A Simple Procedure for Estimating Loss of Life from Dam Failure

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INTRODUCTION

Evaluating the consequences resulting from a dam failure is an important and integral part of any dam safety study or risk analysis. The failure of some dams would cause only minimal impacts to the dam owner and others, while large dams immediately upstream from large cities 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 resulting from dam failure. Included is a procedure for estimating 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.

PROCEDURE FOR ESTIMATING LOSS OF LIFE

The steps for estimating loss of life resulting from dam failure 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: Select appropriate fatality rate.
Step 7: Evaluate uncertainty.

The details of each step are as follows:

Step 1: Determine Dam Failure Scenarios to Evaluate

A determination needs to be made regarding the failure scenarios 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, some tourist areas may be unused for much of the year. The number of time categories (season, day of week, etc.) selected for evaluation should accommodate the varying usage and occupancy of the floodplain. 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.

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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 1, "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 flood storage space. 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 flood storage space, 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 1 provides a means for deriving an initial **estimate** of when a dam failure warning would be initiated for the failure of an earthfill dam. 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 factors into account.

Table 1

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, existing dam-break studies and maps may provide information for the scenarios being evaluated. Sometimes new studies and maps will need to be developed.

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 is to: "Take a snapshot and count the people." The number of people at risk varies during a 24-hour period.

The number of people at risk 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.

Step 6: Select Appropriate Fatality Rate

Fatality rates used for estimating life loss should be obtained from Table 2. The table was developed using data obtained from approximately 40 floods, many of which were caused by dam failure. The 40 floods include nearly all U.S. dam failures causing 50 or more fatalities as well as other flood events that were selected in an attempt to cover a full range of flood severity and warning combinations. Events occurring outside of the U.S. were included in the data set. 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. Use the low severity category if most structures would be exposed to depths of less than 10 ft (3.3 m) or if DV, defined below, is less than 50 ft2/s (4.6 m2/s).

2) Medium severity occurs when homes are destroyed but trees or mangled homes remain for people to seek refuge in or on. Use medium flood severity if most structures would be exposed to depths of more than 10 ft (3.3 m) or if DV is more than 50 ft2/s (4.6 m2/s).

3) High severity occurs when the flood sweeps the area clean and nothing remains. High flood severity should be used only for locations flooded by the near instantaneous failure of a **concrete** dam, or an earthfill dam that turns into "jello" and washes 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. Although rare, this type of flooding occurred below St. Francis Dam in California and Vajont Dam in Italy. The flood severity will usually change to medium and then low as the floodwater travels farther downstream.

The parameter **DV** may be used to separate areas anticipated to receive low severity flooding from areas anticipated to receive medium severity flooding. DV is computed as follows:

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

where:

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

Warning Time influences 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.

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 fatality rate in areas with medium severity flooding should drop below that recommended in Table 2 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.

Flood Severity Understanding also has an impact on the fatality rate. A warning is comprised of two elements: 1) alerting people to danger and 2) requesting that people at risk take some action. Sometimes those issuing a flood warning or dam failure warning may not issue a clear and forceful message because either: 1) they do not understand the severity of the impending flooding or 2) they do not believe that dam failure is really going to occur and hence do not want to unnecessarily inconvenience people. People exposed to dam failure flooding are less likely to take protective action if they receive a poorly worded or timidly issued warning. Warnings are likely to become more accurate after a dam has failed as those issuing a warning learn of the actual failure and the magnitude of the resultant flooding. Precise warnings are therefore more probable in downstream areas. This factor will be used only when there is some or adequate warning time.

The flood severity understanding categories are as follows:
1) Vague Understanding of Flood Severity means 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 the warning issuers have an excellent understanding of the flooding due to observations of the flooding made by themselves or others.

Table 2
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.	
	more than 60	Precise		
		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

Step 7: Evaluate Uncertainty

Various types of uncertainty can influence loss of life estimates. Quantifying uncertainty is difficult and may require significant time to achieve.

Step 1 of this procedure suggests that separate loss of life estimates be developed for each dam failure scenario. 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.

Step 2 suggests that the dam failure be assumed to occur at various times of the day or week. It is recognized that the time of failure impacts both when a dam failure warning would be initiated as well as the number of people who would be at risk.

Step 3 focuses on when a dam failure warning would be initiated. This warning initiation time could be varied to determine sensitivity to this assumption.

Dam failure modeling serves as the basis for step 4. Dam failure 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 these parameters will result in changes in the flood depth, flood width and flood wave travel time. This will lead to uncertainty in the: 1) population at risk, 2) warning time and 3) flood severity.

Estimating the number of people at risk, step 5, may be difficult, especially for areas that receive temporary usage. A range of reasonable estimates could be used.

The last type of uncertainty is associated with the inability to precisely determine the fatality rate, step 6. There was uncertainty associated with categorizing some of the flood events that were used in developing Table 2. Similarly, some of the factors that contribute to life loss are not captured in the categories shown in Table 2. 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 2, 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) historical events can be evaluated to see if there are any that closely match the situation at the site under study.

SUMMARY

History has shown us that dam failures can be deadly. Some dam failures have resulted in hundreds or thousands of deaths. Many other dam failures have resulted in relatively insignificant losses, either because the dam height and resultant peak outflow were small or because the development downstream from the dam was sparse.

This paper provides a tool for estimating loss of life resulting from dam failure. No life loss estimating procedure will be perfect. However, the procedure described in this paper should provide reasonably accurate estimates of the loss of life that would result from the failure of a dam.

Additional information on this subject is available by viewing the paper, “A Procedure for Estimating Loss of Life Caused by Dam Failure,” DSO-99-06, Sedimentation and River Hydraulics, U.S. Bureau of Reclamation, September 1999. It can be accessed