FERC Engineering Guidelines
Risk-Informed Decision Making

Chapter R22

Estimation of Life Safety Consequences

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The purpose of this chapter is to address the consequence side of the risk equation. The starting point for determining the consequences is the assumption that some loading condition has driven the dam to failure or otherwise resulted in an uncontrolled release of water. Chapter R21 provides guidance on determining the breach size and routing the water downstream from that breach, this Chapter, R22, provides guidance on determining impacts on downstream life safety and Chapter R23 provides guidance on determining the economic consequences of dam failure.

R22.1 Introduction and Purpose

Flood water released when a dam fails can be a devastating force. Dam failures in the United States have historically taken many lives and have destroyed much property. By the same token, a number of dams fail each year in the United States without a single life lost. Physical and human factors both contribute to potential life loss, as does a certain amount of chance (USBR 2009).

Four primary factors affect potential life loss in dam failure scenarios:

- The number of people occupying the area inundated by a dam-break flood
- The amount of warning provided in relation to the time required to move to a safe location
- The intensity of the flow to which people are exposed
- The timing of the dam failure (e.g. day or night, summer or winter). Timing can affect both the number of people downstream and the amount of warning time available.

The purpose of this chapter is to explain the theory behind the calculation of life loss consequences. Several current methodologies are discussed that can be used for these calculations. For specifics on how to perform analyses, the reader should refer to the guidance for the particular tool. Multiple levels of analysis will be discussed, with the understanding that risk analysis is not one-size-fits-all, but rather scalable based on the available data and questions to be answered.

R22.2 Life Safety Analysis

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R22.2.1   Levels of Risk – Scalability

Scalability of the determination of consequences is important for adjusting the level of effort of the analysis to the degree of uncertainty acceptable to the risk assessment. For the baseline assessment of a dam that has a very low probability of causing a fatality an in-depth simulation may be an unnecessary waste of resources. On the other extreme, when assessing a dam capable of causing mass casualties it may be necessary to reduce the uncertainty of the estimate to obtain confidence in an annualized life loss. In this case a simulation, taking into account factors such as evacuation rates and routes may be justified. Like most things in risk analyses, consequence estimation should be an iterative or tiered process, starting with the most simple and approximate analysis and working up in complexity as is required to make an informed decision.

The U.S. Bureau of Reclamation (USBR) has identified two categories for analysis of life safety consequences, which they refer to as notional and simulation. Notional refers to the methods that utilize historic dam failure databases to develop empirical formulas to translate the PAR into PLL. The notable limitation of this methodology is that it is limited to the historical record of dam failures, which is dominated by smaller dams (<50 feet high). The most widely used notional method is the Graham Method (1999). Simulation methods attempt to model flood flows, human behavior, traffic patterns, safe havens, and warning times to predict how effective an evacuation would be at getting people out of harm's way.

Multiple levels of complexity are presented below (section R22.3.2) for each of the three life safety consequence factors. These levels are by no means exhaustive, and combinations of several methods can be used (i.e. one method for PAR, and another for PLL). The important factor, again, is that the analysis be rigorous to the extent that the confidence level is high enough to facilitate a dam safety decision, and that all the assumptions in the analysis are well documented and justified.

Generalized levels of Life Loss Prediction

	Effort Level	PAR	PLL	Timing

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Level 1 Risk Analysis	Low	Counting structures on aerial photographs, estimating residents per structure using general U.S. Census data	Assuming all residents in inundation area perish due to flooding.	Assuming all structures are inhabited.
Level 2-4 Risk Analysis	Medium	Using GIS methods with census block data and inundation areas to estimate the PAR.	Using empirical methods to estimate life loss due to warning time and severity of flood (DSO-99-06).	1D flow model interpolated results used for flood timing and velocity. Seasonal changes in population considered.
	High	Door-to-door census and elevation surveying of structures.	Using simulation models to predict movements of residents based on warning time, traffic models, flood wave velocity, etc.	2D flow model gridded results used for flood timing and velocity.

The levels of rigor provided above are in matrix form due to the ability to mix and match among the inputs. The overriding purpose behind refining a life safety analysis is to reduce the uncertainty in the estimate of life loss. The level of uncertainty is largely dependent on the population distribution in the area inundated by the dam failure. Two extreme examples of this are:

- A small number (dozen) of impacted homes are year round residences, all well within the inundation area, and subject to very high increases of depth and velocity. With a simple 1D model we can estimate the PAR with little uncertainty. Obtaining the PLL we could assume that all residents perish, or we could apply DSO-99-06 (USBR 1999) and estimate between 75-100% fatalities.

- The opposite case would be a dam failure inundation area that affects a large urban population in a wide, flat flood plain. There would be a large mix of structure types, which could resist damage and provide shelter over a wide range of flood intensities. The wide flood plain would need a 2D model to accurately estimate the wide range of depths and velocities in the

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impacted areas. The population would need to be accurately estimated, by structure, due to the number of high rise structures, hospitals, schools, and other large population concentrations that cannot be gleaned from the census data. A simulation model could be justified if the population has time for partial evacuation and factors like mobilization and traffic congestion could affect numbers greatly.

In between the two extremes are many other combinations of analyses. Each must be evaluated on a case-by-case basis depending on the downstream area. The level of rigor of the consequence analysis is somewhat independent of the potential failure mode, unless the risk of the failure mode is so close to tolerable that getting a better estimate might make the difference in the decision making.

In general for a screening level analysis (Level 1 Risk Analysis, as per Chapter R24), uncertainty should be kept within one order of magnitude and the low level analyses can be used. More refined tools should be used for higher level risk analyses.

R22.2.2   Data Needed

Inundation Area -
The area inundated by a dam failure should be obtained from a dam breach hydraulic model. The procedure for conducting a dam failure analysis is described in Chapter R21. For risk analysis purposes the inundation area will be the product of a particular failure mode, and there may be many different inundation areas for a single dam. These data are normally supplied as vector files that can be used in a Geographic Information System (GIS) to overlay the impact area with downstream populated areas. For screening level analysis, paper maps may be sufficient.

Flood Depth and Velocity
The severity of the flooding affects the lethality of the flood to the non-evacuated PAR and is determined by the depth and velocity of the water. It takes very little fast moving water to move a car and prevent evacuation, while deep slow-moving flood waters could be navigated by wading or swimming. The depth and velocity of the dam failure inundation should be provided from the hydraulic model.

Timing
There are several factors related to the timing of the flood which affect downstream life loss consequences.
    Travel Time -

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The time for the dam failure hydrograph to travel downstream from the dam and inundate the downstream populated area to a level that will begin to threaten residents (a function of Depth-Velocity). The travel time affects the amount of time available to issue a warning and for the PAR to evacuate. The travel time of the dam failure inundation hydrograph can be inferred from the hydraulic model.

Time of Day -
The time of day can affect the PAR if the area has a large commuter population and the residences and workplaces are not both affected by flooding. The time of day can also have impacts on the detection and assessment of the failure as well as effectiveness of the evacuation, especially if the failure occurs during the middle of the night.

Time of Year -
The time of year has a twofold impact, possibly changing the seasonal PAR and affecting the survivability if the flood occurs in winter.

Census Data

The U.S. Census data is available on the web in two parts. The first part is the TIGER/Line® Shapefile of the census unit. The census blocks can range from an entire county down to a census block that is the size of one city block. The second part of the census information is the data tables that are associated with the census units. Each unit has a unique identifier which corresponds to a row in the database to allow for cross referencing. Useful data fields include the count of permanent residents in each census unit, as well as the average number of residents per structure.

Evacuation Routes

Evacuation routes are used in simulation models (and can be used in notional estimation, if enough information is available) to estimate the life loss of a population at risk. Several factors about the routes can be taken into account in the evacuation simulation, such as:

- Do the routes remain open during the event, or are they submerged and impassible at some time?
- If the evacuation routes are submerged or impassible, does this occur before or after the evacuation area becomes flooded?
- Does the route include bridges which could be impacted by scour or debris?
- Are the evacuation routes of such a capacity to successfully evacuate the PAR?
- Is traffic congestion of the evacuation routes a concern?

Warning/Evacuation Timing

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Timing of the evacuation is needed to compare to the timing of the flood, to determine if a full evacuation will be possible in the time available. In general, the more time that is needed to evacuate, the less successful the evacuation will be.

R22.2.2   Analysis Techniques

R22.2.2.1   Population at Risk Determination

People who live, work, or recreate in, or temporarily pass through inundated areas can be exposed to dambreak flooding. There are several methods to count these people, each with its strengths and weaknesses. For flood failure modes it may be necessary to separate the populations that are flooded before and after the dam failure to determine what portion of the population is affected by the dam breach. A few methods are discussed below.

- Counting homes on aerial photos or paper maps

The Internet provides several useful tools to perform a quick reconnaissance: Google Earth, MapQuest, TerraServer. In this method the inundation area is overlain on the aerial data and homes are counted by hand. Census data from the DataSets tab of the American FactFinder website can be used to quickly determine the average number of residents per permanent structure by county. For more densely populated areas the total population can be multiplied by the percentage of that town that is inundated. Campsites and other transient populations can be estimated and simply multiplied by the time of year they are present. The internet is a good resource for finding the capacity of recreational areas. Everything falling within the inundation area is considered part of the PAR, unless there is flood depth information available that could exclude some of the area from life safety impacts.

- GIS and Census data

Automated processes are usually used to count population at risk for higher levels of study when the threatened population is large. Here, results from flood routing studies are converted into GIS format, and census data are overlain. The entire resident population of a census block is added to the population at risk when census blocks are entirely within inundated areas. When a portion of the census block is inundated, the block's population is multiplied by a fraction proportional to the percent of the block's area that is inundated (called an area-weighted average). Using the area-weighted method assumes that the population in the census block is evenly distributed. A crude upper bound estimate counts the entire population from partially inundated census blocks. Inundated areas can

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include residential tracts, commercial and industrial zones, recreational usage areas, and roads or railroads with high traffic volumes. The number of people in any of these areas can change according to time of day, day of the week, and season of the year, and can increase steadily year by year.

- Surveying and Ground Truthing

The most labor intensive yet most accurate way to determine the PAR is by surveying structure elevations and conducting a door-to-door census of the downstream population. Having accurate structure elevation data can help alleviate errors caused by the resolution of the aerial elevation data (DEM or otherwise), and can help determine exactly how severely a flood will affect the structure (i.e. what is the lowest habitable elevation, foundation type, construction type, etc.). Census data becomes out of date with age, and conducting a door-to-door census as part of the investigation ensures that data is as up to date as possible, and that the correct number of residents, and their times of residency (seasonal, day/night, etc.) are accurate.

While this process may be cost prohibitive for very large downstream populations, it may be a very reasonable method to get the most accurate data for small downstream populations. This is especially true if the decision of whether to do major remediation is based life safety impacts to a very small group.

R22.2.2.2   Flood Severity

Flood severity using the Reclamation's notional method is broken into three categories; low, moderate, and severe. These categories are determined by the depth and velocity of the flooding. Low severity flooding is such that an able bodied adult would be able to wade out of harm's way. Safe havens such as home would still be intact and could be used for shelter. Severe flooding is generally deep and fast flowing water that would be capable of exceeding the structural integrity of a perceived safe haven, be it the second story of a home or a tree. With severe flooding, fatality rates are thought to be higher when the deep and fast-flowing water rises rapidly than when there is a gradual rise to the peak discharge level.

Distinctions between flood severity categories are vague. For instance, five feet of water flowing at 1 foot per second would probably not disturb a two-story brick home, but it certainly would pick up and very likely destroy a mobile home. So for a housing development mostly comprised of brick homes, such flows might be considered low severity, but might be considered moderate severity for a trailer park. Severity categories should be determined using site specific information and engineering judgment. Hazard

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curves are available from FEMA HAZUS model and the USBR Hazard Classification Guidelines for several types of structures. These can give an indication of what flood intensity a safe haven could survive.

R22.2.2.3   Flood/Warning Timing

The speed at which the dam fails (breach development time) and the travel time for the resulting flood wave to reach the location of the population at risk is another factor affecting the mortality rate of the dam failure. With sufficient time, evacuation can be very effective at relocating the populace out of harm's way, but a sudden failure that results in a fast moving flood wave can decimate downstream areas if no warning is received.

There are several factors, or components of warning time, to consider in a consequence analysis that are described more thoroughly in the definitions section above. The time it takes to detect the breach, confirm that it has occurred and notify the downstream residents can collectively be called the warning time. Subtracting this time from the time the flood becomes dangerous at the resident's location (Time to Impact) yields the excess warning time. This excess is the available time for the resident to leave the danger area.

Each of these factors needs to be adjusted for the particular failure mode and the time the failure occurs. A failure in the middle of the day, when operators are on site, could have a very different warning time than the same failure in the middle of the night. These variables should be factored into the timing and accounted for in the discussion of uncertainty.

In general, the historic record indicates that most fatalities from dam failures occur in the first 15 miles downstream (Graham 1999). While this may be a good rule of thumb for dams that fit well within the historic record, it should not replace good engineering judgment for dams that do not fit the record.

R22.2.2.4   Predicted Life Loss Determination

Once the dam breach and flood characteristics have been assigned and the population at risk identified, there are two basic types of analysis to estimate life loss: one is notional, empirically based on a small number of past instances, while the other employs simulation that attempts to model people's response to the situation. Fatality rates for both the notional and simulation methods depend on flood severity, which can be tied to flood depths and velocities.

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The recommended fatality rates from any method can be adjusted when justified by extenuating circumstances. If a particularly devastating earthquake is responsible for dam failure, it is quite likely the earthquake has also devastated infrastructure and communications in population centers in the vicinity. Every aspect of warning (i.e. detection, decision, notification, and dissemination) may be affected, and evacuation routes may be compromised. Emergency management personnel would be responding to several situations and will not be able to devote their entire attention on a developing situation at a dam. It may be reasonable to increase the fatality rates for this case.

- Notional Method - Graham's Method

In developing the notional method, forty flood events were scrutinized and population centers affected by the flooding were categorized. The reported number of fatalities at each population center divided by the estimated population at risk at the time of the flood event defined the fatality rate assigned to each combination of the severity, warning time, and danger perception categories.

To use the notional method to assign fatality rates for hypothetical dam failures, each population center below a dam is assigned a flood severity, warning time, and danger perception category. The fatality rate for the appropriate combination is applied to the estimated population at risk. Reclamation's full notional method has three categories for flood severity, three categories for warning time, and two categories for danger perception.

In the absence of detailed hydraulic modeling Graham's method uses a simple table based on empirical data to estimate the warning time based on the type of failure and whether or not an observer would be present. This table gives the time from the breach that a warning is issued. Timing is then generalized based on distance downstream of the dam.

The fatality rates estimated in this method account for evacuation, and thus no reduction in population at risk should occur prior to applying the fatality rates. FERC's method, used in EAP evaluations breaks warning time into stages: detection, assessment, notification, and dissemination. These times are compared with the hydraulic model to determine the amount of excess time to evacuate.

Human factors can also contribute to life loss due to the choices people make, such as to remain in harm's way when warned to leave and leaving a threatened location too late when there should have been adequate time for evacuation. There can be many reasons why people who are not at risk initially will enter the inundation area either before or

after the peak discharge has reached their location. Not all people who lose their lives as a result of dambreak flooding do so by drowning (for example the stress can trigger heart attacks or other fatal ailments). All of these random factors are accounted for in the notional method, since it is based on historic failures.

- Incremental Hazard

In performing dam safety risk analysis a significant change from Chapter 2 of the FERC Engineering Guidelines must be made in accounting for the incremental damages, specifically fatalities, caused by a dam failure during a flooding event. In traditional IDF analysis a 2-foot incremental rise has historically been used a 'rule of thumb' for determining a significant increase in hazard. This criterion made sense for a screening level assessment of PAR or a hazard rating assessment, but it has no relation to PLL. Simply stating the vertical rise of the flood water tells nothing about the survivability.

To assess incremental hazard for a dam safety risk analysis it is recommended that two inundation maps be prepared, as in an IDF analysis, but instead of comparing flood depth, survivability would be compared. The depth-velocity (DV) grids of each inundation map would be subtracted to yield ΔDV. If the dam failure increased the severity of flooding in a populated area enough to statistically 'assure' a fatality, it would be tallied as a significant consequence of the failure.

For example, an area that would be dry during a flood has a population of 100 people. Due to the dam failure this area would be subjected to low severity flooding that would have an adjustment factor of 0.0003. Multiplied by the population this would result in an increase of 0.03 fatalities. By itself this increase would be negligible, but if there were 33 other areas with the same characteristics there would be a statistical increase of one fatality. Conversely, an area that was already flooded before the dam failure but was not hazardous could suddenly become more dangerous due to an increase in DV. The rapidity of the increase in DV should be considered for either case.
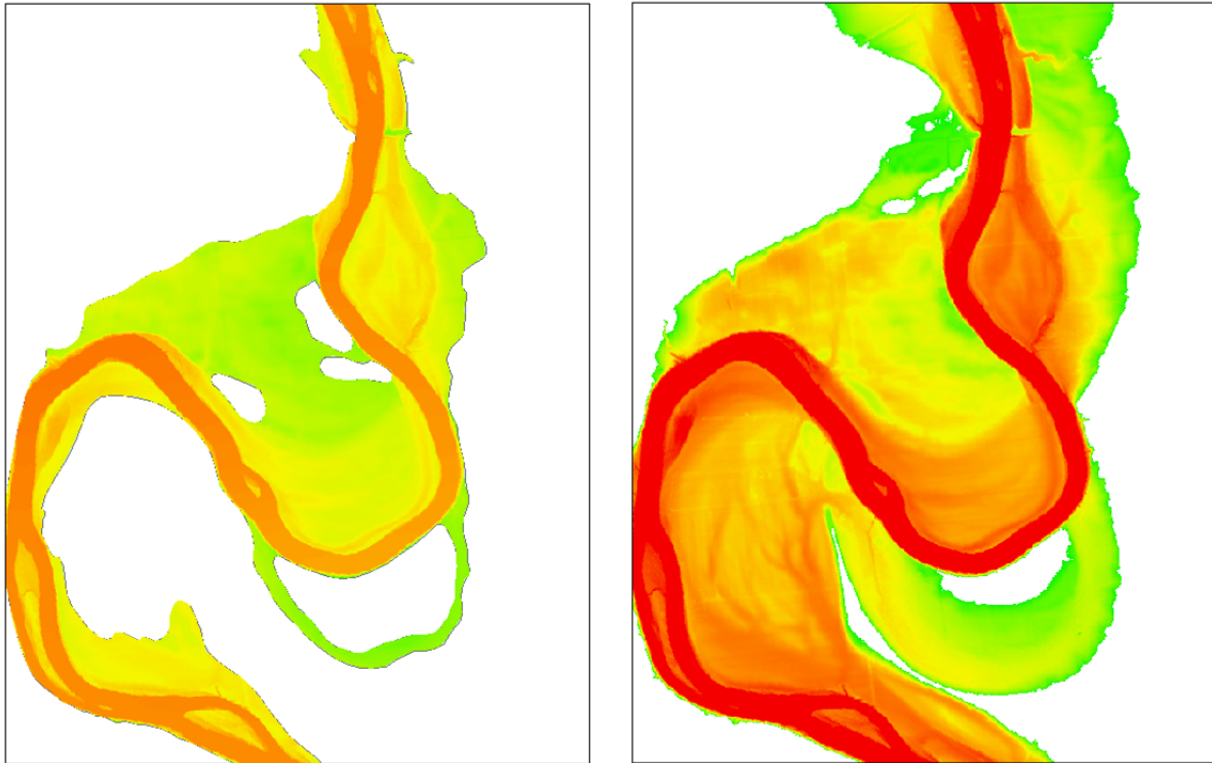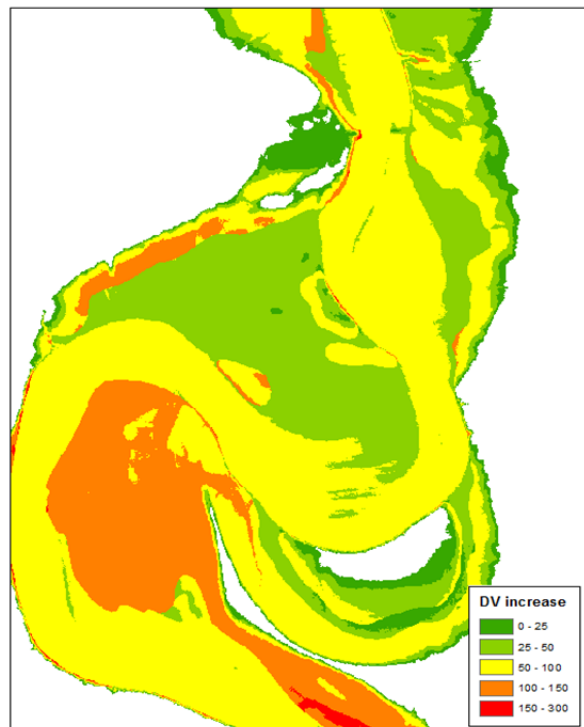
Figure 1 - Example of a Pre-failure (left) and Post-failure (right) flooding depth-velocity grid.

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Figure 2 - Difference in DV due to dam failure. Note the highest ΔDV (in orange and red) is where there was dry land before, while areas that were wet from normal flooding had more modest increases in DV.

- <u>Simulation modeling</u>

Simulation methods use a computer to combine models of dambreak, flood routing, warning dissemination, evacuation, and life loss. Safe areas are designated, populated zones are assigned warning times and choices regarding means of travel (e.g. by car or walking), road and intersection capacities are assigned, and the computer model determines how many people are likely to successfully evacuate. Whereas fatality rates for Reclamation's notional method are multiplied by the initial population at risk, the simulation methods multiply the fatality rate by an estimated fraction of the initial population at risk who might be remaining within inundation boundaries at the time the flood wave arrives. These fatality rates depend on flood severity and upon an assigned shelter survivability category.

Simulation Models

The following is a summary (from the software literature) of the three most commonly used simulation programs.

LIFESim

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

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

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HEC-FIA

A stand-alone, GIS-enabled model for estimating flood impacts due to flooding used by the United States Army Corps of Engineers. The software tool can generate required economic and population data for a study area from readily available data sets and use the data to compute urban and agricultural economic flood damage, area inundated, number of structures inundated, population at risk, and loss of life. These results can be used to inform risk assessments within the dam and levee safety programs as well as the Corps traditional planning process. All damage assessments in HEC-FIA are computed on a structure-by-structure basis using inundated area depth and arrival grids, or hydrograph data. The life loss computation contained in HEC-FIA includes consideration of the effectiveness of warning systems, community responses to alert, and evacuation of large populations.

HAZUS

The HAZUS Flood Model produces loss estimates for vulnerability assessments and plans for flood risk mitigation, emergency preparedness, and response and recovery. The methodology deals with nearly all aspects of the built environment, and a wide range of losses. The user can evaluate losses from a single flood event, or for a range of flood events allowing for annualized estimates of damages. Using the extensive national databases that are embedded in HAZUS, users can make general loss estimates for a region. These databases contain information such as demographic aspects of the population in a study region, square footage for different occupancies of buildings, and numbers and locations of bridges. The HAZUS methodology and software are flexible enough so that locally developed inventories and other data that more accurately reflect the local environment can be substituted, resulting in improved loss estimates.

R22.3 Best Practice for Risk

R22.3.1 Accounting for Uncertainty

"An explicit treatment of uncertainty forces us to think more carefully about such matters, helps us identify which factors are most and least important, and helps us plan for contingencies or hedge our bets". Morgan and Henrion (1990).

From USBR
"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."

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Regardless of which method is used, there is a great deal of uncertainty in all aspects of the life loss estimate. While it is the intent of each method to provide accurate and consistent estimates of loss of life, this goal is difficult to achieve. Inherent in any loss of life estimating methodology is uncertainty associated with natural variability, dependent on chance or luck and arises because of natural and unpredictable variations in the performance of the dam under study. The other type of uncertainty is associated with the lack of, or error in, knowledge about the behavior of the system under study.

Examples of natural variability uncertainty (aleatory):
- Does failure occur when impacted area is crowded with people due to special event?
- Are warnings issued before dam failure?
- Does the failure occur during the light of day or dark of night?
- Is the warning process effective?
- Are roadways impassible prior to the arrival of dam failure flooding?
- Effects of floating debris on flood depths.

Examples of knowledge uncertainty (epistemic):
- Breach shape, ultimate size, and rate of breach development.
- Depth of dam overtopping that causes failure.
- Speed at which the flood travels downstream.
- The factors that will motivate a particular individual to mobilize (begin evacuating).
- The amount of time from the issuance of a warning to when a particular individual mobilizes.
- The percentage of people who do not evacuate.
- Flood depths and velocities that will destroy structures.

Communicating risk to decision makers should be as a range, or better yet, as a graphical depiction. Each source of uncertainty needs to be addressed in the analysis by making an assumption for the most likely case, and the providing justification for the assumption and the likely range of possible values.

Figure 1 is an idealized illustration (the distributions are artificial) of three probabilistic loss of life estimates. The center curve represents a normal distribution of PLL, from zero to the PAR, where the best estimated of PLL is the mean and the uncertainty is represented by standard deviations around the mean. The curve on the left is skewed to the low end of the PAR, indicating that information leading to the estimate of the PLL indicates that either effective evacuation could be achieved or that much of the dam

failure flow will not be life threatening. The curve on the right is skewed to included most of the PAR in the PLL estimate, which would indicate both severe life threatening flows with little to no warning or opportunity for evacuation. In all cases the PAR sets the upper limit for the PLL. It should be noted that there is also uncertainty in the PAR estimate - which is not illustrated in this conceptual diagram.
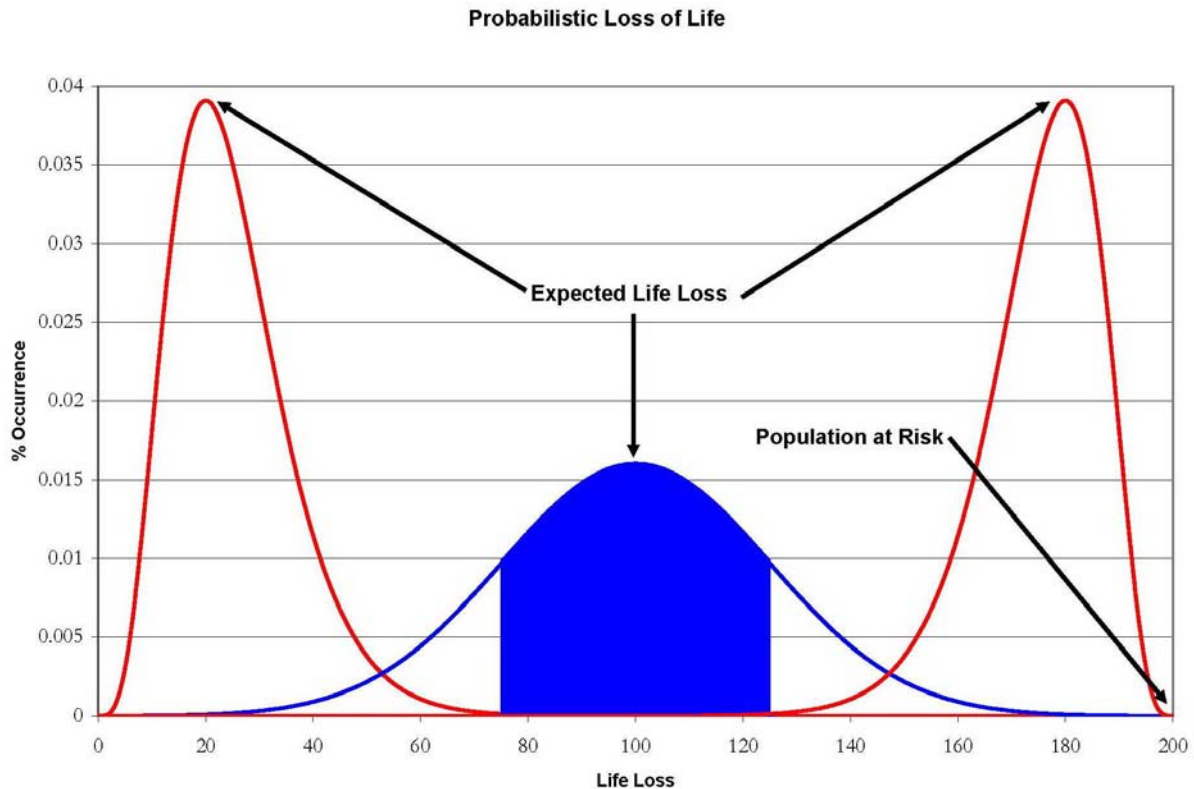

Figure 3 - Example of a probabilistic loss of life estimation.

Appendix A - Definitions

Population at Risk (PAR)
Population at risk is defined as the number of people occupying the area inundated due to dam failure prior to the issuance of any warning or evacuation.

Predicted Life Loss (PLL)
The portion of the PAR that would be predicted to perish due to a combination of flood warning time and intensity of flow. PLL can be expressed as a best estimate or a

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probability density function to illustrate the uncertainty. The PAR represents the maximum possible life loss.

Safe Haven

An area to where members of the PAR can evacuate and avoid the flood wave and ensuing inundation. Safe havens can changes as flood flows change, either due to different flood magnitudes or over time during the same flood.

Warning Time

The time necessary to detect, verify, notify, and disseminate information to the affected population regarding the occurrence of a dam failure or hazardous condition.

Detection time

The time between when the breach occurs and when it is detected. Detection time can be positive if an impending failure is recognized prior to the actual failure or negative if the failure occurs prior to detection. Detection can be by instrumentation, on-site operator, video surveillance, or a passerby. Detection time may be greatly influenced by time of day or year.

Verification (Decision) time

The time between when the breach, or impending breach, is detected and the deciding official (e.g. operator, manager) initiates the Emergency Action Plan (EAP).

Notification Time

The time it takes to call down the list of emergency management officials to begin alerting downstream residents.

Evacuation Time

The time it takes for members of the population at risk to evacuate the inundation area once warning is received.

Dissemination of Information

The time it takes for the dam owner's dissemination of pertinent information to emergency management officials throughout the event to aid in emergency preparedness or response efforts.

Depth-Velocity (DV)

The product of the depth and velocity of floodwater. Used to characterize the severity and survivability of flooding. A DV grid of an inundation area can be output from GIS based hydraulic models.

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