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A Procedure for Estimating Loss of Life Caused by Dam Failure

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by
Wayne J. Graham, P.E.

U.S. Department of Interior
Bureau of Reclamation
Dam Safety Office
Denver, Colorado

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ABSTRACT

Risk assessments and other dam safety studies often require that an estimate be made of the number of fatalities that would result from dam failure. To assist in this effort, an extensive evaluation of dam failures and the factors that contributed to loss of life was conducted.

Every U.S. dam failure that resulted in more than 50 fatalities and every dam failure that occurred after 1960 resulting in any fatalities was investigated with regard to warning, population at risk (PAR) and number of fatalities. These dam failure data are used to provide a historical perspective of the risk associated with the U.S. dam inventory.

Loss of life resulting from dam failure is highly influenced by three factors: 1)The number of people occupying the dam failure flood plain, 2)The amount of warning that is provided to the people exposed to dangerous flooding and 3)The severity of the flooding.

The procedure for estimating loss of life due to dam failure relies heavily on data obtained from U.S. dam failures. The procedure is composed of 7 steps:

1) Determine dam failure scenarios to evaluate.
2) Determine time categories for which loss of life estimates are needed.
3) Determine when dam failure warnings would be initiated.
4) Determine area flooded for each dam failure scenario.
5) Estimate the number of people at risk for each dam failure scenario and time category.
6) Apply empirically-based equations or methods for estimating the number of fatalities.
7) Evaluate uncertainty.

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[1] Hydraulic Engineer, Sedimentation and River Hydraulics Group, Bureau of Reclamation, D-8540, Denver Federal Center, Denver CO 80225-0007. E-mail: wgraham@do.usbr.gov

INTRODUCTION

Evaluating the consequences resulting from a dam failure is an important and integral part of any dam safety study or risk analysis. Some dam failures would cause only minimal impacts to the dam owner and others, while large dams directly above large population centers are capable of causing catastrophic losses. Dam failure can cause loss of life, property damage, cultural and historic losses, environmental losses as well as social impacts. This paper focuses on the loss of life that results from dam failure. Included is a procedure for <u>estimating</u> the loss of life that would result from dam failure. No currently available procedure is capable of predicting the exact number of fatalities that would result from dam failure.

SOME SIGNIFICANT DAM FAILURES

The world’s most catastrophic dam failures occurred in August 1975 in the Zhumadian Prefecture of Henan Province in central China. A typhoon struck, causing reservoirs to swell. Banqiao Dam, 387 ft (118 meters) high, and Shimantan Dam collapsed as did dozens of smaller dams. Millions of people lost their homes. The death toll estimates for these failures varied widely. Approximately 26,000 deaths occurred from drowning in the immediate aftermath of the dam collapses. There were as many as 230,000 deaths if those who died of consequent health epidemics and famine are included.

Europe’s most catastrophic event associated with a dam occurred at about 2240 hours on October 9, 1963. The event occurred 3 years after the completion of Vajont Dam which is located in northern Italy. A 350 million cu. yard (268 million cu. m.) landslide fell within 20 to 30 seconds into the reservoir formed behind the dam. The dam, at the time the world’s second highest, did not fail. However, the effect of this huge mass of material that slid into the reservoir, which was almost at the maximum water level, was a gigantic wave of 40,500 acre-ft (50,000,000 cu. m.) of water that, after rising for 820 ft (250 m) in height, poured both towards the village of Longarone, 1.2 miles (2 km) downstream from the dam, and upstream along the reservoir, flooding the towns of Erto and Casso which were located on the hillsides surrounding the reservoir. About 2,000 people died as a result of this event, with about 1,269 of these occurring in Longarone where the fatality rate was about 94%. At Belluno, about 10 miles (16 km) downstream from Longarone, there was damage to more than 150 houses; luckily, the river dikes in most places prevented spillage into built-up areas. In the downstream valley area, there were few fatalities, even where there was substantial property damage.

More recently, Stava Dam, located in northern Italy, failed at about 1220 hours on July 19, 1985. The failure of this mine waste tailings dam resulted in the death of about 90% of the 300 people at risk in the community of Stava which was located about 0.6 mile (1 km) downstream from the dam.

The United States has also had major dam failures. Data for failures occurring in the United States are provided in more detail to provide the reader with an enhanced understanding of the relationships between dam failure, flooding, population at risk, warning and loss of life. The dam failure data are then analyzed to show trends and patterns.

History shows that the loss of life from dam failure in the United States has diminished with the passage of time. In the late 1800’s and early 1900’s, there were several dam failures with considerable loss of life. The loss of life resulting from dam failure during the 1980’s and 1990’s has been very low. The following is a summary of every dam failure in the United States that caused more than 50 fatalities:

Williamsburg Dam, also known as the Mill River Dam, Massachusetts, failed at about 0720 hours on Saturday May 16, 1874. The dam was 9 years old when it failed. The dam was earthfill with a masonry core wall. The dam was about 43 ft (13.1 m) high and contained about 307 acre-ft (379,000 cubic meters) of water at the time of failure. The reservoir was about 4 ft (1.2 m) below the dam crest at the time of failure. The failure was caused by seepage which carried away fill leading to embankment sliding and then collapse of the core wall. The failure resulted in about 138 fatalities and about 750 people were homeless. All of the fatalities occurred within the first 7 mi (11 km) downstream from the dam. After observing the dam failure, the dam tender traveled by horseback and began warning people downstream.

South Fork Dam, also known as the Johnstown Dam, Pennsylvania, failed at about 1510 hours on May 31, 1889. The dam was 36 years old when it failed. The earthfill dam was 72 ft (21.9 m) high and contained about 11,500 acre-ft (14.2 million cubic meters) of water. The dam failed as a result of overtopping that occurred during a flood caused by a 25-year frequency storm. The failure resulted in about 2,209 deaths, the largest loss of life from any U.S. dam failure. Nearly all of the fatalities occurred within the first 14 mi (22.4 km) downstream from the dam, with most in the town of Johnstown which was 14 mi (22.4 km) downstream from the dam. The number of fatalities was high because portions of the floodplain were densely populated, the flooding destroyed the majority of buildings in downtown Johnstown, and flooding in Johnstown preceding the arrival of dam failure flooding made it difficult for people to respond to the limited dam failure warnings that were issued. The dam tender traveled by horseback to a nearby community about 3 hours before dam failure and a message was then telegraphed to Johnstown describing the danger, but the warning was largely ignored.

Less than a year later, Walnut Grove Dam, Arizona, failed at about 0200 hours on February 22, 1890. The dam was 2 years old when it failed. The timber-faced rockfill dam was 110 ft (33.5 m) high and stored 50,000 acre-ft (62 million cubic meters) of water. During the flood, the dam withstood up to 3 ft (0.9 m) of overtopping for up to 6 hours before the dam failed. The failure resulted in between 70 and 100 fatalities. Many of the people who died were located at a construction camp for a lower dam which was about 15 mi (24 km) downstream from Walnut Grove Dam. Attempts were made to reach and warn people at the downstream construction camp. The distance to the construction camp, as well as the adverse weather, prevented the messenger on horseback from reaching the camp before the dam failure flood wave arrived.

Austin Dam, Pennsylvania, failed at about 1420 hours on September 30, 1911. The dam was 2 years old when it failed. The dam was variously described as being either 43 ft (13.1 m) or 50 ft (15.2 m) high and the reservoir contained either 550 acre-ft (678,000 cubic meters) or 850 acre-ft (1.05 million cubic meters) of water. The concrete gravity dam failed during normal weather conditions as a result of a weakness in the foundation or in the bond between the foundation and concrete. The failure resulted in at least 78 fatalities all of which occurred in the first 2 mi (3.2 km) downstream from the dam. A person living near the dam, after observing the sudden failure, phoned telephone operators in the community of Austin which was 1.4 mi (2.4 km) downstream from the dam.

Saint Francis Dam, California, failed at 2357 hours (about midnight) on March 12-13, 1928. The dam was 2 years old when it failed. The dam was 188 ft (57.3 m high) and the reservoir contained about 38,000 acre-ft (46.9 million cubic meters) of water. The concrete gravity dam failed as a result of structural defects. Weather was normal at the time of the dam failure. The failure resulted in about 420 fatalities. Unlike most of the other U.S. dam failure cases, loss of life did extend for quite some distance downstream from the dam. This perhaps is expected due to the severity of flooding, the larger population centers being quite some distance from the dam, and the darkness and difficulties in warning during the early morning hours. The highest fatality rates, however, were in areas that were close to the dam. For example, at Powerhouse No. 2, located about 1.6 mi (2.6 km) downstream from the dam, the dam failure claimed all of its occupants. In this same area lived the dam tender who also perished in the flood. At the California Edison Construction Camp, located about 17 mi (27 km) downstream from the dam, 89 of the 150 who had been there perished. This is a fatality rate of about 60%. Efforts to warn and evacuate people did not begin until a few hours after the dam failed.

The Buffalo Coal Waste Structure, West Virginia, failed at about 0800 hours on February 26, 1972. The structure did not receive the engineering, design, construction and care of a typical dam and is therefore called a structure and not a dam. The structure, begun in 1970, was continually being modified and enlarged as it was a waste pile used to dispose of material extracted during coal mining. The structure was about 46 ft (14.0 m) high and the failure released about 404 acre-ft (498,000 cubic meters) of water. This coal waste pile structure failed as a result of slumping of the structure face during a 2-year frequency rainfall event. There were 125 fatalities, all occurring in the first 15 mi (24 km) downstream. Warning of people exposed to the flooding began after the structure failed; reaction to the warnings was meager because there had been at least 4 previous false alarms.

Canyon Lake Dam, South Dakota, failed at about 2245 hours on June 9, 1972. The dam was 39 years old when it failed. The dam was about 20 ft (6.1 m) high and about 700 acre-ft (863,000 cubic meters) of water was released during the dam failure. The dam failed as a result of overtopping experienced during the Black Hills Flash Flood. The peak inflow to the reservoir was about 43,000 ft^3/s (1220 m^3/s) and the peak outflow was about 50,000 ft^3/s (1420 m^3/s). Some warning was issued to floodplain residents but those issuing the warnings did not initially comprehend the magnitude of the imminent flooding, nor was there a general awareness that the dam was going to fail. It is sometimes reported that all of the people that died during the Black Hills Flash Flood were victims of the dam failure. This is not correct. Of the 236 people who died, 35 died in the first 3 mi (4.8 km) <u>upstream</u> from the dam and 36 died in other basins not impacted by the dam failure. Approximately 165 of the fatalities occurred downstream from Canyon Lake Dam. Many of these people would have died even if the dam had not failed (or had not existed) due to the catastrophic nature of the flooding. Major flooding in Rapid City would have occurred without dam failure. The exact number of people who died as a direct result of the failure of Canyon

Lake Dam, i.e, the incremental loss of life, will never be known. It is estimated that the failure of Canyon Lake Dam resulted in 33 fatalities. This estimate is based on the assumption that the incremental loss of life downstream from Canyon Lake Dam caused by dam failure was 20% of the total loss of life downstream from the dam caused by the flood.

Table 1, "Dam Failures in the United States Resulting in Fatalities - 1960 through 1998," lists all dam failures in the United States that resulted in 1 or more fatalities during this 39-year time period.

Table 1
Dam Failures in the United States Resulting in Fatalities
1960-1998

Dam	Location	Date of Failure	Age of Dam	Cause of Failure	Dam Height (m)	Volume Released ($10^6 m^3$)	Warning Time (Hours)	People at Risk	Loss of Life
Electric Light Pond	Eagleville, New York	1960	n/a	n/a	7.9	unknown	unknown	unknown	1
Mohegan Park	Norwich, Connecticut	March 6, 1963 9:30 p.m.	110	Piping during elevated level caused by rain.	6.1	0.170	0	500	6
Little Deer Creek	near Hanna, Utah	June 16, 1963 6:13 a.m.	1	Piping during normal weather.	26.2	1.419	0	50	1
Baldwin Hills	Los Angeles, CA	December 14, 1963 3:38 p.m.	12	Piping during normal weather.	20.1	0.863	1 hour and 18 minutes	16,500	5
Swift	northwest Montana	June 8, 1964 10 a.m.	49	Overtopping during major flood event.	47.9	42.31	unknown	unknown	19
Lower Two Medicine	northwest Montana	June 8, 1964 3:30 p.m.	51	Embankment washed out next to concrete spillway walls.	11.0	25.82	unknown	unknown	9
Lee Lake	near East Lee, MA	March 24, 1968 1:25 p.m.	3	Piping.	7.6	0.370	0	80	2
Buffalo Creek Coal Waste	Logan County, West Virginia	February 26, 1972 8:00 a.m.	0	Slumping of dam face during 2-year rain event.	14.0	0.498	0	4,000	125

Dam	Location	Date of Failure	Age of Dam	Cause of Failure	Dam Height (m)	Volume Released ($10^6 m^3$)	Warning Time (Hours)	People at Risk	Loss of Life
Lake "O" Hills	Alaska	April 1972	n/a	Unknown.	4.6	0.059	unknown	unknown	1
Canyon Lake	Rapid City, South Dakota	June 9, 1972 10:45 p.m.	39	Overtopping during catastrophic flood; 245 total deaths from all flooding.	11.3	0.863	0	very large but unknown	33
Bear Wallow	Buncombe County, NC	February 22, 1976 2:30 a.m.	n/a	Rainfall; probable overtopping.	11.0	0.037	0	8	4
Teton	near Wilford, Idaho	June 5, 1976 11:57 a.m.	0	Piping of dam core in foundation key trench during initial filling.	93.0	308.4	1 hour 15 minutes	25,000	11
Laurel Run	near Johnstown, PA	July 20, 1977 2:35 a.m.	16	Overtopped.	12.8	0.555	0	150	40
Sandy Run	near Johnstown, PA	July 20, 1977	63	Overtopped.	8.5	0.057+	0	unknown	5
Kelly Barnes	near Toccoa Falls, GA	November 6, 1977 1:30 a.m.	78	Slope failure. during 10-year flood.	12.2	0.777	0	250	39
Lawn Lake and then Cascade Lake	near Estes Park, CO	July 15, 1982 5:30 a.m./ 7:42 a.m.	79/ 74	Lawn Lake piping during normal weather/ Cascade from overtopping.	7.9/ 5.2	0.831/ 0.031	0	5000	3
D.M.A.D.	near Delta, Utah	June 23, 1983 1:00 p.m.	24	Backcutting caused by collapse of downstream diversion dam	8.8	19.74	1+	500	1

Dam	Location	Date of Failure	Age of Dam	Cause of Failure	Dam Height (m)	Volume Released $(10^6 m^3)$	Warning Time (Hours)	People at Risk	Loss of Life
Nix Lake	near Henderson, Texas	March 29, 1989	55	Overtopping.	7.0	1.030	0	6	1
Evans and then Lockwood	Fayetteville, NC	September 15, 1989 9:30 p.m./ 10:00 p.m.	23/ 30	Each dam failed from overtopping.	5.5/ 4.3	0.089/ 0.039	0?	unknown but large	2
Kendall Lake	Camden, S. Carolina	October 10, 1990 7:00 p.m.	90	Overtopping.	5.5	0.851	0	unknown but large	4
Georgia Dams	217 dams failed throughout state	July 1994	n/a	unknown	unknown	unknown	unknown	unknown	3?
Timber Lake	near Lynchburg, VA	June 22, 1995 11:00 p.m.	69	Overtopping.	10.1	1.787	0	4 lane highway	2
Bergeron Pond	Alton, NH	March 13, 1996 6:50 p.m.	2	Failure occurred in the area of the concrete spillway. Dam not overtopped.	11.0	0.238	0	50	1

Note:

"Warning Time" is defined as the amount of time between the initiation of the dissemination of dam failure warnings and the initiation of dam failure. Many of the entries in this column are zero, indicating that dam failure warnings were not issued prior to dam failure.

"People at Risk" is defined as the number of people in the dam failure floodplain prior to the issuance of any flood or dam failure warnings.

"n/a" indicates that data is unknown or unavailable.

OBSERVATIONS ON DAMS AND DAM FAILURES

In the mid 1980's there were about 5,459 dams in the United States higher than 49 feet (15 meters) and more than 10 times as many, 71,000, that were more than 25 ft (7.6 meters) high. During the period 1960 through 1998, there were more than 300 fatalities resulting from dam failures in the United States. Failure of dams less than 15 meters high (dams too small to be included in the International Commission on Large Dams (ICOLD) Register of Dams) caused 88% of the total number of deaths occurring during this time period. There are certain types of dam failures that have occurred infrequently and thus information on these types of failures and the consequences that would result from these failures is deficient. These failures would include concrete dams, high embankment dams or any type of dam failing as a result of an earthquake.

Surprising as it may seem, most dam failures in the United States have not resulted in fatalities. During the 9-year period from late 1985 to late 1994 there were more than 400 dam failures in the United States. Most of these dams were small and many were unregulated. These dam failures resulted in only 10 fatalities. There were no fatalities from more than 98% of the dams that failed during this time period. It should be noted that many of the 400 dams were small, probably not large enough to be included in the National Inventory of Dams data base. In addition, many of these dams were probably either not classified with regard to hazard potential or classified as low or significant hazard potential dams. Less stringent safety standards usually apply to low and significant hazard dams.

Some interesting and relevant observations were developed from the 1960-1998 dam failure data shown in Table 1:

- Failure of dams less than 20 ft (6.1 m) high caused 2% of the deaths.
- Failure of dams between 20 ft (6.1 m) and 49 ft (15 m) high caused 86% of the deaths.
- Failure of dams less than 49 ft (15 m) high caused 88% of the deaths. These dams are not high enough to be included in the ICOLD inventory.

- There were 5 or less fatalities in 65% of the dam failure events that had fatalities.

- Failure of dams with drainage areas less than 2 sq mi (5.2 sq km) caused 47% of the deaths.
- Failure of dams with drainage areas less than 10 sq mi (26 sq km) caused 75% of the deaths.

Based on knowledge of the location of victims in 16 of the 23 dam failures (representing 87% of the fatalities) that occurred during the 39-year period from 1960-1998:

- 50% of the fatalities occurred 3 mi (4.8 km) or less from a dam that failed.
- More than 99% of the fatalities occurred 15 mi (24 km) or less from a dam that failed.

PREDICTING CONSEQUENCES OF DAM FAILURE

Loss of life sometimes results from dam failure. Loss of life is likely if a dam fails without warning and the failure produces flooding that destroys residential structures. Procedures for estimating loss of life have appeared in several documents. A good summary of these procedures is found in "Predicting Loss of Life in Cases of Dam Failure and Flash Flood," by DeKay and McClelland, 1993. Reclamation has prepared procedures for estimating loss of life and these are contained in "Guidelines to Decision Analysis," published in 1986 and in "Policy and Procedures for Dam Safety Modification Decisionmaking," published in 1989. The procedure presented herein, which includes an explicit procedure for estimating when a dam failure warning would be initiated, incorporates information from the two Reclamation documents as well as, "A Procedure for Estimating Loss of Life Due to Dam Failure," presented at the 1997 (U.S) Association of State Dam Safety Officials Annual Conference.

Procedures for estimating loss of life have also been developed by personnel at British Columbia Hydropower. The procedure is documented in a December 1996 Risk Assessment Report for Hugh Keenleyside Dam. The procedure evaluates the spacial and temporal location of flooding caused by dam failure, the number of people at risk at different locations and times, the time required for warning to be issued and spread to those at risk, the time required for people to begin taking action, the time required for people to escape and the probability that a person caught by the flood water would become a fatality. This procedure is logically sound, but at this time, there are not sufficient data to establish values of the various parameters and their relationship to one another.

It is important to determine the incremental consequence of dam failure. The incremental consequence of dam failure is the additional loss or damage caused by dam failure compared to the event occurring without dam failure. For a dam failure occurring from an earthquake, the incremental consequence would be the additional loss caused by flooding over and above the loss caused by the earthquake. For a dam failure caused by a major flood, the incremental consequence would be the additional loss caused by the dam failure over and above the loss that would have occurred if the dam and reservoir had passed the reservoir inflow without failing.

Factors Influencing Loss of Life Resulting from Dam Failure

Several factors will determine the number of fatalities resulting from dam failure. Included among these are the:

- Cause and type of dam failure.
- Number of people at risk.
- Timeliness of dam failure warnings.
- Flood depths and velocities in the downstream floodplain prior to dam failure.
- Flood depths and velocities resulting from dam failure.
- Availability of sensory clues (sight of floodwater or sounds created by rushing floodwater) to the people at risk.
- Time of day, day of week and time of year of failure.
- Weather, including air and water temperature.
- Activity in which people are engaged.
- General health of people threatened by floodwater.
- Type of structure in which people are located.
- Ease of evacuation.

The number of fatalities resulting from dam failure is most influenced by three of the factors described above. These factors are: 1)The number of people occupying the dam failure flood plain, 2)The amount of warning provided to the people exposed to dangerous flooding, and 3)The severity of the flooding. Without exception, dam failures that have caused high fatality rates were those in which residences were destroyed and timely dam failure warnings were not issued.

Two examples that show the importance of timely dam failure warning are as follows:

Teton Dam, located near Wilford, Idaho, failed at about noon on June 5, 1976. At the time of the failure, the sky was sunny or partly cloudy and the air temperature was a survivable 81 degrees F (27 degrees C). More than 3,000 homes were damaged and more than 700 homes were destroyed. Failure of the dam resulted in flood related injuries to more than 800 people and the death of 11 of the 25,000 people at risk. Failure occurred during the day, warnings to downstream areas commenced about 1 hour and 15 minutes prior to dam failure, and most people were able to evacuate before the house-destroying flood water arrived. The number of fatalities with less warning would have been much higher. For instance, failure of this dam at 3 a.m. probably would have been accompanied by no dam failure warnings and would have resulted in the loss of hundreds of lives.

Laurel Run Dam, located near Johnstown, Pennsylvania, failed in 1977. (Western Pennsylvania has seen 3 major dam failure events: South Fork Dam Failure, Austin Dam Failure and Laurel Run Dam Failure). Failure of this 42 ft (12.8 m) high dam claimed the lives of 40 of the 150 people at risk. Failure occurred at night when most people were asleep and dam failure warnings were not issued in the narrow 3 mi (4.8 km) long valley downstream from the dam. In addition, escape was surely hampered by the rain, lightning and darkness that accompanied the arrival of dam failure flooding. The number of fatalities probably would have been near zero if warnings had been issued to the people in the valley prior to dam failure.

A dam failure during the day will likely cause fewer fatalities than one occurring at night, all other things being equal. The daytime failure will probably be discovered earlier in the failure process and dam failure warnings would likely be issued earlier than if the failure occurred at night. In addition, during the day, news media and public safety agencies are staffed at higher levels, people are awake and people can see or hear the approaching flood water which in itself is a warning or warning confirmation.

Sources of Uncertainty

It is difficult to give a precise estimate of the loss of life that would occur from a dam failure for the following reasons:

- The time of dam failure (day, week, season), conditions existing at the time of failure (clear, rain, snow, darkness) and the number of people at risk at the time of dam failure (seasonal recreational usage, special events) are either unknown or can only be estimated.

- It is not known exactly when a dam failure warning message would be given. Experience indicates that there is sometimes a reluctance to issue dam failure warnings. Examples include the failure to issue warnings before the Buffalo Creek Coal Waste Structure failure in West Virginia, as well as the delay in initiating the dam failure warnings at Teton Dam in Idaho. The operating procedures or emergency plans that may be available for a dam should provide some guidance regarding when a warning would be issued. There is no assurance, however, that a warning would be initiated as directed in a plan. A study investigating loss of life from dam failure can be used to highlight weaknesses in the dam failure warning process and provide some guidance on how improvements in the process would reduce the loss of life.

- The procedure for estimating loss of life is not precise. Even if the time of the failure, conditions existing at the time of failure, number of people at risk, and the time at which warnings are initiated are known with certainty, there will be error in the loss of life estimate.

PROCEDURE FOR ESTIMATING LOSS OF LIFE

The procedure for estimating loss of life can be broken into various steps. Briefly, the steps are as follows:

Step 1: Determine dam failure scenarios to evaluate.
Step 2: Determine time categories for which loss of life estimates are needed.
Step 3: Determine when dam failure warnings would be initiated.
Step 4: Determine area flooded for each dam failure scenario.
Step 5: Estimate the number of people at risk for each failure scenario and time category.
Step 6: Apply empirically based equations or method for estimating fatalities.
Step 7: Evaluate uncertainty.

The steps are now given in more detail.

Step 1: Determine Dam Failure Scenarios to Evaluate

A determination needs to be made regarding the failure modes to evaluate. For example, loss of life estimates may be needed for two scenarios - failure of the dam with a full reservoir during normal weather conditions and failure of the dam during a large flood that overtops the dam.

Step 2: Determine Time Categories For Which Loss of Life Estimates Are Needed

The number of people at risk downstream from some dams is influenced by seasonality or day of week factors. For instance, campgrounds may be unused in the winter and heavily used in the summer, especially summer weekends. The number of time categories (season, day of week, etc.) evaluated should display the varying usage of the floodplain and corresponding number of people at risk. Since time of day can influence both when a warning is initiated as well as the number of people at risk, each study should include a day category and a night category for each dam failure scenario evaluated.

Step 3: Determine When Dam Failure Warnings Would be Initiated

Determining when dam failure warnings would be initiated is probably the most important part of estimating the loss of life that would result from dam failure. Table 2, "Guidance for Estimating When Dam Failure Warnings Would be Initiated," was prepared using data from U.S. dam failures occurring since 1960 as well as other events such as Vajont Dam in Italy, Malpasset Dam in France and Saint Francis Dam in California. An evaluation of these dam failure data indicated that timely dam failure warnings were more likely when the dam failure occurred during daylight, in the presence of a dam tender or others and where the drainage area above the dam was large or the reservoir had space for flood storage. Timely dam failure warnings were less likely when failure occurred at night or outside the presence of a dam tender or casual observers. Dam failure warnings were also less likely where the drainage area was small or the reservoir had little or no space for flood storage, i.e, when the reservoir was able to quickly fill and overtop the dam. Although empirical data are limited, it appears that timely warning is less likely for the failure of a concrete dam. Although dam failure warnings are frequently initiated before dam failure for earthfill dams, this is not the case for the failure of concrete dams.

Table 2, "Guidance for Estimating When Dam Failure Warnings Would be Initiated (Earthfill Dam)," provides a means for deriving an initial estimate of when a dam failure warning would likely be initiated. Guidance has not been provided for the failure of a concrete dam. Estimates for concrete dams must be developed on a case-by-case basis. The use of Table 2, combined with information obtained from any operating or emergency procedure for the dam, should answer the question, "When will a dam failure warning be initiated?" It is easily seen using Table 2 that the amount of dam failure warning for a particular dam will be different based on cause of failure and time at which the failure occurs.

The availability of emergency action plans, upstream or dam-site instrumentation, or the requirement for on-site monitoring during threatening events influences when a dam failure warning would be initiated. Assumptions regarding when a warning is initiated should take these and other risk-reduction actions and programs into account.

Table 2
Guidance for Estimating When Dam Failure Warnings Would be Initiated (Earthfill Dam)

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 mi^2 (260 km^2)	Day	0.25 hrs. before dam failure	0.25 hrs. after fw reaches populated area
		Drainage area at dam less than 100 mi^2 (260 km^2)	Night	0.25 hrs. after dam failure	1.0 hrs. after fw reaches populated area
		Drainage area at dam more than 100 mi^2 (260 km^2)	Day	2 hrs. before dam failure	1 hr. before dam failure
		Drainage area at dam more than 100 mi^2 (260 km^2)	Night	1 to 2 hr. 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 fw reaches populated area
			Night	0.5 hr. after dam failure	1.0 hr. after fw reaches populated area
	Seismic	Immediate Failure	Day	0.25 hr. after dam failure	0.25 hr. after fw reaches populated area
			Night	0.50 hr. after dam failure	1.0 hrs. after fw reaches populated area
		Delayed Failure	Day	2 hrs. before dam failure	0.5 hrs. before fw reaches populated area
			Night	2 hrs. before dam failure	0.5 hrs. before fw reaches populated area

Notes: "Many Observers at Dam" means that a dam tender lives on high ground and within site 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. "No Observers at Dam" means that there is no dam tender at the dam, the dam is out of site of nearly all homes and there is no roadway on the dam crest. These dams are usually in remote areas. The abbreviation "fw" stands for floodwater.

Step 4: Determine Area Flooded for Each Dam Failure Scenario

In order to estimate the number of people at risk, a map or some other description of the flooded area must be available for each dam failure scenario. In some cases, new dam-break studies may need to be prepared. However, existing maps should be used as much as possible to reduce study costs. Judgements will have to be made whether currently published or draft inundation maps reflect the flooding from the various failure scenarios for which loss of life estimates are needed. For instance, a dam failure inundation map based on a failure caused by dam overtopping may not accurately depict the flooding caused by a piping failure with a much lower reservoir level.

Analyses based on the use of dam failure inundation studies and maps leads to uncertainty. Dam break modeling requires the estimation of: 1) The time for the breach to form, 2) Breach shape and width and 3) Downstream hydraulic parameters. Variations in estimates of these parameters can result in changes in flood width, flood depth and flood wave travel time. This can lead to uncertainty in the: 1) Population at risk, 2) Warning time and 3) Flood severity.

Step 5: Estimate the Number of People at Risk for Each Failure Scenario and Time Category

For each failure scenario and time category, determine the number of people at risk. Population at risk (PAR) is defined as the number of people occupying the dam failure floodplain prior to the issuance of any warning. A general guideline it to: "Take a snapshot and count the people." The number of people at risk varies throughout the day.

The PAR will likely vary depending upon the time of year, day of week and time of day during which the failure occurs. Utilize census data, field trips, aerial photographs, telephone interviews, topographic maps and any other sources that would provide a realistic estimate of floodplain occupancy and usage.

Within the Bureau of Reclamation, the Remote Sensing and Geographic Information Group (GIS) can provide products that assist with the estimation of the population at risk. The GIS Group has the capability of estimating population using 1990 population and employment census information in combination with available inundation maps. Caution must be exercised because the 1990 data may not reflect current conditions. In using products from the GIS Group one must recognize that recreationists, campers and other non-permanent occupants are not counted in population census data. Similarly, it is important that double counting not take place. Centers of employment fill as housing units empty and vice versa. It is important to understand the methods used by the GIS Group to mesh flood boundaries with census block data. There is uncertainty in the methods and hence in the population at risk estimates.

Step 6: Apply Empirically-Based Equations or Method for Estimating the Number of Fatalities

Various methods have been suggested for estimating loss of life based on measures of population at risk, warning time and other factors. For background purposes, the Brown and Graham as well as the DeKay and McClelland methods are described. It is recommended that these methods be abandoned and replaced with a new flood severity based method for estimating loss of life. This new method is described in detail.

Knowledge gained in the 1980’s and 1990’s regarding the interrelationship between warning, flood lethality and the number of people at risk allowed the development of procedures to estimate the loss of life resulting from dam failure. It was found that loss of life is highly related to the warning issued to the people at risk. The lethality of flooding (which is a function of flood depth and velocity) is also a major factor, especially in those cases where warnings are not issued or when people are warned but fail to evacuate.

Two different papers were prepared that provided procedures for estimating loss of life from dam failure. In 1988, Brown and Graham published, "Assessing Threat to Life from Dam Failure." In 1993, DeKay and McClelland published, "Predicting Loss of Life in Cases of Dam Failures and Flash Floods." A summary of the procedures, and loss of life estimating equations presented by each pair of authors is presented below.

The Brown and Graham procedure uses equations that were derived from the analysis of 24 dam failures and major flash floods, shown in Table 3. The concepts contained in the Brown and Graham paper were incorporated into Reclamation’s "Policy and Procedures for Dam Safety Modification Decisionmaking" (1989) and equations from this document are presented below.

Warning time used in the equations is defined as the elapsed time between the initiation of an official evacuation warning to the public and the arrival of dangerous flooding at the population at risk. Warning time must therefore consider the time it takes for flood water to reach the community or group of people at risk.

When warning time is less than 15 minutes:
Loss of Life = .5(PAR)

When warning time is between 15 and 90 minutes:
Loss of Life = $PAR^{.6}$

When warning time is more than 90 minutes:
Loss of Life = .0002(PAR)

It can easily be seen that the loss of life estimated using these relationships will vary widely depending upon the warning. With 5000 people at risk, loss of life from dam failure could be as much as 2500 people if these people are located in an area that receives less than 15 minutes of warning. The loss of life would only be 1 if the people are located in an area that receives more than 90 minutes of warning.

Table 3
Dam failures and Floods used by Brown and Graham

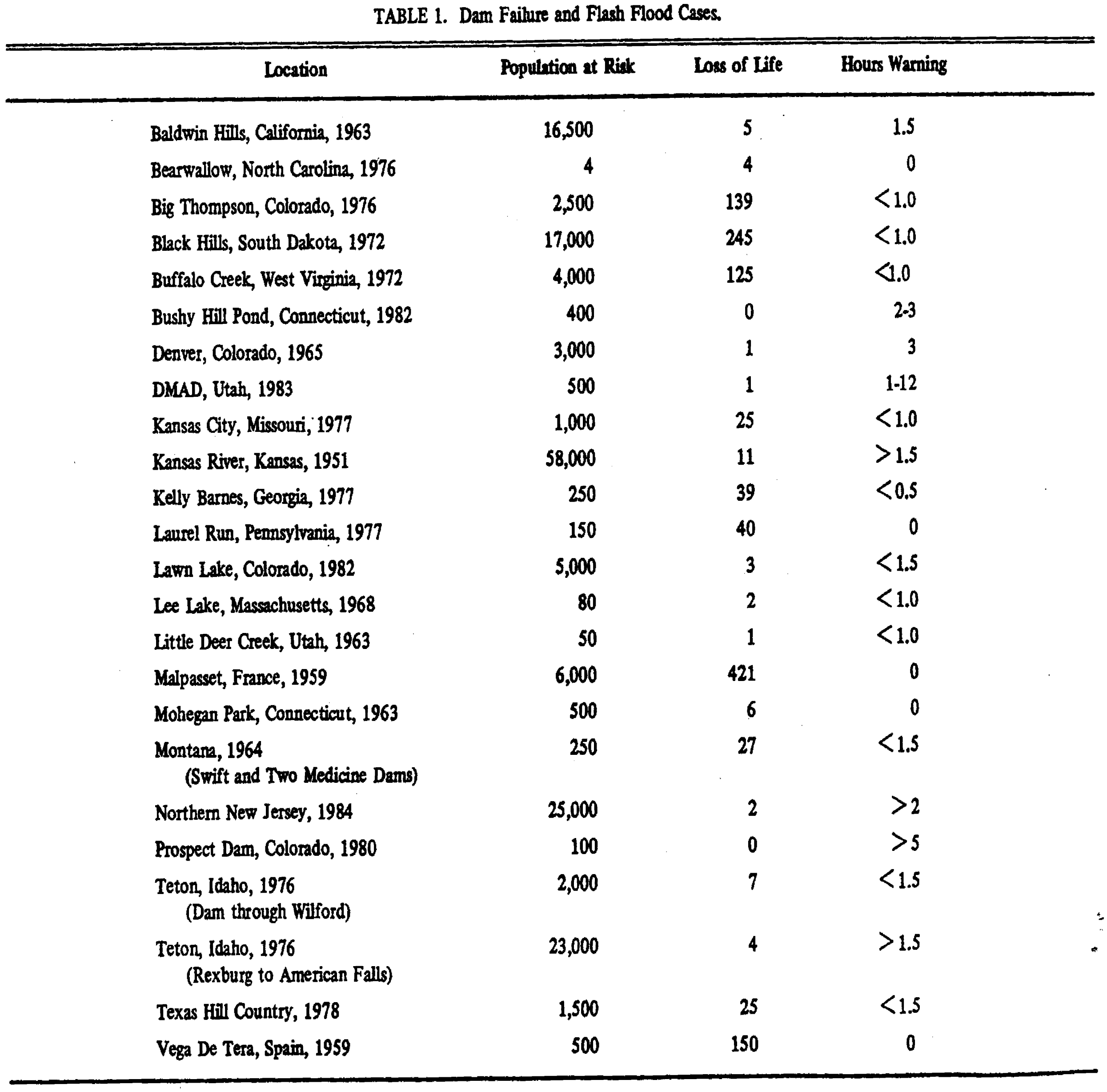

TABLE 1. Dam Failure and Flash Flood Cases.

Location	Population at Risk	Loss of Life	Hours Warning
Baldwin Hills, California, 1963	16,500	5	1.5
Bearwallow, North Carolina, 1976	4	4	0
Big Thompson, Colorado, 1976	2,500	139	<1.0
Black Hills, South Dakota, 1972	17,000	245	<1.0
Buffalo Creek, West Virginia, 1972	4,000	125	<1.0
Bushy Hill Pond, Connecticut, 1982	400	0	2-3
Denver, Colorado, 1965	3,000	1	3
DMAD, Utah, 1983	500	1	1-12
Kansas City, Missouri, 1977	1,000	25	<1.0
Kansas River, Kansas, 1951	58,000	11	>1.5
Kelly Barnes, Georgia, 1977	250	39	<0.5
Laurel Run, Pennsylvania, 1977	150	40	0
Lawn Lake, Colorado, 1982	5,000	3	<1.5
Lee Lake, Massachusetts, 1968	80	2	<1.0
Little Deer Creek, Utah, 1963	50	1	<1.0
Malpasset, France, 1959	6,000	421	0
Mohegan Park, Connecticut, 1963	500	6	0
Montana, 1964 (Swift and Two Medicine Dams)	250	27	<1.5
Northern New Jersey, 1984	25,000	2	>2
Prospect Dam, Colorado, 1980	100	0	>5
Teton, Idaho, 1976 (Dam through Wilford)	2,000	7	<1.5
Teton, Idaho, 1976 (Rexburg to American Falls)	23,000	4	>1.5
Texas Hill Country, 1978	1,500	25	<1.5
Vega De Tera, Spain, 1959	500	150	0

Source: "Assessing the Threat to Life from Dam Failure," published in <u>Water Resources Bulletin</u>, Vol. 24, No. 6, December, 1988.

DeKay and McClelland, supported by funding received from the Bureau of Reclamation, expanded on the work begun by Brown and Graham. They submitted the report entitled "Setting Decision Thresholds for Dam Failure Warnings: A Practical Theory-Based Approach" to Reclamation on December 31, 1991. In 1993 they published "Predicting Loss of Life in Cases of Dam Failure and Flash Flood" in the publication *Risk Analysis*. The events used by DeKay and McClelland, shown in Table 4, are the same as those used by Brown and Graham. DeKay and McClelland also included a few events that were not used by Brown and Graham. The DeKay and McClelland procedure demonstrated that loss of life is related to the number of people at risk in a nonlinear fashion. They also found that loss of life is greater in situations where the flood waters are deep and swift. DeKay and McClelland have a separate equation for high and low force conditions. Their equation, as it appears in *Risk Analysis*, for high force conditions, i.e., where 20% or more of flooded residences are either destroyed or heavily damaged is:

$$\text{Deaths} = \frac{\text{PAR}}{1 + 13.277(\text{PAR}^{0.440})e^{[2.982(\text{WT}) - 3.790]}}$$

Their equation for low lethality conditions, i.e., where less than 20% of flooded residences are either destroyed or heavily damaged is:

$$\text{Deaths} = \frac{\text{PAR}}{1 + 13.277(\text{PAR}^{0.440})e^{[0.759(\text{WT})]}}$$

where PAR is the number of people at risk and WT is warning time in hours. Warning time (WT), as used by Dekay and McClelland, is the time in hours from the initiation of dam failure warning until the dam failure floodwater reaches a community or other group of people. Warning time must therefore consider the time it takes for flood water to reach the community or group of people. When dam failure warnings do not precede the arrival of dam failure flooding in an area, WT would be zero. A negative warning time should not be used in these equations.

A major difference between the procedure developed by DeKay and McClelland and that of Brown and Graham is that warning time is treated as a continuous variable by DeKay and McClelland; whereas Brown and Graham utilized discrete bins and placed warning time into 2 or 3 categories.

DeKay and McClelland cautioned against using their equations for dams that fail without warning above areas with very large populations at risk. They also stated that their equations should not be applied to cases like Vajont, in which a massive landslide displaced nearly the entire contents of a reservoir. The Brown and Graham procedure as well as the DeKay and McClelland procedure both conclude that loss of life is much greater in those areas that receive little warning compared to those areas that receive more than an hour or so of warning. The value of adequate dam failure warning in reducing loss of life from dam failure can not be overemphasized.

Table 4
Dam Failures and Floods used by DeKay and McClelland

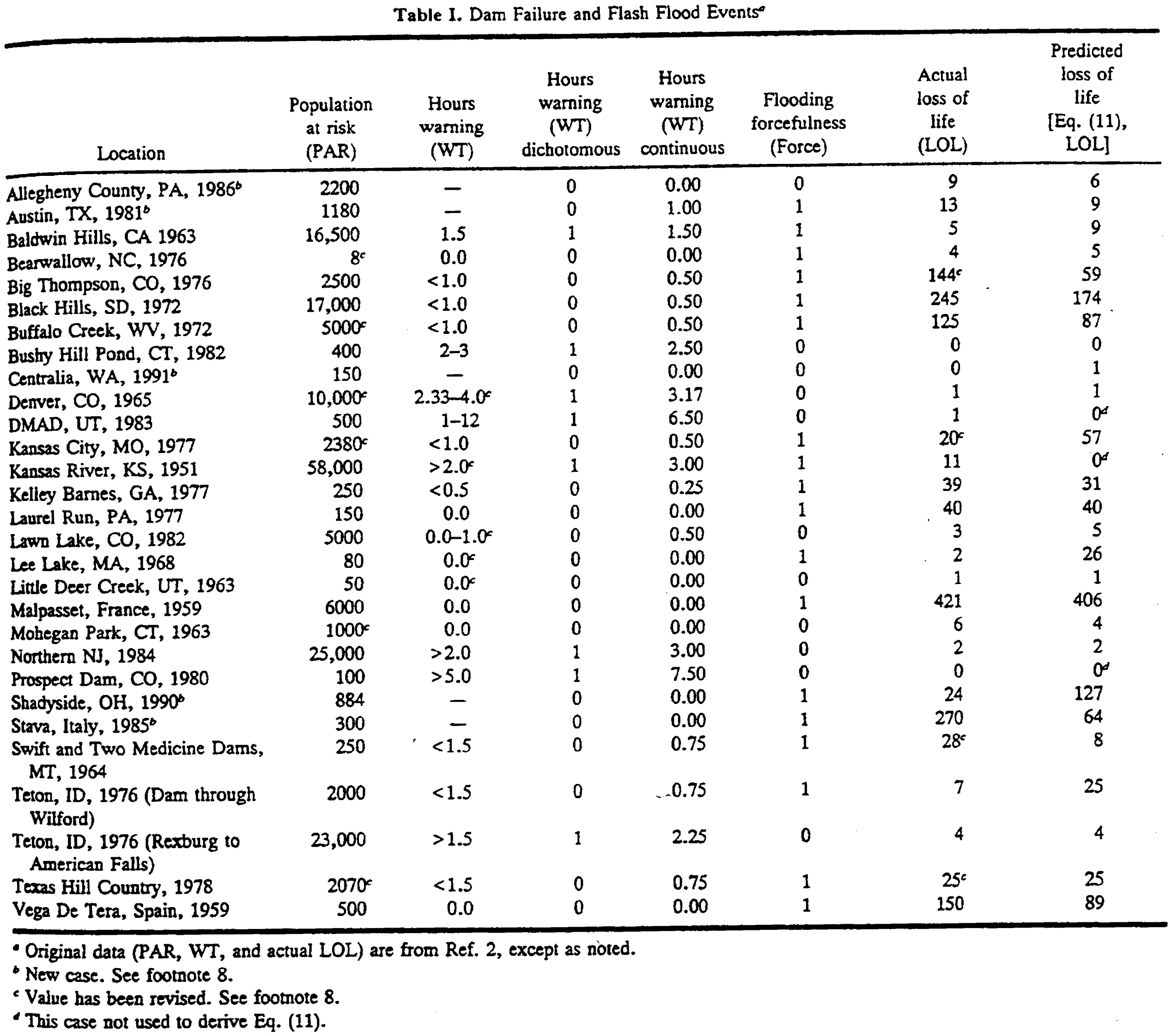

Table I. Dam Failure and Flash Flood Events[a]

Location	Population at risk (PAR)	Hours warning (WT)	Hours warning (WT) dichotomous	Hours warning (WT) continuous	Flooding forcefulness (Force)	Actual loss of life (LOL)	Predicted loss of life [Eq. (11), LOL]
Allegheny County, PA, 1986[b]	2200	—	0	0.00	0	9	6
Austin, TX, 1981[b]	1180	—	0	1.00	1	13	9
Baldwin Hills, CA 1963	16,500	1.5	1	1.50	1	5	9
Bearwallow, NC, 1976	8[c]	0.0	0	0.00	1	4	5
Big Thompson, CO, 1976	2500	<1.0	0	0.50	1	144[c]	59
Black Hills, SD, 1972	17,000	<1.0	0	0.50	1	245	174
Buffalo Creek, WV, 1972	5000[c]	<1.0	0	0.50	1	125	87
Bushy Hill Pond, CT, 1982	400	2–3	1	2.50	0	0	0
Centralia, WA, 1991[b]	150	—	0	0.00	0	0	1
Denver, CO, 1965	10,000[c]	2.33–4.0[c]	1	3.17	0	1	1
DMAD, UT, 1983	500	1–12	1	6.50	0	1	0[d]
Kansas City, MO, 1977	2380[c]	<1.0	0	0.50	1	20[c]	57
Kansas River, KS, 1951	58,000	>2.0[c]	1	3.00	1	11	0[d]
Kelley Barnes, GA, 1977	250	<0.5	0	0.25	1	39	31
Laurel Run, PA, 1977	150	0.0	0	0.00	1	40	40
Lawn Lake, CO, 1982	5000	0.0–1.0[c]	0	0.50	0	3	5
Lee Lake, MA, 1968	80	0.0[c]	0	0.00	1	2	26
Little Deer Creek, UT, 1963	50	0.0[c]	0	0.00	0	1	1
Malpasset, France, 1959	6000	0.0	0	0.00	1	421	406
Mohegan Park, CT, 1963	1000[c]	0.0	0	0.00	0	6	4
Northern NJ, 1984	25,000	>2.0	1	3.00	0	2	2
Prospect Dam, CO, 1980	100	>5.0	1	7.50	0	0	0[d]
Shadyside, OH, 1990[b]	884	—	0	0.00	1	24	127
Stava, Italy, 1985[b]	300	—	0	0.00	1	270	64
Swift and Two Medicine Dams, MT, 1964	250	<1.5	0	0.75	1	28[c]	8
Teton, ID, 1976 (Dam through Wilford)	2000	<1.5	0	0.75	1	7	25
Teton, ID, 1976 (Rexburg to American Falls)	23,000	>1.5	1	2.25	0	4	4
Texas Hill Country, 1978	2070[c]	<1.5	0	0.75	1	25[c]	25
Vega De Tera, Spain, 1959	500	0.0	0	0.00	1	150	89

[a] Original data (PAR, WT, and actual LOL) are from Ref. 2, except as noted.
[b] New case. See footnote 8.
[c] Value has been revised. See footnote 8.
[d] This case not used to derive Eq. (11).

Source: "Predicting Loss of Life in Cases of Dam Failure and Flash Flood," published in Risk Analysis, Vol. 13, No. 2, 1993.

Limitations of Loss of Life Estimating Equations

The empirical data set used by Brown and Graham, and DeKay and McClelland, in developing the loss of life estimating equations did not include some types of events and warning scenarios. Most of the dams in the data set were smaller structures. Only 7 of the dams used in developing the equations were more than 49 ft (15 m) high. The data set included many more earthfill dams than concrete dams. The data set included no dams that failed due to an earthquake. The equations may not be applicable for use with dam sizes, dam types, failure causes, flood severity and warning scenarios not reflected in the data set.

Most notably under represented in the empirical data set used by Brown and Graham, and DeKay and McClelland, were events that caused severe flooding, either with or without warning. As a result, the equation for high lethality is deficient when used to predict life loss for dam failures that result in truly catastrophic flooding. The following example explains this problem in more detail: St. Francis Dam, a concrete structure located north of Los Angeles, failed at about midnight, March 12-13, 1928. Warnings did NOT precede dam failure. Within a period of just a few minutes, the area immediately downstream from the dam changed from one of no flooding to one where the flood covered the valley floor to a depth of nearly 100 ft (30 m). Imagine rapidly moving water, with a depth as high as a ten story tall building, battering a typical campsite, mobile home or single family house! There were not many people living immediately downstream from the dam; if there had been, the loss of life from this dam failure would have been much greater. Assume for a moment that there had been 10,000 people living near the river in the first few miles downstream from the dam. The DeKay and McClelland equation for high lethality and a warning time of zero predicts a life loss of about 550 people, which is a fatality rate of slightly less than 6%. This seems far too low for this situation. A fatality rate of 80 to 100% would be more appropriate for flooding of this type, a rate that is similar to what happened in Longarone, located a short distance downstream from Vajont Dam in Italy. The DeKay and McClelland equation for high lethality and no warning results in a fatality rate of 55% if 10 people are at risk but only 5.5% if 10,000 people are at risk.

A similar problem exists if it is assumed that a warning goes out a few hours before dam failure. Reclamation has generally assumed that the loss of life would be about 1 person for every 5,000 at risk if the warning is issued to the risk area at least 1.5 hours before flooding occurs in the area. Such a small fatality rate probably is not realistic with very catastrophic flooding. The loss of life is going to be directly related to the number of people who do not receive the warning or ignore the warning and remain in the risk area. The same percentage (80 to 100%) of the people remaining would likely become fatalities if exposed to the type and severity of flooding that occurred immediately downstream from St. Francis Dam or Vajont Dam. It may be very difficult to determine how many people will not evacuate. If a warning does not reach people or if people do not believe the warning or if they do not believe that their life is at risk, then these people are more likely to remain in the danger area.

When Brown and Graham originally developed their life loss estimating equations, they thought that it was logical for the fatality rate (the number of fatalities as a fraction of the population at risk) to decrease as the population at risk increased. The assumption was that as the population increased, or became more dense, warning and communication facilities would be more advanced. Probably what was observed, unknowingly, is that as the population at risk increased, the area under consideration was increasing in size and was therefore including areas where the flooding was less lethal. The Brown and Graham as well as the DeKay and McClelland data bases probably contain many cases demonstrating that there is an inverse relation between population at risk and flood lethality. This means that as the population at risk increased, the flood lethality (or flood severity) decreased. Large populations do not fit into narrow canyons - hence larger populations are situated in the flatter areas where the lethality is usually reduced.

Some questions regarding the validity of the equations developed by Brown and Graham as well as Dekay and McClelland remain. Do the equations give accurate results when large numbers of people are exposed to truly catastrophic flooding? Should the fatality rate vary so much for different population sizes? Does adequate warning time result in low fatality rates? - Or is adequate warning most likely to occur for benign floods and these floods are not very lethal, regardless of the warning?

Some Floods are Benign While others are Catastrophic

Dam failure can result in flooding that can be broadly divided into 3 damage categories: low, medium and high. The first would be where homes are flooded but not destroyed. Even without any warning, the fatality rate for dam failures that cause this type of flooding is often 0% and almost always less than 1%. Many of the dam failures that resulted in flooding described by DeKay and McClelland as having a "low force" would fit this category. Many of the more than

400 dams that failed in the United States from 1985 to 1994 would also fit this category.

The second type of flooding resulting from dam failure is that which causes the destruction of homes and businesses. Trees and some homes remain and these trees or rooftops may provide temporary refuge until the flooding recedes. Without warning, the fatality rates for dam failures causing this type of flooding have ranged from a few percent up to about 25% or more. Dam failures that resulted in flooding described by DeKay and McClelland as having a "high force" would fit this category.

The third type of flooding is that which occurs very suddenly and is truly of catastrophic magnitude. The floodplain is swept clean. Houses are crushed, washed away and there is little or no trace of their prior existence when the flood water recedes. The landslide-generated wave at Vajont Dam, Italy caused this type of flooding in Longarone. The failure of Stava Dam in Italy and St. Francis Dam in California also caused this type of flooding immediately downstream from each structure. Mine tailings dams and concrete dams seem to have the capability of producing this type of flooding due to the short failure times for these dams. Without warning, the fatality rates for dam failures causing this type of flooding have ranged from about 50% up to about 100% for areas immediately downstream from the dam.

FLOOD SEVERITY BASED METHOD FOR ESTIMATING LIFE LOSS

Recognizing weaknesses in the Brown and Graham, and the DeKay and McClelland equations, a new method for estimating life loss has been developed. The method still uses results from steps 1-5; only the process for determining the loss of life based on the population at risk has changed. The method developed provides recommended fatality rates based on the flood severity, amount of warning and a measure of whether people understand the severity of the flooding.

This new method was developed using an enlarged data set which totaled approximately 40 floods, many of which were caused by dam failure. The 40 floods include the data used by Brown and Graham, Dekay and McClelland, nearly all U.S. dam failures causing 50 or more fatalities, and other flood events that were selected in an attempt to cover a full range of flood severity, warning and flood severity understanding combinations. The following paragraphs describe the terms and categories that form the basis for this methodology.

Flood Severity along with warning time determines, to a large extent, the fatality rate that would likely occur. The flood severity categories are as follows:

1) Low severity occurs when no buildings are washed off their foundations.

2) Medium severity occurs when homes are destroyed but trees or mangled homes remain for people to seek refuge in or on.
3) High severity occurs when the flood sweeps the area clean and nothing remains. Although rare, this type of flooding occurred below St. Francis Dam and Vajont Dam.

Warning Time is the other factor that is important in determining the fatality rate. The warning time categories are as follows:

1) No warning means that no warning is issued by the media or official sources in the particular area prior to the flood water arrival; only the possible sight or sound of the approaching flooding serves as a warning.

2) Some warning means officials or the media begin warning in the particular area 15 to 60 minutes before flood water arrival. Some people will learn of the flooding indirectly when contacted by friends, neighbors or relatives.

3) Adequate warning means officials or the media begin warning in the particular area more than 60 minutes before the flood water arrives. Some people will learn of the flooding indirectly when contacted by friends, neighbors or relatives.

Flood Severity Understanding is the last factor that has an impact on the fatality rate. The relative understanding of the flood severity is a function of the distance or time from the dam failure or the source and origination of flooding. The farther one is from the source of the flooding, the greater the likelihood that the warning will be precise and accurate. This is because people have seen the flooding in upstream areas, they understand the damage potential of the flooding and the warnings are 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. A warning of potential flooding, before it actually occurs (because a dam has not yet failed or during a flash flood in which the true flood magnitude is often not known until after the event is over), may not be understood by the warning issuers and would therefore be difficult to describe. Recipients of this warning will therefore not get an accurate picture of the flooding about to occur and may not evacuate at all or not as quickly as they should. This factor will come into consideration only when there is some or adequate warning.

The flood severity understanding categories are as follows:

1) Vague Understanding of Flood Severity means that the warning issuers have not yet seen an actual dam failure or do not comprehend the true magnitude of the flooding.

2) Precise Understanding of Flood Severity means that the warning issuers have an excellent understanding of the flooding due to observations of the flooding made by themselves or others.

Summarizing, flood severity can have 3 categories, warning time can have 3 categories, and flood severity understanding can have 2 categories. Flood severity understanding does not apply when there is no warning. There are therefore 15 different combinations possible.

Table 5 shows the 40 flood events placed in the categories corresponding to the definitions given above. 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. Some floods are listed more than once, so from the 40 flood events evaluated, 50 individual entries were made. As an example, Baldwin Hills Dam had approximately 100 people in an area that had medium flood severity, adequate warning and precise flood severity understanding. Baldwin Hills Dam also had 16,400 people in an area that had low flood severity, adequate warning and precise flood severity understanding. Baldwin Hills Dam, therefore, is listed twice in Table 5.

Some categories, such as low severity, adequate warning, have many different entries included in Table 5. This is because there have been many cases where warnings have been issued for benign floods. Some categories, such as high flood severity, some or adequate warning, 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, "Fatality Rates Derived from Case Studies," summarizes data from the case studies evaluated. The table contains the fatality rates for the events presented in Table 5. Values presented include the average of the fatality rates for each category as well as the range. As an example, if there were 3 cases for one particular category, and the fatality rates were 0.01, 0.09 and 0.11, the average was shown as .07 and the range was shown as 0.01 to 0.11.

Table 5

HIGH FLOOD SEVERITY (Area is swept clean, nothing remains)											
WARNING TIME	FLOOD SEVERITY UNDERSTANDING	EVENT	GENERAL LOCATION	DATE	DAM FAILURE?	COMMENTS	$\frac{Q-Q_{2.33}}{\text{FLOOD WIDTH}}$ ($ft^{2/s}$)	NUMBER OF PEOPLE AT RISK	MILES FROM DAM FOR PEOPLE AT RISK	DEATHS	FATALITY RATE
None/Low		Vega De Tera Dam	Spain	1-10-1959	Yes, concrete	125 of 150 buildings destroyed	200	500	3	150	0.30
		Bear Wallow Dam	NC	2-22-1976	Yes	House at bottom of hill buried by debris, soil and rock	n/a	8	1	4	0.5
		St. Francis Dam, Cal. Edison Construction Camp	CA	3-13-1928	Yes, concrete	60 foot flood depth	n/a	150	17	89	0.60
		Armero Lahar	Columbia, South America	12-13-1985	Volcanic eruption caused flooding (mud flow)	Mayor contacted but didn't believe community was at risk. Flood traveled at about 25 mph.	n/a	27,000	37	22,000	0.81
		Stava Dam	Italy	7-19-1985	Yes, mine dam	100 foot flood depth	n/a	300	1	270	0.90
		Vajont Dam	Italy	10-9-1963	No, flood caused by landslide into reservoir	At Longarone, 10 miles farther downstream there were few casualties	n/a	1348	1.5	1269	0.94
		Malpasset Dam	France	12-2-1959	Yes, concrete	100 foot flood depth	n/a	30	0	30	1.00
		St. Francis Dam	CA	3-13-1928	Yes, concrete	How could you survive?	963	n/a	0	n/a	1.00
Some	Vague										
	Precise										
Adequate	Vague										
	Precise										

Table 5 - Continued

MEDIUM FLOOD SEVERITY (Buildings are destroyed. Trees/crushed houses provide refuge)											
WARNING TIME	FLOOD SEVERITY UNDERSTANDING	EVENT	GENERAL LOCATION	DATE	DAM FAILURE?	COMMENTS	$\frac{Q-Q_{2.33}}{\text{FLOOD WIDTH}}$ ($ft^{2/s}$)	NUMBER OF PEOPLE AT RISK	MILES FROM DAM FOR PEOPLE AT RISK	DEATHS	FATALITY RATE
None/Low		Little Deer Dam	Hanna UT	6-16-1963	Yes	Young camper died	n/a	50	?	1	.020
		Buffalo Creek Coal Waste Dam	Man WV	2-26-1972	Yes, coal waste	Informal warnings	20-143	5000	0-14	125	.025
		Shadyside Flood	Shadyside OH	6-14-1990	No	WRI-91-4147 reference	n/a	884	-	24	.027
		Austin Dam	Austin PA	9-30-1911	Yes, concrete	11 to 30 minutes warning	143	2000	1.5	78	.039
		Lawn Lake Dam, Roaring River	Estes Park CO	7-15-1982	Yes	Noise provided alert. Major channel changes.	n/a	25	0-3	1	.040
		Big Thompson Flood	Estes Park CO	7-31-1976	No	Most received no warning	131	2500	-	144	.058
		Malpasset Dam	Frejus, France	12-2-1959	Yes, concrete	10 ft high entering Frejus	n/a	6000	0-7	391	.065
		South Fork Dam	Johnstown PA	5-31-1889	Yes	At Johnstown, major flooding in community before dam failure	100-166	19806	14	1756	.089
		Mill River Dam	Williamsburg MA	5-16-1874	Yes	Some received few minutes warning	25	750	3-7	138	.184
		South Fork Dam	Johnstown PA	5-31-1889	Yes	At Woodvale	166	1247	13	314	.250
		Laurel Run Dam	Johnstown PA	7-20-1977	Yes	Night	200-400	150	0-3	40	.270
		Kelly Barnes Dam	Toccoa GA	11-6-1977	Yes	Night, excludes dorm	96	100	1	36	.360
		Heppner Flood Disaster	Heppner OR	6-14-1903	No	Depth only 5 feet!	72	470	-	200	.430
Some	Vague	Black Hills Flood	Rapid City SD	6-9-1972	No/Yes	3000 injured	42	17000	-	245	.014
	Precise	Teton Dam, Wilford	Idaho	6-5-1976	Yes	The victims had been warned	82	600	8-9	5	.01

Table 5 - Continued

MEDIUM FLOOD SEVERITY (Buildings are destroyed. Trees/crushed houses provide refuge)											
WARNING TIME	FLOOD SEVERITY UNDERSTANDING	EVENT	GENERAL LOCATION	DATE	DAM FAILURE?	COMMENTS	$\frac{Q-Q_{2.33}}{\text{FLOOD WIDTH}}$ $(ft^{2/s})$	NUMBER OF PEOPLE AT RISK	MILES FROM DAM FOR PEOPLE AT RISK	DEATHS	FATALITY RATE
Adequate	Vague	Arkansas River Flood	Pueblo CO	6-3-1921	No	Floodplain depths up to 15 feet	17.3	2000	-	100	0.05
	Precise	Baldwin Hills Dam, between dam and Sanchez Drive	Los Angeles CA	12-14-1963	Yes	Multiple warnings, day	200	100	0-0.5	0	0.0
		South Fork Dam	Johnstown PA	5-31-1889	Yes	At South Fork	166	200	2	5	.025
		South Fork Dam	Johnstown PA	5-31-1889	Yes	At East Conemaugh	166	2000	11	52	.026
		South Fork Dam	Johnstown PA	5-31-1889	Yes	At Mineral	357	200	7	16	.080

Table 5 - Continued

LOW FLOOD SEVERITY (Buildings are not washed off foundations)											
WARNING TIME	FLOOD SEVERITY UNDERSTANDING	EVENT	GENERAL LOCATION	DATE	DAM FAILURE?	COMMENTS	$\frac{Q-Q_{2.33}}{\text{FLOOD WIDTH}}$ ($ft^{2/s}$)	NUMBER OF PEOPLE AT RISK	MILES FROM DAM FOR PEOPLE AT RISK	DEATHS	FATALITY RATE
None/Low		South Davis County Water Imp. Dist. #1 Dam	Bountiful UT	9-24-61	Yes	No warning	16	80	0-1	0	0.0
		Seminary Hill Reservoir	Centralia WA	10-5-91	Yes	No warning	13	150	0-1	0	0.0
		Allegheny County Flood	PA	5-30-86	No	9 homes destroyed, 76 major damage	n/a	2200	-	9	.004
		Mohegan Park Dam	Norwich CT	3-6-63	Yes	5 died in mill collapse	n/a	1000	0-2	7	.007
		Lee Lake Dam	East Lee MA	3-24-68	Yes	6 houses destroyed; 20 damaged	n/a	80	0-5	2	.025
Some	Vague	Lawn Lake Dam, Aspenglen Campground	Estes Park CO	7-15-82	Yes	Victims warned, but not of dam failure	n/a	275	7	2	.007
		Brush Creek Flood	Kansas City KS	9-12-77	No	17 deaths were automobile related	25	2380	-	20	.008
		Austin Flood	Austin TX	5-24&25-81	No	11 deaths were automobile related	n/a	1180	-	13	.011
		Texas Hill Country Flood	TX	8-2-78	No	Nearly placed in medium severity	n/a	2070	-	25	.012
	Precise	Quail Creek Dike (Dam)	St. George UT	1-1-89	Yes	No buildings destroyed?	31	1500	17	0	0.0

Table 5 - Continued

LOW FLOOD SEVERITY (Buildings are not washed off foundations)											
WARNING TIME	FLOOD SEVERITY UNDERSTANDING	EVENT	GENERAL LOCATION	DATE	DAM FAILURE?	COMMENTS	$\frac{Q-Q_{2.33}}{\text{FLOOD WIDTH}}$ ($ft^{2/s}$)	NUMBER OF PEOPLE AT RISK	MILES FROM DAM FOR PEOPLE AT RISK	DEATHS	FATALITY RATE
Adequate	Vague										
	Precise	Phoenix Area Flood	Phoenix AZ	2-80	No	11 of 13 bridges destroyed	n/a	6,000	-	0	0.0
		Bushy Hill Pond Dam	Essex CT	6-6-82	Yes	Night	n/a	300	0-2	0	0.0
		Lawn Lake Dam, downstream from National Park	Estes Park CO	7-15-82	Yes	Good warning	n/a	4,000	8-14	0	0.0
		Prospect Dam	CO	2-10-80	Yes	Not much damage	4	100	?	0	0.0
		South Platte River Flood	Denver CO	6-16-65	No	Up to 4 hours warning	19	10,000	-	1	.0001
		Passaic River Basin Flood	Northern NJ	4-84	No	Sluggish flood	n/a	25,000	-	2	.0001
		Flooding from Hurricane Agnes	PA only	6-92	No	>3500 dwellings or mobile homes destroyed. Water rose much slower than in many dambreak floods	n/a	250,000	-	48	.0002
		Kansas River	Eastern Kansas	7-51	No	Sluggish major flood, up to 30 feet deep	25-56	58,010	-	11	.0002
		Teton Dam (Rexburg to Amn. Falls)	ID	6-5-76	Yes	Some homes destroyed	n/a	23,000	15-156	5	.0002
		Great flood of 1993	Midwest US	1993	No	Sluggish flood	n/a	150,000	-	38	.0003
		Baldwin Hills Dam, between Sanchez Drive and Coliseum	Los Angeles CA	12-14-63	Yes	Multiple warnings, day	67	16,400	0.5-1.0	5	.0003
		DMAD Dam	Delta UT	6-23-83	Yes	Benign flooding, transient died	n/a	500	15	1	.0020

Table 6
Fatality Rates Derived from Case Studies
(Use Table 7 for selecting fatality rates)

Flood Severity	Warning Time (minutes)	Flood Severity Understanding	Fatality Rate (Fraction of people at risk that died)	
			Average	Range
HIGH	no warning	not applicable	0.76	0.3 to 1.00
	15 to 60	vague	No case fit this category.	
		precise	No case fit this category.	
	more than 60	vague	No case fit this category.	
		precise	No case fit this category.	
MEDIUM	no warning	not applicable	0.14	0.02 to 0.43
	15 to 60	vague	0.014	only one case
		precise	0.01	only one case
	more than 60	vague	0.05	only one case
		precise	0.035	0.0 to 0.080
LOW	no warning	not applicable	0.007	0.0 to 0.025
	15 to 60	vague	0.0095	0.007 to 0.012
		precise	0.0	only one case
	more than 60	vague	No case fit this category	
		precise	0.0003	0.0 to .002

GUIDANCE ON USING THE FLOOD SEVERITY BASED METHOD FOR ESTIMATING LIFE LOSS

Table 7, "Recommended Fatality Rates for Estimating Loss of Life Resulting from Dam Failure," contains recommended fatality rates for each of the 15 different combinations of flood severity, warning time and flood severity understanding. The fatality rates shown in Table 7 were derived from those shown in Table 6. Some changes were made in preparing Table 7 from Table 6 so that there was a consistent pattern in the fatality rates. The changes were based on judgement rather than any statistical analysis of the data. The suggested fatality rate range shown in Table 7 does not always capture the full range shown in Table 6. For those categories in which there were few or no cases, judgement was used in estimating a fatality rate and in developing a suggested range. In determining whether the flood severity is low, medium or high, use the following guidance:

1) Use low severity for locations where <u>no</u> buildings are washed off their foundation.

2) Use medium severity for locations where homes are destroyed but trees or mangled homes remain for people to seek refuge in or on.

3) Use high flood severity only for locations flooded by the near instantaneous failure of a concrete dam, or an earthfill dam that turns into "jello" and goes out in seconds rather than minutes or hours. In addition, the flooding caused by the dam failure should sweep the area clean and little or no evidence of the prior human habitation remains after the floodwater recedes. Nearly all of the events used in defining this category caused very deep floodwater that reached its ultimate height in just a few minutes. The flood severity will usually change to medium and then low as the floodwater travels farther downstream.

4) In determining whether flooding is low severity or medium severity, use low severity if most of the structures will be exposed to depths of less than 10 feet and medium severity if most of the structures will be exposed to depths of 10 feet or more. (Note that low severity flooding can be quite deadly to people attempting to drive vehicles).

Another method that can be used to separate low severity flooding from medium severity flooding is to use the parameter DV where:

$$DV = \frac{Q_{df} - Q_{2.33}}{W_{df}}$$

And:

Q_{df} is the discharge at a particular site caused by dam failure.

$Q_{2.33}$ is the mean annual discharge at the same site. This discharge can be easily estimated and it is an indicator of the safe channel capacity. As discharges increase above this value, there is a greater chance that it will cause overbank flooding.

W_{df} is the maximum width of flooding caused by dam failure at the same site.

The units of DV is d^2/s or depth times velocity, thus the term DV. 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. The parameter DV should provide a good indication of the severity (potential lethality) of the flooding. As the peak discharge from dam failure increases, the value of DV increases. As the width of the area flooding narrows, the value of DV again increases.

Low flood severity should be assumed, in general, when DV is less than 50 ft^2/s (4.6 m^2/s). Medium flood severity should be assumed, in general, when DV is more than this value.

The warning time for a particular area downstream from a dam should be based on when a dam failure warning is initiated and the flood travel time. For instance, assume a dam with a campground immediately downstream and a town where flooding begins 4 hours after the initiation of dam failure. If a dam failure warning is initiated 1 hour after dam failure, the warning time at the campground is zero and the warning time at the town is 3 hours.

The preponderance of dam failure data indicates that a high percentage of life loss resulting from dam failure occurs in the first 15 mi (25 km) downstream from a dam that has failed. For smaller dams this distance is considerably less than 15 mi (25 km). Loss of life, as a percentage of people at risk, becomes very small more than 15 mi (25 km) downstream from a dam for two main reasons. First, these downstream areas receive warning that usually is much better than the warning, if any, issued in areas nearer the dam; and second, the energy exhibited by the flood is lessened, the flood rises at a slower rate and the leading edge of the flooding usually moves at a slower rate in these downstream areas. Based on these empirical data and recognizing that the failure of some large dams could result in loss of life patterns or characteristics that are not observable with this same data base, loss of life studies should extend downstream from a dam for 30 mi (50 km). There may be some very high dams, or those storing very large quantities of water, where severe flooding could extend for 100 miles (161 km) or more downstream from the dam. In these cases, loss of life studies may be extended more than 30 mi (50 km) downstream from the dam. In general, however, life loss more than 30 mi (50 km) downstream from a dam should be very small compared to the life loss estimated for the areas nearer the dam. It is not anticipated that the life loss downstream from mile 30 (50 km) would change the results of a dam safety recommendation.

Table 7
Recommended Fatality Rates for Estimating Loss of Life Resulting from Dam Failure

Flood Severity	Warning Time (minutes)	Flood Severity Understanding	Fatality Rate (Fraction of people at risk expected to die)	
			Suggested	Suggested Range
HIGH	no warning	not applicable	0.75	0.30 to 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 to 0.35
	15 to 60	vague	0.04	0.01 to 0.08
		precise	0.02	0.005 to 0.04
	more than 60	vague	0.03	0.005 to 0.06
		precise	0.01	0.002 to 0.02
LOW	no warning	not applicable	0.01	0.0 to 0.02
	15 to 60	vague	0.007	0.0 to 0.015
		precise	0.002	0.0 to 0.004
	more than 60	vague	0.0003	0.0 to 0.0006
		precise	0.0002	0.0 to 0.0004

Closing Comments on the Flood Severity Based Method

High Severity flooding is not well represented in the data base. In order to estimate loss of life for these events, there is a need to determine the number of people who will remain in the dam failure floodplain after warnings are issued. At this time, no guidance is being provided on this topic.

Medium Severity flooding results in a wide range of fatality rates, especially when there is no warning. Factors that influence this range would include: do some people evacuate in response to environmental clues, are people awake, is it night and is it raining? Laurel Run and Kelly Barnes dam failures both had high fatality rates and in each case the events occurred at night and no knowledge of impending dam failure was available to people at risk. The Heppner, Oregon Disaster, with the highest fatality rate, was a very unusual case. A USGS Water Supply Paper stated, "It seems almost incredible that a flood of a depth of only 5 feet above the general level of the town should cause such a loss of life....Nearly all of the houses simply rested on posts or open foundations of stone....So they lifted off their foundations and floated away like boats." The USGS learned that "No building that can be lifted from its foundation and swept away should be allowed in the area of a possible flood." - The beginnings of floodplain management concepts, nearly 100 years ago!

Low Severity flooding results in low fatality rates, regardless of the quantity and quality of warnings. The people writing about these floods at the time frequently commented on the low fatality rates. Examples include: Kansas River Flood of 1951: "And the wonder is that the death list was not longer." Hurricane Agnes flooding of 1972: "The death toll of 117 was light considering the severity of the widespread floods." Phoenix area flooding of 1980: "Three people died in Arizona, a surprisingly low number considering the magnitude of the damage."

Using the recommended fatality rates based on the flood severity, warning time and flood severity understanding, can produce results much different than the results obtained with the Brown and Graham or DeKay and McClelland equations. For instance, take a community of 10,000 people exposed to medium severity flooding with 1.5 hours of warning. The Brown and Graham equations predicts 2 fatalities and the DeKay and McClelland equation for high lethality predicts about 7 fatalities. The fatality rate in Table 7 for precise warning issued more than 60 minutes before flood arrival results in a predicted 100 fatalities.

The fatality rate in areas with medium severity flooding should drop below that recommended in Table 7 as the warning time increases well beyond one hour. Repeated dam failure warnings, confirmed by visual images on television showing massive destruction in upstream areas, should provide convincing evidence to people that a truly dangerous situation exists and of their need to evacuate. This should result in higher evacuation rates in downstream areas and in a lowering of the fatality rate.

Step 7: Evaluate Uncertainty

Estimating loss of life from dam failure is an art as much as it is a science. There may never be a procedure available that will provide precise and accurate estimates of the loss of life that results from failure.

There are various types of uncertainty that can influence loss of life estimates. One type of uncertainty deals with the cause of dam failure. Step 1 of this procedure suggests that separate loss of life estimates be developed for each failure cause of interest. Various causes of dam failure will result in differences in downstream flooding and therefore result in differences in the number of people at risk as well as the severity of the flooding. Dam failure modeling, which serves as a basis for developing dam failure flood boundaries, flood severity and flood wave travel times, is also fraught with many types of estimates and uncertainty. Another type of uncertainty, generally random in nature, is the time of day, time of week and time of year that failure occurs. Step 2 of this procedure suggests once again that separate loss of life estimates be developed for various possible combinations. The time at which warning is initiated and the number of people at risk may depend upon the time at which failure occurs.

Additional uncertainty is associated with when warnings would be initiated. Step 3 and Table 2 provide guidance on when warnings would be initiated. Other warning scenarios may be equally or more likely. Uncertainty associated with warning initiation can be evaluated by varying the assumption regarding when a warning would be initiated.

The last type of uncertainty is associated with the inability to precisely determine the fatality rate. There was uncertainty associated with categorizing some of the flood events that are included in Table 5. Similarly, some of the factors that contribute to life loss are not captured in the categories shown in Tables 6 and 7. This type of uncertainty can introduce significant, but unknown, errors into the loss of life estimates. Some possible ways of handling this uncertainty would be to 1) use the range of fatality rates shown in Table 7, 2) when the flooding at a particular area falls between two categories (it is unclear if the flood severity would be medium or low, for example) the loss of life estimates can be developed using the fatality rate and range of rates from all categories touched by the event and 3) the events cataloged in table 5 can be evaluated to see if there are any that closely match the situation at the site under study.

SUMMARY

The procedure described herein provides a method for estimating the loss of life resulting from dam failure. The procedure was developed using data from about 40 floods, many of which were caused by dam failure. The procedure suggests that fatality estimates be developed for different failure causes and for different times of the day, week or year. The procedure contains guidance on when a dam failure warning would be issued and this warning initiation is based on the drainage area at the dam, the number of formal and informal dam observers, and the time of day (or night) when failure occurs. The procedure then provides fatality rates for converting population at risk to probable life loss. The fatality rates are a function of flood severity, warning time for each group of people at risk, and flood severity understanding. This last factor will influence the quality and accuracy of the warning messages and will influence the response taken by people at risk. The procedure provides a discussion of uncertainty and how it can be evaluated.

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