Hall dormitory (with approximately 75 occupants at the time of the flood), there was an average of approximately one fatality per flooded trailer and more than one fatality per flooded permanent residence. In 5 residences at 'residence row,' where the dam failure increased flood levels by 10 to 12 feet from pre-failure levels, 13 of the 22 people in the homes when the dam failure flood arrived died in these homes or in the process of escaping. This represents a fatality rate of approximately 0.6 (Foster: 50-68 and Sanders). The dam was not rebuilt.

The drainage area at Toccoa Falls College, 0.8 miles downstream of the dam, is 6.2 square miles. The peak discharge at this location resulting from dam failure was 24,000 ft3/s. The 10-year flood at this location is 1,260 ft3/s. The ratio of the dam failure peak to the 10-year flood peak discharge is approximately 19. At a location 4.5 miles downstream of the dam, the drainage area is 12.8 square miles. The peak discharge resulting from dam failure was 6,380 ft3/s at this location and the 10-year flood is 1,960 ft3/s, resulting in a ratio of dam failure discharge to 10-year flood peak discharge of approximately 3.3.

Ka Loko Dam, Hawaii – Failed in 2005

Ka Loko Dam was located in the northeast section of the island of Kauai in Hawaii. The dam was of earthfill construction and constructed in 1890 to provide a water supply for sugar cane production.

The dam failed at approximately 5:30 am on Tuesday, March 14, 2006. Sunrise on this day was at 6:47 am The dam, at the time classified as a low hazard potential structure, probably failed from overtopping after several weeks of very unusual, but not unprecedented, rainfall. Failure may have been caused by a reduction in spillway capacity that occurred in the late 1990's when "earth was moved into the emergency spillway, apparently as part of a grading process that created flat building sites around Ka Loko Reservoir" (Godbey report). Ka Loko Dam, as listed in the National Inventory of Dams, had a dam height of 44 feet and a maximum storage of 1,400 acre-feet.

Factors Affecting the Loss of Life Resulting from the Failure of Ka Loko Dam

Positive Factors	Negative Factors
Not Controllable	
• Minimal development in flooded area; only two or three structures were damaged or destroyed. • Some people were alerted to the flood by the tremendous noise. • A downstream dam was overtopped but did not fail, thus preventing an additional surge of water from moving downstream.	• Dam failed before sunrise (5:30 am). Flood swept through populated area in the dark. • No one lived within sight of dam. • The destroyed structures were very close to the stream, thus exposed to full force of flood. • Steep stream gradient (1.7 feet per 100 feet) resulted in high flood velocities (at location where structures destroyed).
Controllable	
	• No one was on site to observe the dam as it deteriorated. • Likelihood of dam failure was not recognized until water swept through populated area. • No plans or procedures were established, and no consideration had been given to how to warn and evacuate people. • No dam failure warnings issued before dam failure. • No dam failure warnings issued after dam failure.

The warning and evacuation represent a worst-case scenario. Although Kauai was under a flash flood watch when the dam failed, this probably provided no cause for alarm to people downstream of the dam. No one was at the dam when it failed. No warnings were issued in the 3.8-mile flood path between the dam and the Pacific Ocean. Environmental cues may have alerted some people to the danger. The flood made tremendous noise. One person was quoted as saying, "It sounded like 10 jet engines coming at us. Trees were cracking. You couldn't hear yourself talk."

At least one vehicle was swept off of Kuhio Highway, the main island road located 2.3 miles downstream from the dam. The three occupants survived. Most reports indicate that only two homes were destroyed. The homes were located approximately 2.7 miles downstream of the dam. None of the seven people in these homes at the time of the flood survived.

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Appendix B: Issuance of Dam Failure Warnings for Historical U.S. Dam Failures

The table included in this appendix provides information on when warnings have been initiated for 29 U.S. dam failures. As shown in the table below, warnings were not initiated prior to dam failure in most of these cases. The guidance for estimating when dam failure warnings would be issued, shown in table 2 of DSO-99-06 was developed using this and other data.

Timing of Dam Failure Warnings

<table>
<tr><th rowspan="2">Cause of Failure</th><th rowspan="2">Special Considerations</th><th rowspan="2">Time of Failure</th><th colspan="2">Were warnings initiated prior to dam failure?</th></tr>
<tr><th>Many Observers at Dam [1]</th><th>No Observers at Dam [2]</th></tr>
<tr><td rowspan="4">Overtopping or failure during very high reservoir levels before overtopping occurs</td><td rowspan="2">Small Flood Storage Space</td><td>Day</td><td>Buffalo Creek (no) [1.1]*</td><td></td></tr>
<tr><td>Night</td><td>Timberlake (no) [4.4]
Evans and Lockwood (no) [0.9 at Evans]
Kendall (no) [10.5]
Canyon Lake (no) [51 below Pactola Dam; 371 total]</td><td>Bushy Hill Pond (yes, 3 hours before failure) [0.7]
Laurel Run (no) [7.9]
Bear Wallow (no) [n/a]
Kelly Barnes (no) [4.6]
Taum Sauk (no) [0.0]
Ka Loko (no) [n/a]</td></tr>
<tr><td rowspan="2">Large Flood Storage Space</td><td>Day</td><td>D.M.A.D. (yes, 1 hr before failure) [7270]</td><td></td></tr>
<tr><td>Night</td><td></td><td></td></tr>
<tr><td rowspan="2">Static (full reservoir, normal weather)</td><td rowspan="2"></td><td>Day</td><td>Baldwin Hills (yes, 1.3 hr before failure)
Teton (yes, 1.25 hr before failure)
Hadlock Pond (no)
Big Bay Lake (issued same time dam failed)</td><td>Lawn Lake (no)
Little Deer Creek (no)
Lee Lake (no)
Mohegan Park (no)
Bergeron Pond (no)
Seminary Hill Reservoir No. 3 (no)
Gros Ventre Slide (no)
Prospect Valley Reservoir (no)</td></tr>
<tr><td>Night</td><td></td><td>Iowa Beef Processors Waste Disposal Pond (no)
South Davis County Water Imp. Dist. Res. No. 1 (no)
Sage Creek (5:00 am to 6:00 am, May 4) no
Box Reservoir (8:45 pm, May 21) no</td></tr>
<tr><td>Seismic</td><td></td><td>Day or Night</td><td></td><td></td></tr>
</table>

Includes information from earthfill dams only. Numbers inside brackets [1.1] represent the drainage area at the dam site in square miles; n/a means information not available.

[1] A dam tender lives on high ground and within sight of the dam, OR the dam is visible from the homes of many people, OR the dam crest serves as a heavily used roadway. These dams are typically in urban areas.

[2] There is no dam tender at the dam, the dam is out of sight of nearly all homes, and there is no roadway on the dam crest. These dams are typically in remote areas.

Appendix C: Derivation of Fatality Rates for Dam Failure

Fatality rates contained in DSO-99-06 were developed based on an analysis of approximately 40 flood events, many of which were caused by dam failure. The 40 floods include data used by Brown and Graham [1988] and DeKay and McClelland [1993]; nearly all U.S. dam failures causing 25 or more fatalities, and other flood events that were selected in an attempt to cover the full range of flood severity, warning time, and flood severity understanding combinations. The events analyzed included:

- Early United States dam failures, including:
  - Mill River Dam;
  - South Fork Dam; and
  - St. Francis Dam.
- Dam failures and similar events outside the United States, including:
  - Vega De Tera, Spain;
  - Stava, Italy;
  - Malpasset, France; and
  - Lahar at Armero, Columbia.
- Flash floods, including:
  - Big Thompson Canyon, Colorado; and
  - Shadyside, Ohio.
- Slowly rising floods, including:
  - Kansas River flood of 1951; and
  - Mississippi River flood of 1993.
- Recent United States dam failures, including:
  - Teton, Idaho;
  - Laurel Run, Pennsylvania; and
  - Kelly Barnes, Georgia.

For each flood event evaluated, a determination was made regarding the flood severity category, warning time category, and flood severity understanding category that most accurately described the situation at a particular location. This information is shown in table 5 of DSO-99-05. Some events are listed more than once, so from the 40 events evaluated, 50 individual entries appear. As an example, Baldwin Hills Dam had approximately 100 people in an area that had medium flood severity, adequate warning time, and precise flood severity understanding. Baldwin Hills Dam also had 16,400 people in an area that had low flood severity, adequate warning time, and precise flood severity understanding.

As shown in table 5 of DSO-99-06, some categories, such as low severity and adequate warning time, have many different entries. This is because there have been many cases where warnings have been issued for benign floods. Some categories, such as high flood severity with some or adequate warning time, have no entries. This is because warnings have not been issued prior to the failure of dams like St. Francis or Malpasset, or prior to the non-failure catastrophic flood that originated from the landslide generated wave at Vajont Dam.

Table 6 in DSO-99-06 summarizes the fatality rates for the events included in table 5 of DSO-99-06. Values presented include the average of the fatality rates for each category as well as the range. As an example, there were five entries for the category of low severity with a warning time of none/low. These entries, and their fatality rates, are as follows:

- South Davis County Water Improvement District No. 1 Dam, fatality rate of 0.0;
- Seminary Hill Reservoir Dam, fatality rate of 0.0;
- Alleghany County flood, fatality rate of 0.004;
- Mohegan Park Dam, fatality rate of 0.007; and
- Lee Lake Dam, fatality rate of 0.025.

The average of the aforementioned fatality rates is 0.007, and the range shown in the table is 0.0 to 0.025.

Homeland Security