RECLAMATION

Managing Water in the West

RCEM – Reclamation Consequence Estimating Methodology

Interim

Guidelines for Estimating Life Loss for Dam Safety Risk Analysis

U.S. Department of the Interior
Bureau of Reclamation

July 2015

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Foreword

Reclamation's approach to estimating the consequences from dam failure is primarily rooted in empirical interpretation of dam failure and flood event case histories. The procedure utilized by Reclamation since 1999, as documented in Dam Safety Report No. DSO-99-06, has been based on an analysis of dam failures, flash floods, and regional floods. The new methodology continues to rely on case history data to guide the selection of fatality rates; however, additional world-wide case histories have been added to the data set. This new methodology is very similar to Reclamation's previous procedure, but relies now on a graphical representation of fatality rate as a function of flood severity and warning time. Flood severity is now defined quantitatively in terms of DV (product of flood depth and velocity). It is believed the new methodology represents a more transparent and defensible means of portraying life loss estimates.

This new methodology has been reviewed multiple times during its preparation. An initial draft was studied and reviewed by Reclamation's Risk Cadre, a collection of individuals well versed in risk-informed dam safety methodology. Concurrent with that review, a total of 20 Reclamation dams were evaluated to compare the estimated life loss determined from DSO-99-06 and from the new methodology. This was done to verify that the methods are comparable and result in similar estimates. The final draft was then subjected to two levels of review. The first consisted of two independent reviews undertaken separately by Dr. Bas Jonkman, a researcher and published expert in life loss estimation associated with TU Delft University, Netherlands; and by Gregg Scott, a highly experienced and well respected practitioner in the field of dam safety risk analysis. In addition, Reclamation's Dam Safety Advisory Team (DSAT) reviewed the final drafts concurrently with the independent reviewers.

The general consensus of the reviewers was that the new methodology represented an improvement to Reclamation's empirical life loss estimating approach. As such, a DSAT decision meeting held in February 2014 led to the decision to immediately begin implementation of the new methodology. The implementation consisted of applying the new methodology to all higher level Reclamation dam safety studies (Issue Evaluation and Corrective Action Studies) as well as a number of Comprehensive Review studies. Beginning in 2015, RCEM became the consequences estimating procedure for all dam safety studies.

As with any new methodology, it is expected that some refinements may be identified once Reclamation gains more experience in the process. As such, the methodology is being issued as "interim" guidance, with the expectation that applicable revisions or clarifications will be made at a later date if necessary, with subsequent "final" documents issued at some point in the future. The initial version was published in February 2014. The current revision dated July 2015 features adjustments to some of the case history data points and other minor revisions. Its printing coincides with the initial printing of the "RCEM – Reclamation Consequence Estimating Methodology - *Interim* Dam Failure and Flood Event Case History Compilation."

Glossary

Case history data
A compilation of over 60 cases of natural floods and dam failure floods that form the basis of the empirical life loss estimating procedure. These case histories are described in a companion document, "RCEM – Reclamation Consequence Estimating Methodology - *Interim* Dam Failure and Flood Event Case History Compilation."

Confidence
A qualitative measure of belief that the life loss estimate, and all the data and assumptions used to estimate the life loss, are correct (i.e. the general order of magnitude of the values are judged to be reasonable).

Consequences
Although the consequences of a dam failure can include a number of factors including economic losses, environmental impacts, loss of cultural resources, etc., Reclamation primarily just considers loss of human life as the primary measure of consequences from dam failure.

DSO-99-06
A Reclamation report issued in 1999, entitled "A Procedure for Estimating Loss of Life Caused by Dam Failure," which outlined Reclamation's empirically-based method for estimating life loss. This new methodology is considered a revision and enhancement of the 1999 work.

DV
A measure of the severity of flooding at a given point, as determined by maximum depth (D) of flooding multiplied by maximum velocity (V) of the flood flows.

Emergency Action Plan (EAP)
A plan developed to outline how Reclamation and local authorities respond to an emergency at a Reclamation dam. The plan includes discussion of when to implement warnings of an impending dam failure, whom to contact, and timing of the necessary actions.

Emergency management officials
The local officials in a community responsible for issuing warnings in the event of a dam failure (or similar serious incident).

Fatality rate
The rate (or percentage, expressed in decimal form) of expected fatalities estimated to result from dam failure, applied to the total pre-failure, non-evacuated population at risk. The fatality rate multiplied by the PAR gives the estimated number of lives lost.

Flood severity
A measure of the damage potential or lethality of a flood flow. Within Reclamation's DSO-99-06, flood severity was classified as low, medium, or high. With this new methodology, DV quantifies the intensity of flooding.

Flood severity understanding
Used in DSO-99-06, this was a measure of how well the PAR understands the warning, influenced by the quality or forcefulness of the warning. With this new methodology, flood severity understanding is not an explicit factor in the process.

Life loss
Within Reclamation, the number of people estimated to lose their life due to dam failure. Generally just the direct life loss; typically not including secondary or indirect life loss that may result from the complications and stress that may result from failure of a dam.

Population at risk (PAR)
Those people present in the inundation flood zone prior to dam failure. The PAR may include permanent residents and transient individuals such as recreationists, or travelers in autos, buses, etc.

Potential failure mode
A credible way in which a dam may fail, such as from internal erosion, flood overtopping, or earthquake-induced slope failure and crest loss. Typically, potential failure modes are listed in three categories: static, or failures under normal operations; hydrologic, or failures under flood loading; and seismic, or failures under earthquake loading.

Uncertainty
A qualitative or quantitative measure of the range or spread of reasonable outcomes of potential life loss. Uncertainty is used to portray variability or a range of values for estimated life loss, rather than relying solely on single point estimates.

Warning time
The amount of warning that the PAR would be expected to receive in the event of dam failure. Specifically, the amount of time between receiving the warning and the advent of the threatening flood flows. There are two different warning categories considered in RCEM described below.

> *Adequate warning*
> An undefined amount of time that would allow most of the PAR to understand the threat posed by dam failure, to take reasonable actions to leave the inundation plain and to successfully move to a safe location. However, even if given adequate warning, there are a multitude of reasons that people may choose not to leave, or are unable to leave. "Adequate" cannot be defined as an exact amount of time because adequate warning is very dependent on site specific conditions. For example, 30 minutes may be an adequate warning for residents of a small town to evacuate; but it may take many hours of warning to enable a large city to evacuate.
>
> *Little or no warning*
> A limited (but undefined) amount of time that essentially results in most or much of the PAR receiving an inadequate notification (reflecting quality and timeliness of the

warning) of an impending failure and a resulting inability to get out of the inundation plain (or seek adequate shelter from flooding).

Warning quality
The forcefulness and clarity of any warning received by the PAR.

Introduction

This document provides guidance on Reclamation's empirically-based method for estimating consequences from dam failure in terms of loss of human life. The approach is similar to the approach that Reclamation has used since 1999 as the primary tool for estimating loss of life (DSO-99-06). DSO-99-06 provided suggested fatality rates to be applied to downstream populations subjected to dam breach flows, considering the warning time, flood severity, and flood severity understanding. This RCEM methodology involves consideration of these same elements as well as other factors when selecting a fatality rate for a given exposed population, and features a graphical presentation of fatality rates versus warning time and flood severity. DSO-99-06 was based on the analysis of dam failures, flash floods and other floods located primarily in the United States. Additional case histories were investigated for the RCEM methodology and both the original DSO-99-06 case histories and the additional case histories are summarized in the *Dam Failure and Flood Event Case History Compilation* [1]. This document details and explains the RCEM methodology. A third document completes the initial series of the RCEM methodology and provides *Examples of Use* [2]. A fourth document, planned for a later date, will explain and provide guidance on the use of numerical models, in particular the Life Safety Model (LSM) to estimate life loss due to dam failure.

Reclamation's approach to estimating life loss is primarily rooted in empirical interpretation of dam failure and flood case histories. The RCEM methodology continues to rely on case history data to guide the selection of fatality rates. The fatality rates are applied to the full population at risk (PAR). These rates reflect the impact of evacuations that occurred in the case histories, but do not explicitly quantify evacuation of downstream populations. The likely success of evacuations is something that should be considered when selecting ranges for fatality rates using the RCEM methodology.

While the standard approach for Reclamation is to use the RCEM empirical methodology for estimating loss of life consequences, Reclamation does see a key role for the use of numerical models. These tools are very useful for identifying possible scenarios that might develop when large urban populations are subjected to dam breach flood flows. Under these conditions, the models are useful for identifying the potential for successful evacuations and for providing a better understanding of the distribution of a mobile population at risk when the flood wave hits.

Background on DSO-99-06

The failure of Reclamation's Teton Dam in 1976 and other dam failures in the 1970s brought about within the United States a renewed awareness of risks posed by dams. Following the failure of Lawn Lake Dam in 1982, Reclamation developed dam failure loss of life estimating procedures for internal agency use. These efforts were described in the December 1988 paper, "Assessing the Threat to Life From Dam Failure," published in the Water Resources Bulletin of the American Water Resources Association. Efforts to enhance Reclamation's dam failure loss-of-life estimating procedures continued through the 1990s, culminating with the publication of

"A Procedure for Estimating Loss of Life Caused by Dam Failure," DSO-99-06 [3], prepared for Reclamation's Dam Safety Office in September 1999.

The DSO-99-06 procedure has been widely used for estimating loss of life resulting from dam failure. The procedure was based on an analysis of dam failures, flash floods, and floods, the majority of which were located in the United States. Dam failures used in developing the method included every dam failure in the United States that caused more than 50 fatalities, dam failures in the United States from 1960 through 1998 that resulted in 1 or more fatalities, and a very cursory analysis of more than 400 dam failures in the United States that occurred from 1985 to 1994. It is worth pointing out that there is no case history that involves a very large PAR downstream from a dam. For situations like this (not particularly common at Reclamation dams), special thought needs to be given to the evacuation potential, and possible consideration should be given to the use of a numerical model to estimate life loss.

The dam failure data provide insights into factors that influence when warnings are initiated for dam failure. These factors include type of dam, failure cause, drainage area at the dam, time of day when failure occurs, and if observers were at or near the dam when the failure occurred. The dam failure data also provide insights into how fatality rates (percentage of pre-evacuation population at risk who die) vary with the amount of warning people in various areas receive, the degree to which those issuing the warning fully comprehended the magnitude of the flood danger and respond to it, and the flood severity (largely a measure of the ability of the flood to wash buildings off of their foundation). In practice, flood severity has been assigned using several methods: qualitatively, based on visual or verbal descriptions of flood damage; based on flood depths; based on the product of estimated flood depth and velocity (DV); or based on discharge divided by floodplain width (which was the primary method of establishing DV values in Table 5 of DSO-99-06). Rate of rise is another factor that has been considered in high DV conditions.

The DSO-99-06 procedure contained general guidance for estimating when a dam failure warning would be initiated, although specific factors that would influence warning for a particular dam and failure mode scenario were often considered and used as a basis for overriding these values. This time varied depending upon the type of dam, failure cause or mechanism, size of drainage area, time of day (or night), and whether a dam tender or lay people are usually near the dam. Warning initiation time could vary from the guidance provided in the procedure based on dam surveillance and monitoring, specifics related to failure development and progression, dam specific emergency action plans, or other factors. Evacuation was not explicitly evaluated but was incorporated into fatality rates that use the pre-evacuation population at risk. Fatality rates were based on flood severity, warning (time), and warning quality. Typically, fatality rates were lower in downstream areas due to increased warning time, improved warning quality, and reduced flood severity. Failures that occurred during the night typically had significantly higher fatality rates than daytime failures.

For reference purposes, the fatality rates from DSO-99-06 are included in Appendix A.

Advantages and Strengths of DSO-99-06

The DSO-99-06 procedure was described as being useful, robust, easy to understand, and easy to apply while producing plausible, defensible results. Specific strengths were as follows:

a. Three variables that have played dominant roles in dam failure outcomes - flood severity, warning time, and warning quality - were used in the procedure. The procedure thus had a common-sense feel to it.

b. Loss of life relationships (fatality rates) were based on judgment. The suggested ranges had credible relative magnitudes and progressed in a logical sequence. Fatality rates were more than 1,000 times greater for areas that received no warning and high severity flooding than for areas that received hours of accurate and forceful warning and low severity flooding.

c. The area downstream from the dam could be divided into as many different reaches (evaluation units at various distances downstream from the dam) as were necessary to accurately portray differences in warning time, warning quality or understanding, flood depths, flood velocities, "wall of water" or "rate of rise" characteristics, typical housing or shelter characteristics, etc.

d. The procedure provided results that were generally consistent, which was important when risks at various dams were compared and prioritized across Reclamation's inventory.

e. If basic information was available, the cost to perform a study using the procedure was relatively low.

f. The procedure and the key factors that led to the selection of fatality rates were easy to understand and it was easy to explain what characteristics or assumptions drove a given life loss estimate.

g. The procedure could be used with varying levels of input information – from inundation boundaries plotted on a quad sheet to digitally produced, one-and two-dimensional hydraulic modeling results, which could be overlain on GIS maps along with census data and other key information.

h. The dam failure case history data provided insights into factors that influenced when warnings are initiated for dam failure. These factors included type of dam, failure cause, time of day when failure occurs, and if observers were at or near the dam when the failure occurred.

Other organizations have taken a different approach to estimating life loss consequences due to dam failure. For example, the U.S. Army Corps of Engineers (USACE) relies on numerical models such as LifeSim and Simplified LifeSim (HEC-FIA) to estimate loss of life. The models attempt to account for evacuation by tracking the progress of simulated individuals within and outside of the flood plain and applying mortality rates only to the non-evacuated populations that are subjected to flood flows. The mortality rates are empirically derived and are applied to individuals based on the flow characteristics they are exposed to and whether they are on foot, in vehicles or within shelters. If individuals are in shelters, the characteristics of the shelter they are in would affect the applicable mortality rate. While the numerical modeling approach can be more detailed and can predict traffic and evacuation patterns, it does require a large number of assumptions. In Reclamation's experience, the selection of key parameters for a numerical exercise requires as much judgment as selecting fatality rates for a given set of conditions and is subject to similar uncertainty and variability. It may also be easier to understand and explain the loss of life estimates from the empirical approach than it would be to understand and explain results from a numerical model. There is no inherent advantage in using a numerical model for most Reclamation dams; however, there are exceptions. Numeric models can however be useful to aid in the estimation of evacuation of highly populated urban areas, where traffic congestion can play a major role.

Reasons for Change

Overall, DSO-99-06 has served Reclamation very well. It has been used to estimate loss of life consequences for virtually every risk analysis that Reclamation has performed to date since its release. The results have been generally consistent, the basis for the estimates is easy to understand and the results seem to make sense. The RCEM methodology has a similar foundation to that of the DSO-99-06 document. Both are empirical methods that rely on case history data to shape the recommended values for fatality rates. Both methods rely on similar parameters on which to base the fatality rates – including the population at risk, warning times, and flood severity (characterized more definitively by the DV parameter in the RCEM methodology). As a result of the similarities between the two approaches, significant differences are not expected for estimates derived from the two methods. Trials have been conducted as part of the development of the RCEM methodology, in which the results from DSO-99-06 and the results from the 2014 methodology were compared for a number of dams. The results were generally consistent and it is expected that the new method will not significantly change life loss estimates at most Reclamation dams or the relative ranking of dams within Reclamation's inventory. These trial results are discussed in more detail at the end of this document.

There were several reasons for a revision to the DSO-99-06 approach:

1. Fatality rates for high severity flooding were not well defined in DSO-99-06, and only one set of fatality rates was provided (for high severity flooding with no warning). It was recommended in DSO-99-06 that the suggested fatality rate be applied to the full population at risk for a case with no warning and that the fatality rate be applied to a reduced population at risk (using judgment to account for potential evacuation of people from the flood plain) for scenarios with "some" or "adequate" warning. A reason for the lack of adjusted fatality rates for high severity flooding with warning is that case histories were not available for these conditions. There was also limited guidance on what constitutes high severity flooding. The parameter DV was used to delineate between low and medium severity flooding (with a DV of 50 ft^2/s serving as the dividing line). However, the guidance for delineating between medium and high severity flooding was qualitative – with medium severity described as occurring "when homes are destroyed but trees or mangled homes remain for people to seek refuge in or on," and high severity flooding described as occurring "when the flood sweeps the area clean and nothing

remains." High severity flooding was also described as a rare condition. The guidance for applying high severity flooding was as follows:

> "Use high flood severity only for locations flooded by the near instantaneous failure of a concrete dam, or an earthfill dam that turns to "jello" and goes out in seconds rather than minutes or hours."

In general, DSO-99-06 discouraged categorization of flood severity higher than medium for embankment dams. However, case histories show that DV values can go much higher than the interim threshold value of 160 ft^2/s that represents the upper limit of medium severity flooding.

In the RCEM methodology, flood severity is not singularly defined by rigid categories of low, medium, and high. The DV parameter is used to define flood severity and is used to identify a broad range of fatality rates from which an appropriate and site-specific fatality rate range can be chosen. The RCEM methodology includes DV values well into the range of what would likely have been considered high severity flooding when DSO-99-06 was used. The methodology also formalizes some of the interim guidance that had been provided on how to distinguish between medium and high severity flooding.

2. An advantage of DSO-99-06 was that the method was straightforward and easy to use. If an inundation study was available for the potential failure mode being considered and current residential and transient population data was available, simple calculations could be performed to arrive at loss of life estimates. If the same assumptions were made regarding warning time and flood severity understanding, repeatable results could be achieved. A downside of the method was that it was easy for people using it to lose sight of the fact that there is a lot of uncertainty in predicting loss of life and to ignore the specific and sometimes unique characteristics of their situation. The RCEM methodology requires more judgment on the part of individuals or teams selecting fatality rates and requires that the selection be supported by a detailed discussion. This approach is considered to be more realistic, given the inherent uncertainty in making loss of life estimates.

3. With DSO-99-06, there was sometimes confusion on how to select fatality rates with long warning times. The guidance in DSO-99-06 was to apply fatality rates to the full population at risk (assuming no evacuations take place). The reason for this is that the fatality rates that were derived from case histories already had evacuation embedded in the calculations. Applying the recommended fatality rates to a reduced population due to evacuation could result in double counting the benefits of evacuation. This reasoning makes sense but becomes somewhat questionable when large populations at risk are exposed to breach outflows with many hours (or possibly even days) of warning. This was dealt with in different ways by individuals or teams developing life loss estimates, but no guidance was provided, mostly because case histories were not available for large populations exposed to flood flows with lots of warning. Although there continues to be a paucity of case histories with the expanded data set for the RCEM methodology,

guidance is now provided *(*in the companion *Examples of Use* document) on how to use judgment when considering these cases.

4. There was a tendency to not acknowledge the significant uncertainty in predicting fatality rates (using single point estimates rather than a range) when individuals or teams applied DSO-99-06. Fatality rates for the various conditions defined in DSO-99-06 are presented as single value suggested fatality rates and then a suggested range is also provided. Individuals and teams (more often at the CR level) would often present the loss of life estimates as a single value. This implies a degree of confidence that is probably unjustified for loss of life calculations where there are many variables that are hard to estimate.

5. DSO-99-06 was based on a limited number of case histories (40 case histories total but some case histories provided more than one data point, which resulted in about 50 cases). Some categories are represented by few or no case histories. Categories with limited or no support include high severity flooding with some warning (15-60 minutes), high severity flooding with adequate warning (greater than 60 minutes) and medium severity flooding with some warning. As part of the development of the RCEM methodology, existing case histories were reviewed and re-evaluated, additional case histories were researched, and many new data points were developed.

6. When the DSO-99-06 recommended fatality rates are compared with DV values, it is apparent that there are abrupt changes in those fatality rates at the boundaries between flood severity categories. However, the empirical case history data support a smoother transition of fatality rate between flood severity categories. Therefore, one objective of the new methodology is to allow for a smoother transition of fatality rates over the entire range of possible DV values.

Basis for Graphical Approach

Establishing a Relationship between Flood Severity and Fatality Rate

The graphical approach to estimating the fatality rate utilized in this RCEM methodology is very similar to the tabular approach described in DSO-99-06, which is empirical and provides recommended ranges based on case history data. However, the graphical approach involves greater consideration of the case history database for making judgments about fatality rates than simply using the DSO-99-06 tables. DSO-99-06 recognized the following factors that influence fatality rates:

- Flood severity (three categories: low, medium, and high)
- Warning time (three categories: no warning or < 15 minutes; some warning or 15-60 minutes; and adequate warning or > 60 minutes)
- Flood severity understanding (two categories: vague and precise)

Analysis of the case histories indicates all of these factors influence the fatality rate for a flood. However, the data available from the case history information varies and for a given historical event, it can be difficult to ascertain the category for each factor. In many cases the necessary data are limited, questionable, not consistent between sources, or non-existent. The paragraphs that follow provide a basis for establishing a relationship between flood severity and fatality rate as the foundation for the graphical approach. This relationship was established by studying the case history database and extracting what was judged to be the best available information.

Flood severity, measured in terms of DV, has a significant influence on fatality rate. Case history data indicate that the highest observed fatality rates are associated with the highest estimated DV values. When the flood severity is lower, there is a general trend of lower (or no) fatalities; however, there is greater scatter in the fatality rates for lower flood severity values. For this updated methodology, the numerical measure of flood severity, DV, was estimated for each case history event using available documentation and engineering judgment. The confidence level in the estimated DV varied depending on the amount and quality of the available information.

It is recognized that evacuation has a significant influence on the number of fatalities from a flood. Obviously, for cases where the maximum number of people were evacuated, the fatality rate with respect to the original PAR was lower – independent of the DV value. However, the case history data do not provide a meaningful way to extract PAR evacuation information such that a relationship involving evacuation as a primary parameter can be established. Therefore, for the graphical approach, evacuation is considered implicitly through the parameter of warning time – i.e., greater warning time results in lower fatality rates because a greater portion of the PAR is able to evacuate the flood area.

The amount of warning received by a PAR is typically part of the case history documentation. For the same event, there may be several different population groups, and each may have received a different amount of warning time. A review of the case history data indicates that in most cases, the PAR received either little to no warning, or hours of warning. The way that "some" warning was defined in DSO-99-06 is as a relatively narrow window of time (between 15 and 60 minutes), and thus most cases have warning times that tend to fall outside of these limits. For many of the older case histories (i.e. prior to about the mid-1900s) communication networks and emergency management systems were not in place to enable warning. In addition, there may have been a general reluctance to issue a warning too soon, with operating personnel instead waiting until failure was more certain or there may have been a lack of understanding that dam overtopping could lead to dam failure. Finally, many dams that failed featured relatively small reservoirs and resulted in flooding that attenuated within minutes or a few hours of failure. For these reasons, with older case histories, receiving hours of warning was rare.

The flood severity understanding factor used in DSO-99-06 is the most subjective variable and the influence of this factor on fatality rates from the case history database is generally intuitive; i.e., the greater the understanding of the flood severity, the lower the fatality rate. There is no quantitative way of measuring flood severity understanding, and there is no way of measuring the understanding of each person in the PAR. For example, for a given event where the flood severity understanding may have been "precise" for the majority of the PAR, those that died may have had a "vague" understanding. In the RCEM methodology, flood severity understanding is considered a factor that can influence fatality rate but there is not a direct quantitative relationship.

Given the above considerations, the basis or foundation for the graphical approach involves establishing continuous relationships between flood severity and fatality rate for different warning time scenarios. Because of the relative lack of case histories with "some" warning time, only two warning time scenarios, little to no warning and adequate warning, are used in this RCEM methodology. The influence of flood severity understanding is considered in a more subjective way and can be used to provide support for a higher or lower fatality rate in a given flooded area, depending on the anticipated flood severity understanding.

Graphical Approach – Suggested and Overall Limits

Two charts were developed for selecting fatality rates using the graphical approach, as listed below:

- Fatality Rate vs. DV for Little or No Warning – Figure 1
- Fatality Rate vs. DV for Adequate Warning – Figure 2

(Note that definitions of these warning categories are in the Glossary)

Both of these charts include 11 points that reflect case histories with "partial" warning, as opposed to "little or no" or "adequate" warning. These are cases where the amount of warning was not clear, where warning may have been different for various portions of the PAR, or where the warning was marginal with respect to providing the PAR with enough time to successfully evacuate. Since these cases fall in between little or no warning and adequate warning, they are included on both charts (and are clearly portrayed as solid blue squares).

Each chart includes dashed lines that represent "suggested" and "overall" limits for fatality rates over the full range of DV values. The suggested limits were selected visually based on the most representative case history data points for each warning time scenario, with no mathematical or statistical formulation of the curves. Cases with questionable data were given less influence on the suggested range. The overall limits, also established visually, are intended to represent the upper and lower bounds of fatality rates, between which nearly all case history data falls. The limits shown are not intended to be used by estimators directly, but rather they are intended to help the estimator interpret the data trends from the case histories. For example, the range of overall limits for little to no warning and a DV of 50 ft^2/s covers over four orders of magnitude; however it is unlikely that the range of uncertainty in the fatality rate for a given project would span that full range. The next section describes how the overall and suggested limits were developed based on key case history data.

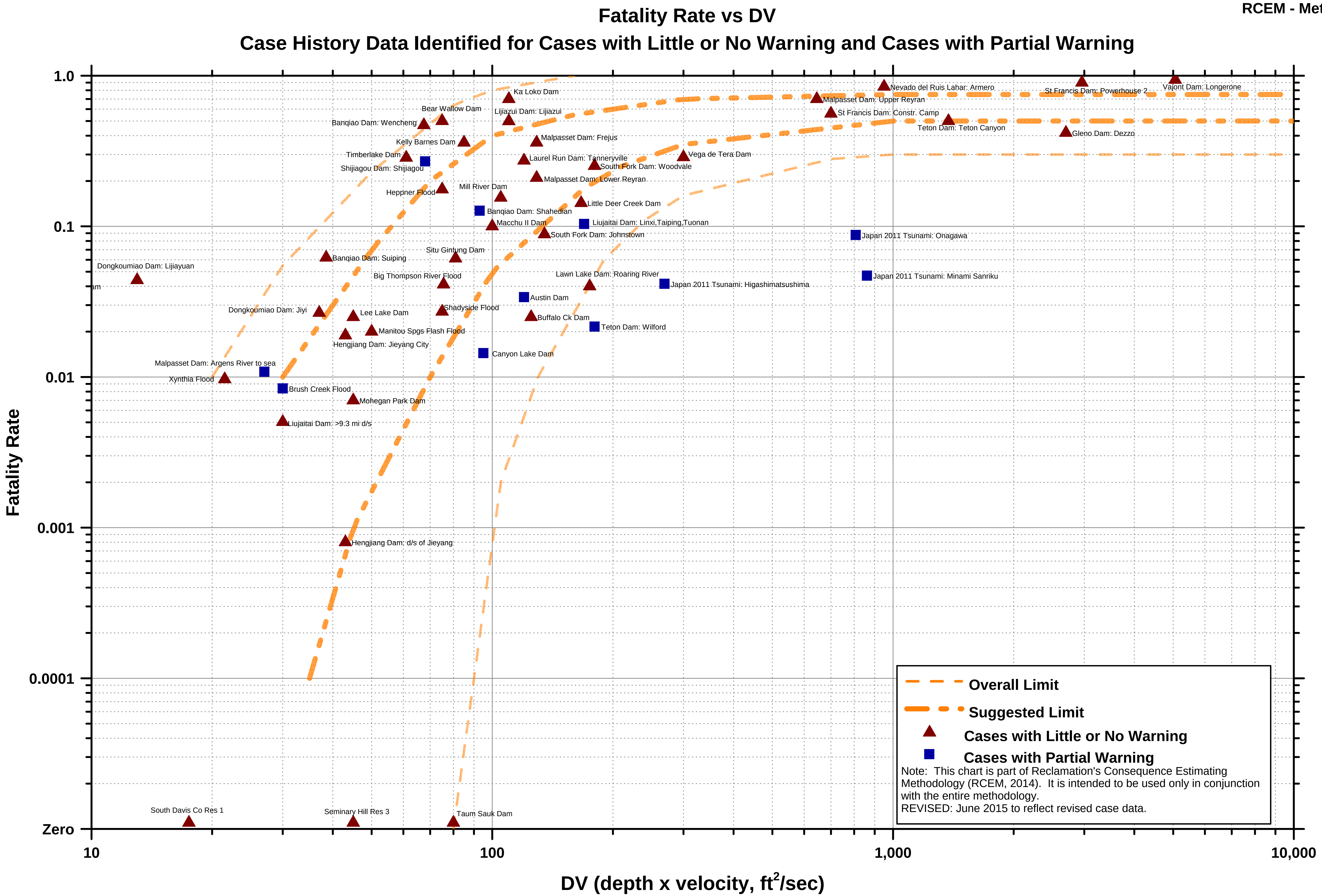


Figure 1 - Fatality Rate vs. DV - Case History Data Identified for Cases with Little or No Warning and Cases with Partial Warning

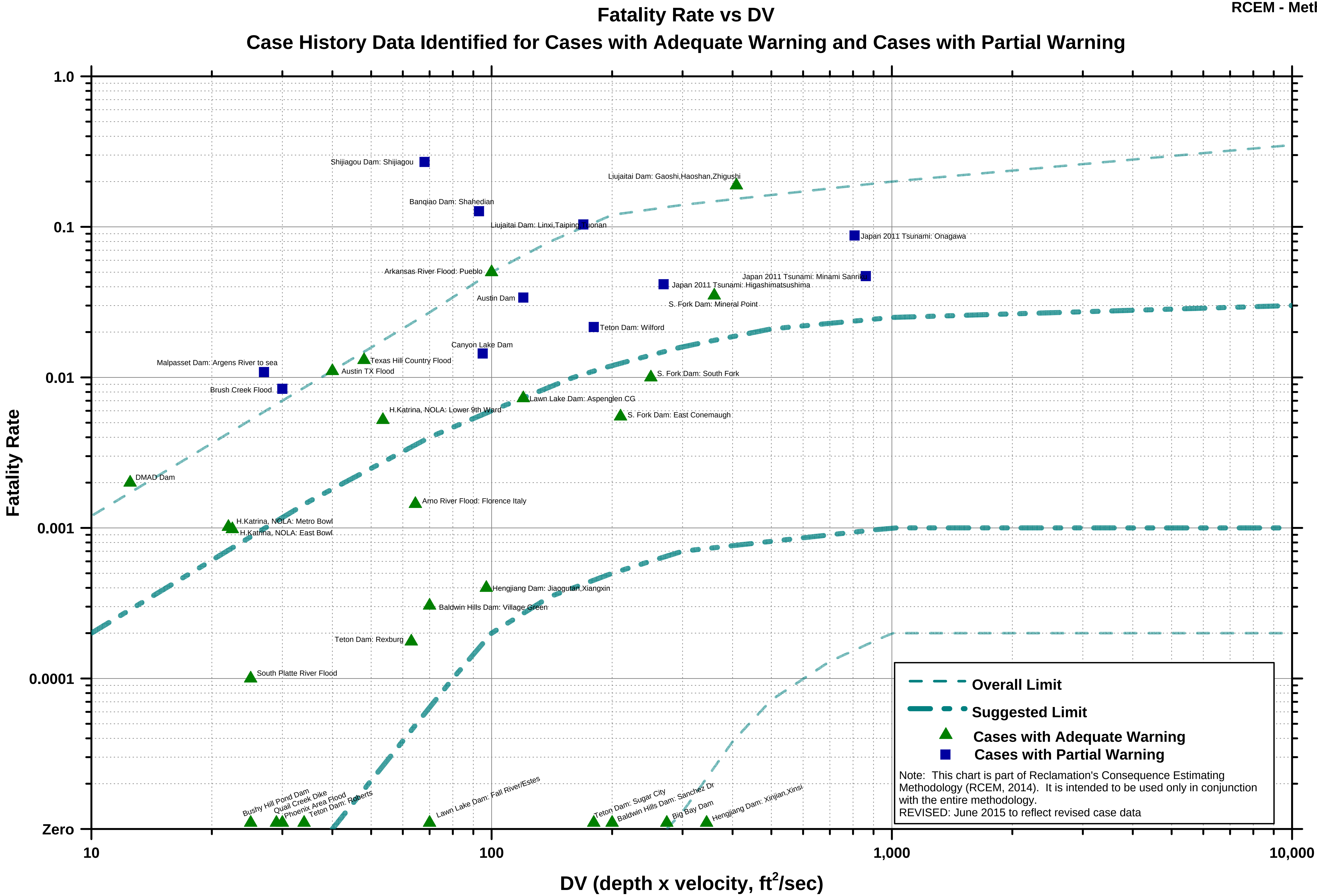


Figure 2 - Fatality Rate vs. DV - Case History Data Identified for Cases with Adequate Warning and Cases with Partial Warning

A Detailed Examination of the Suggested Limits and Key Case Histories

In order to understand the basis for the suggested limits in the RCEM graphical approach, it is helpful to examine some of the most influential case histories, as described in the two sections that follow.

Fatality Rate vs. DV for Little or No Warning (See Figure 1)

When little or no warning was given, the fatality rates for most of the case histories are generally 0.01 or greater. Interestingly, nearly all of the cases with some warning (plotted as blue squares) typically have fatality rates of around 0.01 to 0.1. There are three dam failure cases where there were zero fatalities and the estimated DV was between 10 and 80 ft^2/s - Taum Sauk Dam, Seminary Hill Dam, and South Davis County Dam. However, there are no case histories with zero fatalities for DV values greater than 80 ft^2/s; thus, 80 ft^2/s was selected as the lowest DV value for which there would be no fatalities. The lower bound of the overall limit increases sharply after a DV of 80 ft^2/s because of the generally high fatality rates for case histories with little or no warning. For DV values greater than 160 ft^2/s (previously a consideration for high severity flooding), most of the case histories have fatality rates of 0.05 or greater, and the lower bound overall limit peaks at 0.3, as was reflected in the DSO-99-06 tables for high severity flooding with no warning. Lawn Lake (Roaring River) and Buffalo Creek are case histories that help define the lower bound overall limit line for cases with little or no warning; these are modern cases where there is greater confidence in the data.

The upper bound overall limit for DV values less than 160 ft^2/s (previously considered low and medium severity flooding) was selected based primarily on two cases, the Ka Loko Dam and Bear Wallow Dam failures. For higher DVs, there are numerous, well documented case histories such as St. Francis, Vajont and Malpasset (upper Reyran) that demonstrate high fatality rates. The upper bound overall limit is assumed to be 1.0 for extremely high DVs (high severity flooding) with little or no warning.

The suggested limits for DV values less than 160 ft^2/s were selected to (1) represent an increasing trend of fatality rate with DV value that roughly parallels the overall limits described above, and (2) capture the DSO-99-06 suggested values within the suggested limits for most of the DV range. In addition, the suggested limits are less influenced by the three cases discussed above with no fatalities, because two of the cases involved extremely small dams and reservoirs, and in the third case because it is almost inconceivable that no one died in the Taum Sauk failure. As such, the suggested limits tend to be closer to the upper bound of the overall limit than the lower bound. For example, for a DV of about 30 ft^2/s or greater, the minimum suggested fatality rate is about 0.0001.

Fatality Rate vs. DV for Adequate Warning (See Figure 2)

The upper and lower bounds for the overall limits were based on the adequate warning case histories. The upper bound of the overall limit was established by the DMAD case, the Austin Texas flood, the Texas Hill Country flood, the Arkansas River flood in Pueblo, and Liujaitai

Dam. The upper bound of the suggested limit was influenced by the three Hurricane Katrina cases, Lawn Lake Dam failure (Aspenglen campground), and the three South Fork Dam failure cases. This is appropriate because today's estimated worst case fatality rates should be lower than the fatality rate in 1889, as a result of improved communications and emergency management planning. The majority of the cases with fatality rates higher than the three South Fork Dam failure cases had partial warning, and therefore did not significantly influence the upper bound suggested limit.

The lower bound of the suggested limit was influenced by the Baldwin Hills case (downstream of Sanchez Dr.) and the cases with zero fatalities. For the initial portion of the lower bound suggested limit line, a DV of 40 ft^2/s was selected as the highest DV value for which there could be no fatalities with adequate warning, even though several modern dam failure cases [e.g. Teton (Sugar City), Lawn Lake (Fall River), and Big Bay] had zero fatalities at some or all downstream locations with higher DV values.

There are few cases to help define the lower bound of the overall limit. The two cases with zero fatalities and DV values greater than 200 are Big Bay Dam and Hengjiang Dam. Since the Big Bay case history had zero fatalities with an estimated DV of 300 ft^2/s, and there is greater confidence in this case compared to Hengjiang Dam, this limit was selected as the lowest DV value for which there would be no fatalities with adequate warning.

There are no cases with adequate warning that involved DV values greater than 1,000 ft^2/s, so there is little basis for establishing overall and suggested limits (both upper and lower bound) in this area. However, the data trends were used to extend the overall and suggested limit curves. The cases indicate there is a wide range of possible fatality rates with DV values greater than 100 ft^2/s.

It is apparent from the case history data that no to very low life loss is possible at high DV values. When selecting the lower portion of fatality rate ranges, factors such as the length of warning, ability to evacuate, and time of day should be considered. In good conditions, very low (or even zero) fatality rates are possible. However, there may always be some individuals that refuse to evacuate or make poor choices when responding to warnings.

Considerations for the Use of the Graphical Approach

There are a number of factors to be considered in the use of the graphical approach, as was also the case with DSO-99-06. Following is a discussion of key considerations and recommendations regarding the use of this approach.

Compare your Dam to the Case Histories

Reclamation's life loss estimating procedure is an empirical approach involving the assignment of fatality rates developed from flooding case histories. For any individual or team evaluating the potential life loss resulting from failure of a particular dam, the dam and downstream area should be compared to the case histories (as presented in the *Case History* document). If conditions at the dam being analyzed reasonably match a particular case history, or if there are important similarities, consideration should be given to using the fatality rate data from that historical event as a starting point for selecting the fatality rate range for the dam being studied. As a caution, however, recognize that the observed fatality rate from a particular case history is specific to the warning scenario, time of day and year, etc. that actually occurred. Small changes to the time when the failure occurred (day versus night) and other variables could have drastically changed the fatality rate.

It is also important to realize that a great many Reclamation dams and reservoirs are of sufficient size (both in structural height and reservoir capacity) to be not well represented by the available case histories. In addition, improved communications, access and infrastructure present today may serve to lower fatality rates with respect to case histories which occurred long ago. These factors should be considered when reviewing potentially representative case histories.

Even if no available case history appears to apply to the dam being evaluated, significant value will be obtained from reviewing the case histories and understanding how they were used to develop the current life loss estimating procedure. Furthermore, it is not necessary that a dam being analyzed has a relevant or similar case history. It is the collective results from all the case histories that led to the establishment of the fatality rate ranges shown in the graphs. Based on generalized estimates of DV and warning time, a specific case can be plotted on the appropriate graph. This is a starting point; while the estimated fatality rate should generally fall near or within the suggested bounds, unusual circumstances may justify exceeding the upper or lower bounds of the curves.

Use Judgment

The estimation of life loss requires considerable thought, evaluation, and judgment. There is no simple approach to the complex task of estimating how many lives will be lost in a dam failure. Rather than rely on a “cookbook” approach where fatality rates are selected with little thought, the process should involve a careful consideration of the potential variables and uncertainties. Each variable, including PAR, flood severity, and warning time, will affect life loss estimates in each area or reach of a downstream inundation flood plain. ***Do not attempt to simply apply numbers from the graphs – think about what you are assuming and why!*** Assumptions and assignments of values should be justified by describing the reasons for selecting various categories of warning, flood severity, and other key variables.

Similarly, do not make this evaluation overly complicated. DV values and fatality rates should have ranges to reflect the uncertainty, so detailed estimates to multiple decimal points are not needed.

Carefully Define Flood Reaches

Reclamation’s approach to estimating life loss has been to separate downstream flooding into multiple reaches, recognizing that different downstream areas have varying PAR, varying levels of flood severity, and varying warning times. This typical practice remains in place for the RCEM methodology. However, it is worth emphasizing that this delineation of flooding reaches should be done with care. A large number of reaches can produce an unnecessary complexity, particularly if conditions are expected to be similar for long stretches of the inundation plain. In general each reach should be small enough that a reasonably consistent fatality rate could be expected, considering both warning time and flood severity. However, there are exceptions when different types of PAR are within a reach (campers versus permanent residents, for example) or when day/night or seasonal PAR varies. When working with 1D inundation modeling results, reaches should to the extent possible have the same expected level of flood severity (i.e., don't identify a reach that would feature a wide range of DV values unless there is good peak flow information and topography to reasonably estimate differing DV values). Two-dimensional inundation modeling results will generally more clearly show lateral variation in flood severity. When working with 2D inundation boundaries, reaches are typically defined by differences in PAR density (rural vs. urban) and warning time.

Use DV Values to the Extent Possible

The RCEM relies on estimated ranges of DV values to guide the selection of fatality rates instead of the descriptive "flood severity" classifications used in DSO-99-06. Actual case history data were used to estimate DV values and fatality rates and to develop the graphs used in this RCEM methodology. If an inundation map exists, there is most likely an inundation study report that formed the basis for the mapping. An effort should be made to locate a copy of the inundation study report, as it may provide key information about flood flows and depths at various downstream reaches which in turn can be used to estimate the average DV at various points. In addition to looking through DSDAMS and the Dam Safety Files, ask TSC inundation mapping specialists as well as regional and area offices for assistance in locating inundation reports.

However, inundation study reports and thus estimates of the DV may not always be available. For those cases, some information may exist on inundation maps to suggest flood flows and width of flooding, which can be converted to an estimate of DV. In other cases, past dam safety studies, particularly loss of life studies, may have already classified downstream flooding as low, medium, or high severity. If it is truly impossible to estimate DV, these descriptive categories can be used as a guide to estimate a range of DV values.

Recognize that DV Values May Vary Within a Given Reach of the Flood Plain

In a given reach of flooding, some of the PAR may be near the river and thus subject to higher DV values, while others may be farther away and subject to considerably smaller values of DV. Two-dimensional inundation modeling results can be classified according to ranges in flood severity to account for this phenomenon and aid in the selection of appropriate fatality rates. In studies based on one-dimensional inundation models, it may appear difficult to identify much delineation, although comparing flood depths to topography may provide information on depths to which an average flood wave velocity could be applied. In the event that DV values and thus flood severity are expected to vary, it may be appropriate to divide the reach into two different DV classifications, with a portion of the PAR subject to a certain DV (or range of DV), while the other portion of the PAR subject to a different DV value or range. An example of this type of breakdown is included in the *Examples of Use* document. It is not necessary to assign a single DV value or range to an entire reach. However, if different ranges are assigned, judgment should be applied and a case built for why the flood severity is expected to vary.

Consideration of Flood Severity Understanding

This variable was a consideration in the DSO-99-06 methodology, but is not explicitly used in the revised graphical approach. This is primarily due to the fact that available case histories provide limited data on flood severity understanding. For example, for the DSO-99-06 category of warning time greater than 60 minutes, there is only one case history of "vague" understanding. Furthermore, DSO-99-06 did not differentiate between a vague or precise understanding when the warning is less than 15 minutes. Thus, the graphical approach does not use this variable. However, if an estimator or a team believes that the warnings will be clear and forceful, fatality rates could be assumed to range more toward the lower end of the curves. On the other hand, if warnings are expected to be vague or poorly understood, the team might select fatality rates from the upper portion of the curves. In other words, the level of flood severity understanding could be part of the case built to justify a particular fatality range.

Warning Times

Whereas DSO-99-06 utilized three different categories of warning times, the revised graphical approach has simplified warning to two categories and thus two graphs – "little to no warning" (which is meant to imply the affected PAR receives no or extremely limited notification of the impending flood wave) and "adequate warning" (which is meant to imply that the PAR receives a timely notification of the failure and can take action to seek appropriate shelter or to evacuate). The reduction to two warning categories was done because there were many case histories where warning time could not be clearly identified plus there was a paucity of cases with 15 to 60 minutes of warning. There are no specific or explicit criteria that are used to define the terms "little to no warning" or "adequate warning," since the amount of time to constitute an "adequate" warning likely varies with the type of PAR distribution, difficulties of evacuation, and other variables.

Thus teams are encouraged to assess the PAR in question, and consider whether the warning is likely to provide a chance that people will be informed of the flooding and be able to move to safety, or not. This will include an assessment of the likelihood that a failure will be detected in a timely manner, the ability of local officials or the public to issue a formal or informal warning, the travel time of the flood wave, and similar factors. For example, a sudden dam failure that results in virtually no warning may suggest fatality rate ranges near the upper portions of the "little to no warning" curve, while many hours or even days of warning to a PAR far downstream will likely lead to selection of fatality rate ranges near the bottom of the "adequate warning" curve. As another example, a failure that occurs at night may suggest fatality rate ranges near the upper portions of the curves, while a daytime failure may lead to a selection of fatality rate ranges from the lower portions of the curves.

In those cases where the warning is thought to be somewhere between "little" and "adequate," teams could consider selecting a range of fatality rates somewhere between those indicated by the two sets of different curves.

As with the assignment of DV values, it is not critical that only one warning category be assigned to an entire reach. A distribution of warning times (e.g., 25 percent chance of little or no warning and 75 percent chance of adequate warning) can be assigned to any or all reaches. Examples of the use of this type of distribution are included in the *Examples of Use* document. The use of distributions or single warning categories within a reach are a matter of team preference. However, since fatality rates can vary greatly depending on warning time, as a minimum, any variation in warning should be trialed to determine the sensitivity to overall life loss estimates (and reported if significant).

Consider the Components of Warning Time

Warning time is broken into stages: detection of the threat, decision to issue warning, notification of the downstream PAR, and warning dissemination. Detection of a developing dam failure situation could be by automated instrumentation or by routine visual inspection by project personnel. Quite often, in seepage-related incidents, a hiker or fisherman raises the initial alarm. After the unusual situation is noticed, some time is required before project and emergency personnel can assess the situation and decide that there is a reasonable chance it will develop into a condition that cannot be controlled. Then, the notification of those responsible for spreading the warning can take some time. The actual warning to the population at risk can be transmitted in many ways, each with its own degree of effectiveness. The wording of the warning message can itself be important, either giving people a clear perception of the danger or not. Warning can also spread by word of mouth (or social media) through friends, family, neighbors, and concerned citizens. People who are at risk, but are not warned verbally, can still perceive danger by hearing an unusual sound or seeing a rapidly rising flow of water.

Assessment of the warning and evacuation process may include consideration of the following issues:

- Failure of the dam or its impending failure may need to be visually verified by emergency officials, particularly if the dam is unattended, before warning is issued. Lack of phone service in remote areas could cause delays in getting warnings and evacuation orders issued.
- The decision to order evacuations must be made by those responsible. There can be issues related to public trust or potential liability that may delay issuing an evacuation order.
- People may receive warning or an order to evacuate, but delay evacuation or choose not to leave at all. The timeliness of evacuation has been found to be related to how serious the risks are perceived by the public. To some degree, perception of the seriousness of risk has been tied to the quality or forcefulness of the warning that is received.
- Some people may choose not to evacuate. Reasons for this include: warnings may not be taken seriously; elderly persons or disabled persons may have too much difficulty attempting to evacuate; people may not evacuate for fear of looting; people may not believe that the flood impacts will be severe enough to endanger them; people delay evacuation to protect personal property such as pets or livestock
- Persons who do not attempt to evacuate or who attempt to evacuate at the last minute can be placed in critical situations where a number of factors may influence their survival. The flood depths, the severity of flooding (often quantified as depth times velocity, DV), the strength of a temporary shelter, and a person’s physical condition will influence the survival chances of PAR exposed to flooding.

- Some people may not receive warning.
- Densely populated urban areas need more time to evacuate. These are special situations where traffic congestion may play a role in the ability to evacuate. Persons attempting to evacuate in advance of flooding may get stuck in traffic, resulting in exposure to flooding. In many situations, evacuating to a large, sturdy building, or staying in one's home may be safer than attempting to leave the area in a vehicle. Note that life loss numerical simulations use transportation network models and attempt to address traffic congestion issues during flood events.
- Demographics can play a role in whether people will evacuate. During Hurricane Katrina many of the poorest people did not leave New Orleans simply because they did not have a car, had no money or had no place to go.

Case histories provide some examples of human behavior in relation to flood risk and evacuation:

- The failure of the Machhu II Dam in India in 1979 killed as many as 10,000 people. Once warned, some people didn't leave because they lived above the highest flood levels that had occurred during their lifetime.
- Teton Dam failure in 1976 (11 fatalities) and Lawn Lake Dam failure in 1982 (3 fatalities) both contained fatality incidents where people who had safely evacuated re-entered the flood zone to retrieve possessions, thinking that they had more time before the arrival of flooding.
- The eruption of the Nevado del Ruiz volcano and the deadly lahar mudflow flood at Armero, Columbia in 1985 killed about 22,000 people. Most residents of Armero didn't evacuate because the severity of risk was downplayed by local officials.
- St. Francis Dam failed in 1928, killing more than 400 people. Some who heard the approaching flood waters could not conceive of a dam failure flood and thought the sounds to be due to a windstorm.

Experience indicates that there is sometimes a reluctance to issue dam failure warnings. The operating procedures or emergency action plan that may be available for a dam or levee should provide some guidance regarding when a warning would be issued. There is no assurance, however, that a warning will be initiated as directed in a plan. A study investigating loss of life from dam failure can be used to highlight weaknesses in the dam failure warning process and provide some guidance on how improvements in the process could reduce the loss of life. Sensitivity analysis should be used to provide information on how significant warning issuance is related to the uncertainty in a life-loss estimate.

For most breach mechanisms where the breach progression is observable prior to catastrophic failure of the dam, the time when a warning is issued should be determined by first estimating the time when a major problem would be acknowledged by officials relative to the time of dam failure. This is, of course, highly variable depending on the timing of the breach process with respect to the presence of a dam tender or other observer at the site.

The time to acknowledge that a major problem exists for these failure modes is the time frame from when it is determined that a failure is likely imminent to the point that it is decided that the dam breach warning and evacuation process should be initiated by notifying the responsible authorities. For CR-level studies, insight on the potential timeframes could be obtained by questioning Reclamation area office personnel responsible for a given dam. For higher level dam safety evaluation, the time lag between acknowledgement of a major problem and when an evacuation order would pass from the dam owner to the responsible emergency management officials (and then from those officials to the public) should be estimated based on the judgment of dam operations and local emergency management officials with jurisdiction in the downstream areas.

The amount of time it takes from when the evacuation warning is issued by the responsible agency (warning issuance) until the population at risk receives that warning is dependent on the warning system or process that is used to disseminate that warning. A typical warning would be received by the population through a variety of means. For example, the first group of people would typically receive warning 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 that warning via word of mouth. For additional detailed information on early warning systems and emergency management, refer to the *Best Practices* chapter on Consequences of Flooding.

Effect of Evacuation

For dam failures that are expected to result in adequate warning times, the effectiveness of evacuation efforts becomes a critical consideration and can dramatically affect the fatality rate. Evacuation will be a significant factor for large downstream population centers, based on the number of people involved, warning logistics, and availability of evacuation routes. Estimators should make all possible attempts to understand the population center in question including the demographics of the population (the elderly or tourists may be less likely to evacuate or understand evacuation routes), the distance from higher ground or safe refuge, the number and clarity of available exit routes, the possibility of restricted or congested access points such as bridges or narrow roads, and any other factors that could impact evacuation.

The inventory of case histories does not include examples of dam failure flooding that resulted in life loss with long travel times and considerable evacuation. In cases where advance warning is expected to provide plenty of time for an effective evacuation, the low end fatality rates would likely be assumed. If evacuation is expected to be difficult and warning times marginal, higher fatality rates might be assumed.

As mentioned earlier, the effects of evacuation are embedded in the case history data. In other words, for those cases where adequate warning was given to the PAR, the lower fatality rate (compared to a similar DV with no warning) is undoubtedly due in large part to people leaving the inundation plain. Nonetheless, the selection of fatality rates should carefully consider the effectiveness of potential warnings and the resulting impacts of evacuation in any case where "adequate" warning is assumed, as discussed in the previous paragraph.

Consider any Unusual Aspect of the Flooding or Inundation

Potential life loss from a dam failure flood may vary depending on the nature of the PAR and their surroundings. For example, it takes a higher DV factor to destroy a well-built house than to destroy or wash away a trailer home. Similarly, relatively low DV flooding could sweep away cars at road crossings or tents at campgrounds. Thus, it is important to recognize whether the PAR are permanent residents in stable structures (the number of floors is also important) or are located in more vulnerable housing, and whether the PAR are in cars or in campgrounds. Higher fatality rates should be considered for the more vulnerable PAR.

Some dam failure floods, depending on the nature of the inundated areas, may carry more debris than might be typical. Such debris may include timber, destroyed property, ice, and other materials that may be encountered in the flood plain. Case histories tend to indicate higher fatality rates when debris-laden flood waters cause havoc and destroy areas of presumed safe refuge, even in low severity flooding.

Certain dam failure modes, such as seismic overtopping of a dam, may result in a sudden and large breach of an embankment or concrete dam that leads to an immediate “wall of water” that begins to travel downstream. The case histories tend to indicate that fatality rates are higher when this type of flooding occurs, so a team should consider selecting fatality rates from the higher portion of the curves, particularly for the PAR near the dam where no warning to limited warning is expected. For inundated areas further downstream, it is possible that the “wall of water” will attenuate and not be as severe.

Some inundated population areas may have a downstream topographic restriction such that the flooding begins to back up floodwaters resulting in gradually increasing depths. Although the depths of flooding may be large enough to indicate moderate DV values (medium severity flooding), the velocities may be extremely low. In these cases, consideration should be given to the depths of flooding and the likelihood that trees and rooftops would provide refuge, or the potential for much of the PAR to safely flee the slowing rising waters if uphill areas are within reach.

The rate of rise for flood flows (if available) should be considered when selecting fatality rates. When the rate of rise exceeds 10 feet in 5 minutes, values near the upper ends of the fatality rate curves should be considered. When the rate of rise is less than 10 feet in 5 minutes, values within the suggested limits of the fatality rate curves may be more appropriate.

Extreme loading conditions that lead to dam failure, such as an intense storm or large earthquake, may create a number of problems involving downed bridges and phone lines, inaccessible roads, and general chaos associated with damaged buildings, rescue efforts, and similar issues. These conditions may present significant difficulties in warning downstream PAR of a dam failure and effecting a successful evacuation. Thus, for potential dam failure modes involving very severe loadings, consideration should be given to such factors as the potential damage to surrounding infrastructure and the ability to effectively warn and evacuate.

Some floods having a very long travel time to the downstream PAR may be caused by a very slowly developing failure mode and resulting dam breach or may occur at a facility or community with an extremely advanced emergency management program and early warning system. None of these cases can guarantee zero fatalities, but it is nevertheless important to recognize that for potential dam failures with more than one favorable aspect, it is possible that life loss might be quite low. As evidenced by the case histories, there have been a number of dam failures that resulted in no fatalities.

These are only a few examples of the many conditions that might lead to unique flooding or inundation circumstances for a particular dam failure. Teams are encouraged to consider what type of breach (size and rate of development) might be expected for a particular failure mode, as well as what type of flooding would likely occur at various locations along the downstream flood plain. Consultation with a consequences expert is recommended for complex situations.

Use of Independent Estimates and Team Approach

There will be a great deal of judgment involved in the development of life loss estimates. This is not only true of this revised methodology, but for any consequence evaluation. Given the many variables and resulting uncertainty in life loss estimates, it is not unexpected that two different individuals may end up with differing life loss estimates for a given failure mode. To improve the quality of the life loss estimates, it is recommended that the team consider having two of their members independently estimate the various parameters and resulting life loss. Then the team can discuss both estimates to better understand any differing assumptions or estimates. This process of employing independent assessments and then engaging a team discussion can provide great value in considering varying viewpoints and arriving at a consensus estimate of estimated life loss (which admittedly contains significant uncertainty).

Application of the Procedure

Estimation of life loss resulting from a dam failure requires consideration of many factors - some of the major factors are listed below.

- The potential failure mode for the dam
- The assumed breach parameters
- The extent and severity of downstream flooding
- The time of day (or season) of the flooding
- Flood wave travel time
- Assumptions of warning (timing; effectiveness) and evacuation (easy vs. difficult; routes)
- The downstream population at risk
- The fatality rates

The full consideration of all these factors is a complex problem that requires (1) detailed modeling of the physical processes (breach characteristics and flood routing), (2) estimation of human responses, and (3) the estimation of the performance of technological systems such as warning and evacuation systems, transportation systems and buildings under flood loading. Using empirical data from case histories of dam failures and other similar events, this procedure provides a practical approach to this complex problem of estimating life loss for use in dam safety risk analysis.

The procedure for estimating life loss involves completion of 10 tasks as summarized in Table 1 below. A detailed discussion of each task is included in the subsections that follow. Note that with each task, the selected values should be justified (a case built for the estimates or assumptions).

Table 1 – Summary of Tasks for Estimating Life Loss

Task	Description
1	Select dam failure scenarios (e.g. sunny day, flood, etc.) that correspond to dam potential failure modes
2	Select appropriate time categories (e.g. day/night, seasonal, weekend/weekday, etc.)
3	Review and evaluate flood inundation mapping and define appropriate reaches or areas flooded (by river reach, town, etc.) for each dam failure scenario
4	Estimate flood severity range (i.e. DV range) for the flooded areas. Some towns or river reaches may have PAR in multiple DV ranges, depending on the flood characteristics (see Task 4 discussion below). Justify the estimates.
5	Estimate the population at risk (PAR) within each reach for each failure scenario, DV range and time category. Justify the estimates and provide any referenced resources.
6	Estimate when dam failure warnings would be initiated (depends on many factors, suggest using range; see Task 6 discussion below). Estimate the warning time categories for flooded areas (e.g. little to no warning, adequate warning, or between the two; see Task 6 discussion below). Justify the estimates.
7	For each PAR reach, use the graphical approach to estimate an appropriate fatality rate range based on DV values, warning time and other considerations. Justify the estimates.
8	Estimate life loss range for each PAR reach by applying appropriate fatality rate range limits to each PAR. Sum the life loss estimates for each PAR to get the total estimated life loss range. Estimate life loss range for different dam failure scenarios as needed in Task 1.
9	Evaluate how uncertainties and variability in various parameters affect overall uncertainties in life loss estimates. Perform sensitivity studies if needed. Identify areas of higher and lower uncertainty.
10	Build the case for the life loss estimates by documenting all assumptions and references used. Discuss confidence in the life loss estimates.

Task 1 – Select dam failure scenarios (e.g. sunny day, flood, etc.) that correspond to dam potential failure modes

The loss of life caused by dam failure flooding may be highly dependent on the potential failure mode, which includes consideration of any loading being applied to the structure and the response of the structure to the loading. Failure scenarios for dam safety risk analysis are typically identified from the findings of a Potential Failure Mode analysis. For the purposes of dam safety risk analyses, potential failure modes usually fall into three categories: static, seismic, and hydrologic. Within each category, there may be specific details for a potential failure mode, such as: overtopping due to a 50,000-year inflow, liquefaction and slumping of a dam crest due to seismic loading, or internal erosion due to concentrated seepage along an outlet works conduit. There are many possible site-specific potential failure modes for dams.

It is worth noting that the while the case histories contain dam failures caused by static and hydrologic loadings, none of the cases are associated with dam failure due to seismic loading.

Thus, when considering potential life loss resulting from earthquake-induced dam failure, additional thought needs to be given to any additional factors associated with an earthquake. For example, will warning systems fail due to downed phone lines or cell towers, will bridges be damaged and impact evacuation routes, or will people be trapped in homes or structures and be unable to easily escape floodwaters?

When considering the dam failure scenarios to select, the breach characteristics need to be evaluated. Different potential failure modes may have similar, or widely varying, breach dimensions and resulting outflows. For example, a spillway-related potential failure mode may have a much lower breach outflow than a flood overtopping potential failure mode. Similarly for an embankment dam, a seismic potential failure mode that involves liquefaction of soil materials is more likely to result in a rapid breach formation than a seismic embankment cracking potential failure mode, because a rapid loss of freeboard can occur with liquefaction. In addition, the speed with which the breach develops can impact many key life loss estimating factors such as warning time, size of inundation area, and flood severity. In some cases, where embankment dams consist of compacted clayey materials or with large rockfill shells, breach size and outflow may be limited because of the erosion resistance of the embankment materials.

While there may be a significant range of dam failure scenarios, it is not necessary to estimate life loss for every scenario; similar dam failure scenarios can be grouped together and the estimated life loss range can capture some of the variability in the dam failure scenarios. For example, life loss may be estimated for failure of a limited number of concrete dam monoliths and then also for the failure of all monoliths.

Task 2 - Select appropriate time categories (e.g. day/night, seasonal, weekend/ weekday, etc.)

The first step in this task is to evaluate if various time categories are needed to estimate life loss. In general, different time categories may be needed if the PAR varies significantly over time. If there is no significant variation in PAR over time and there are very long warning times for downstream populations, so that a judgment can be made that there would not be a significant difference between day and night conditions, this task is not necessary and one time category is used for the life loss estimate.

The time of day, day of week, and month or season during which the dam failure takes place may strongly influence the resulting loss of life. Case histories of dam failure flooding events have shown that warning and response can be much weaker during nighttime hours, resulting in significantly higher fatality rates. An additional set of DV vs. fatality rate plots that indicate whether the case histories occurred during the day or at night are included in the Appendix. The time of day can have a significant influence on life loss for situations where the PAR is very close to the dam, and less of an influence where the PAR is many hours downstream. Consideration of different time categories can help with sensitivity analyses and can help estimate ranges of PAR and life loss.

The time categories can be based on:

- Time of day – The time of day affects where people may be located and can affect the ability of PAR to respond to warning and to effectively evacuate. Typically, more fatalities have occurred during night time flood events, due to people sleeping, darkness, decreased ability to spread warning and a slower evacuation response. In most cases, except for cases where there are very long warning times, both day and night scenarios should be considered.
- Weekday/Weekend – The day of the week can, in some cases, have an effect on life loss estimates. Recreational areas such as campgrounds, or along rivers where fishing or boating are popular, will see higher PAR numbers on weekends. Conversely, these areas may be unoccupied much of the time during weekdays and non-peak seasons.
- Seasonal variation – For areas with significant recreational (transient) PAR, there may be large differences in numbers of PAR present between summer and winter months. Seasonal variation might also consider the reservoir level. For example, internal erosion dam failures are more likely to occur when the reservoir is at or near historic high levels (e.g. spring and early summer), and flood-induced failures are more likely during months that typically produce extreme rainfall and/or floods for watersheds in the vicinity of the dam.

Task 3 – Review and evaluate flood inundation mapping and define appropriate reaches or areas flooded (by river reach, town, etc.) for each dam failure scenario

Flood inundation modeling is a critical part of the life loss estimation process and is typically performed by a specialist who has a broad understanding of hydraulic modeling, dam safety issues, consequence assessments, and Geographic Information Systems (GIS). The flood inundation model provides estimates of the inundation areas, the severity of flooding, and flood wave travel times. It requires assumptions about the type of breach that will occur.

Dam failure inundation mapping is important for each dam failure scenario identified from Task 1. If existing dam failure inundation maps are available, their adequacy to represent the flooding for the scenarios identified needs to be assessed. For instance, a dam failure inundation map based on the overtopping failure of a 120-foot-high embankment dam may be an adequate representation of the flooding that would occur if the dam failed with the reservoir level three feet below the dam crest, whereas it probably would not adequately represent the flooding if the dam failed with the reservoir level 25 feet below the dam crest. In the latter example a new analysis may be needed, depending on the overall risks posed by the dam and the justification to perform new analyses to better define risks.

When considering the adequacy of a dam failure inundation study, the following should be evaluated:

- Failure scenario - Is the failure scenario portrayed in the existing study comparable to the desired scenarios for the new study? For example, a new inundation study may be justified if the current study seeks to evaluate a sunny day failure with normal reservoir levels, but the existing inundation study is based on a Probable Maximum Flood (PMF)

inflow where the inflow volume of the flood increases the breach outflow volume by 100 percent over sunny day conditions.
- Breach parameters – Are the breach parameters for the existing study realistic? Are they significantly different from the desired breach parameters of the failure scenario to be evaluated by the risk analysis? An example might be a situation that involves a large concrete gravity dam. The existing inundation assumed failure of the entire dam, all the way to the foundation. Recent finite element structural analysis indicates that the dam, when subjected to the most severe of loading conditions, would only breach to the upper one third of its height (due to stress concentrations at an elevation where there is an abrupt change in dam section). In a situation like this, a new inundation study may be justified.
- Downstream conditions – There are many examples of older inundation studies that were performed with one-dimensional (1D) hydraulic models where the downstream terrain contains populated areas that are very flat. The modeling cross sections may extend over very wide areas, sometimes exceeding several miles in width. Two-dimensional (2D) hydraulic models do a more accurate job of modeling flood flow over wide flat flood plains, but 2D models were typically not used for flood inundation applications until about the late 1990s. For older 1D inundation studies when relatively flat terrain exists, a new inundation study using 2D modeling and appropriate terrain data may improve the accuracy in estimating overall flood extent, the intensity of flooding, and travel times, and thus may be beneficial.
- Potential impact to estimated risks – There will be cases where only one inundation map is available, and that study is likely to have been based on a hydrologic dam failure. Assuming that study applies to a sunny day failure, with a likely lower breach flow, is admittedly somewhat conservative. However, if the (conservative) estimated life loss results in annualized life loss risks below guidelines, there would be limited justification for conducting additional inundation studies. Conversely, if the estimated risks are very near the guidelines, new inundation studies may be justified.

Flooded areas downstream from the dam can be divided into several different locations or river reaches. When deciding how to divide the inundation area, the following factors should be considered:

- Residential versus transient PAR;
- Occupancy type (e.g., tent in a campground versus one-story dwelling);
- Varying occupancy considering season, time of day, or other factors (e.g., manufacturing facilities, summer resort areas, campgrounds, picnic areas, fishing spots, boating areas, etc.);
- Population density (e.g., scattered residences, small town, large city);
- Flood characteristics (i.e., flood depths, DV, rate of rise);
- Warning characteristics (i.e., timing, amount, and quality) and evacuation capability.

For additional detailed information on inundation mapping, refer to the *Best Practices in Dam and Levee Safety Risk Analysis* [4] chapter on Consequences of Flooding.

Task 4 – Estimate the flood severity range (i.e., DV range) for the flooded areas.

Flood severity has a significant influence on fatality rate. In general, case history data indicates that the highest estimated fatality rates are associated with the highest estimated DV values. When the flood severity is lower, there is greater observed scatter in the fatality rates, most likely because other factors (such as the amount of warning, the forcefulness of the warnings, the response of the PAR to warning, as well as evacuation opportunities or constraints) are more significant at the lower DV values. Estimation of flood severity for a dam failure is particularly important for this RCEM methodology because the graphical charts provide relationships between DV and fatality rate.

Mapping of DV can be produced from 1D or 2D inundation modeling results and the DV maximum inundation boundary can be used to assess zones of various levels of flood severity. Note that 2D hydraulic modeling can provide greater accuracy when assessing lateral variation of DV. Flooding depths are an important measure of flood severity as well. Deeper water can make evacuation on foot impossible, submerge roads, float cars and mobile homes, and make structures uninhabitable. Fatality rates can be influenced by flood depths and velocities, as well as rate of rise.

The potential for collapse of buildings within the flood zone can be a measure of the potential for fatalities, assuming people are present when the flood arrives. Most residential buildings would be vulnerable to major damage and/or collapse when flooding DV is within the range of 80 to 160 ft^2/s.

Flood severity is quantified in terms of depth multiplied by velocity of flow, or DV. Although the parameter DV is not representative of the depth and velocity at any particular structure, it is representative of the general level of destructiveness that would be caused by the flooding. DV increases as peak discharge from dam failure increases, or it may decrease as the width of the inundated area increases.

Most commonly, DV can be quantitatively estimated at any location by dividing the flood flow (ft^3/s) by the flood width (ft), or by multiplying average flood depth and average velocity as obtained from hydraulic modeling output information. However, there are a number of ways that DV can be estimated depending on the availability of flood information. Some of these ways include:

- The estimated flood discharge at a point divided by the inundation width
- The depth of flooding multiplied by the velocity of flooding at a particular point (whether at the center of the river channel or in the floodplain adjacent to the river channel)
- The estimated flooding depth (from mapping) multiplied by a velocity based on flood travel time

For this methodology that features the use of a log scale for the data, relatively small ranges in the DV parameter (perhaps factors of 2 or 3, for example) may not significantly impact the fatality rate, depending on the location in the curve where the values fall. For example, when looking at the curves, fatality rates might change very little for DV values ranging from 300 to 900 ft^2/s, but could change significantly for DV values ranging from 50 to 150 ft^2/s. Although it is important to estimate DV as carefully as possible, it is not critical that the resulting calculation is completely "accurate." Rather, a range of DV can be estimated using different approaches above and with varying input assumptions. In fact, the actual DV values in a given flood reach probably do vary appreciably, so providing a range may be the best way to represent conditions. In most cases, this range can be used with the graphs to come up with a reasonable fatality rate range.

Suggested approach if inundation studies and/or maps are not available

Nearly every Reclamation dam has some downstream inundation information, and in some cases it is as little as a map with little or no depth or travel time information. In most cases, an inundation study that formed the basis for the maps was performed, and likely exists. However, it may take considerable effort to track down the study; evaluators must check with Reclamation consequences specialists in the Denver office, as well as area and regional office staff. By using the maps, the study if available, breach outflow estimates, and existing topography, DV along various reaches can usually be estimated.

There are very few Reclamation dams that do not have an inundation study or map. In these situations, the PAR and estimated life loss are low. For these limited number of cases, an alternate approach can be to utilize the "flood severity categories" defined in DSO-99-06 (and expanded herein). **Evaluators are cautioned that this approach should only be used if no inundation studies and/or maps are available.**

The following guidance is provided to assist with selection of the flood severity category:

- Low flood severity occurs when no buildings are washed off their foundation. In general, most structures are exposed to flood depths of less than 10 feet. The parameter DV is less than 50 ft^2/s for low flood severity.
- Medium flood severity occurs when homes are destroyed but trees or mangled homes remain for people to seek refuge in or on. Generally, many structures may be exposed to flood depths of greater than 10 ft. The parameter DV is greater than 50 ft^2/s for medium flood severity.
- High flood severity occurs when the flood sweeps the area clean and nothing remains. DV exceeds 160 ft^2/s. Rate of rise is estimated to be at least 10 feet every 5 minutes.

The likely flood severity category is estimated by considering dam height, estimated breach outflow, reservoir volume, downstream channel topography and other factors. After estimating the likely flood severity category, select a representative DV range and select a fatality rate range considering all the factors described in this methodology. For many (if not all) Reclamation dams, a life loss study exists that estimated the flood severity category. Evaluators should scrutinize the factors that were used to select the flood severity category and independently conclude that the flood severity category can be supported with known information and sound judgment.

There may be justification to perform an inundation study to better understand the flood conditions (depths, velocity, travel time, etc.) if the any of the following conditions exist:

- Life loss sensitivity studies indicate the selected fatality rate and estimated life loss is sensitive to factors that are assumed with little or no technical basis (e.g. 30 minutes warning vs. 2 hours of warning; low severity vs. medium severity flooding for PAR with little or no warning).
- The number of residents downstream has increased in recent years, making it difficult to assess the PAR.
- The type of PAR has changed from mostly transient (recreational or seasonal) to more permanent residents (cabins, mobile homes, etc.)

Task 5 – Estimate the population at risk (PAR) within each reach for each failure scenario, DV range, and time category

After the DV values have been estimated in each flooded area, the PAR in each area is estimated. For each combination of failure scenario, DV range, and time category identified in Tasks 1, 2, and 4, the number of people at risk is estimated. PAR is defined as the number of people occupying the dam failure flood plain prior to the issuance of any warning or evacuation.

It is typical to divide the inundation area into locations with common flood and warning characteristics, with the other factors having a smaller influence. If 2D mapping is available, the maps might indicate that DV varies significantly over a limited area, likely due to topographic effects. For a given population reach downstream of the dam, populations experiencing low severity, medium severity and high severity should be separated out.

At a very basic level, the development of a PAR estimate can be as simple as visiting the area downstream of a dam and counting houses in the inundation zone. PAR can also be obtained using the inundation mapping data overlaid with census data. Reclamation's internal application Tessel (which includes GIS mapping software) is a powerful tool that can be used to simplify this process. The most accurate data for residential PAR estimation is at the level of the census block. When the flood inundation boundary can be overlaid with the census block data in a GIS, the number of inundated PAR households can be calculated. Partially inundated census blocks must be treated separately. If the residences are evenly distributed within the partially inundated block, a percent inundated estimate can be applied to the total number of households within that block. If the distribution of residences within a partially inundated block is more concentrated in specific locations, then the recommended approach would be to manually count the houses in the inundation zone. Finally, the total number of inundated residences is multiplied by an average household size that is specific to the area of interest (which can be obtained from census data), to obtain the estimated residential PAR.

The use of census block data to obtain residential PAR for life loss estimation is a simplifying assumption. If more detailed information is known about where people may be located during daytime hours, then this information can be used to develop daytime-specific life loss scenarios. Care must be taken not to double count PAR when looking at non-residential PAR distributions. For example, consider the case of a manufacturing plant that is located immediately downstream from a dam. The plant has about 400 employees present during daytime hours. The proximity of the dam to these employees puts them at the highest level of risk in the event of dam failure. However, the residential location of these employees is unknown. Some may live in the flood zone at locations further downstream, and because of this they may be double counted. In this case though, the fatalities close to the dam can be assumed to be high and persons living downstream in the floodplain are assumed to have much more time to evacuate with a likely lower fatality rate, so that the issue of potentially double counting does not introduce major errors. Double counting of PAR when considering non-residential situations should be evaluated on a case-by-case basis to avoid the possibility of overestimating fatalities.

Another type of PAR that is frequently estimated is recreational or transient PAR. This would include persons occupying campgrounds, fishing, boating or hiking along a river, etc. Evaluating a range for PAR is particularly relevant when the PAR is primarily recreational or transient. Recreational PAR estimates can be obtained through site visits and/or by consulting with land use and recreation management groups who oversee these areas. In some cases, visitation numbers data may be available, or in other cases, campground hosts or park rangers may have a general idea of user numbers. Typically, recreational PAR will vary by time of year and day of week, with higher numbers in the summer months and on weekends. For recreationists, consideration should be given to the likelihood they would be present for hydrologic failure modes that may involve rainy weather and/or rising stream levels.

Another consideration for the PAR for hydrologic potential failure modes is the effect of large spillway releases prior to failure of the dam. Large spillway releases may inundate residences for portions of the PAR near the stream channel and result in this portion of the PAR being evacuated prior to dam failure. If this is the case, the incremental PAR should be used, which is the total PAR impacted by dam failure minus the PAR impacted by spillway releases. However, consideration should be given to the fact that some of the PAR impacted by the spillway releases may evacuate from their homes but relocate to homes of friends or family or designated shelters still within the inundation boundaries for dam failure. Perhaps the spillway releases could cause flooding that would complicate evacuation efforts. Thus, judgment should be used to adjust the portion of the displaced PAR that is subtracted from the full PAR.

Task 6 – Estimate when dam failure warnings would be initiated and estimate the warning time categories for flooded areas (e.g., little to no warning, adequate warning, or between the two)

Although the graphical method utilizes **the time that warning reaches the PAR**, it is important to understand that the warning process consists of several steps, including detection of a failure in progress, initiation of warning by emergency management officials or others, and flood wave travel time. The time at which dam failure warnings are *initiated* is defined as the time at which public safety officials, using assistance from the media (as applicable), begin informing the public of the imminent dam failure danger and directing people at risk to either immediately evacuate or begin evacuation preparations.

In the most ideal situation, a dam breach in progress would be detected, well in advance of the beginning of catastrophic outflows, and warnings and a strong evacuation order would be issued to downstream PAR without delay, with all of the PAR moving safely out of the flood zone by the time flooding arrives downstream. Dam failure and flash flood case histories indicate the ideal situation does not always develop. The sequence of events that takes place is often a mix of physical and social phenomena combined with some element of chance or luck.

The issuance of warning by officials and subsequent PAR decisions regarding evacuation are critical factors that impact the potential for life loss. Flood wave travel times provide an estimate of arrival time for flooding and can be used as a basis for warning time assumptions in cases where warning is issued after the beginning of flood releases.

Flooding case histories show that, in general, the number of fatalities decreases as the distance downstream increases, but increasing distance by itself is not what decreases the life loss potential. Potential life loss decreases when the travel time begins to exceed the amount of time required to warn and evacuate the PAR. Another result of increasing distance is the attenuation (reduction) in flow that occurs. However, flow depths and velocities can increase downstream if the flood plain transitions from a wider valley to a narrow canyon.

Selection of the actual warning provided to the public is described below. Evacuation, or the lack thereof, is accounted for in the fatality rates (using the pre-evacuation PAR) described in Task 7.

Assumptions regarding when dam failure warnings for a particular dam would be initiated can be based on an analysis of the monitoring/detection, decision making, and notification systems or procedures for the dam. It is also important to consider whether the warnings are likely to be formal or informal. Estimators should consider the effectiveness of any informal warnings (word of mouth between neighbors), or whether strong warnings will be issued by officials (and how long that might take). In many cases it may be appropriate to estimate reasonable best case and worst case situations to bracket the time when warnings would be initiated. This range of values can be used to estimate a range of warning times. For higher level dam safety studies such as Issue Evaluations and Corrective Action Studies, it may be appropriate to discuss warning and evacuation plans with local emergency management officials.

General considerations for estimating when dam failure warning would be initiated:

- Refer to the case history data and look for similar situations.
- Warnings are generally issued earlier if there are many observers at the dam (i.e., if a dam tender lives on high ground and within sight of the dam, dam is visible from the homes of many people, or the dam crest serves as a heavily used roadway). With many people casually observing the dam, there is a greater likelihood that someone would recognize an abnormal situation and notify officials/authorities.
- Warnings are generally issued earlier if the dam fails during daylight hours. Visual cues of impending failure can be observed with the benefit of visibility brought about by daytime when most people are awake, allowing for consultation, coordination, and minimal delay.

- When warnings do not precede dam failure, people who are in downstream areas and observe or are exposed to the flooding may recognize the cause of the flooding, and provide notifications that ultimately result in dam failure warnings being initiated further downstream.
- For overtopping failures of embankment dams, small drainage areas may be capable of producing large floods that quickly overwhelm reservoirs that have small flood storage space. Weather conditions may prevent people from reaching the dam site to monitor the situation. Warnings may not precede dam failure for dams having little flood storage space located on small drainage basins.
- If an earthquake is responsible for dam failure, it is possible the earthquake has also devastated infrastructure and communications in population centers in the vicinity. Every aspect of warning (i.e. detection, decision, notification, and dissemination) may be affected, and evacuation routes may be compromised. Emergency management personnel would be responding to several situations and may not be able to devote their entire attention on a developing situation at a dam.

Although empirical data are limited, it appears that timely warning is not likely for the sudden and complete failure of a concrete dam. For example, no warnings were initiated prior to the 1928 failure of St. Francis Dam in California. Refer to the *Case Histories* document for additional examples of concrete dam failure consequences. However, there may be exceptions if a failure mode at a concrete dam involves a slow erosion of the foundation or features a hydrologic failure mode with a large drainage areas and forecasting measures. These type of cases could result in lengthy warnings.

The warning time for a particular location downstream from a dam would depend not only on when dam failure warning is initiated, but also on how long it takes flood water to travel from the dam to the location of interest. For example, if a dam is located in an urban area, with many observers nearby, it might be reasonable to estimate that daytime warning would be initiated 1-2 hours before dam failure (assuming there is an ongoing failure mode that can be detected early). If it takes 2 hours for the leading edge of the flood wave to travel from the dam to a downstream location (this would be obtained from an inundation study), warning is therefore initiated 3-4 hours before the flooding arrives at this location and starts to impact the most at-risk portion of the area. It might take several minutes or hours, depending upon flood characteristics, before the maximum water levels are reached at this location.

The case history data generally indicates higher fatality rates for less warning time, and vice versa. However, because of the large number of factors that influence each case, similar fatality rates may result from different cases with different warning times. For the purpose of estimating **when warning reaches the PAR** using this RCEM methodology, two warning time categories are used:

- Little to no warning: A limited (but undefined) amount of time that essentially allows most or much of the PAR an inadequate notification of an impending failure and a resulting inability to get out of the inundation plain (or seek adequate shelter from flooding).

- Adequate warning: An undefined amount of time that would allow most of the PAR to understand the threat posed by dam failure, and take reasonable actions to leave the inundation plain or move to a completely safe location. However, even if given adequate warning, there are a multitude of reasons that people may choose not to leave, or are unable to leave. "Adequate" cannot be defined as an exact amount of time because adequate warning is very dependent on site specific conditions. For example, 30 minutes may be an adequate warning for residents of a small town to evacuate; but it may take many hours of warning to enable a large city to evacuate.

After estimating the warning time range for each location, a judgment is made as to which warning category would best represent that location. The distinction is important because in Task 7, fatality rates are estimated using either a chart for "little or no warning" or a chart for "adequate warning." The exact determination of how many minutes or hours of warning is not as important as the general category selected. As discussed below under Task 7, the expected warning time (and quality) is a consideration (along with other factors) when selecting the upper and lower limits of the recommended and overall fatality rates.

Task 7 – For each PAR reach, use the graphical approach to estimate an appropriate fatality rate range based on flood severity, warning time and other considerations.

This task involves using all of the information available for a dam failure scenario to estimate fatality rate ranges for each PAR area. For PAR areas that are judged to receive little or no warning, Figure 3 is used, and for PAR areas that are assumed to receive adequate warning, Figure 4 is used. Each chart includes dashed lines that represent "suggested" and "overall" limits for fatality rates over the full range of DV values. The suggested limits provide a starting point for estimating the fatality rate range. The selected fatality rate can be increased or decreased, based on all of the relevant factors for each specific PAR area. The limits shown are not intended to be used by estimators directly, but rather they are intended to help the estimator interpret the approximate data trends from the case histories. For example, the range of overall limits for little warning and a DV of 50 ft^2/s covers about three orders of magnitude (when including no life loss cases); however it is unlikely that the range of uncertainty in the fatality rate selected would span that full range. Typically, the selected fatality rate range would be expected to span about one order of magnitude. Judgment should be applied and a case should be built for selecting a fatality rate range that is most appropriate for the situation being evaluated. It is acceptable to use a fatality rate range with limits above or below the overall limits, as long as a case is built for the estimated range, particularly that portion of the range that is beyond the limits of the case history data. For example, recreationists along the river may generally be in the stream with no way to be warned of a dam failure. In this case, there could be a very high fatality rate for a low DV, as they can be easily swept away by higher flows.

The rate of rise for flood flows (if available) should be considered when selecting fatality rates. Case histories indicate higher fatality rates are associated with rapidly rising water (greater than or equal to 10 feet every 5 minutes).

Rate of rise information can be extracted from detailed 1D and 2D hydraulic modeling studies. Newer inundation studies, completed by Reclamation can usually be used to obtain this information. For situations where the most recent flood inundation study is older, and/or less detailed, the estimation of rate of rise becomes more of a challenge.

Rate of rise can be roughly approximated by comparing the arrival time of the leading edge flood wave to the arrival time of peak flooding. A difference in these two values of 30 minutes or less can be considered to meet rate of rise criteria for high severity. The dam failure study report may also contain information that can be used in deriving flood depths and rate of rise.

Older 1D model studies that do not provide data for both leading edge and peak arrival travel times should not be used to provide estimates for rate of rise. In these cases, a revised inundation study is recommended. For situations where time and budget do not allow for the completion of a revised inundation study, the consequence analyst can choose to apply extra judgment to the estimation of a high severity rating. First, the DV values must be greater than or equal to 160 ft^2/s. High rate of rise values are meant to imply the presence of a "wall of water." Since rate of rise cannot be evaluated for some of these older studies, other criteria for which to base judgment include:

- Breach formation time. A dam which fails very quickly will tend to produce high rate of rise, particularly at downstream locations that are close to the dam. Examples of cases where dams fail suddenly and may produce high severity flooding include instantaneous failure of concrete dams and liquefaction "crest slumping" failure of embankment dams. A steep narrow downstream channel will limit flood attenuation and may extend the downstream limits of high severity flooding.
- Cases where DV is much higher than 160 ft^2/s (maybe 500 to 600 ft^2/s and higher), such as what occurred downstream of St. Francis Dam (2,960 ft^2/s at powerhouse No.2) and Malpasset Dam (1,076 ft^2/s on its upper reach), may be assumed to contain high severity flow solely on the basis of high DV.

The selection of fatality rates based on DV values typically involves a PAR consisting of people living in and seeking shelter in single family homes. In selecting the appropriate fatality rate for a given dam, however, evaluators must consider the type of shelter that most people would call "home" at each reach identified in Task 4. For example, people in structures such as tents, recreation vehicles, tent trailers, mobile homes, etc. would be at much greater risk than someone residing in a high rise building. From a damage perspective, the same DV value may lead to low fatalities for people in substantial concrete structures and higher fatality rates for people in lower quality shelters such as tents or mobile homes. Similarly, people in autos or on foot would be likely to perish at much lower DV values than people in a typical house. For the RCEM methodology, the estimated DV range is used to estimate fatality rates, but the fatality rate can be adjusted higher or lower for a given DV range based on the type of shelter (or lack of shelter) being considered in the flooded area.

Guidance for indirect loss of life

Case history data indicates that most of the life loss associated with dam failure has resulted from direct exposure to the floodwater. Deaths indirectly linked to dam failure, such as those caused by injury or illness associated with evacuation, clean up, repair, or loss of electricity have been inconsistently recorded in past dam failures and the fatality rates in this document may not capture such indirect fatalities. There is no need to take additional steps to calculate indirect life loss.

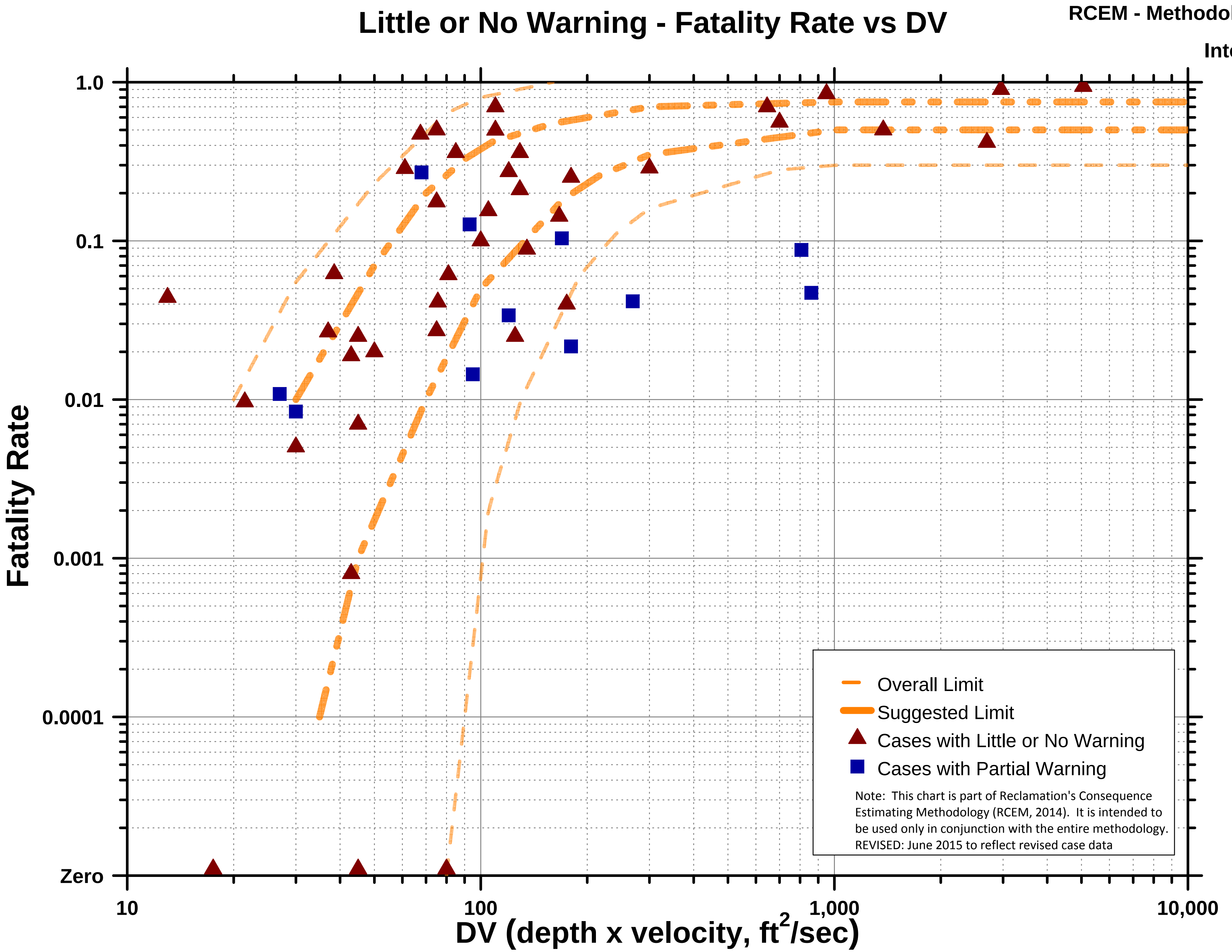


Figure 3 - Fatality Rate vs. DV for Little or No Warning

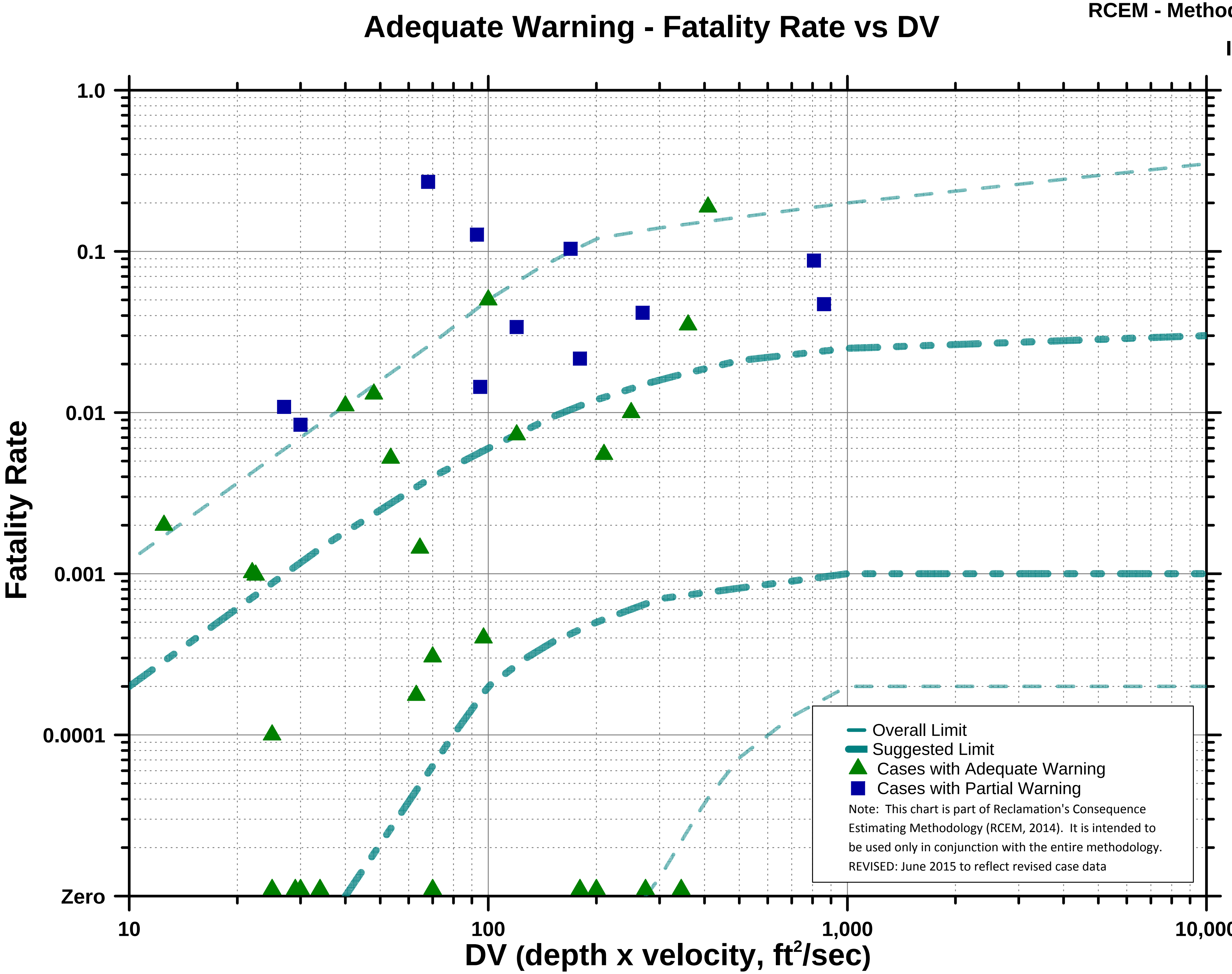


Figure 4 - Fatality Rate vs. DV for Adequate Warning

Task 8 – Estimate life loss range for each PAR reach by applying appropriate fatality rate range limits to each PAR reach.

The range of estimated life loss for each specific PAR reach (corresponding to a location, warning time, or flood severity) is determined by simply multiplying the appropriate fatality rate range limits by each PAR estimate. For each dam failure scenario, the life loss estimates from each PAR reach are summed to get the total estimated life loss range.

In addition to providing the range of total fatalities, a "best estimate" should be provided. This best estimate may be the mean, a value derived by using suggested point values within each reach, or a weighted average between seasonal or day/night combinations. There is no "correct" way to determine this best estimate; it is up to the estimating team to build a case for how to best represent the best estimate within the total estimated life loss range.

One caution to consider is re-think the simplifying approach often used to develop a mean estimate from the day and night estimated life loss. Rather than assume each scenario is equally likely, carefully consider the amount of daylight or "awake" hours and the likelihood that a failure would occur entirely within the night. A possible approach to consider is to weight the two different estimates by a probability of a 0.65 likelihood for a daytime failure and a 0.35 likelihood for a night time failure. This might be considered to better represent the average 8 hours out of 24 that individuals will be asleep (and not watching television or other available media that may be broadcasting warnings), as well as reflect the possibility that a dam failure may take some time to develop and could be detected in daylight hours prior the full breach actually occurring.

Task 9 - Evaluate how uncertainties and variability in various parameters affect overall uncertainties in life loss estimates.

As evidenced by case histories, there can be a large range of fatality rates from dam failure flooding. This is not surprising, considering the variability in PAR, severity of flooding, and warning time. However, even within a given category of flood severity or warning time there can still be a wide range of fatality rates. These differences may result from having some of the PAR located near the river and some of the PAR located farther away and thus less likely to feel the brunt of the flood flows. Similarly, not all warnings are issued in the same manner, and different populations may respond quite differently to warnings.

The graphical approach features "overall" limits to observed fatality rates; these are essentially envelope curves that cover the majority of case history data points. Within the overall limits are a set of "suggested" limits. Even these suggested limits typically show significant differences between the upper and lower curve. Thus, case histories confirm the uncertainty and variability inherent in the potential loss of life due to flooding. It is important to recognize this uncertainty, and properly reflect it in final estimates by portraying life loss as a range, often with an order of magnitude difference between upper and lower bounds. For example, a report could state "The life loss resulting from a seismic overtopping failure of the embankment is expected to range from 10 to 100." If there is a reasonable expectation of a "best estimate" value somewhere with a broad range, an additional sentence such as "The best estimate is expected to be 50 lives lost."

It is important to define whether the "best estimate" is the mean, median, mode, or some other value, and to provide a justification for why such a "best estimate" is judged appropriate.

Finally, the estimating team should consider what type of probability distribution should be applied to any reported range. It is not unusual for a life loss range to be reported as a uniform distribution, which implies that the life loss really could fall anywhere within the range with equal likelihood. This would result in a mean estimate in the middle of the range, reflecting a belief that the team finds no compelling reason that the life loss would be expected to fall in either the high or low end of the range. However, if the estimators believe there are compelling reasons that the "best estimate" will be skewed to the low or high end of the range, a different distribution can be selected to reflect this belief. The importance of discussing and selecting a probability distribution function cannot be overstated, particularly for higher level dam safety studies.

The types of distributions available, and how they are utilized in life loss estimates, will typically depend on the level of the study. For CR-level assessments, parameter ranges or distributions are often portrayed in spreadsheet calculations. For Issue Evaluation studies, Monte Carlo simulations may be utilized. The *Examples of Use* document illustrates different ways of reflecting uncertainty using distributions. The process utilized is not nearly as important as the thought and rationale behind the development of specific ranges and distributions.

Sometimes, the confidence in an estimate, as well as an understanding of uncertainty, can be enhanced by a simple sensitivity analysis. Instead of assuming only a point estimate for a particular parameter in a consequences analysis, consider calculating the resulting range in life loss for different values of that variable. Example variations in a sensitivity analysis include:

- The PAR could be varied, possibly due to a variable transient population, or to reflect a range of inundation limits if differing breach parameters are expected to produce an appreciable difference in the extent of downstream flooding

- The DV values (flood severity classification) could be varied, since there may be uncertainty in the depths and velocities of flooding in various portions of the inundated areas

- Warning times could be varied, to reflect the variable nature of when warning decisions might be made or to account for the potential differences between a day and night failure

Approaching a life loss evaluation in this manner will likely provide a better idea of the potential range of life loss to be expected (better define the uncertainty), as well as improve the confidence in the estimate.

Task 10 – Build the Case for the Life Loss Estimates

Building the case for the selected life loss estimates is a key requirement. This RCEM methodology requires more judgment and discretion than the DSO-99-06 method. The case for the consequence estimates should be developed in a loss of life study report (or the

Consequences Section of a Comprehensive Review) and a summary should be included in the overall dam safety case presented in the Technical Report of Findings. In the August 2011 Interim Dam Safety Public Protection Guidelines [5], the dam safety case is defined as follows:

> *The Dam Safety Case is a logical set of arguments used to advocate a position that either additional safety-related action is justified, or that no additional safety-related action is justified at any given (current) time. It is sometimes referred to simply as "the case."*

The case for the life loss estimates should address the key inputs that are included in the preparation of the loss of life estimates, including: available inundation studies and the failure scenarios and breach assumptions that they are based on, the flow characteristics defined by the inundation studies, the accuracy of census or other information used to estimate the population at risk along the inundated area, the basis for assumptions of when warning would be issued, any limitations on warning effectiveness and/or evacuation of the population at risk, any unique site specific factors, and an overall rationale for the selection of fatality rates. The case for the consequences should convince the reader and ultimately the decision makers that the loss of life estimates are reasonable.

The case for the loss of life estimates should discuss the uncertainty inherent in the estimates and the confidence that the risk analysis team has in the estimates. Uncertainty is inherent in loss of life estimates, and estimates should be presented as a range rather than a single value. If there are significant uncertainties regarding key assumptions that are considered in developing the loss of life estimates, sensitivity analyses should be performed to demonstrate how different assumptions can affect the estimates. This information can then be used to qualify the confidence that the team has in the estimates and the overall findings. If the sensitivity studies indicate only small differences in the life loss estimates, confidence will be higher in the estimates. Even if the loss of life estimates are sensitive to the assumptions, if the overall findings are not changed based on the sensitivity studies, the overall confidence in the findings may remain moderate to high. For example, although the life loss estimates may vary by a factor or 2 or 3 depending on assumptions (indicating a lower confidence in the estimated life loss), the total mean annualized life loss estimate may still remain in the area indicating decreasing justification to take action.

Comparison of RCEM Results with DSO-99-06

In the process of the development of the new methodology, comparison trials were conducted. Approximately 20 Reclamation dams were selected to represent a cross section of facilities that featured different types of dams, different dam heights, varying reservoir sizes, different potential failure modes, various types of inundation studies, and differing downstream PAR. Life loss was estimated for these dams using both RCEM and DSO-99-06. The goals of the trial process included determining whether life loss values estimated by the two different methods varied; recognizing the reasons for any difference in estimated values; and determining whether RCEM will result in appreciably different dam safety risks and conclusions.

Observations and Conclusions from the Trials

Relative Comparison between DSO-99-06 and RCEM

One observation from the trials was that the estimated life loss values from both procedures typically fell in the same general range. No estimates varied by an order of magnitude. When total life loss was less than 100, best estimates typically only varied by a fraction to less than 3 times. At higher life loss estimates, the maximum difference was about a factor of 6 (a case of a slow seismic failure).

The differences usually occurred for two conditions; flood loadings and rapid (often seismic) failures. There are reasonable explanations for both of these cases.

In most trials, RCEM resulted in lower life estimates than DSO-99-06 for hydrologic failure modes. The case history data clearly show that fatality rates can be very low when adequate warning is provided. RCEM shows a lower bound of fatality rates for these cases than was provided in DSO-99-06. Since a Reclamation dam is typically under 24-hour surveillance in the event of unusual reservoir levels associated with severe floods, it is expected that timely observance of most hydrologic failure modes would generally result in adequate warning.

Conversely, the trials showed that RCEM frequently results in higher life loss estimates than DSO-99-06 for rapidly developing failures. This is particularly true when a significant PAR is located in a canyon. Rapid failures can produce high DV values in narrow reaches. Whereas DSO-99-06 tended to discourage the use of high severity flooding fatality rates for embankment dams, the case history data tend to show that rapidly developing failures with high DV values and limited warning will result in high fatality rates.

Impacts to Dam Safety Decisions

Risks were plotted on f-N charts for 12 dams. For each case, the total risk did not change in relative position with respect to the guidelines in a single case. In other words, if total risk exceeded guidelines with DSO-99-96 life loss estimates, it remained above guidelines with RCEM estimates. The converse, if the total risks was below guidelines, is true as well. Thus, based on the (limited) trial results, no major dam safety findings regarding the need for additional actions at a given dam would likely change.

Furthermore, individual findings about the specific potential failure modes and targeted actions would likely not change for 11 of the 12 dams. Although some risks were closer (either higher or lower) to thresholds in a few cases, it is doubtful that any fundamental actions would change. At one dam that was the exception, using DSO-99-06 estimates, total risks exceeded guidelines, with the primary failure mode being spillway overtopping erosion. The risks posed by foundation liquefaction and flood overtopping failure modes were at or very new the guidelines. However, for RCEM life loss estimates, the total risk remained above guidelines and plotted in the same general position, but the critical failure modes changed. With RCEM, the primary risk driver became foundation liquefaction, while the two hydrologic failure modes plotted below guidelines due to lower estimated life loss. Thus, the impact of RCEM at this dam may be to re-evaluate which potential failure modes should be the focus of additional dam safety studies.

General Conclusions

1. Evaluators found the process fairly easy to comprehend and follow, and generally similar to DSO-99-06.
2. Evaluators agreed that RCEM appears to be an improvement to DSO-99-06.
3. Since RCEM utilizes a database of case histories that is 50 percent larger than DSO-99-06, it may have a more credible empirical founding.
4. Estimated life loss by the two procedures resulted in life loss estimates in the same general range.
5. Differences do exist for the cases of hydrologic failures, where RCEM tends to predict lower fatality rates than DSO-99-06. The RCEM results are in line with case history data that show quite low fatality rates for a wide range of DV values when adequate warning is provided.
6. Another difference exists for rapid failures, especially when the flooding encounters relatively narrow downstream reaches. In these cases, high DV values and limited warning lead to high fatality rates in RCEM. With DSO-99-06, the higher fatality rates were generally discouraged for embankment dams.
7. RCEM requires more judgment than DSO-99-06, and as such, life loss should be evaluated in a team setting.
8. The limited trials suggest that fundamental changes to dam safety decisions will not be likely.

References

1. “RCEM – Reclamation Consequence Estimating Methodology - *Interim* Dam Failure and Flood Event Case History Compilation,” Bureau of Reclamation, Denver, Colorado, February 2014.

2. “RCEM – Reclamation Consequence Estimating Methodology – *Interim* Examples of Use,” Bureau of Reclamation, Denver, Colorado, February 2014.

3. “A Procedure for Estimating Loss of Life Caused by Dam Failure,” Dam Safety Office Report DSO-99-06, authored by Wayne J. Graham, Bureau of Reclamation, Denver, Colorado, September 1999.

4. “Best Practices in Dam and Levee Safety Risk Analysis,” Bureau of Reclamation and U.S. Army Corps of Engineers, December 2012.

5. “*Interim* Dam Safety Public Protection Guidelines – A Risk Framework to Support Dam Safety Decision-Making,” Bureau of Reclamation, Denver, Colorado, August 2011.

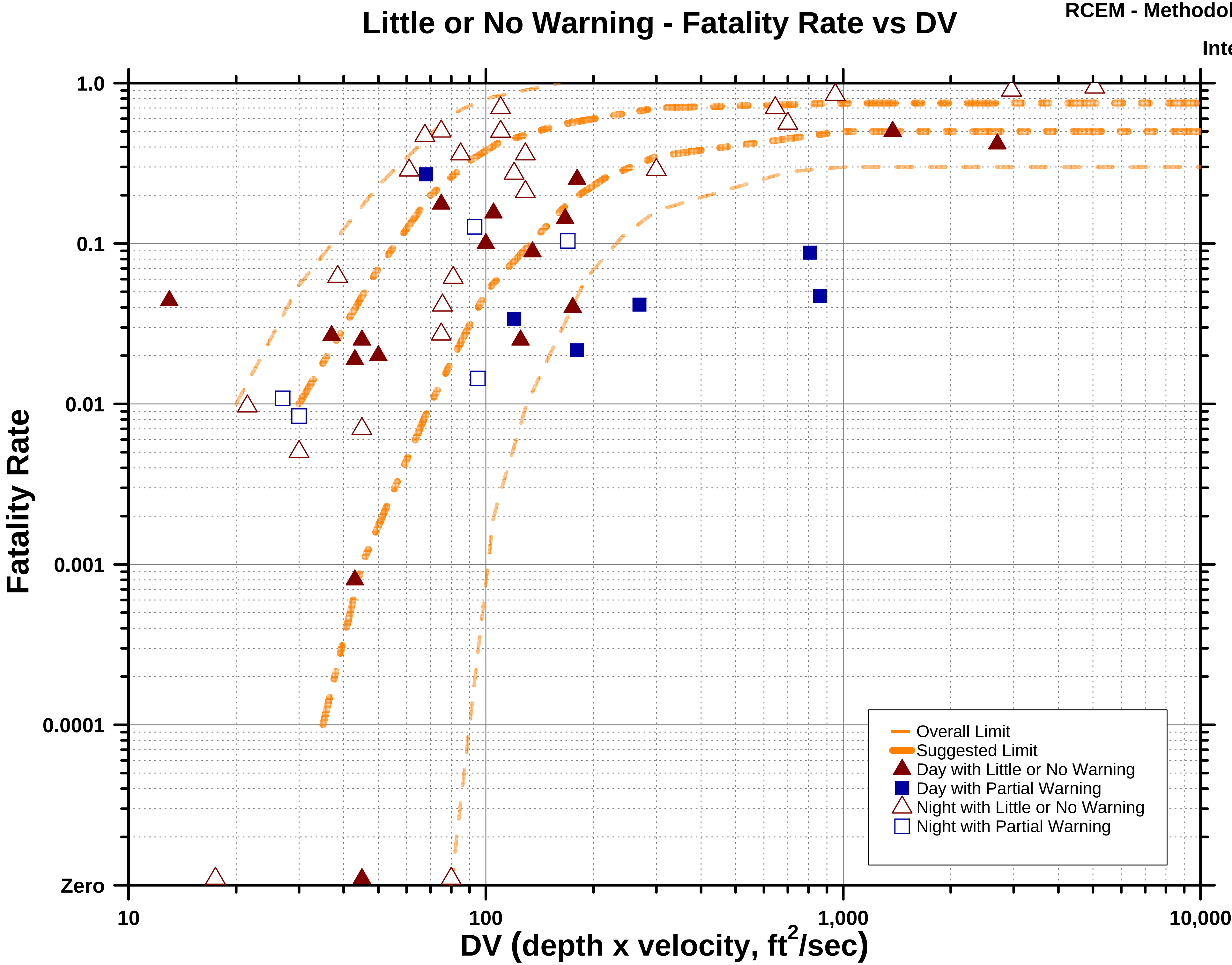
Appendix A. DSO-99-06 Fatality Rates

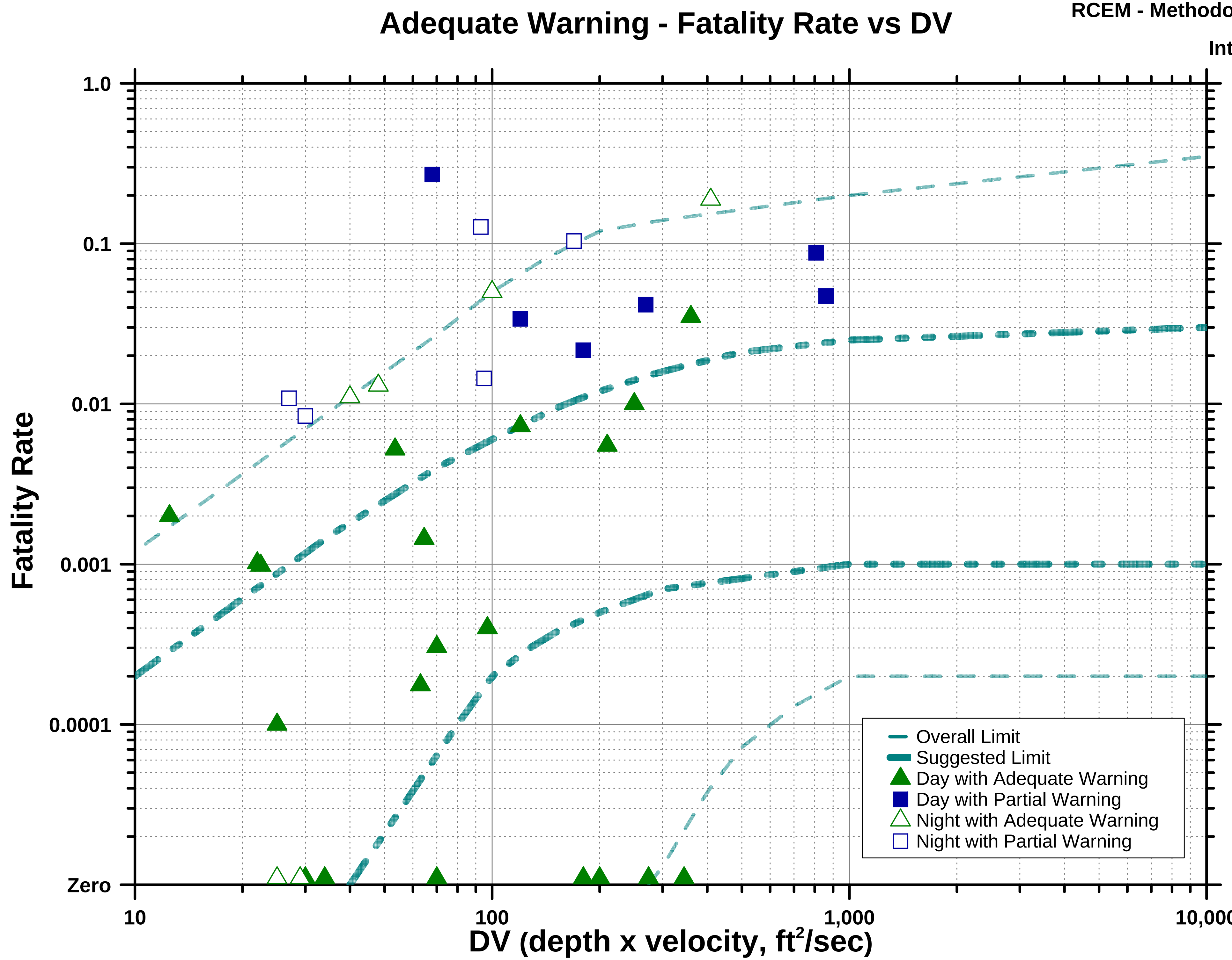
Flood Severity	Warning Time (minutes)	Flood Severity Understanding	Fatality Rate (Fraction of people at risk projected to die)	
			Suggested	Suggested Range
HIGH	No warning	Not applicable	0.75	0.30 – 1.00
	15 to 60	Vague	Use the values shown above and apply to the number of people who remain in the dam failure floodplain after warnings are issued. No guidance is provided on how many people will remain in the floodplain.	
		Precise		
	More than 60	Vague		
		Precise		
MEDIUM	No warning	Not applicable	0.15	0.03 – 0.35
	15 to 60	Vague	0.04	0.01 – 0.08
		Precise	0.02	0.005 – 0.04
	More than 60	Vague	0.03	0.005 – 0.06
		Precise	0.01	0.002 – 0.02
LOW	No warning	Not applicable	0.01	0.0 – 0.02
	15 to 60	Vague	0.007	0.0 – 0.015
		Precise	0.002	0.0 – 0.004
	More than 60	Vague	0.0003	0.0 – 0.0006
		Precise	0.0002	0.0 – 0.0004

Appendix B. DV vs Fatality Rate with Cases Differentiated by Day and Night

Little or No Warning – with cases differentiated by day and night

Adequate Warning – with cases differentiated by day and night


Little or No Warning - Fatality Rate vs DV
Fatality Rate
1.0
0.1
0.01
0.001
0.0001
Zero
10
100
1,000
10,000
DV (depth x velocity, ft²/sec)
Overall Limit
Suggested Limit
Day with Little or No Warning
Day with Partial Warning
Night with Little or No Warning
Night with Partial Warning


Adequate Warning - Fatality Rate vs DV
Fatality Rate
1.0
0.1
0.01
0.001
0.0001
Zero
10
100
1,000
10,000
DV (depth x velocity, ft²/sec)
Overall Limit
Suggested Limit
Day with Adequate Warning
Day with Partial Warning
Night with Adequate Warning
Night with Partial Warning