ESTIMATING LOSS OF LIFE FROM DAM FAILURE WITH HEC-FIA

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Abstract This paper describes a loss of life estimation approach that is commonly applied within the risk informed portfolio management process of the US Army Corps of Engineers (USACE) Dam Safety Program and the USACE Critical Infrastructure Protection and Resilience Program (CIPR). Focus is on methodology and application of the Hydrologic Engineering Center’s Flood Impact Analysis Model (HEC-FIA), which provides capabilities to efficiently estimate various consequences for a specific flood event.

HEC-FIA is a stand-alone, GIS-enabled model for estimating flood impacts due to a specific flood event. The software tool can generate required economic and population data for a study area from readily available data sets and use those data to compute urban and agricultural flood damage, area inundated, number of structures inundated, population at risk and loss of life. All damage assessments in HEC-FIA are computed on a structure-by-structure basis using inundated area depth grids.

INTRODUCTION

The USACE Dam Safety Program and the USACE Critical Infrastructure Protection and Resilience Program (CIPR) rely on efficient dam failure consequence estimates to feed into their respective risk informed management activities. These activities include prioritization of security measure implementation, rehabilitation activities, and additional studies and investigations.

Within the risk-informed framework, an estimate of the incremental consequences due to dam failure for both life-safety and economic impacts is critical to success. These consequence estimates are primarily determined by the temporal and spatial distribution of flooding due to dam failure, the initial distribution of people and property within the resulting flooded area, and the redistribution of people and property over time as a result of warnings and evacuations. For this, hydraulic modeling and consequence estimation procedures are needed to estimate and compare the consequences of dam failure and the associated risk across the entire portfolio of more than six hundred dams that are owned, operated, and maintained by the USACE. Given the interdependence of the dam failure analysis and consequence estimation models, additional tools are needed to efficiently extract, transfer, and update model results. Tools to achieve this are readily available due to advancements in the use of Geographic Information Systems (GIS).

BACKGROUND

Until recently, development of consequence estimates for dam failure scenarios has been a relatively low priority within USACE. Traditional dam safety management practices only considered consequence estimates when making project specific modification decisions. Detailed consequence estimates were seldom required to support these decisions since a dam safety modification could be justified simply by demonstrating the potential for one or more fatalities. The priority and relative magnitude of dam safety issues under past USACE practices was primarily focused on performance and adherence to design standards and did not explicitly consider the potential consequences of failure. As a result, dam failure consequence estimates for most dams within the portfolio do not exist, are outdated, or lack sufficient detail to adequately inform the USACE portfolio management activities.

DAM FAILURE ANALYSIS

The most common tools for modeling dam failures in USACE are HEC-GeoRAS and HEC-RAS. HEC-GeoRAS is a set of ArcGIS tools specifically designed to process geospatial data for use with the Hydrologic Engineering Center’s River Analysis System (HEC-RAS). HEC-RAS is a software tool that performs one-dimensional steady and unsteady flow river hydraulics calculations, sediment transport-mobile bed modeling, and water temperature analysis. The software can be used to perform dam failure analysis for the majority of dams in the USACE portfolio where a one-dimensional analysis is appropriate. (Two-dimensional hydraulic modeling approaches are applied when floodplain characteristics downstream of the dam in question require them.) These programs are endorsed by the USACE Hydrology, Hydraulics,
and Coastal Community of Practice (HH&C CoP), receive continued support within the agency, and are publicly available from HEC (www.hec.usace.army.mil). The link between these hydraulic tools and GIS facilitates the use of readily available and existing data sets, efficient model development, and processing of results. New data and information can be readily incorporated into existing models when improved accuracy is needed. Once a current georeferenced HEC-RAS model is available for a dam, the models can be updated as necessary when new information is available.

The dam failure model must be of sufficient detail to generate two pieces of information for input into the consequence estimate modeling effort: 1) a maximum inundated area depth grid and 2) information on the timing of the flood wave as it progresses downstream of the study dam. Other papers (Margo et al, 2009) go into detail on the various levels of modeling detail that may appropriate depending on the decision being made.

CONSEQUENCE ESTIMATION

Since most decisions being made within the Dam Safety and CIPR Programs are initially life safety related, the focus of this paper is on the methodology applied by USACE for estimating population at risk (PAR) and loss of life.

Life Loss Estimation – Background Life loss has commonly been estimated for dam safety risk assessments using a method developed by the USBR (1999). However, the limitations of this semi-empirical approach and others that preceded it are widely recognized and have resulted in the development of simulation approaches such as LIFESim (Aboelata and Bowles, 2005) and the Life Safety Model (LSM) (BC Hydro, 2006). Requirements for a typical application of LIFESim can be met from readily available data including Census, FEMA’s HAZUS-MH, USGS Seamless and output from a dam-break inundation model, such as HEC-RAS or DAMBRK. LSM requires additional, more detailed, structure-specific and person-specific data.

As defined within the LIFESim framework, estimation of the magnitude of life loss resulting from a dam failure, whether due to a major natural event (such as a flood or an earthquake), a design or construction defect, or a successful adversarial attack, requires consideration of the following three groups of factors:

The dam-failure flood event, including the dam breach location, geometry and rate of breach development, the reservoir pool level, the time of day, detection time of the dam-failure event relative to failure initiation, and the extent, velocity, depth and arrival times throughout the downstream inundation area.

The number and location of people exposed to the dam-failure flood event, including the initial spatial distribution of people throughout the downstream inundation area, the effectiveness of warnings, the response of people to warnings, the opportunity for and effectiveness of evacuation, and the degree of shelter provided by the setting where people are located (structure, vehicle, on foot, etc.) at the time of arrival of the dam-failure flood wave.

The loss of life amongst the threatened population who remain in the inundation area at the time of arrival of the dam-failure flood wave. Loss of life estimates at a specific location take into consideration the physical character of the flood event and the degree of shelter provided by the setting where people are located at the time of arrival and after the flood wave has passed for those who survive it.

Clearly, the full consideration of all these factors is a very complex problem that requires dynamic spatially-distributed modeling of the physical processes (dam breach and flood routing), human responses, and the performance of technological systems (such as warning and evacuation systems, transportation systems and buildings under dam-failure flood loading). However, this paper describes a practical approach to this complex problem that can provide life-loss estimates for use in dam safety risk assessment with a reasonable level of effort.

Life Loss Estimation – USACE Methodology Depending on the requirements of the consequence assessment, two methodologies that implement the base LIFESim theory can be applied to estimate flood
related loss of life. These methodologies are applied through two separate tools – the LIFESim Modeling System is applied for loss of life estimation using the LIFESim methodology and the Hydrologic Engineering Center Flood Impact Analysis (HEC-FIA) program is applied for loss of life estimation using the Simplified LIFESim methodology.

The focus of this document is on describing application and guidance related to the Simplified LIFESim methodology, which will be the most commonly applied tool for estimating loss of life in support of Corps’ risk assessments. The LIFESim and Simplified LIFESim procedures described herein are based on the foundation of knowledge gained from an in-depth analysis of case histories conducted by McClelland and Bowles (2002).

SIMPLIFIED LIFESIM (HEC-FIA)

The Simplified LIFESim methodology is applied within the HEC-FIA software program. The applicability depends on the goals of the assessment as well as the characteristics of the study area. The main differences between the Simplified LIFESim methodology applied within HEC-FIA and the LIFESim methodology are as follows:

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

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

Arrival Times - In Simplified LIFESim, flood arrival time at a structure is computed by interpolating cross-section hydrograph output from a one-dimensional hydraulic model or from a grid that contains arrival time values. The full version of LIFESim computes flood wave arrival time by accessing a time-series of depth and velocity grids for the entire flood event throughout the inundated area. Both models can utilize output from a two-dimensional model.

Importantly, since the Simplified LIFESim methodology is derived from the LIFESim approach, a specific application Simplified LIFESim can be scaled up to the full version by developing and gathering the necessary supplemental data.

Simplified LIFESim Inputs: Inputs required by HEC-FIA to compute life loss and direct property damage are described below:

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

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

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

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

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

Inundation Data for Each Flood Scenario: The Simplified LIFESim methodology requires an estimate of
the time of arrival of the flood wave for each structure. The arrival time represents the end of the
opportunity to evacuate a structure, and by default, is defined in HEC-FIA when the depth initially
becomes greater than 2 feet and it is assumed that people will choose to evacuate vertically in a structure
instead of trying to move horizontally to a safer location.

There are two methods for estimating and entering flood wave arrival times in HEC-FIA. Currently, for
dam breaks modeled with HEC-RAS, the most efficient procedure for estimating flood wave arrival time is
to use hydrograph output at each cross-section and storage area. HEC-FIA contains capabilities to load
cross-section and storage area geospatial information used in the HEC-RAS model, and access the
corresponding HEC-DSS (Data Storage System) files to determine the time at which the flooding depth
first reaches 2 feet at each cross-section. It linearly interpolates the arrival time at the structure using the
station information of the structure and the upstream and downstream cross-sections. For structures that fall
within a storage area, arrival times are computed by using the stage hydrograph for that specific storage
area (no interpolation is necessary). Since the flood wave progression is highly dependent on the failure/no-
failure scenario and the specific failure mode, a different set of hydrographs must be developed and
provided for each scenario to properly estimate arrival times.

The other method available for entering flood wave arrival times in HEC-FIA is with an arrival time grid.
Arrival time grids are the most efficient approach for using 2-dimensional dam failure hydraulic results to
estimate life loss in HEC-FIA. Each cell in the arrival time grid must contain the date and time at which
the depth in that cell initially becomes larger than 2 feet for the specific failure or no-failure scenario being
studied.
Warning issuance times: The Warning Issuance Time is defined as the time at which an official evacuation order is released from the responsible emergency management agency to the population at risk. The actual process of breach initiation, detection, evacuation warning, and dam failure is illustrated in Figure 1 for a dam failure scenario where the breach is detected prior to actual dam failure, although other sequences can be handled in LIFESim and Simplified LIFESim. Life-loss estimates are highly sensitive to warning issuance time and other relationships that affect the effectiveness of warning and evacuation processes for the population at risk. There is significant uncertainty in the model parameters that represent these processes. In the typical USACE risk assessment the goal is to obtain “bets estimates” for these parameters and through the implementation of guidance and a consistent procedure to reduce differences between risk assessments. Sensitivity studies can also be used to provide some information on the effects of uncertainties on life-loss estimates. LIFESim also provides an uncertainty analysis capability that provides for explicit consideration of the uncertainties and provides confidence intervals for life-loss estimates as illustrated in Aboelata et al (2005).

For the purposes of this discussion, the parameters illustrated in Figure 1 are defined as follows:

- **Major Problem Acknowledged**: Time when seepage (or evidence related to other failure mode) is determined to be significant enough that dam failure is likely. Successful intervention is no longer considered probable. Leads to notifying public of impending dam failure.

- **Evacuation Notification from dam owner to EMAs**: Time when observed increase in seepage or other failure mode has been determined to be significant enough to notify EMAs to start the warning and evacuation process.

- **Failure**: Time when rising limb of flow hydrograph through breach begins to increase rapidly. Represents time corresponding to “Trigger Failure” parameter in HEC-RAS dam breach input.

- **Warning Opportunity Time Window**: Amount of time between when the dam owner discovers significant seepage progression that could lead to impending dam failure and actual Failure. Positive value if significant evidence related to failure mode is discovered prior to failure initiation, negative if after failure.

- **Breach formation time**: Amount of time between Failure and when breach reaches full width and depth. Corresponds to “Full Formation Time” parameter in HEC-RAS dam breach data.

![Figure 1. Detection and warning timeline for observed seepage failure scenario](image)

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

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

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

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

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

1) Assume the safe location is anywhere that the maximum inundated depth for a given flood scenario is less than 2 feet. Create a polygon representing this hazard boundary.

2) Load the hazard boundary into HEC-FIA and provide a nominal speed at which evacuating people could travel along the assumed straight-line distance. This nominal speed is less than the actual speed along the road network because the distance is greater through the road network than along a straight-line path as represented in Simplified LIFESim.

3) HEC-FIA will compute the time required to evacuate by determining the distance from each structure to the safe boundary and then dividing that distance by the nominal speed.

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

- **Chance Zones:** in which flood victims are typically swept downstream or trapped underwater, and survival depends largely on chance; that is, the apparently random occurrence of floating debris that can be clung to, getting washed to shore, or otherwise finding refuge safely. The historical fatality rate in Chance Zones ranges from about 38 percent to 100 percent, with an average rate over 91 percent.

- **Compromised Zones:** in which the available shelter has been severely damaged by the flood, increasing the exposure of flood victims to violent floodwaters. An example might be when the front of a house is torn away, exposing the rooms inside to flooding. The historical fatality rate in Compromised Zones ranges from zero to about 50 percent, with an average rate near 12 percent.

- **Safe Zones:** which are typically dry, exposed to relatively quiescent floodwaters, or exposed to shallow flooding unlikely to sweep people off their feet. Depending on the nature of the flood, examples might include the second floor of residences and sheltered backwater regions. Fatality rate in Safe Zones is virtually zero and averages 0.02 percent.

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

HEC-FIA assigns lethality zones based on the evacuation outcome for people starting in each structure and the height of the structure. The logic followed by HEC-FIA for assignment of evacuation outcome categories is described below. After the determination of evacuation outcome is made, then lethality zones are determined. Certain parameters in the lethality zone assignment process are set by default in HEC-FIA, but should be reviewed during the application process to insure that they are representative of the study area region:
1) **Cleared**: the people that evacuate safely do not receive a flood lethality zone assignment.

2) **Caught**: the people that get caught evacuating are assigned to the Chance Zone.

3) **Not mobilized**: the people that stay in structures are assigned to flood lethality zones based on maximum depth of flooding over the entire flood event and the height of the structure (the full version of LIFESim also accounts for water velocity when categorizing structures into flood lethality zones). The assumption in Simplified LIFESim is that people evacuate to the level above the highest habitable level in the structure (e.g. the roof or an attic).

   a) For any structure: if event maximum depth < 2 feet or less than the first floor height (fh) of structure, then no flood lethality zone assignment is made and the people are grouped with the Cleared evacuation category;

   b) If 1-story structure:

      i) if event maximum depth < fh + 13 feet then assign to Safe Zone;

      ii) if event maximum depth ≥ fh + 13 feet and < fh + 15 feet then assign to a Compromised Zone;

      iii) else event maximum depth ≥ fh + 15 feet then assign to a Chance Zone.

   c) For each additional story, add 9 feet to the depth criteria in b) to determine flood lethality zone.

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

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

The entire probability distributions of fatality rates for each Flood Lethality Zone are used in LIFESim when the uncertainty analysis option is selected.

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

1) **Obtain the dam-failure flood wave arrival times** for each structure. The arrival time is the time at which the depth of flooding at the location of the structure is estimated to be large enough that the inhabitants of that structure will choose to stay in the structure and evacuate vertically instead of risk leaving the structure. The default value in HEC-FIA is 2 feet. HEC-FIA estimates arrival times for each structure by interpolating them off of the hydrograph data provided at the nearest upstream and downstream location to each structure or by selecting it from the arrival time grid in the specific cell where the structure is located.

2) **Calculate the warning time** for each structure by finding the difference between their respective dam-failure flood wave arrival times and the public warning issuance time. Warning time indicates the amount of time that the population of each structure has to receive a warning and mobilize.

3) **Compute the time required to evacuate** for each structure, which is an estimate of the amount of time it would take for the people in a structure to evacuate to a safe location after they have mobilized.

4) **Combine** the user defined warning and mobilization curves into one relationship that represents the number of people who have both received a warning and mobilized.
5) Compute the percentage of people in each **Evacuation Outcome Category**. For each structure, estimate the percentage of its occupants that fall into each of three possible evacuation categories at the time of arrival of the dam-failure flood wave. This estimate computes fractions of people in individual structures. When the results are summed for the inundated area, it will provide an estimate of the total life risk for the specific scenario.

6) For each structure, assign a **lethality zone** to the people in each evacuation outcome.

7) Calculate the **overall fatality rate for the occupants initially assigned to each structure** by summing the following fatality rates for each evacuation outcome category:

   a) The fatality rate for evacuation outcome category 1 (Cleared) is 0.

   b) The fatality rate for evacuation outcome category 2 (Caught) equals the percentage of people caught evacuating multiplied by 0.91.

   c) The fatality rate for evacuation outcome category 3 (Not mobilized) equals the percentage of people that stayed in the structure multiplied by fatality rate for the flood zone (depends on maximum inundation depth at the structure).

8) Calculate the **life-loss estimate for each structure** by multiplying the initial population of each structure by its respective overall fatality rate (from Step 7).

9) Calculate the **total life-loss estimate** by summing the life-loss estimates for all structures.

![Figure 2. Assignment of Evacuation Outcome Categories](image)

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

**SUMMARY**

The USACE has developed a scalable dam failure analysis and consequence estimation procedure to support the scalable framework of the USACE dam safety and critical infrastructure protection and resiliency programs. The approach provides a consistent and compatible methodology for developing dam failure models and estimating the consequences due to dam failure at varying levels of detail and accuracy. Preliminary dam failure floodplain and consequence estimates for initial screening can be developed in a matter of days. These models can then be updated and improved with additional data and refined modeling techniques to support more detailed assessments. The use of existing datasets and GIS tools facilitates the efficient development of the models to support initial assessment and routine updating of the models.

**REFERENCES**


