CONSEQUENCE ESTIMATION for DAM FAILURES

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ABSTRACT

HEC-FIA is 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 compute contained in HEC-FIA includes consideration of the effectiveness of warning systems, community responses to alert, and evacuation of large populations.

HEC-FIA is also capable of analyzing economic and life safety benefits from various non-structural flood damage reduction measures, including installation of flood warning systems, public education campaigns, and flood-proofing or raising of individual structures. These estimates can be computed with uncertainty for single catastrophic failures, so that decision makers can be aware of which parameters contribute the most uncertainty to the life loss estimations.

INTRODUCTION

The Modeling, Mapping, and Consequence (MM&C) Production Center has been established to support the USACE Dam Safety Program and the USACE Critical Infrastructure Protection and Resilience Program (CIPR). Both programs rely on the MM&C for efficient dam failure consequence estimates to feed into their respective risk informed management activities including prioritization of security measure implementation, rehabilitation activities, and additional studies and investigations. The processes are decision driven, meaning that the level of detail and accuracy required must be appropriate to support the decision being made within a reasonable level of confidence. The relative accuracy required to get a "right" answer must not be taken out of the context of the decision to be made. Too much effort can divert limited resources away from other critical dam safety needs just as too little effort potentially leads to poor

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decisions. The decision-driven nature of this risk management process requires methods that can be easily scaled to the appropriate level of effort needed.

Within the risk-informed framework, an estimate of the incremental consequences due to dam failure, when compared to the same event given no failure, for both life-safety and economic impacts is critical to successfully assessing the consequences attributed to the catastrophic failure of the dam alone. These consequence estimates are primarily determined by the temporal and spatial distribution of the additional 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 both the events with and without failure. 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

Over the years, dam failure models have been developed using a number of different dam break computer programs, modeling techniques, parameter estimation methods, and output capabilities. Most of the existing dam failure models for USACE dams were developed during the 1980s for the primary purpose of supporting the preparation of inundation mapping for Emergency Action Plans (EAPs). These models are typically not suitable to properly inform risk assessment activities because they are outdated, do not address the full range of dam failure and no-failure flood events, and cannot be readily incorporated into a GIS framework for interaction with current consequence estimation models.

Development of consequence estimates for dam failure scenarios has been a relatively low priority within USACE until recently. Traditional dam safety management practices only considered consequence estimates when making project specific modification decisions and the methodology was not consistently applied. 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 and compatibility with a GIS framework.

DAM FAILURE ANALYSIS

The approach now used by the MM&C for dam failure analysis risk assessments is to develop new models using HEC-GeoRAS, RASMapper, 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). RASMapper is the standalone GIS platform designed to develop input to HEC-FIA, flood inundation mapping, and other GIS related data outputs for 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 can be done within HEC-RAS or through other approaches 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 tool being used to model dam failure must be of sufficient detail to generate two pieces of information for input into HEC-FIA to estimate the associated consequences: 1) a grid of maximum depths and 2) associated timing and duration 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 be appropriate depending on the decision being made.

CONSEQUENCE ESTIMATION

Although most decisions being made within the Dam Safety and CIPR Programs are primarily life safety related, the need for accurate, rapid, and dependable economic related consequences, and the ability to weigh the economic losses against life safety risks is a necessity as floodways become more populated. This paper covers the methodology applied by USACE for estimating various economic losses, population at risk (PAR), and loss of life through HEC-FIA.

Background Economic Consequence Estimation with HEC-FIA

HEC-FIA was designed to estimate consequences from a single flood event for the purpose of determining how much damage was prevented by the projects in the watershed for a specific event. More detailed economic analysis is able to be done in a single event calculation than in an annual maximum frequency based damage calculation because there is more information associated with the timing, duration, and preparation for the specified event. The shape and timing of the hydrograph associated with a particular dam failure could dramatically change the damage assessment, for example the difference in damages from a sunny day failure compared to those from a failure with sufficient warning time. Slow and steadily rising water gives habitants more time to reduce content damage, floodproof their homes, and evacuate to safety, whereas sunny day failures can cause more damage due to the population having less time to prepare and react. Longer durations have greater impacts on agricultural damages, and the shorter duration floods have less impact on crops, but both damage estimates are highly dependent on when the flood happens in the season, so if identically sized events actually happened in different seasons the flood damage to crops could be significantly different even if the hydrograph shapes were the same.

To improve upon traditional USACE damage calculations where only stage is used in the calculation, HEC-FIA has attempted to take more damage driving parameters into account for the calculation of consequences. This paper will briefly discuss the methodology for the different damage calculations that HEC-FIA can compute.

Agriculture Data

One of the largest problems facing regional economists in the district offices when they are trying to compute any type of impact is a lack of recent and usable data. Agricultural damage calculation is very difficult to analyze without information on where the crops are located within the floodplain, how much value has been put into the crops, and the duration of flooding. To solve the problem of data availability and data consistency HEC-FIA was designed to directly import data from multiple readily available data resources associated with agricultural data. There are three typical methodologies that are used, depending on what type of data the user prefers to use. If the user knows where specific crops are planted they can create a polygon that represents the area planted in different crop types. Alternatively, they can use information from the Federal Emergency Management Association HAZard United States (FEMA HAZUS) database that stores the percentage of cropland planted with different crops at the census tract level or the user can use the National Agricultural Statistical Survey Cropland Data Layer (NASS-CDL) which defines crop type at three quarter acre grid cells. The program allows the user to enter in the geospatial information from these data sources to define the areas planted for different crops.

After geospatial location of crop information is determined, the user will have to define the crop value, yield per acre, and the harvest cost for the crops. This information will be used to help determine the value in the field for any day of the year, and specifically for the time at which the flooding occurs. This data is more difficult to find, but typically is available from the regional land grant university through their agriculture extension agency. From the data associated with regional crop budgets and practices the user will have to define a curve that represents the value added to the field to manage the crop for every day of the year. This curve represents the actions and processes taken or done by the farmer to bring his crop from seed in the ground to seed in the market.

The formula for calculating seasonal damages is broken into two pieces, the seasonally based value as a function of date and crop specific parameters, and the damage as a function of duration.

$$S(t,c) = (a \cdot \big(V(c) - H(c)\big)) \cdot B(t)$$

Where:
S = seasonally based value as a function of date and crop type
t = date
a = the area of the gridcell in acres
c = crop type
V = the value as a function of crop type
H = the harvest cost as a function of crop type
B = the % of the total crop value that is available to be flooded due to the crop budget

$$D(t,d) = S(t,c) \cdot L(d,c)$$

Where:
D = damage to the crop as a function of date and duration
d = duration of flooding
L = the loss for the crop as a function of duration and crop type

Structure and Content Damages.

To compute the economic damages associated with structures and their contents HEC-FIA looks first at structure attributes like value, occupancy type, damage category and foundation height. In order for HEC-FIA to know the information necessary to compute structure and content damages, the user is required to input a detailed structure inventory defining various attributes about each individual structure. The process of collecting the required inputs can be very time consuming and potentially prohibitive due to costs, depending on the scope of the project. To alleviate some of that cost HEC-FIA has created a methodology to use the FEMA HAZUS database to create structure inventories with required attributes quickly and in an automated fashion.

There are essentially four methods to generate a structure inventory in HEC-FIA: using the HAZUS database, a parcel database, a point shapefile, or through manual entry by the user. Although all the methods require some database and GIS pre processing, some of the methods are much cleaner and quicker than others. This paper will discuss the methodology for the HAZUS based inventory and the parcel inventory and some of the limitations associated with each.

For reconnaissance level studies or a screening level analysis, HEC-FIA has the capability to generate a structure inventory for an area using the database that comes with the FEMA HAZUS-MH tool. When HEC-FIA generates the inventory from the HAZUS database, it imports the necessary attributes for a damage assessment using HEC-FIA, and splits the structures into forty different structure occupancy types (to distinguish heavy industrial from light industrial etc.) and four different damage categories (to distinguish residential from industrial) depending on data collected and defined for each census block. Since the amount of time to conduct reconnaissance studies and rapid screening assessments is small and the available budget associated with the studies is small, HEC-FIA provides this method to generate a structure inventory from available data to describe the risk associated with individual events with an affordable level of effort. When a structure inventory is generated using the HAZUS data, it should be checked against aerial imagery to ensure that it is representative of the study area. A few of the shortcomings of the structure inventories generated by HEC-FIA using the HAZUS database are the geographic placement of the structures and the value of the structures. The placement of the structure inventory is uniformly geographically distributed within each census block since the structure database is stored at the census block level. The methodology to compute exposed structure value within the HAZUS database is based on the RS Means methodology and regional averages, therefore, the values (and the number of structures) are subject to occasionally being misrepresentative of the populations, and the values are not necessarily depreciated replacement values. These exposed values for each occupancy type within a census block are then divided evenly among all structures of that occupancy type within the census block, so if there are some industrial structures that are significantly more valuable than other industrial structures within a census block you are evaluating there may be issues with the method used to assign value to the structures from the HAZUS database. One of the benefits is that as a part of the import process from HAZUS, the population from the census information is contained within the database and used to populate each individual structure for life loss calculation purposes. Users can move structures within the map window of HEC-FIA if it is necessary in order to combat some of the issues of the uniform geographic placement within a census block, and edit structure values structure by structure to deal with value averaging issues.

The most detailed inventory would be a surveyed point shapefile with all the attributes of the structure inventory assigned to each point and direct stage-dollar damage functions

defined for each unique structure. However, the cost to generate such an inventory is typically not justified by the generally marginal improvement in the results, since many other methods are available to do similar levels of detail with less effort. The quickest way to get reasonably close to the detail achieved by a point shapefile is to use a parcel shapefile database to define the attributes and the centroid of each parcel to represent the point for each structure. The necessary attributes that need to be defined to construct such an inventory for economic damage are foundation heights, structure type, depreciated replacement value, content value (or a ratio of content to structure value), structure category, and unique structure names. One major shortfall of this methodology is that the process of populating the structures with people so that life loss estimations can be made is difficult to accomplish. To aid the user in making life loss calculations with parcel inventories, HEC-FIA has incorporated a tool that uses the census information stored in the HAZUS database to populate the structures contained within the parcel database inventory using the same methodology as it does for the HAZUS generated structures. The description of that methodology is detailed below in the life loss portion of this paper. The obvious major benefit of using parcel inventory is geographic placement, below are two images, one using HAZUS to geo-locate the structures, and the other using parcel data. The inventory generated by HAZUS is spread out much more and the parcel data inventory shows the structures clustered closer together in populated areas but both databases contain a similar number of structures across the entire study. In the images the lighter (orange) colored shapes are parcels, and the darker (red) colored shapes represent census blocks.

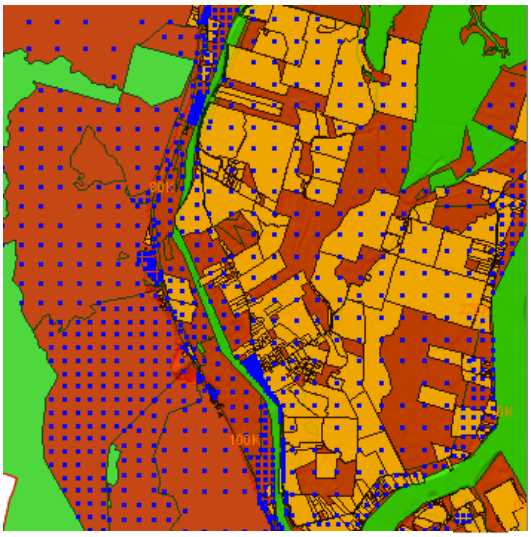


Figure 1. HAZUS generated

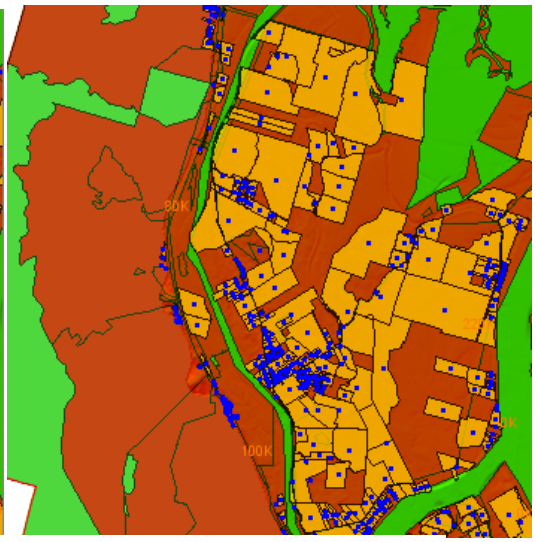


Figure 2. Parcel generated

Once the structure data is imported into the HEC-FIA project, the inundation data will be imported into HEC-FIA as depth grids. Although all you need to compute structure damages in HEC-FIA is a depth grid, adding a grid of the maximum product of depth and velocity achieved over a simulation will allow a more detailed structure damage calculation, arrival time grids and duration grids or hydrograph data at cross sections from the hydraulic model are required for agriculture damage estimates, and arrival times and depth grids are required for life loss estimations.

For structure and content damages HEC-FIA will then look at each structure and identify the depth at the structure from the gridded data, and associate that depth with the depth damage curve defined by the structure occupancy type which will result in amount of damage for each structure impacted. If the user chooses they can individually assign structure damage curves to each structure taking into account the unique damages associated with each structure. Similar processes will be happening coincidentally with the content depth damage curves. The resulting damages will be stored at each individual structure, and at predefined geographic areas, so that users can query the damages at the individual structure level or at larger regional levels. All information generated can be exported through a point shapefile representing each structure damaged by the event so that GIS tools can be used to display, and analyze results in any way the user wishes.

One of the major benefits to using a single event model is the ability to use temporality in the damage calculation, not only for agricultural damage estimates but also for other consequences. In HEC-FIA, if the correct information is supplied, the program can look at the event being studied while taking into account previous flooding that may have degraded the value of the structure inventory. HEC-FIA can also estimate the value of the structure over time as it is being rebuilt, so that if multiple event hydrographs are supplied where structures are repeatedly flooded, the damage calculation will not damage the structure at full value during the subsequent events unless it has had sufficient time to rebuild to full value.

Life Loss Estimation - Background

Life loss for dam failure 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 database, USGS Seamless, and output from a dam-break inundation model, such as HEC-RAS, MIKE21, or DAMBRK. LSM requires additional, more detailed, structure-specific and person-specific data.

LIFESim is a detailed life loss estimator that evaluates hydraulics, evacuation, and population characteristics across the entire duration of the studied event or failure. It evaluates both depth and velocity grids across regular or irregular time steps; these grids are developed to describe the differences in breach location, breach geometry, breach development, and loadings through complex hydraulic modeling efforts. The grids are used to describe the arrival time of water, the maximum depth of water, and the maximum product of depth and velocity. The hydraulic outputs are used to evaluate the complex interaction between the flood wave and the people, structures, and infrastructure in the flooded area. As a part of the interaction of the people and structures to the flood wave, LIFESim evaluates the population's response to warning issuances and their ability to evacuate safely across the road network. The model evaluates the degree of shelter that is provided by the locations that the population is located at the arrival of the flood wave, and allows individuals to evacuate upward in structures, or attempt to reroute their evacuation route to avoid impassable roads. Once the degree of shelter is determined appropriate fatality rates are assigned to the population to estimate the life loss potential for any event. For more detail on this process, and the detailed calculations, refer to Consequence Estimation for the Herbert Hoover Dike Dam Safety Modification Study Risk Assessment by Woodrow Fields.

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 portion of the 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.

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 vehicle or human stability, and therefore water velocity only influences the loss of life estimate based on the structure stability criterion. 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 human or vehicle away will also experience depths large enough to inundate that human or vehicle, making the ultimate fatality rate 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 to appropriately account for vehicle and human stability.

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, the Simplified LIFESim methodology contained in HEC-FIA still draws on the foundation of knowledge gained from an in-depth analysis of case histories conducted by McClelland and Bowles (2002). In addition, since the Simplified LIFESim methodology is derived from the LIFESim approach, a specific application of Simplified LIFESim can be scaled up to the full version by developing and gathering the necessary supplemental data.

Simplified LIFESim Inputs

A technical description of the process and computations contained in HEC-FIA to estimate life loss following the Simplified LIFESim methodology is provided later in this paper. For instructions on using HEC-FIA, download the HEC-FIA User's Manual from www.hec.usace.army.mil. 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 the elevation of the safe location 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: The processes for building a structure inventory described above provides an opportunity for the Simplified LIFESim methodology to be done on a structure by structure basis. There are a few data requirements that are unique to the structure inventory for life loss purposes. Each structure must have a ground elevation, population for day and night and over and under the age of 65, and the number of stories for the structure at a minimum, its construction type, and its foundation type is required for assigning fatality rates if depth and velocity are contributing to the destruction of structures and therefore impacting the overall life loss calculation.

The number of people in a structure often varies between day, night, 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, or areas of high tourism. 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. Additionally this methodology splits the population into the category of being over or under the age of 65 since those individuals over 65 have been shown to be at higher risk of life loss in flood events. In this methodology the population distribution between day and night on weekends is being treated to be the same as during the weekdays.

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. The user has the ability to define population increases and decreases at the impact area level, which could represent neighborhoods, towns, or counties. Another way to approximate the effects of seasonal variations in population or population changes is to take the final life loss 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 once that depth is achieved at a structure.

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 can be generated using 2-dimensional dam failure hydraulic models, or directly computed through HEC-RASMapper, these grids can be used to estimate life loss in HEC-FIA. Each cell in the arrival time grid must contain the time at which the depth in that cell initially becomes larger than 2 feet (or the non-evacuation elevation being analyzed) relative to some specific point in time for the specific failure or no-failure scenario being studied. This relative time needs to be used when defining the time window of a simulation so that the warning issuance can be delivered at the correct time relative to the breach.

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. 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 screening assessment the goal is to obtain "best estimates" for this parameter and other parameters and through the implementation of guidance and a consistent procedure to reduce differences between implementation of these parameters in evaluating and ranking the screening assessments.

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 the analysis, this describes the general framework. For the purposes of this discussion, the parameters illustrated in Figure 1 are defined as follows:

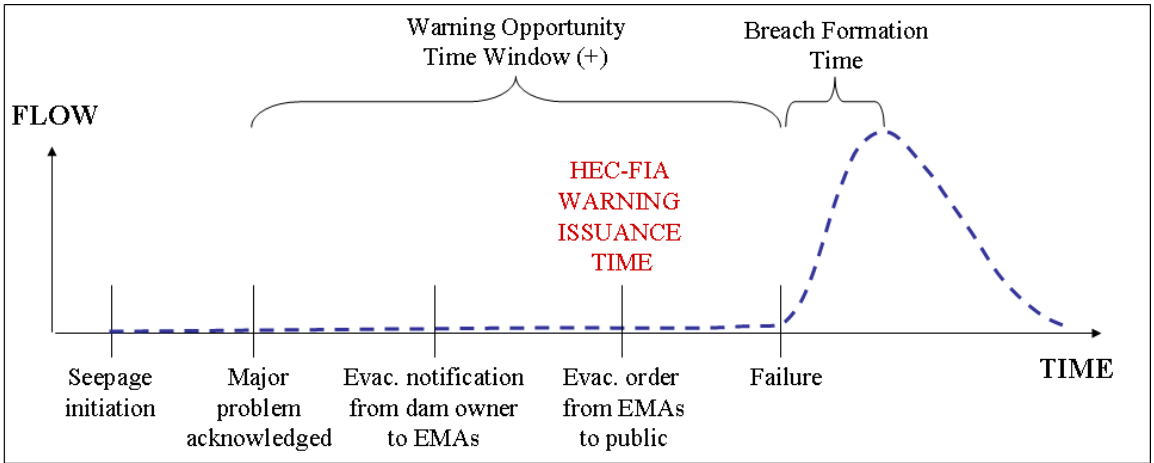
- **Major Problem Acknowledged**: Time when seepage (or evidence related to other failure mode) is determined to be significant enough that dam failure is likely. Successful intervention is no longer considered probable. Leads to notifying public of impending dam failure.

- **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



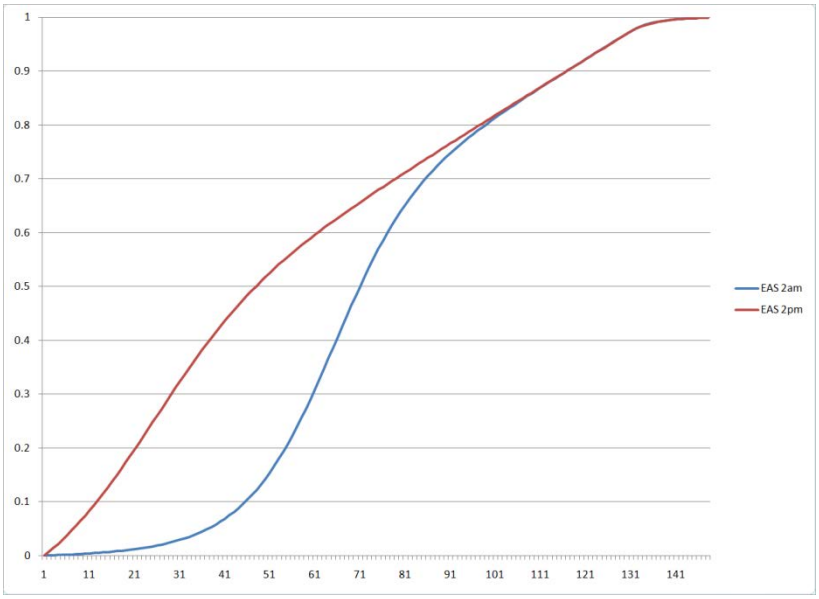
dam breach data.

Figure 1. Detection and warning timeline for observed seepage failure scenario

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 management 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 be alerted through the primary warning process (e.g. Emergency Alert System), but then a secondary warning process would begin that includes emergency responders and the general population spreading the meaning of the warning via word of mouth. The speed at which a warning would disperse through the population would depend on the type of warning being issued and the time of day that the warning was issued. The daily activity budget of a population is used to evaluate the effectiveness of different warning systems over time. As you can see in the image below the effectiveness of the EAS system at 2am is substantially different than the EAS system at 2PM due to the change in the populations activity. 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 (Rogers and Sorensen 1991).

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).

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. The user can describe the evacuation time for each structure individually, which gives the user the capability to model evacuation as a pre-process and input the results of evacuation times per structure instead of relying on the assumptions within the model.

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 uses velocity to determine if a structure is capable of surviving the flood event. Therefore, assignment to a specific lethality zone for a given structure is based on the maximum instantaneous depth times velocity for survivorship and final depth of flooding at that structure given its ability to provide safe haven, and the height of that structure. By including the height of the structure, the very significant impact of vertical evacuation is accounted for in the Simplified LIFESim methodology.

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

1) **Cleared**: 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 maximum depth of flooding over the entire flood event and the height of the structure. 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 structure 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 where the population is under 65:

   i) if the structure totally survives and event maximum depth < fh + 13 feet then assign to Safe Zone, if structure partially survives, and maximum depth < fh +13 ft then assign to compromised zone:

   ii) if the structure totally survives or partially survives the event and 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. Depending on occupancy type the fatality rates for over 65 the lethality zone thresholds can be set lower.

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 HEC-FIA when the uncertainty analysis option is selected.

<u>Simplified LIFESim Methodology</u>

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 or by selecting it from the arrival time grid in the specific cell where the structure is located.

2) Calculate the **warning time** for each structure by finding the difference between their respective dam-failure flood wave arrival times (from Step 1) and the public warning issuance time. Warning time indicates the amount of time that the population of each structure has to receive a warning and mobilize, and through the warning diffusion curve determine the percent of the population that was warned.

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 to 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 category as described in the previous section.

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

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

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

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

8) Calculate the **life-loss estimate for each structure** by multiplying the initial population of each structure (from Step 2) by its respective overall fatality rate (from Step 7).

9) Calculate the **total life-loss estimate** by summing the life-loss estimates for all structures (from Step 8).

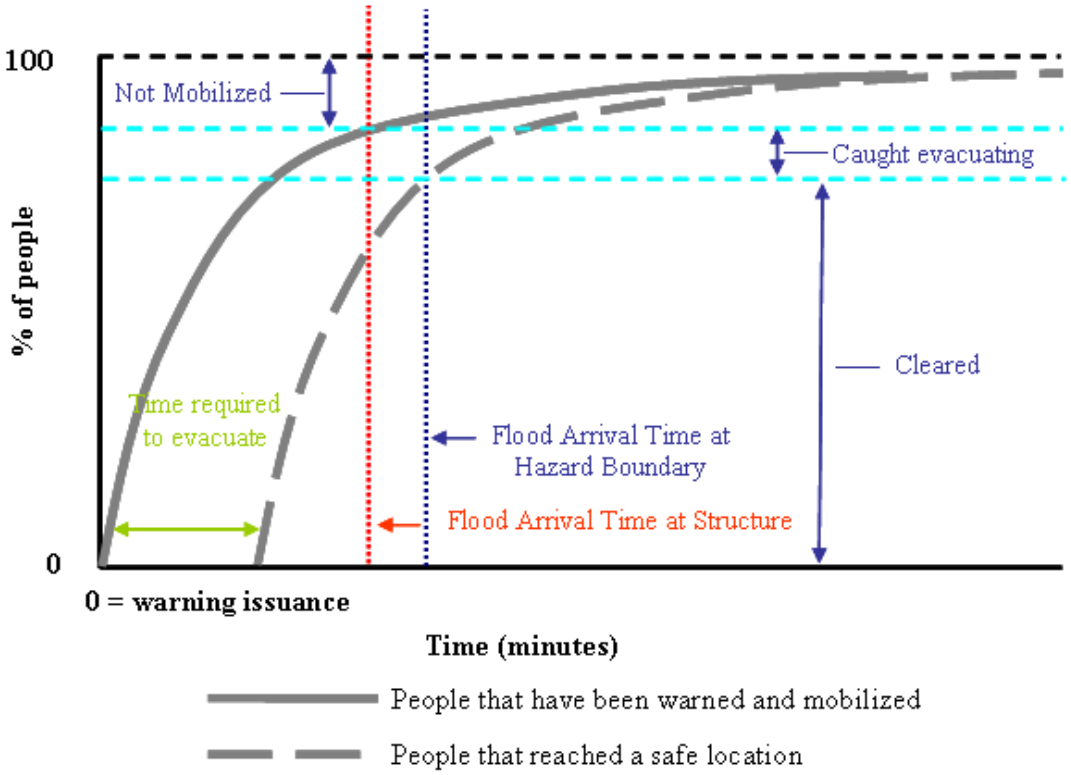


Figure 2. Assignment of Evacuation Outcome Categories

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 option to run HEC-FIA in uncertainty model provides the preferred approach to obtaining probabilistic estimates using uncertainty analysis if time and resources are justified.

Non-Structural Measures

One of the key features in HEC-FIA is the ability to quickly analyze non structural measures for both economic and life loss. The user is given the opportunity to raise houses, move houses, and provide ring levees around houses to alter the economic damages. Doing these types of non structural measures will also have an effect on the life loss estimates by changing the fatality rates that will be assigned to structures when they are raised, or by removing the house from areas of significant depth through relocation. In addition to these non structural measures, HEC-FIA can quickly facilitate the analysis of improving warning systems to improve the speed of warning diffusions, or decreasing the amount of time required for the warning to be issued by changing the procedures outlined in the EAP for a particular project. These nonstructural measures will also possibly reduce the economic losses by allowing sufficient lead time for the

population to remove vehicles and move structure contents to higher elevations inside their structures. HEC-FIA can also allow the users to create locations for shelter in place protection from floodwaves, and by shortening evacuation routes make it possible for people to quickly get to safety through vertical evacuation in structures designed to withstand the floodwave.

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.

Being able to compute these results with multiple alternatives allows the user to identify the parameters that impact the consequence estimates the most, and allow planners to come up with the most appropriate way to reduce the risk associated with our large portfolio of dams. The analysis of non-structural measures allows the user to find ways to reduce risk of economic and life loss within their floodplain.

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