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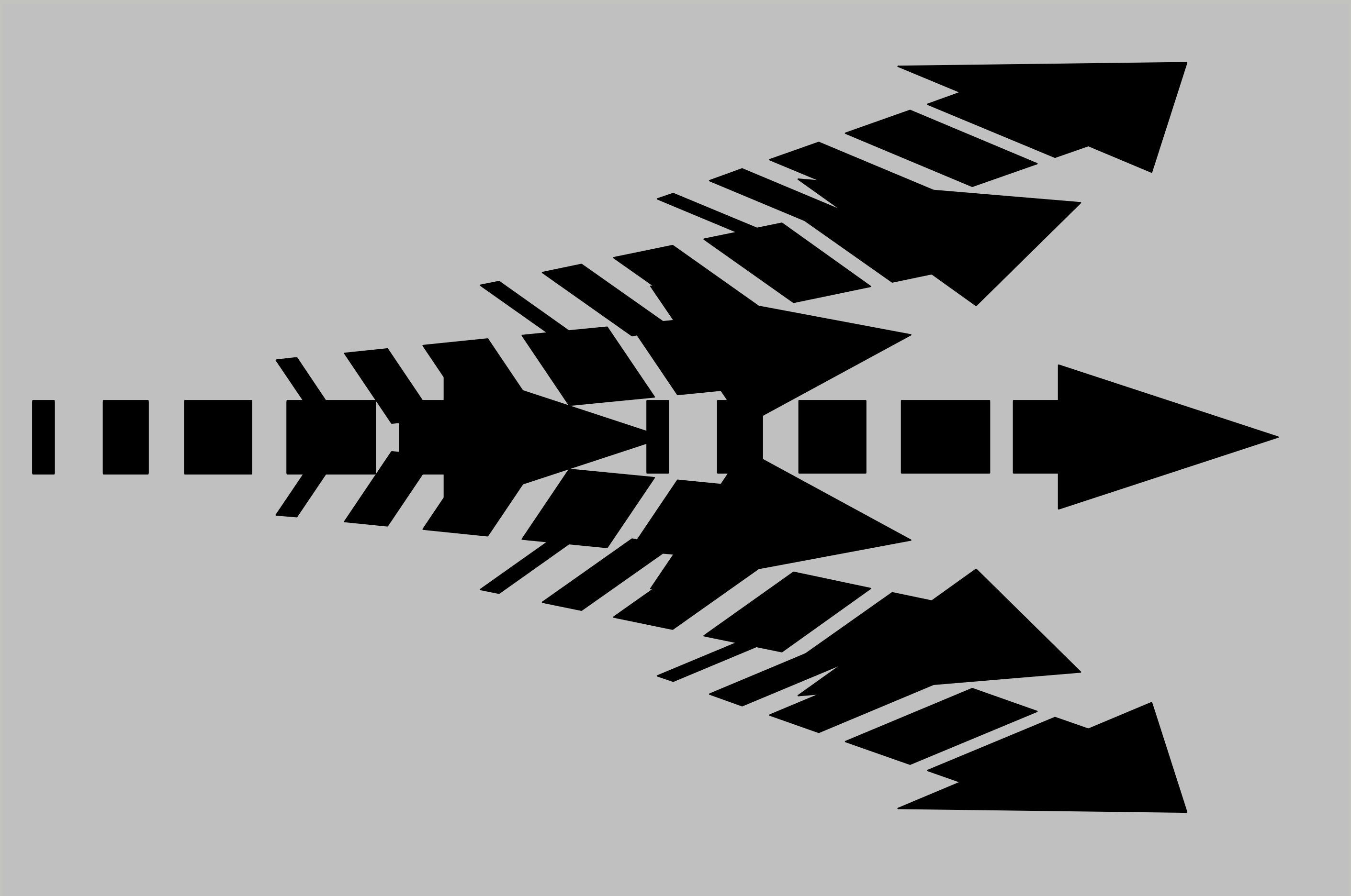
ESTIMATING LIFE LOSS FOR DAM SAFETY RISK ASSESSMENT--A REVIEW AND NEW APPROACH



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ESTIMATING LIFE LOSS FOR DAM SAFETY RISK ASSESSMENT--A REVIEW AND NEW APPROACH

by

Duane M. McClelland and David S. Bowles

Prepared for

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ABSTRACT

Estimating Life Loss for Dam Safety Risk Assessment

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Duane M. McClelland and David S. Bowles

Estimating Life Loss for Dam Safety Risk Assessment explores the need for a new life-loss model in dam safety risk assessment, historical foundations on which that model can be built, and issues that are critical for a successful life-loss model to address. After critiquing existing life-loss models, the work presents a summary of historical insights that were derived by characterizing flood events on the level of subpopulations at risk, using nearly 100 carefully defined variables. Building upon both conceptual and historical insights, the work culminates by presenting the conceptual basis for a new life-loss model that remains under development.

Chapter I introduces the topic of dam safety risk assessment and the central role that life-loss estimation plays in that field. Chapter II discusses important preliminary considerations in model development. Chapter III provides a detailed review of previous life-loss models that pertained to floods, including a critique of each. Chapter IV explores the DeKay-McClelland model in detail and raises serious concerns regarding its future use. Chapter V defines nearly 100 variables and their respective categories for use in characterizing flood events. Chapter VI provides a detailed outline of historical insights that relate to flood events in one of 18 logical categories. Chapter VII explores relationships between certain characterizing variables that may prove useful in life-loss estimation. Chapter VIII provides a summary, conclusions, and recommendations for future research. Appendices A through D provide material related to over 900 pages of unpublished working documents developed while characterizing 38 flood events and nearly 200 subpopulations at risk.

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ACKNOWLEDGMENTS

This report is a product of the U.S. Army Corps of Engineers Institute for Water Resource and the Risk Analysis for Dam Safety Research Program managed by the Engineering Research and Development Center.

The purpose of this research project was to apply, test and evaluate risk analysis methods for dam safety investment decisions. The expectation is that the methods applied will provide information to assist in developing Corps dam safety risk analysis guidelines and procedures.

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Special thanks are due to Wayne Graham with the United States Bureau of Reclamation in Denver, who generously shared his files, his expertise, and his friendship; Scott Nelson at the Center on the Performance of Dams at Stanford University (National Performance of Dams Program), whose files supplemented those of Graham; and previous modelers such as DeKay, whose model faces a fierce critique in this report but whose efforts were critical in advancing the state of the art.

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PREFACE

Jeana, my youngest, looked up at me and asked, “Mommy, is this the end of time?” I said, “No, honey, the end of time will come with fire, not water.” Just as I said that, a transformer hit the train trestle, and fire was shooting out everywhere, and then the railroad trestle came down in the water. That just about scared Jeana to death. (Deitz and Mowery, 1992, p. 184, quoting Barbara Spears who lived through the Buffalo Creek dam failures.)

The water over the crest was more than 10 ft in depth, and was rising at the rate of 18 inches an hour. The fall of the water was about 40 ft, and the roaring and surging that it produced can be better imagined than described. It was grand and awe inspiring, and nothing in my opinion could in any measure compare with it, except the falls of Niagara.

While thus gazing with awe on a sight such as I had never before witnessed, I noticed a sudden commotion of the waters near the center of the dam. For a moment the water where the commotion occurred seemed to recede, but it was only for a moment. It then shot upward in a tremendous spout to a height of perhaps 50 ft as if in gleeful fury, and I saw that the dam was giving way. The commotion spread toward the east end of the dam, and there was a trembling of the earth. The mighty waters roared and plunged with an indescribable fury, and the river, which a moment before had presented a scene of graceful grandeur as it curved over the dam, was turned into a seething maelstrom, so awful and so terrible that nothing save the pen of a Dante or a Byron could do it justice.

I was appalled and entranced. My feelings were such as I had never before and never again hope to experience. Suddenly above the dismal roar of the surging raging waters there came a cry. “The dam is breaking, the dam is breaking.” The sound of the cry was as dismal as that of the maelstrom, and people shuddered and their blood seemed chilled, although the sun shone warmly from a cloudless sky. When the break occurred the distance from the crest of the wave as it rolled over the dam to the water below was about 40 ft in height and of great width and length suddenly released from confinement, and you will have a faint idea of the scene that I witnessed at the great dam across the Colorado River yesterday morning, a few minutes before 11 o'clock. It was a scene that beggars all description, and as the waters plunged and roared and seethed and foamed they seemed to laugh in utter scorn at the futile attempts of man to bridle them. (McLemore, 1900, p. 252, describing the failure of Austin Dam in Texas. Some typographical errors have been corrected.)

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CHAPTER I

INTRODUCTION

Preview

Dam safety risk assessment depends on credible estimates of life loss for hypothetical failure events in order to quantify risk and make decisions about the construction, rehabilitation, or removal of dams. Unfortunately, improvement in life-loss estimation has been one of the most intransigent aspects of the field, causing some decision makers to seriously doubt the credibility of analysts' estimates. To attempt a significant step forward in our ability to model life loss, this report intends to do the following:

1. Introduce the topic of dam safety risk assessment and the central role that life-loss estimation plays in that field.

2. Discuss important preliminary considerations in model development.

3. Provide a detailed review of previous life-loss models that pertain to floods and thoroughly critique each.

4. Explore the DeKay-McClelland model in detail.

5. Identify, define, and label variables that impact life loss and develop means by which they might be used to characterize events.

6. Identify numerous historic flood wave events and thoroughly characterize as many as time allows, focusing on dividing the impacted populations into subpopulations whenever possible, and justifying every characterization in print for the reference of future researchers.

7. Provide a detailed outline of historical insights that arise during the characterization process.

8. Provide a foundation for a companion working document that will present a new conceptual life-loss model with guidance on its implementation and recommendations for future research.

Background

High hazard, low frequency events have the potential to cause considerable damage to property and loss of human life. Some events are outside human control, such as hurricanes, tornadoes, earthquakes, and precipitation-induced floods. Some events are a direct result of human or engineering failures, such as airplane crashes, toxic chemical spills, or accidents at nuclear reactors. Dam failures generally fall in between these extremes, sometimes resulting from faulty design under otherwise favorable environmental conditions and sometimes failing despite superior engineering after being overwhelmed by an extreme flood, earthquake, or latent geotechnical defect.

Unfortunately, it is impossible to so overdesign every dam that no dam will ever fail. Theoretically, there always remains the possibility that a dam might have received a hidden and critical flaw during construction, that there is a latent weakness in the soil or rock supporting the dam, that the dam will deteriorate with time, or that a loading greater than previously anticipated might occur. On a practical level, there are insufficient disposable resources to improve the safety of every dam without limit.

When one considers that many small, isolated dams have little potential for causing damage while others tower above densely populated regions and could kill thousands if failure occurred, it makes sense to design some dams for a higher level of safety than others. A reasonable criterion governing the design requirements for a dam is the risk it poses to lives, property, the environment, or other considerations. Focusing on the most important criterion—the risk to human lives—risk depends on the likelihood of dam failure and the likelihood that lives will be lost given a failure. Annualized risk to human lives can be defined as follows, where the summation is over all failure modes:

> risk = Σ(probability of any possible failure circumstance)*(expected number of fatalities attributable to that failure circumstance)

Society has a vested interest in protecting lives by requiring due diligence from dam safety officials and engineers. One can be diligent by following strict, deterministic rules embodied in an engineering code, or one can seek to better understand the true nature of risk by quantifying it probabilistically. Generally, deterministic approaches have governed in the past, while probabilistic risk assessment has gained increasing credence and popularity over the past two decades.

At the risk of oversimplification, deterministic approaches seek to surpass minimum standards with limited regard to the precise reduction in risk accomplished, the quickest or most economical means of reducing risk, or the order in which dam safety rehabilitation projects should be approached within a portfolio of dams. Instead, a dam is designated as adequate or inadequate based on a set standard, such as its ability to retain or pass the probable maximum flood without failure. Standards may be raised or lowered based on a dam's hazard classification (its ability to kill people or damage property), but this classification is not strictly probabilistic and is usually limited to three categories.

Probabilistic risk assessment seeks to meet or surpass minimum standards by explicitly quantifying the risk associated with the status quo and each proposed rehabilitation alternative (including dam removal). In this case, the standard might not be the retention of a particular flood, but the minimization of risk to life, property, the environment, or other considerations.

Whether this standard results in more or less risk than a deterministic approach depends on the criteria set by decision-makers. Regardless, a probabilistic approach requires detailed consideration of every conceivable failure mode and consequence, forcing analysts to consider the unique aspects of each dam, some of which might otherwise be overlooked. It also requires risk to be specifically quantified. This allows decision-makers to compare the rate and degree of risk reduction between alternative rehabilitation sequences, to perform detailed cost-risk reduction analyses, to prioritize dams within a portfolio, and to allocate limited funds where they will do the most immediate good.

In many cases it can be demonstrated that enslavement to a deterministic standard will cause less risk reduction, reduce risk more slowly, or squander valuable resources on minimal risk improvements when compared to alternative solutions discovered during the risk-assessment process. However, it is important to remember that probabilistic risk assessment is simply one of many nonbinding tools to guide the choices of decision-makers: risk assessment itself does not force any particular decision and it can be used harmoniously as a complement to more traditional, deterministic methods of dam safety assessment.

Overview of Risk Assessment and the Need for Improving Estimates of Life Loss

Dam safety risk assessment is like a stool that stands on three legs. These legs quantify the likelihood that various initiating events (hydrologic, seismic, structural/internal, mechanical, or human error) will occur; the likelihood that the dam would fail given these initiating events; and the likelihood that, given a failure, the resulting flood wave would result in various levels of damage. Analysts use event-tree models with either discrete branches or probability distributions to quantify the risk posed by each combination. Adding a seat to the stool involves modifying these event trees to explore the risk-reduction provided by various remedial upgrades.

Quantifying the risk in this way helps dam safety decision-makers identify the potential vulnerabilities of a given dam, understand which vulnerabilities are most important, and identify which dams in a portfolio are most urgently in need of attention. It also allows decision-makers to compare the cost-benefit relationships for each remedial possibility and to target limited funds in ways that maximize the risk-reduction benefits in the shortest period of time.

The meaningful quantification of risk depends on credible estimates of the damages that would result from each significant failure scenario. Loss of human life is generally accepted as the most important consequence so it often dominates dam-safety decisions. Unfortunately, the confidence with which life loss can currently be estimated is low. This high level of uncertainty applies to both statistical confidence limits and to expert opinion. As such, this single limitation is a critical hindrance to the credibility and value of dam-safety risk assessment results. Indeed, some would like to push the stool over on its weak leg and abandon probabilistic risk assessment altogether.

The Problem and the Primary Goal

Life-loss estimation is difficult because floods are remarkably unique and the dynamics that affect life loss are amazingly complex. Fortunately, relatively few dams have caused life loss and the amount of life loss has often been lower than people might intuitively expect. Unfortunately, this makes good historical data on life loss rare and empirical studies challenging. However, whether a model is based on an analytical description of human-flood interactions or whether it is based on a regression equation derived from historic dam failures, confidence in the model must depend on its correlation to actual life-loss/flood-wave dynamics. Empirical research cannot be avoided.

It would belie the inherent uncertainty endemic to dam failure life-loss estimation if this current work sought to offer a final solution. Instead, it is hoped that by expanding the database of historic dam failures, by offering detailed critiques of existing life-loss models, and by exploring new variables, a new model might be developed that can be used with greater confidence than has been possible in the past. Also, since the quality of any model will be limited by the quality of empirical information, a central goal of this work is to provide an extensive database with sufficient documentation to serve as the starting point for future research. In light of the evolving nature of this specialized field, this may be the greatest contribution of this report.

Important Terms and Symbols

Chapter V defines nearly 100 different variables that affect life loss. For now, however, it is important to introduce a few key terms that will be used frequently in the text. Loss of life refers to the number of people who perish. It has frequently been shortened to LOL in the past, but it will generally be shortened to L in this text to be consistent with conventions introduced later. The population at risk is the number of people who would get wet from a flood if they did not evacuate. The exact nuances of the phrase are not important at this point, but it has historically been shortened to PAR and will be written as Par in this text. The threatened population is a subset of Par that fails to evacuate before the flood wave arrives. It will be shortened to Tpar. Warning time is the time between the first warning to reach Par and the subsequent arrival of the flood wave. It will be coded as Wt. When a symbol is followed by the subscript i, the symbol refers to a subPar (Par_i), unless a specific term is defined with the subscript (for example, as defined in Chapter V, Wt_i can refer to individual warning time or the warning time for a subPar, depending on context). Many of the symbols in this text, including Par, Tpar, and Wt, will be used for both the singular and plural forms of the underlying names.

Because nearly 100 characterizing variables will be defined in Chapter V, a variable name followed by its symbol in parentheses will often be used as an aid to the reader. This convention will generally not be followed, however, when symbols are used multiple times in the same context or when they are used in equations. Also, it is assumed that the reader will memorize the symbols presented above—Par, Tpar, L, and Wt; Par_i, Tpar_i, L_i, and Wt_i—and their derivatives that will be defined later (for example, average warning time, Wt_{avg}).

As a further aid to the reader and future researchers, Appendix D contains abbreviated definitions of every symbol defined in Chapter V and their means of coding, both alphabetized by symbol and presented by symbol name in the order they are defined in Chapter V.

Organization of the Paper

Chapters I and II present the nature of dam safety risk assessment, the important role life-loss estimates play within that field, theoretical considerations relevant to model development, and the difficulty of selecting an unbiased data set for regression analyses.

Chapter III presents every important, flood-related life-loss model that had been developed or proposed up to 1998. The chapter describes the contributions and shortcomings of each model in detail and concludes with a summary of essential model components and considerations for representing those components.

Until recently, the DeKay-McClelland regression equation DM-2d (presented in Chapter III) was the dominant life-loss equation in use. However, it has often been used in a manner inconsistent with its development and in violation of the assumptions that must be satisfied for its estimates to be considered reliable. Hence, Chapter IV explores this equation at length, raising important questions about its credibility and its usefulness.

Chapter V provides an extensive list of variables that pertain in some way to life loss associated with dam failures or catastrophic flood waves. Although many of these variables were identified in some form by previous researchers (see Table 8 in Chapter III), this is the first time that most of them have been given specific names, symbols, definitions, and categories by which they can be coded. Other variables, especially those that show the greatest promise for estimating life loss, have been defined for the first time and play a critical role in the proposed model presented below. All the variables are summarized in easy-to-use reference guides in Appendix D.

Chapter VI provides the historical and theoretical foundations on which one or more new models can be developed. Table 16 details the ways in which people perish during floods and Table 17 details ways in which people survive floods. Table 18 then offers a way to break issues that affect the rate of life loss into 18 logical categories. The remainder of the chapter catalogues numerous historical insights that are useful for gaining a good understanding of the real-world dynamics within each category. These insights are supported by event characterizations fully recorded in unpublished working documents that underlie the examples and summaries in Appendix B and the master chart of characterized values in Appendix C; as well as by other failure events that have been studied but not yet characterized.

Chapter VII presents important goals for a life-loss model and explores relationships between potentially promising characterizing variables and concepts important to life loss. Chapter VIII presents a summary, conclusions, and recommendations for future research.

Appendices A through D provide material related to over 900 pages of unpublished working documents developed while characterizing 38 flood events and nearly 200 subpopulations at risk. A template was developed to standardize these characterizations, and they followed the guidelines and definitions presented in Chapter V.

CHAPTER II

PRELIMINARY CONSIDERATIONS IN MODEL DEVELOPMENT

Attendant Circumstances and the Uniqueness of Flood Events

All else being equal, life loss following a dam failure would be largely determined by evacuation characteristics and flood dynamics. However, there are a number of factors which contribute to the uncertainty inherent in any life-loss outcome. Many of these are not amenable to analysis at this time, but an awareness of the issues helps one understand how complicated and unique flood events can become.

First, two phrases should be defined. Attendant circumstances are detrimental and usually transitory conditions that accompany a specific type of dam failure and that make life loss more likely. Susceptibility to loss of life is an inherent property of a community that is independent of transitory influences. Just as insurance companies recognize that certain categories of drivers are more susceptible to accidents than others, some communities are more susceptible to fatalities. Attendant circumstances and susceptibility to life loss combine to influence life-loss outcomes.

To get a feel for the uniqueness of each failure event, one can begin with the cause of failure. The nature of the attendant circumstances for the three main failure modes—hydrologic, seismic, and internal—are likely to be quite different. A probable maximum flood (PMF) can loosely be defined as a flood resulting from the most runoff-producing combination of meteorologic and hydrologic events that are physically credible; that is, the worst flooding that can be expected to occur. Storm conditions capable of causing a PMF-level flood event may include hurricane-force winds, certainly would include local flooding, and would likely provide inhospitable environmental conditions including extreme darkness and risks of hypothermia. The risk of injury due to driving accidents, falling trees and limbs, live power lines, and airborne debris would be heightened. Power outages would be extremely likely, especially where wires were above ground, and they could be expected on a wide scale, requiring hours or days to repair. Evacuation notification would be hampered and evacuation itself could expose people to extreme hazards like flooding, falling trees, undermined roads, and accidents while driving in darkness without street lights in driving rain. Such conditions might make decision-makers reluctant to issue an evacuation order prior to the initiation of an actual dam breach. A delay would reduce people's danger if no failure occurred, while greatly increasing their danger if a failure did occur.

A seismic failure would expose the Par to a different set of hazards. Streets might buckle, individuals could become trapped in rubble or buildings in the path of the flood, power lines and gas mains might break causing fires and blocking streets, bridges could collapse, escape routes might become blocked, traffic lights would probably fail, and emergency crews would be delayed or overtaxed.

A piping or internal failure is unlikely to experience any unusual attendant circumstances.

Compounding the attendant circumstances surrounding a particular failure mode are the attendant circumstances associated with the timing of the event. Traffic hazards and potentially lethal cold could accompany a failure in winter. Evacuations are more difficult at night than during the day due to difficulties in notifying families, the extra time individuals require to respond, and the extra hazards that come with darkness. Human response patterns are likely to be different when families are together (evenings, weekends, and holidays) than when they are apart (work hours).

A community's susceptibility to life loss is governed by such factors as the size of the dam, the distance from the dam, the nature of early warning systems, the slope of the valley, the width of the valley, the location of the houses, the tendency of the population to be in the open or within buildings, barriers to evacuation like backyard fences, the age and mobility of the population, the height of structures, and numerous other factors.

Significantly, traditional variables like flood depth and forcefulness, the size of the Par, and the warning time do not take attendant circumstances into account. Attendant circumstances have been lumped indiscriminately into single data sets in earlier efforts to estimate life loss from dam failure floods

The preceding introduction to the uniqueness of flood events suggests several lines of preliminary inquiry.

1. Cause of dam failure: Can all dam failures be grouped into a single statistical population, or should dam failures be analyzed according to failure mode, attendant circumstances, or other refining criteria? What if the resulting data sets would be too small to be statistically useful? Can flash floods be included with dam failures in a common data set?

2. Magnitude of storm: In light of the unique attendant circumstances found in extreme storms, does the weather influence loss of life, or just the size of the flood? In other words, is the expected loss of life due to a probable maximum flood (PMF) comparable to the loss of life expected from a flood of the same volume produced by a lesser storm over a larger basin? How can one reasonably predict the life loss in a PMF-level event if no such event has been witnessed in the modern era?

3. Magnitude of seismic event: Can one expect loss of life following a maximum credible earthquake (MCE) to be the same as from a flood of the same volume following a sunny-day failure? How can one predict L in a MCE-level event if no such dam failure has been witnessed in the modern era?

4. Effects of attendant circumstances on traditional variables:

    a. Flood forcefulness: Does woody debris deposited from a storm increase the lethality of a flood? Does rubble from an earthquake? Is it reasonable to assume that the lethality of a given velocity/depth ratio is the same for piping, hydrologic, and seismic failures?

b. Size or location of population at risk (Par): Do routine schedules (population distributions) apply during severe storms or shortly after seismic events, or will schools, campgrounds, and businesses be closed and empty? Do people swarm outside following severe earthquakes, placing themselves in greater danger?

c. Warning time (Wt): Under what conditions do phone systems become jammed or severed and how does this affect the dissemination of warnings? Is the average warning time the important variable, the initial warning time, or some other characterization of warning time?

d. Characteristics of Par: What effect do buildings play in sheltering Par? How do children, the elderly, the infirmed, recreationists, or those who speak a minority language impact estimates of life loss? What about false alarms or prior flood experience?

e. The nature of probability: Is an empirically-based prediction necessary, or can expert opinion offer estimates of life loss with equal credibility? How would one become an expert?

Delimiting a Data Set: When Should Fatality-Free Failures Be Included?

More than 400 dams failed in the United States from late 1985 to late 1994—most of them small and many unregulated—and less than 2% of these resulted in fatalities (Graham, 1998). A small dam failure or a partial dam failure is easy to overlook; without something spectacular, little public interest is aroused. Consequently, smaller dam failures may get ignored when life loss (L) = 0, even if life loss was highly probable. Recognizing this, where is the cutoff for dams that should be included in a data set as hazardous, yet yielding L = 0 by chance, versus those that were never truly hazardous? In other words, which zero-life-loss events should one include?

Two dangers exist. If only dams with actual life loss are included in a data set, then the resulting regression equation is likely to overestimate expected life loss, finding it at every turn. If all dam failures are included in a data set, the number of zero-fatality events are likely to dominate those with life loss and skew an equation toward underestimation for truly hazardous events. Unfortunately, the dividing line is subjective.

This section and the next will present bias-producing shortcomings to the data set produced by the United States Bureau of Reclamation (USBR). The reason is simple: Beginning in 1986 and culminating in 1989, they produced the most prominent data set of lethal dam failures and flash floods. This data set was explored by Brown and Graham (1988) and later expanded by DeKay and McClelland (1991, 1993b)—developers of prominent life-loss models and equations that are presented in Chapters III and IV.

The USBR (U.S. Bureau of Reclamation, 1989) has concluded that its equations are biased to overestimate life loss since the underlying data set excludes nearly all zero-fatality events. To test this, they screened an extensive database of flash floods occurring in May, June, July, or August of 1983 and 1984. Beginning with all floods that caused loss of life, or at least $50,000 in damages, they then discarded events with unreliable estimates for Par. Combining the 66 that remained, Par numbered 25,000 and L numbered 25. Using the regression equations developed by Brown and Graham (U.S. Bureau of Reclamation, 1989), and assuming the cases would by typified by inadequate warning, their regression procedure would have predicted a total of 1,559 deaths for these 66 events. Moreover, 86% of the flash floods resulted in no life loss. The USBR concluded that their equations were conservative.

While their method raises questions of its own, such as the appropriateness of mixing flash floods and dam failures and whether they treated Wt in a realistic manner, it does highlight the difficulty in selecting the ideal data set. Ultimately, *all* data sets are potentially biased, leading to regression equations that are likely to be most accurate when applied to events like those in the data set. Hence, a data set can favor high-lethality events, low lethality events, or any subset in between. The bias may not be the level of life loss, but another factor like the relative length of warning times, the relative size of Par, the ease with which people evacuate, the time of day or night, the size of the reservoir, or any one of dozens of other variables. Unless all possible variable combinations are included in the data set in a representative manner, bias is unavoidable.

Recognizing this, several observations can help define the type of data set that best serves the practitioner. First, overestimation of life loss is undesirable because it may cause dam owners to spend money on safety improvements rather than more worthy projects. Underestimation of life loss is undesirable because it might lead to unsafe dams going without rehabilitation, needlessly increasing society's risk. However, slight overestimation is probably the lesser of the two evils.

There are several possible ways to minimize the risk of bias. First, rather than arbitrarily adding zero-life-loss events to a data set, one could compile a separate database of such events and compare them to events with only a few deaths. It is possible that distinguishing characteristics will appear that will clarify the boundary. Second, if relationships can be developed for which life loss (L) has a linear relationship with the most important variables, bias will be minimized. Third, large Par could be broken down into subPar. If some of these subPar are examples of zero life loss, they might help define the boundary between lethal and safe conditions because it is known that the same event with different conditions was capable of taking lives. Fourth, if subPar are highly homogeneous, they can be grouped according to bins. In this way, the key conditions that lead to incipient life loss can better be identified and used to screen new subPar or global events.

Going Beyond the Data Set: When Should a Regression Equation Be Viewed as Inapplicable?

As pointed out by Graham (1998) and DeKay and McClelland (1993b), the Bureau of Reclamation's data set includes no dam failures caused by earthquakes, nor any dams above very large Par (greater than 10,000) for which warning time was near zero. It contains no failures due to PMF-level flooding, terrorist attacks, or landslides into the reservoir. No large, modern, concrete dams and few concrete or tall dams are included in the failure set, with only 7 exceeding 15 meters in height. Since they code Wt dichotomously with the highest value at 45 minutes, longer warning times do not enter directly into their equations. The USBR's data set was also limited to failures occurring after 1950 in countries with comparable levels of development to those in the U.S.[1] Hence, the largest U.S. dam disaster—the failure of South Fork Dam near Johnstown, Pennsylvania, in 1889, in which 2,209 people died—was omitted; as was the largest non-Biblical flooding disaster in world history, when China's Banqiao and Shimantan Dams, along with dozens of smaller dams, failed in 1975, killing at least 26,000 people and possibly more than three times that many. As more variables are considered, more unique failure scenarios are found to be missing or underrepresented.

More recent western failures were also omitted either due to lack of data or because they were viewed as uncharacteristically unique. A classic example of the latter reveals the potential for a catastrophic dam failure to virtually annihilate significant populations downstream. Consider Vaiont Dam in northern Italy on October 9, 1963. Wayne Graham describes this event in a draft report:

> A 270 million cu. m. landslide fell within 20 to 30 seconds into the lake formed behind the dam. The dam, at the time the world's second highest, did not fail. However, the effect of this huge mass of material that ran into the lake, which was almost at the maximum water level, was a gigantic wave of 50,000,000 cu. m. of water that, after rising for 250 m in height, poured both towards Longarone, 4 km downstream from the dam, and towards the lake, partly running over the towns of Erto and Casso. About 2000 people died as a result of this event. The fatality rate was about 94% in the community of Longarone [1269 out of 1348 residents; U.S. Bureau of Reclamation, 1989] which was about 2.0 kilometers downstream from the dam. At Belluno, about 16 kilometers downstream from Longarone, there was damage to more than 150 houses, however, the river dikes in most places prevented spillage into built-up areas. (Graham, 1998, p. 4-2)

The 875-ft high concrete arch dam, then the highest arch dam in the world, was overtopped by more than 300 ft, and up to 230 ft of water filled Longarone. Most of the 79 survivors lived in a cluster of houses out of reach of the flood waters (U.S. Bureau of Reclamation, 1989). Downstream, there were reportedly few fatalities in Belluno, despite substantial property damage. Apparently, once the flood wave attenuated to a point where it

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[1] Examples for which development levels are important include communication systems, flood control systems, transportation systems, construction standards for buildings; and construction, maintenance, and monitoring standards for dams. The USBR data set was also limited to cases having sufficient information for parameter quantification (U.S. Bureau of Reclamation, 1989).

resembled more moderate dam failures, and given the additional warning time provided by extra distance, life loss more closely approximated that found in the USBR data set. Nevertheless, about 700 people perished in communities other than Longarone, both upstream and downstream from the dam, so the cataclysmic nature of the failure mode proved consistently lethal in ways that are beyond the scope of most modern dam failures.

An example of a large concrete dam that failed in the U.S., and which was excluded from the USBR data set, is St. Francis Dam. It failed at midnight under normal weather conditions when California was much less populated than it is today. The 57.3-m high structure, impounding 4.69 million cubic meters of water, failed due to structural defects, killing about 420 people and claiming lives for an unusually extended distance downstream. Although it is common for deaths to be restricted to the first 24 km (Graham, 1998), 84 out of 150 people located 27 km from the dam at the California Edison Construction Camp perished—a fatality rate of 56%. Closer to the dam, death rates in isolated Par_i were 100%. Warning and evacuation efforts did not begin until a few hours after the dam had failed (Graham, 1998).

Such case studies remind us that the USBR data set is limited, covering only a narrow selection of failure modes, magnitudes, and attendant circumstances. DeKay and McClelland (1993b) specifically advised that their equation should not be used for events like Vaiont and St. Francis Dams. The point of this extended discussion is that, at present, the empirical data available are not sufficiently comprehensive to justify rigid enslavement to any regression equation or set of equations that might be developed. If reason suggests that a hypothetical event will be unlike those underlying an equation, analysts must reserve the right to adjust their estimates accordingly. Analysts should never forsake reason in slavish reliance on a readily available formula.

CHAPTER III

HISTORIC METHODS FOR ESTIMATING LOSS OF LIFE IN THE EVENT OF A DAM FAILURE OR A FLASH FLOOD

Introduction

Historic methods for estimating the expected loss of life in the event of a dam failure fall into two main categories—those that are empirically based and those that rely on parameters considered to be theoretically important, but for which insufficient data exist to calibrate them empirically. Several models in each category deserve review. The dominant empirical approaches have been developed for the United States Bureau of Reclamation, first by Brown and Graham (1988), then by DeKay and McClelland (1993b). Brown and Graham (1988) built on the conceptual model developed at Stanford University by McCann et al. (1985) for the Federal Emergency Management Agency (FEMA). Quite recently, B.C. Hydro of Canada has rejected the empirical models and developed a new conceptual model (Assaf, Hartford, and Cattanach, 1998). While having some theoretical appeal, and offering promise, at the time of this writing the parameters in this model had not been sufficiently calibrated to yield results worthy of high confidence. These models, as well as several others, are summarized below.

Ayyaswamy and Others, 1974

The Model

Colleagues at UCLA prepared four reports for the U.S. Atomic Energy Commission to evaluate the probabilities and potential consequences to ground-based Par[1] of dam failures, airplane crashes, catastrophic toxic chemical spills, and meteorites striking nuclear reactors. The first report addressed dam failure, focusing exclusively on “complete and instantaneous dam failure, with total release of the impounded water . . . . Dam failure is equated with the probability of an intensity IX or X earthquake [on the Modified Mercalli earthquake intensity scale] in the dam area” (Ayyaswamy et al., 1974, p. 3). Earthquakes were emphasized due to their relative frequency in California, the location of 11 dams chosen for model application.

The approach had five main components: 1) a computer model to estimate the probability of a magnitude IX or X earthquake, 2) a flood routing methodology yielding travel time and inundation zones, 3) the use of census data to quantify Par during the day and during the night, 4) a curve expressing the evacuation rate, and 5) a mortality relationship based on flood depths.

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[1] Like “deer,” Par will be used in this paper for the singular form (population at risk) and the plural form (populations at risk). The same will hold true for derivatives of Par like subPar, Par_i, Tpar_i Ptpar_i, and other variables like Wt.

Recognizing that the model was breaking new ground, the authors considered the estimated risk to be a first approximation. They recognized that their computer model relied on uncertain frequency relationships and soil conditions, and that other earthquake models existed and could later be developed. They also noted that only 2 out of 18 dams in a previous study had failed completely when subjected to earthquakes, so the theory that a IX or X magnitude earthquake would necessarily cause an uncontrolled release of water was not valid (Duke, 1960).

Details of the model can be summarized as follows. Flood routing relies on Manning's equation,

$$Q = \left(\frac{1.49}{n}\right) A R^{2/3} S^{1/2} \quad \text{(English units)}$$

using the Normal Depth Method with Manning's-n values ranging from 0.05 to 0.11. Analysts must account for changes in the flow regime at obstructions in the channel. Where an upstream failure overtops a second dam, the subsequent outflow is predicted using equations for rectangular, broad-crested weirs.

Once the flood depths are known, the fatality rate is considered to be 100% wherever flood depths reach 10 ft and 0% elsewhere. Hence, population at risk (Par) reflects the number of individuals who could be submerged to 10 feet if they did not evacuate. Since this can be greater during the day in a setting where businesses occupy the floodplain near the river, life loss (L) is calculated separately for day and night failures. At the time the model was proposed, Par was estimated using the 1970 census tracks from the U.S. Bureau of the Census.

To obtain L, analysts incrementally reduce Par by the percentage of people able to evacuate over increments of flood-wave travel time. They first develop an evacuation rate histogram based largely on experience. Numerically integrating this, they produce a smooth evacuation curve. Time is measured from the moment of failure (the time of the earthquake) until the wave reaches the center of each reach. The loss function is applied to that fraction of Par that fails to evacuate. Reaches are delineated using uniform increments of distance from the dam.

Contributions

This model broke new ground by attempting life-loss modeling for the purpose of assessing dam safety. It recognized the unique danger posed by large-magnitude earthquakes and it identified the five major components of almost all consequence models:

1. The likelihood a failure will occur, based on the probability various loadings will occur and that the dam will fail under each of those loadings;

2. Flood mapping to define the flood zone;

3. The quantification of Par by relating census data to the flood zone;

4. The reduction of Par through an evacuation function dependent, at least in part, on the amount of warning time; and
5. The application of a loss function to those who remain in the flood zone when the flood arrives.

Importantly, the model recognizes that not all individuals who get wet will lose their lives and that the size of Par changes with the time of day.

Shortcomings

In the 11 cases to which the model was applied by the authors, losses ranged from 11,000 to 260,000 deaths, exceeding the historical record for dam failures in the United States by several orders of magnitude. While the model lacked both calibration and refinement, the high estimates for L should not be discarded out of hand. It is safe to say that few if any historical dam failures involved instantaneous dam failure due to an extreme earthquake at a large reservoir above a densely populated area. On the other hand, since the estimates generally exceed the historical life loss from the world's worst dam failure events, the model may be overly conservative even for instantaneous dam failures. This was a general trend in the early days of dam safety loss estimation.

The second, third, and fourth components of the model, numbered above, need refinement. Their method of flood mapping was based on unrealistic assumptions. Manning's equation assumes a steady-state flow condition, which bypasses the effects of attenuation, turbulence, and momentum that dominate instantaneous flood waves. Modern methods of flood routing using a dynamic model like DAMBRK or FLDWAV should yield more realistic results.

With respect to their loss function, empirical functions are more defensible than an arbitrary fatal/nonfatal division at a depth of 10 ft.

While evacuation curves could be customized, the authors presented only one set (see Ayyaswamy et al., 1974, p. 36 – 37). These curves assume that 50% of the population can be evacuated in the first hour, 75% within two hours, and that complete evacuation requires more than 10 hours. While this may be realistic for heavily urbanized areas, it is counter-historical for smaller communities and is probably overly conservative for the riverside swath likely to see depths over 10 ft. In any case, the curves do not appear to have been empirically based. Also, warning time is assumed to be identical to wave travel time in all cases, which appears to be unrealistic for an instantaneous, earthquake-induced dam failure.

None of these shortcomings reflect poorly on the authors, however, since they encouraged refinement of these results through future research. In their words, "the conclusions should therefore be regarded as mainly illustrative and very tentative" (Ayyaswamy et al., 1974, p. 6).

Friedman, 1975

The Model

Friedman (1975) developed a broad model that could be applied to virtually any natural hazard: he addressed earthquakes, hurricanes, floods, tornadoes, wind, and hail. He calculated a loss potential index based on four factors: 1) a natural hazard generator used to determine the frequency of earthquakes or storms by section of the United States; 2) local conditions that modify the severity pattern proposed by the natural hazard generator; 3) Par, defined as the number of persons exposed to the hazard and their geographic distribution based on an 85,000 point grid system crisscrossing the U.S. and input into a computer database from 1970 census data; and 4) the vulnerability of the Par, which is its susceptibility to life loss during an event of a given severity. These four factors represent the five common components identified under Ayyaswamy's model: determination of the probability of a failure, mapping the flood inundation area, quantification of Par; modification of Par or a loss function to account for temporal, spatial, or local conditions; and application of a loss function.

Recognizing that losses in natural hazards are not random with respect to time and place among a population, Friedman asserted that losses must be estimated over an entire area, rather than independently at individual sites. The natural hazard generator produces smooth contours across the U.S., but these are made more jagged through adjustments for local conditions. In this sense, if a community occupied more than one contour, Par would be effectively divided into subPar.

Friedman's four model components interact collectively to generate a Loss Potential Index. Several types of qualitative interaction are illustrated in Table 3.1.

Friedman did not consider dam failures directly, but he applied his model to general flooding and to flash floods by developing a computer simulation model for the U.S. Department of Housing and Urban Development (HUD). This information was then used in the development of the U.S. National Flood Insurance Program. He did not use the national grid system in his model to calculate Par; instead, he used the 1970 Census to determine the number of structures in each of 5,539 cities. He then determined the percentage of these that were located in the flood plain from HUD data collected by the U.S. Army Corps of Engineers, the Tennessee Valley Authority, and the U.S. Geological Survey. He divided each floodplain into six zones representing different levels of hazard

Table 3.1. Examples of qualitative relationships among Friedman's model components (adapted from Friedman, 1975, Table I-1, p. 4. An * indicates that the example originated with Duane McClelland, who tried to follow Friedman's general logic pattern)

Natural Hazard Generator	Local Conditions	Par	Vulnerability	Loss Potential Index
weak	good	sparse	low	very low
weak	good	moderately dense	moderate	low*
weak	good	dense	high	moderate*
moderate	good	sparse	moderate	low*
moderate	medium	moderately dense	moderate	moderate
moderate	poor	dense	moderate	high
moderate	poor	moderately dense	high	high
moderate	medium	dense	moderate	high
Severe	medium	moderately dense	high	high
Severe	poor	dense	high	very high

based on the return period of floods of various depths. The number of dwellings were converted to Par by assuming each dwelling housed an average of 3.0 people, based on summary tabulations of the 1970 Census data.

The loss function was based on the estimated number of buildings expected to be damaged. Using the annual flood tabulations of the American Red Cross, he assumed one casualty would follow every 170 damaged dwellings, or every 85 dwellings in the case of flash floods. Empirical studies of selected cities indicated that cities of different size showed no variation in the distribution of dwellings across flood zones. Every city and every zone was assigned the same ratio of commercial to residential structures as a first approximation.

Contributions

The greatest strength of Friedman's model is that it recognizes that losses will vary across the floodplain, so every city is divided into six subPar based on depths. This helps customize the model to local conditions. Each subPar has a unique risk since the probability of inundation decreases as the annual exceedance probability (AEP) of floods decreases.

Shortcomings

Unfortunately, while monetary damages increase with depth based on relationships provided by the Federal Insurance Administration, the life-loss functions do not distinguish between major and minor damages. Thus, while the loss functions are presumably based on historical records, there is no way to account for the relative forcefulness of a flood or the height of the buildings.

Friedman accounts for spatial distributions but not for temporal distributions. That is, there is no evacuation function, so no distinction is made between events having long or short warning times. Perhaps this was omitted because warning time can be much more nebulous in cases of general flooding than for dam failures.

Petak and Atkisson, 1982

The Model

The natural disaster model developed by Petak and Atkisson (1982) can be generalized into a three-step procedure: 1) quantification of a hazard curve for a region (AEP vs. intensity of event), 2) quantification of a vulnerability envelope or vulnerability probability distribution (expected structural damages vs. intensity of event at the location of the structure), and 3) an exposure distribution (how many of each type of structure, parcels of property, people, etc., are exposed to each intensity level). These three components—hazard, vulnerability, and exposure—are then related sequentially in an event tree to generate values for annualized risk. Ideally, the three components are integrated and automated via a computer model.

They treated structural damage as fundamental. “Typically, estimates of other types of losses such as death, building content loss, unemployment, and homelessness were related to the expected levels of damage to buildings” (Petak and Atkisson, 1982, p. 105).

Although dam failures were not considered in isolation, they addressed riverine flooding by dividing the floodplain into regions according to frequency of flooding, as shown in Table 3.2. They apportioned the floodplain based on the work of previous authors, including Friedman (1975).

Contributions

The strengths of this approach are twofold. First, this was one of the first empirical approaches since this method used data from actual natural disasters to predict the loss of life as a function of the expected economic damages due to flooding (or any of 7 other types of disasters).[2] Second, it recognized the importance of subPar, thus allowing L to vary with flood depths by adopting different empirical damage functions for each flood zone. Grigg and Helweg (1975) first reported the damage functions, but Petak and Atkisson modified them slightly.

Shortcomings

Although the approach was empirical, the available data were limited and not characteristic of dam failures. Instead of using flood data, they assumed that deaths from

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[2] Earthquake, tornado, hurricane, severe wind, storm surge, tsunami, wind.

hurricanes were evenly divided between storm surges (the rising of a large body of water due to low local pressures and strong winds) and direct wind impacts. Flood losses were then assumed to follow the same patterns as those for storm surges: 0.0956 deaths per million dollars of damage to buildings

The drawbacks to this approach are obvious. First, storm surges are a rising of seawater that can last for hours, that is generally not instantaneous but progressive, and that will be as wide as the local coastline, rather than confined to a channel and its floodplain. In other words, it is very different from a dam failure. Second, arbitrarily dividing deaths due to flooding and wind into a 50:50 ratio undermines the validity of an empirical function. Third, assuming a linear relationship between economic damages and fatalities ignores the importance of variables like warning time, evacuation pathways, the height of buildings, and other factors affecting mobility. Fourth, economic damages make a poor surrogate for Par: not only are the number of people in an area not necessarily proportional to the economic damages, but a Par consisting of backpackers, tent campers, fishermen, or rafters would not be included at all, even though they might face the greatest threat from a dam failure. The authors themselves acknowledged many of these shortcomings.

Table 3.2. Distribution of subPar by flood return period for the model by Petak and Atkisson (Petak and Atkisson, 1982, p. 117)

Hazard Zone	Return Period of Flood (years)	Fraction of Dwellings in Each Hazard Zone
A	2 – 5	0.135
B	5 – 10	0.150
C	10 – 25	0.200
D	25 – 50	0.245
E	50 – 100	0.270
F	more than 100	1.000

McCann and Others, 1985: Stanford/FEMA Model

The Model

McCann et al. (1985) recognized the importance of dividing a population at risk into subPar. Their overall procedure can be summarized using the sequence of steps in Figure 3.1.

Route the flood wave to determine its depths and boundaries. ⇒ Plot these on a topographic map. ⇒ Superimpose the location and characteristics of all structures onto the map. ⇒ Divide the map into zones [subPar] according to distance from the dam and maximum depth of inundation. ⇒ Apply a loss function to each subPar. ⇒ Sum to determine total loss of life.

Figure 3.1. Sequence of steps for the Stanford/FEMA Model (adapted from McCann et al., 1985, Figure 6.1, p. 6-2).

This model allows the use of any modern flood routing method, but a single method should be used consistently on all dams in a portfolio if a portfolio risk assessment is desired. McCann et al. advocated the use of the National Weather Service (NWS) software program DAMBRK for those familiar with it, as it represented the state of the art in dynamic flood wave modeling in 1985. More recent versions of DAMBRK are still widely used today. This program requires inputs describing the inflow hydrograph, the reservoir topography, the height of the dam, the depth of the reservoir pool, channel cross sections and related topography of inundated areas, and an estimate of Manning's n values. Proposed alternatives to DAMBRK were the Soil Conservation Service's dam break flood routing procedure, a simplified NWS dam break program called SMPDBK, and a method by the USBR (see McCann et al., 1985, p. 6-5 to 6-6). In each case, the assumptions chosen—for example, the rate of breach development needed for SMPDBK—are stated to be less important than their consistent application across dams in a portfolio.

Analysts draw lines of consistent depth on a topographic map of the inundation area, then cross-hatch these lines at set distances from the dam—say every mile. Matched pairs of the resulting closed polygons (one on each side of the river) are combined to form subPar, though they need not be matched in pairs if the zoning is dissimilar.[3] Zones should be selected or subdivided as necessary to represent contiguously similar land use (primarily residential or primarily business). Analysts fill these polygons with coded symbols to locate structures. Life loss (L) is estimated by using equations SF-1a and SF-1b and then summing across all subPar.

$$L_i = \phi(d_i) * r_i * P_i \qquad \text{(SF-1a)}$$

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[3] If this is difficult to picture, consider that a straight reach resembles the neck of a guitar. Since lines of equal depth will roughly parallel the stream channel, the strings represent depth and the frets mark the distance from the dam. Each resulting rectangle represents a subPar.

$$L_i = \phi(d_i) * r_i * p_i * N_i \qquad \text{(SF-1b)}$$

where $\phi(d_i)$ = fraction of people losing their lives as a function of depth,

r_i = fraction of people present when the flood wave arrives among Par (r_i is designated $Tpar_i$ in the current work),

P_i = population in a population at risk (P_i is designated Par_i in the current work),

N_i = number of people occupying a zone during business hours, and

p_i = percent of time a given zone is occupied.

Notice that the equations are identical, except that the first applies to a residential area and the second applies to a more transitory business district (or to a recreational area using the same logic). The concept is a simple definition: loss of life equals the number of people being flooded at each depth (r*P or r*p*N) times the percent who should perish at that depth [ϕ(d)].

The percent who perish is a function of depth, tabulated in Table 3.3. The flooded are those who remain on the floodplain when the flood wave arrives, an estimate based on daily occupational patterns, evacuation estimates, the quality/timeliness of the flood warning system, the distance downstream or flood travel time, and the type of land use patterns. Table 3.4 offers suggested values. Analysts can modify the suggested values to reflect their perception of the local conditions. Values for P (population at risk), N (number of people occupying a zone during business hours), and p (percent of time a given zone is occupied) must be estimated from local records, observations, and conversations with local officials.

Contributions

This model provides great flexibility in assigning values to parameters by allowing the analyst to consider local conditions and to consider factors not explicitly in the equation, such as evacuation effectiveness and the quality of a flood warning system.

Table 3.3. Values proposed by McCann et al. for $\phi(d)$ (McCann et al., 1985, Table 6.2, p. 6-9)

Depth of Inundation (ft)	Fraction of Lives Lost
2	0.00
4	0.05
6	0.20
8	0.40
10	0.60
12	0.80
>12	0.85

Table 3.4. Values proposed by McCann et al. for r (adapted from McCann et al., 1985, Table 6.3, p. 6-9)

	No Warning System				Good Warning System			
	Distance from the Dam (miles)							
	<10	20	30	50	<10	20	50	100
Typical Rural Area	1.00	0.80	0.20	0.10	0.70	0.40	0.10	0.00
Typical Residential Area	0.70	0.50	0.10	0.00	0.50	0.20	0.00	0.00

The model also recognizes the variation in hazard faced by people in different locations, and the importance of subdividing Par without having to track individuals.

Shortcomings

The great shortcoming of the model is that the value of every parameter depends on subjective estimates without empirical calibration. This is compounded by the fact that a different fatality rate must be specified for each uniquely defined set of subPar. Moreover, how does one adjust a scale up or down when it is unknown whether the original scale is high or low?

The model's creators suggested additional shortcomings. They acknowledged that travel time is a more meaningful way of dividing Par than distance downstream, but they chose distance out of convenience. Also, they recognized that life loss cannot be related to flooding depth alone; flooding velocity is equally or more important. Velocity was ignored, however, to simplify the model.

Significantly, like developers of the previous methods, the authors of the Stanford/FEMA approach considered their model too simplistic to allow analysts to predict loss of life with high confidence or accuracy. In fact, they offered it only as a simplified, preliminary tool for those who had not yet developed procedures of their own.

Subsequently, this model was slightly refined by the Institute for Water Resources of the U.S. Army Corps of Engineers, as is described later in this chapter.

Paté-Cornell and Tagaras, 1986

The Model

> *Paté-Cornell and Tagaras (1986) suggested a general method for predicting life loss based on adjusting a base casualty rate according to the efficacy of a warning system. Once again, the five main elements of most models can be identified: determination of the probability of a failure, mapping the flood inundation area, identification of the Par, application of a loss function, and modification of Par, that function, or its prediction based on temporal, spatial, or local conditions.*

They proposed that analysts use the average historical rates of dam failures unless local conditions and expert judgment allow more refined estimates. They give no guidance on routing the dam break, but they assume it is possible to distinguish two zones: the wave path (zone 1) and the inundation area (zone 2). These are not defined, but the distinction is important to their model since the loss function assumes a 50% casualty rate in zone 1 and no casualties in zone 2, making zone 1 the only region containing life loss or a population at risk, depending on your perspective. The loss function is pseudo-empirical in the sense that it is an intuitive estimate based on a review of failures like the one at Malpasset.[4]

They suggest that Par in zone 1 should be reduced according to the quality and timeliness of any early warning system. Again they give no guidance, leaving the reduction up to the judgment of the analyst.

This model bears considerable similarity to that first developed by Ayyaswamy et al. (1974). Here, instead of assuming a 100% fatality rate at depths of 10 ft and 0% elsewhere, the assumption is a death rate of 50% in the main path of the flood and 0% closer to the peripheries. Both models allow Par to be reduced through evacuation. However, rather than calculating separate losses for day and night, Paté-Cornell and Tagaras suggest averaging Par over the two time frames.

Contributions

The model emphasizes the importance of an early warning system in facilitating a timely and effective evacuation effort and in reducing the risk associated with a dam failure. The thrust

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[4] Malpasset had a fatality rate of 50% only if zone 1 is defined so as to force this result; taking Par more broadly, a Par of about 6,000 people was inundated and several hundred people died. In any case, the loss function appears to have been derived as a first-cut, intuitive estimate, and rates much higher than 50% have been observed in other failures, such as the failures of Vaiont or Stava Dams in Italy.

of their work was to increase the benefit-cost ratios in economic analyses to justify the construction of dams and to support dam safety remediation projects.

Shortcomings

Like Ayyaswamy's model, this model relies on intuitive estimates of life-loss rates without true empirical support. The authors were not, however, attempting to offer a refined model. Rather, they were demonstrating the importance of incorporating risk when calculating benefit-cost ratios, thus providing justification for future model development and the implementation of early-warning systems.

Institute for Water Resources' Revision of the Stanford/FEMA Model, 1986

On pages 23 – 28, Lee at al. (1986) summarize and illustrate changes made to the Stanford/FEMA model by the Institute for Water Resources (IWR) within the U.S. Army Corps of Engineers. In brief, IWR replaced river miles as a surrogate for warning time with warning time itself.

Lee et al. (1986, p. 23) refer to the source as the IWR with the reference, "Institute for Water Resources (1986a)," under the apparently truncated title "Interim Procedures," but their draft report does not include a bibliography so no additional reference information is provided. According to personal conversations with Dr. David Moser (1998) at IWR, any changes made to the Stanford/FEMA model were made by Lee et al. (1986), and are contained in their report. The Australian National Committee on Large Dams (1994) supports this assertion when they mention 1986 risk assessment procedures under development at the U.S. Army Corps of Engineers that fell short of providing a life-loss estimate.

Regardless of the source or nature of these historic model modifications, current practice within the Corps of Engineers is to estimate Par, but to stop short of making specific loss of life estimates.[5] While loss of life is referred to in Corps policy documents, it is completely omitted in practice.

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[5] The current Corps practice of omitting loss of life calculations was explained at a meeting in Los Angeles on August 14, 1998. The purpose of the conference was the second-stage of a demonstration risk assessment involving members of the Los Angeles District, IWR, observers from other Corps offices around the country, and personnel from Corps headquarters in Washington D.C.

Brown and Graham: United States Bureau of Reclamation (Brown and Graham, 1988; U.S. Bureau of Reclamation, 1986, 1989)

The Model

An official presentation of the methods developed within the USBR was published as a technical memorandum in 1986.[6] Subsequently, Brown and Graham published "Assessing the Threat to Life from Dam Failure" in 1988 and the method was formally repeated in 1989 with the publication of the 1989 interim guidelines, "Policy and Procedures for Dam Safety Modification Decisionmaking [sic]." Reclamation intentionally "tried to build upon the Stanford/FEMA model . . . by considering additional factors, and by developing an empirical basis for model coefficients" (Brown and Graham, 1988, p. 6).

The method presents a five-step procedure: 1) develop inundation maps for each combination of loading and dam-safety alternatives to quantify Par, 2) estimate corresponding warning times, 3) apply life-loss equations to generate baseline projections of life loss for each failure scenario, 4) adjust these baseline estimates using site-specific characteristics, and 5) compare each scenario's life-loss estimate to that for the "no action" alternative to produce an incremental life-loss projection.

In 1989, the incremental comparison was changed from "fix vs. no fix" to "failure vs. no dam" to reflect the difference between losses given a dam failure and those that would result were the dam not present at all. To minimize the number of separate failure analyses that are required, it is recommended that loading conditions and dam-safety alternatives should be grouped together or combined into a single increment whenever their disparate consequences are expected to show little difference.

Several things suggest the importance of using local experts to help in the analyses:

1. Accurate estimation of Par in step 1 requires knowledge of dynamic recreational activities below the dam, fluctuations in Par with time, and other variations not necessarily captured in census data.

2. Estimates of warning time require not only knowledge of wave travel time but also the routines of the dam keepers, the nature of the early warning system, possible pitfalls in the emergency action plan, and the accessibility of subPar for warning notification.

3. Adjustments to the baseline life-loss estimates require subjective judgements based on local conditions.

The life-loss equations rely on two independent variables: Par and warning time. Par should be subdivided into subPar whenever warning time is expected to vary significantly with

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[6] Lee et al. (1986) apparently found the same information in a 1985 USBR report, but their bibliography was never included in their draft document so no further reference information was provided.

distance. In this way, the river is divided into reaches of varying length based on judgments about the distribution of Par. For example, a fish hatchery at mile 1, followed by a YMCA camp at mile 3, a popular fishing reach along miles 7 – 10, and a town at miles 20 through 21 would suggest four subPar, each with its own warning time.

To account for seasonal or diurnal fluctuations in these subPar, each important time frame is assigned an average subPar$_j$ value (Par$_{ij}$) and associated with a P_t value representing the probability that the failure mode will occur during the designated category of time. Notice that the P_t value is not merely the proportion of the year represented by a time category, but represents the likelihood that the failure will occur during that time category. For example, if hydrologic failures are more likely during a 3-month summer thunderstorm season, those 3 months will be assigned a P_t value greater than 0.25. The weighted Par$_{ij}$ are then the product of P_{tj}*Par$_{ij}$, where subscript i indicates the subPar in question and j identifies the time category in view.

Warning time (Wt) is the next important variable to quantify. Schematically, the conceptualization of the inputs to life loss can be presented in a flow chart like Figure 3.2. The calculation of warning time involves estimating the flood wave travel time to the midpoint of each Par$_i$ and adjusting that value upward or downward based on estimates of whether the breach is anticipated or detected after its development and the time it takes to warn the Par$_i$ after detection. Together, this entails those parts of Figure 3.2 that lead up to "warning time for Par."

In determining warning time, it is important to consider the processes of detection, notification of the proper authorities, decision-making, mobilization, and dissemination of a public warning on an event-specific basis. Is there a chain of command? Can each link be reached at a moment's notice at all times? Does the dam owner have authority/responsibility to notify the public directly, or must that decision be passed on to local authorities? Is the failure mode under consideration likely to become evident hours or days prior to actual breach development? Will communication systems remain functional? Are means available to warn fishermen, campers, isolated residents, or other members of the Par cut off from mainstream communication channels?

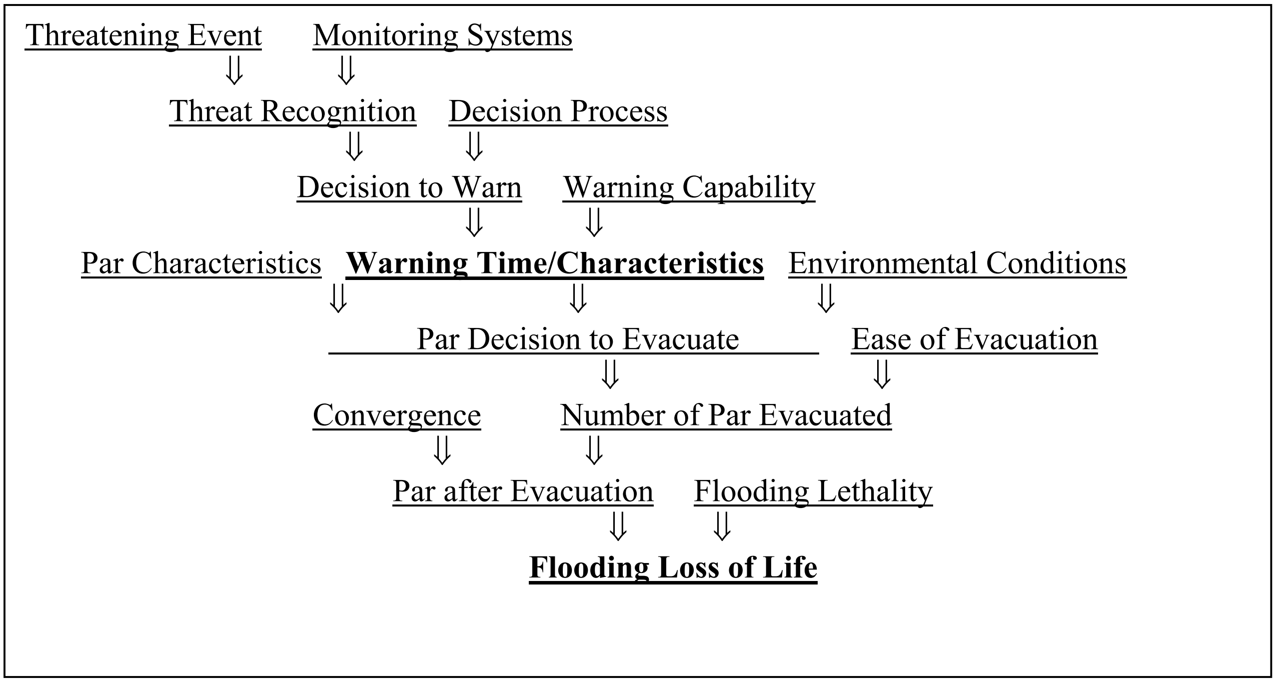

Figure 3.2. Flow chart of variables affecting loss of life (reformatted from U.S. Bureau of Reclamation, 1989, Figure 1, p. III-28).

To calculate the baseline loss of life, each weighted P_{tj}*Par_{ij} is entered into one of three empirical functions, and then the associated estimates of life loss (L_{ij}) are summed together. Equation BG-1a is for warning times less than 1.5 hr and equation BG-1b is for warning times greater than 1.5 hr. Equation BG-1c was not originally part of the model, but it was added in 1989 for cases with warning times less than 15 minutes and depths greater than 3 ft. It makes no difference whether the P_{tj} values (the probability that the failure mode will occur during the designated category of time and inundate Par_{ij}) are applied to the subPar directly or to the unadjusted life loss (L_{ij}) results. Hence, the functions are presented here without the P_t factors using the symbols for life loss (LOL) and population at risk (PAR) used by Brown and Graham (Brown and Graham, 1988; U.S. Bureau of Reclamation, 1989):

$$\text{Warning} < 1.5 \text{ hours: } LOL_i = PAR_i^{0.6} \qquad \text{(BG-1a)}$$

$$\text{Warning} \geq 1.5 \text{ hours: } LOL_i = 0.0002 * PAR_i \qquad \text{(BG-1b)}$$

$$\text{Warning} < 15 \text{ minutes (depth} > 3 \text{ ft): } LOL_i = 0.5 * PAR_i \qquad \text{(BG-1c)}$$

These relationships were developed by analyzing 23 cases of dam failure or flash flood that occurred since 1950 in North America or Europe and that were judged to be large-scale events for which relatively complete documentation was available. The specific events are listed in Table 3.5. DeKay and McClelland (1993b) added Allegheny County, Pennsylvania; Austin,

Table 3.5. The data set used by DeKay and McClelland in 1993, estimations using equations DM-2d, DM-3b, and DM-4 and the root mean square errors of each (includes material from DeKay and McClelland, 1993b, Table I, p. 197)

	Locations	Par	Hours Warning (Wt) Brown & Graham	Hours Warning (Wt) Continuous	Flooding Force	Actual Loss of Life	Predicted Loss of Life Eq. DM-2d	Predicted Loss of Life Eq. DM-3b	Predicted Loss of Life Eq. DM-4 (Variables Used By Brown & Graham)	Average Prediction Eq. DM-2d and Eq. DM-3b
1	Allegheny County, PA, 1986	2,200	----	0	0	9	6	11	109	8
2	Austin, TX, 1981	1,180	----	1	1	13	9	7	12	8
3	Baldwin Hills Dam, CA, 1963	16,500	1.5	1.5	1	5	9	6	20	8
4	Bear Wallow Dam, NC, 1976	8	0.0	0	1	4	5	11	5	8
5	Big Thompson, CO, 1976	2,500	< 1.0	0.5	1	144	59	61	47	60
6	Black Hills, SD, 1972 (Canyon Lake Dam)	17,000	<1.0	0.5	1	245	174	184	129	179
7	Buffalo Creek Coal Waste Dam, WV, 1972	5,000	<1.0	0.5	1	125	87	91	67	89
8	Bushy Hill Pond Dam, CT, 1982	400	2-3	2.5	0	0	0	0	0	0
9	Centralia, WA, 1991	150	----	0	0	0	1	2	26	1
10	D.M.A.D. Dam, UT, 1983	500	1-12	6.5	0	1	0	0	0	0
11	Denver, CO, 1965 (South Platte River)	10,000	2.33-4	3.17	0	1	1	1	0	1
12	Kansas City, MO, 1977	2,380	<1.0	0.5	1	20	57	59	45	58
13	[a]Kansas River, KS, 1951	58,000	>2.0	3	1	11	0	0	2	0
14	Kelley Barnes Dam, GA, 1977	250	<0.5	0.25	1	39	31	37	22	34
15	Laurel Run Dam, PA, 1977	150	0.0	0	1	40	40	63	26	52
16	Lawn Lake Dam, CO, 1982	5,000	0.0-1.0	0.75	0	3	5	9	43	7
17	Lee Lake Dam, MA, 1968	80	0.0	0	1	2	26	44	19	35
18	Little Deer Creek Dam, UT, 1963	50	0.0	0	0	1	1	1	14	1
19	Malpasset Dam, France, 1959	6,000	0.0	0	1	421	406	527	185	467
20	Mohegan Park Dam, CT, 1963	1,000	0.0	0	0	6	4	7	72	5
21	Northern NJ, 1984	25,000	>2	3	0	2	2	3	1	2
22	[a]Prospect Dam, CO, 1980	100	>5	7.5	0	0	0	0	0	0
23	Shadyside, OH, 1990	884	----	0	1	24	127	176	67	152
24	Stava dams, Italy, 1985	300	0.0	0	1	270	64	95	38	79
25	Swift and [Lower] Two Medicine Dams, MT, 1964	250	<1.5	0.75	1	28	8	7	8	7
26	Teton Dam, ID, 1976 (Dam through Wilford)	2,000	<1.5	0.75	1	7	25	23	26	24
27	Teton Dam, ID, 1976 (Rexburg to American Falls)	23,000	>1.5	2.25	0	4	4	5	6	5
28	Texas Hill Country, 1978	2,070	<1.5	0.75	1	25	25	24	27	24
29	Vega De Tera Dam, Spain, 1959	500	0.0	0	1	150	89	127	50	108
	Root Mean Square Error						50	53	76	50
	[a] Not used in equation derivations (omitted as outliers)									

Texas; Shadyside, Ohio; Stava, Italy; and Centralia, Washington.[7] Brown and Graham divided the Teton failure into an upper and lower subPar. They considered the upper Teton subPar and Lawn Lake to be outliers and omitted them from their data set.

The authors treated warning time dichotomously and then trichotomously because they did not believe that warning time could be estimated with sufficient accuracy to justify a continuous treatment. In both the dichotomous and trichotomous approaches, the cutoffs in warning time were not based on rigorous statistical analyses, but rather on what appeared to be reasonable divisions of the data set.

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[7] Teton Dam failure was divided into 2 subPar.

According to Brown and Graham, equation BG-1a has an R^2 value of 0.6, indicating that as warning time decreases, other factors besides the size of Par and length of warning time influence life loss. For greater warning times, equation BG-1b has a reported R^2 value of 0.87, indicating a decreasing influence by other factors. The exponential nature of the first curve suggests that there are aspects of larger population centers (advantages in terms of warning dissemination and public safety resources, for example) that decrease the proportion of lives lost when warning time is less than 1.5 hr. Beyond 1.5 hr and when warning times are less than 15 minutes, these advantages disappear because evacuation either nears completion or has insufficient time to progress.

The baseline estimates of life loss are meant only to represent a first cut. Central to the USBR method is the subjective adjustment of these values for each Par_{ij} based on the remaining elements in the flow chart of Figure 3.2. A summary of each chart heading subsequent to warning time follows. The reader is referred to the source documents for more details.

1. **Warning characteristics**: Warning time is defined globally as the elapsed time between initiation of a public warning within Par_i and the onset of flooding at that Par_i. Warning characteristics go further to describe the rate, extent, and believability/urgency of the warning dissemination.
2. **Par characteristics** include descriptors such as age, mobility, prior awareness, experience, knowledge of how to respond, information networks, degree of family dispersion, attitudes, and prior false alarms or misinformation.
3. **Environmental conditions** are local conditions such as heavy rain, darkness, earthquake damage or the like.
4. **Par decision to evacuate** refers to the public response.
5. **Ease of evacuation** is the combined effect of environmental conditions, distance to safety, availability of transportation, and the likelihood that bridges or bottlenecks will become impassable.
6. **Number of Par evacuated** are those who escape prior to the arrival of the flood.
7. **Convergence** is the movement of people into the flood zone, including safety officials, curiosity seekers, and those who return to help others or retrieve belongings. Convergence-related deaths are usually few in number, but are not uncommon.
8. **Par after evacuation** quantifies the number present when the floodwaters arrive, either due to convergence or to evacuation shortcomings.
9. **Flood lethality** is the potential of a flood to cause deaths, based on its depth, velocity, temperature, and debris load.

Adjustments to the baseline loss of life figures based on these additional considerations are left to the judgment of the analyst. However, the analyst should “lower the fatality estimates substantially if the floodwaters will be less than two feet deep and moving at less than three feet per second” (Brown and Graham, 1988, p. 15). At the other extreme, estimates should be raised to as high as a 90% fatality rate if warning time is near zero (less than 5 minutes) and the flood wave will destroy virtually every structure in the flood plain.

In all cases, the results are presented as a range of likely outcomes. When no dominant variable suggests the direction in which a baseline estimate should be adjusted, the baseline estimate is taken as the expected value, and a high and low estimate are predicted based on the 95% confidence interval for each equation. For equation BG-1a, the confidence limits are found by changing the exponent to 0.5 and 0.7. For equation BG-1b, the coefficient is changed to 0.00014 and 0.00022. Brown and Graham do not suggest confidence limits for equation BG-1c (U.S. Bureau of Reclamation, 1989).

When one or more critical variables can be identified and significant uncertainty surrounds the variable(s), high and low estimates are derived based on selecting high and low estimates of each variable and performing a sensitivity analysis. When estimates of life loss appear to be extremely high or low, a most likely estimate can be displayed along with historic minimums and maximums from the data set for those cases which most closely resemble the one in question.

Contributions

There are many strengths to the USBR method. To begin with, it attempts an empirical calibration based on historic failure events. In this process, there is recognition that the historic cases are heavily influenced by factors beyond warning time and Par alone, creating a large variance about the expected values generated by the regression functions. Rather than claiming more confidence in the baseline estimates than is warranted, the method seeks to make reasonable adjustments to these estimates based on a case-specific consideration of other variables. Even then, the results are displayed as ranges or envelopes, rather than a single value, thus reducing any bias introduced by individual analysts. Perhaps the greatest strengths are the identification of pertinent factors that had previously been overlooked and the accrual of a data set upon which future work could be built.

Shortcomings

There are at least six shortcomings to the USBR method. First, although recognizing that warning time is critically important, the trichotomous treatment severely limits the precision with which loss of life can be explored.

Second, the regression equations themselves lack sophistication. For example, it would be desirable to refine equation BG-1a by including a multiplicative coefficient, and equation BG-1c appears to be an “eyeball” estimate based on very few data points with no formal statistical analysis. The use of round numbers for both coefficients and exponents makes it clear the estimates are not intended to be precise, although this is not unreasonable given the large variance in life loss, and given that the equations are intended only to yield a first-cut estimate.

Third, there is some question as to the basis for the reported R^2 value for equation BG-1a. A visual perusal of the graphs in the source documents might leave some readers feeling uneasy. Feeling uneasy themselves, another group within the USBR attempted to duplicate the results to test the accuracy of the R^2 value. According to the internal memorandum, using the same data and excluding the same outliers, they generated the following refined equation with an R^2 value of only 0.47 (Hyatt, 1985):

$$LOL = 0.51 * PAR^{0.62} \tag{BG-2}$$

They suggested that perhaps the reported value was an R value instead of R^2, or was based on a transformed variable, rather than L itself. In any case, even the reported R^2 value of 0.6 presents an incentive to this researcher to develop a more refined function.

Fourth, while the equations are meant to be applied on a subPar basis, the only historic case that was subdivided was the Teton Dam failure, and then one of the two subPar was omitted as an outlier. This raises questions regarding whether the sum of the parts of an analysis is the same as a single application to the whole. In the case of equation BG-1a, this is clearly not the case, since the life-loss relationship to Par is not linear.

Fifth, the data set, while an excellent beginning, is noticeably small—especially after it is subdivided to form two or three distinct data sets for two or three different equations. As this set is appropriately expanded, it should generate more confidence in any resulting regression equations. Significantly, the USBR practice was to use the subsequent relationship developed by DeKay and McClelland (1991, 1993b) until recently, when another approach was developed by Graham (1999). Supported by USBR funding, DeKay and McClelland (1991, 1993b) advanced Reclamation's work by expanding the data set and applying a more rigorous approach to regression analysis. Graham himself recommends the use of the DeKay-McClelland equation over the ones he helped develop, although he also recommends going beyond Dekay-McClelland and is actively developing new procedures (Graham, 1998, 1999).

Sixth, the use of weighted Par_{ij} should only be adopted if estimated life loss is linearly related to Par, which, for equation BG-1a, it is not.

A final comment bears mentioning that applies to any approach that seeks a mean estimate of annualized life loss rather than a probability distribution of life loss: The model yields only a point estimate of an average value that is itself uncertain and subject to confidence limits. Also, if estimated life loss (lives) is needed, as is the case if societal risk is to be characterized using charts that relate the frequency of events to the number of lives lost (F-N curves), then weighted Par_{ij} should not be used.

Lee and Others for the Institute of Water Resources, U.S. Army Corps of Engineers, 1986

The Models

Lee et al. (1986) at the Oak Ridge National Laboratory, U.S. Department of Energy, prepared three methods for predicting loss of life from floods. Their focus included flash floods and dam failures, but was not limited to catastrophic events. The authors compiled additional information shedding light on the mechanisms resulting in life loss. For example, summarizing a variety of studies, they suggested the following circumstances for life loss:

1. being trapped in a structure by rising water
2. being swept out of a structure
3. being in a structure that fails
4. attempting to cross flood waters
5. being caught in flood water while in the floodplain
6. attempting to rescue others in flood waters
7. attempting to drive across a flood-way
8. attempting to boat or raft on flood waters. (Lee et al., 1986, p. 11, capitalization omitted)

To these were added four reasons people drown: the flood stage is life-threatening, people receive inadequate warning time, they respond too slowly, or they do the wrong thing.

In addition to their three models, Lee et al. also extended the USBR model, though their extension does not appear to have been adopted (or even recognized) within the USBR. Reintroducing the outliers Brown and Graham (U.S. Bureau of Reclamation, 1986) excluded from their data set (Lawn Lake and Upper Teton), they estimated the case-study warning times to the nearest 15 minutes instead of dichotomously. Where insufficient data existed to estimate these directly, they set “less than 1.0 hour” to 45 minutes and “more than 1.5 hours” to 75 minutes. The reason for reducing the values greater than 90 minutes to 75 minutes is not explained. Formulating a new approach to regression, they generated the following equation (symbols used in this text have been substituted for those used by Lee et al. (1986), as noted below):

$$\log(L) = 0.67\log(Par) - 0.014(Wt) \qquad \text{(L-1a)}$$

which reduces to

$$L = e^{0.67\log(Par) - 0.014(Wt)} \qquad \text{(L-1b)}$$

where L = life loss

Par = population at risk (Lee at al. used P for Par), and

Wt = warning time (Lee et al. used W for Wt).

This equation has an adjusted R^2 value of 0.89, which is significant at less than the 0.0001 level.

For their own regression equation, Lee et al. assembled a new data set consisting of 47 floods, most of which resulted in loss of life, and all of which occurred in the United States between 1963 and 1985. When consistent with these selection criteria, cases from the USBR data set were included. Their approach was to compile a list of factors that might affect either the size of the threatened population (those remaining in the flood zone when the flood arrives) or the lethality of the flood; record these along with data on life loss and Par for the aforementioned floods; identify general trends, outliers, and lack of data within the data set; formulate alternative life-loss equations and calibrate them to the data; analyze each equation statistically to select the best one; and compare the results with those for the Brown and Graham (U.S. Bureau of Reclamation, 1986) equations and the IWR adaptation of the Stanford/FEMA model (Lee et al., 1986).

As expressed using the symbols chosen by Lee et al., the form of the equations was limited in each case to

$$\frac{L_{ij}}{P_{ij}} = p(\overline{x}_{ij}, \overline{y}_{ij}) \qquad \text{(L-2)}$$

where the subscripts refer to reach i and flood zone j after the two-part division of subPar in the Stanford/FEMA model;

L = loss of life,

P = population at risk (herein uses Par for P),

p = the probability of life loss of an individual in reach i and flood zone j, which is a function of vectors $\overline{x}$ and $\overline{y}$,

$\overline{x} =$ a vector of variables affecting the ratio of deaths to the threatened population ($\overline{x} =$ a bold **x** in Lee et al., 1986), and

$\overline{y} =$ a vector of variables affecting the size of the threatened population relative to the population at risk, P ($\overline{y} =$ a bold **y** in Lee et al., 1986).

This equation is an adaptation of the Stanford/FEMA equation

$$L_i = \phi(d_i) * r_i * P_i \qquad \text{or} \qquad \frac{L_i}{P_i} = \phi(d_i) * r_i \qquad \text{(SF-1a)}$$

in which the variables $\phi(d_i)*r_i$ are replaced by an individual probability of survival, p, and subdivision by both reach (i) and zone (j) are made explicit.

The variables considered for vector **x** were:

1. number of residences damaged and the extent of economic damages
2. depth of the flood (data available for only about half of cases)
3. velocity of the flood wave (data generally unavailable)
4. discharge (cfs; data available for about half of cases)
5. breach of dam (1 = breach, 0 = no breach)
6. topography of the inundation area (1 = wider floodplain, 0 = narrow canyon)
7. special characteristics of the Par, such as very young or old
8. unique facilities: hospitals, retirement homes, schools, recreation areas, etc.
9. type of structures (data unavailable, not used)
10. number of roads and bridges crossing the river in the inundated area (data unavailable, not used)

The variables considered for vector **y** were:

warning time
1. experience or knowledge of flooding in the local area within 10 years (1 = yes, 0 = no)
2. existence of hospitals, retirement homes, schools, recreation areas or other unique facilities (each dichotomous, 1 = existence of such a facility, 0 = not present)
3. day or night (1 = day, 0 = night)
4. time of day
5. proportion of elderly and young (data unavailable, not used)
6. effectiveness of the evacuation plan and system (coded after Sorensen and Neal in Lee et al. (1986) as needs improvement, fair, or good)
7. evacuation traffic (data unavailable, not used)
8. size of population
9. urban vs. rural situations

After preliminary analyses, only six variables were found to be statistically significant at the 0.05 level when regressed individually against life loss (L) and in stepwise refinements: L, Par, warning time; and dummy variables indicating previous experience with flooding within the last 10 years, whether or not the area was urbanized, and the depth of flooding at peak stage. Lee et al. suggested several reasons why the others were not found significant: the sample was small; the variables affected L, but not sufficiently to be significant when dummy coded and used apart from the more dominant variables; multicolinearity may have hidden their affect when used in stepwise regression analysis with the dominant variables; and a variable sometimes had a significant impact on one case, but not on the cases as a whole.

Using these six remaining variables and experimenting with many different approaches, Lee et al. developed two regression equations, each based on a logistic (also called logit) equation.

In general, the logit relationship can be expressed as follows:

$$p = \frac{\exp(\overline{\beta})}{1+\exp(\overline{\beta})} = \frac{1}{1+\exp(-\overline{\beta})} \quad \text{where} \quad \ln\left(\frac{p}{1-p}\right) = \overline{\beta} \qquad \text{(L-3a and L-3b)}$$

where p = a fraction between 0 and 1.0 (notice the use of lower case p here rather than upper case P used by Lee et al. to represent Par), and

$\overline{\beta}$ = a function of zero or more variables, their transformations and their coefficients, including a possible constant. This is sometimes designated by $\overline{\beta}'\overline{x}$. In the text, the function's constant will be represented by β_0, the subsequent coefficients sequentially by β_i, and the entire function will be indicated by $\boldsymbol{\beta}$ in bold type.

Equations L-3a and L-3b are equivalent following manipulation; the left side of equation L-3b is called the logit transformation, while the middle and right side of equation L-3a are equivalent expressions for the inverse transformation, yielding the value of the proportion p directly.

The logit transformation is used most often when p represents the probability that an individual outcome will be a "success" during independent trials of a binomial experiment (Agresti, 1996). In the treatment by Lee et al., p was defined as life loss divided by population at risk. Using symbols in Lee et al., this would be p = L/P. Using symbols advocated in this report, p is designated with an upper case P such that P = L/Par. For Lee et al., p represents the probability that an individual at risk dies given the conditions defined by the function $\boldsymbol{\beta}$. Put another way, p is the proportion of lives that would be lost in a given flood if each life were an independent Bernoulli trial.

The two equations making the final cut are quite similar, except that the first omits urbanization as a dummy-coded variable and the second omits depth. The reason depth was not included in the second regression is that only 22 out of 47 cases in the data set provided sufficient information upon which a regression could be performed. Equation L-4 proved to be the equation Lee et al. recommended for use out of the two, in part because of the intuitive value of including a description of the flood, and in part because it slightly outperformed equation L-5 when applied to the data set in a semi-Bayesian manner (see below). Notice that these two equations fulfill the requirements of equation SF-1a, as desired.

$$\frac{L}{P} = \frac{\exp\left\{-6.2 + 3.1\left[\frac{1}{1+Wt}\right] - 0.00034(Wt * P)^{0.5} - 0.0077P^{0.5} + 1.4E + 0.0039D\right\}}{1+\exp\left\{-6.2 + 3.1\left[\frac{1}{1+Wt}\right] - 0.00034(Wt * P)^{0.5} - 0.0077P^{0.5} + 1.4E + 0.0039D\right.} \quad \text{(L-4)}$$

$$\frac{\mathrm{L}}{\mathrm{P}} = \frac{\exp\left\{-0.18 + 1.7\left[\frac{1}{1+\mathrm{Wt}}\right] - 0.00044(\mathrm{Wt} * \mathrm{P})^{0.5} - 0.0092\mathrm{P}^{0.5} + 0.26\mathrm{E} - 0.18\mathrm{U}\right\}}{1+\exp\left\{-0.18 + 1.7\left[\frac{1}{1+\mathrm{Wt}}\right] - 0.00044(\mathrm{Wt} * \mathrm{P})^{0.5} - 0.0092\mathrm{P}^{0.5} + 0.26\mathrm{E} - 0.18\mathrm{U}\right.} \quad \text{(L-5)}$$

where L = loss of life

P = Par

Wt = warning time in minutes (Lee et al. used W)

E = experience with floods in the last 10 years (1 = yes; 0 = no)

D = depth of flooding at peak stage (feet above flood stage)

U = denotes an urbanized area (1 = urban area with pop. ≥ 10,000; 0 = otherwise)

As with any treatment of historical data, the model-developers were forced to quantify many variables using "a considerable degree of subjective judgement" (Lee et al., 1986, p. 51). Like the regression by Brown and Graham, only the Teton Dam failure was divided into subPar, although it was intended that subPar be used in application. The model coefficients were determined using maximum likelihood methods. The corresponding t-statistics and levels of significance for each coefficient are presented in Table 3.6.

The implications of using a logit transformation will be explored in detail in Chapter IV when critiquing the approach developed by DeKay and McClelland (1991, 1993b). A few observations will be sufficient at this point.

First, the logit transformation has the reasonable characteristic of restricting the proportion of life loss to values between 0.0 and 1.0. In contrast, using L or p = L/P directly in a regular least-squares regression without the transformation of L/P or β would permit values of life loss to exceed the Par or drop below zero in extreme cases.

Second, Lee et al. treated the individual as the fundamental dependent variable, effectively increasing the number of observations from 47 floods to 459,234 members of Par. This has two dangers that were pointed out by DeKay and McClelland (1991). By increasing the sample size in this manner, it increases the power of the statistical tests, allowing statistical significance to be discovered for variables that have very little real-world impact. More fundamentally, such an analysis presumes independence and Bernoulli similarity for each individual encountering a large-scale flood event. Clearly this is not true, as the threat to life posed by a flood varies dramatically with space, time, the event, and the individuals involved. Fatalities are often clustered in a way that defies independence. On a practical level, the proportion of lives lost in events involving large Par will statistically dominate the proportion of lives lost in events threatening small Par.

Table 3.6. Regression t-statistics and levels of significance for the coefficients in equations L-4 and L-5 (Lee et al., 1986, p. 58 – 60)

Variable Coefficients in Sequence	Equation L-4		Equation L-5	
	t-Statistic	Level of Significance	t-Statistic	Level of Significance
β_0	-31.5	0.0000	-1.8	0.0624
β_1	20.7	0.0000	15.3	0.0000
β_2	-6.6	0.0000	-8.3	0.0000
β_3	-7.4	0.0000	-10.6	0.0000
β_4	9.9	0.0000	3.2	0.0014
β_5	2.6	0.0099	-1.86	0.0624

> The fact that each individual is treated as a statistical observation means that past flood events with greater populations at risk are statistically more important when estimating the empirical function than flood events in which there were few people at risk. Computationally, each individual, rather than each flood event, would carry equal statistical weight. (Lee et al., 1986, p. 61)

Lee et al. see this as a benefit, since every individual is treated equally. DeKay and McClelland (1993b), however, rightly point out that we are not distinguishing between individuals but between the unique mix of variable values that define each event. The event offers the critical information for evaluation, not each individual. Furthermore, it is important to accurately predict life loss (L) in events involving both large and small Par.

The implications of equations L-4 and L-5 are similar to those for the USBR formulations: L is nonlinear with respect to Par, L decreases with increasing warning time, and the influence yielded by the magnitude of Par decreases as warning time increases. Statistically, warning time is the most significant factor affecting L. Advancing the USBR method, several considerations which were used to adjust Brown and Graham's baseline estimates have been formally incorporated into the equations: prior flood experience within 10 years can retard a community's response during evacuation due to overconfidence; the greater the urbanization, the more efficient the warning and evacuation procedures; and the deeper (more lethal) the flood waters, the greater the loss of life. Interestingly, urbanization was not found significant when depth of flooding was included.

Lee et al. (1986) applied both of their equations to their data set, along with the USBR best estimate and upper and lower bounds, and the IWR version of the Stanford/FEMA model. This has been duplicated in full in Table 3.7 since it demonstrates the performance of each approach, and it identifies the complete data set under question. Though Lee et al. did not include a list of sources cited, they did include an appendix listing sources for every case in this data set.

In all fairness, several biases should be pointed out regarding the values reported above. First, only two of the three USBR equations were available to Lee et al. in 1986 and no subjective adjustments were applied, so the estimates represent only a first cut. Likewise, the Stanford/FEMA/IWR estimates were produced using the unadjusted tables provided with that model. Second, equation L-4 cannot be applied directly to 25 of the cases since they were missing adequate information on depth. For these, Lee et al. arbitrarily assigned the mean depth found by averaging the depth over the 22 cases that could be quantified. For equation L-5, in those cases where data were unavailable to dummy code the degree of urbanization, the equation was applied sequentially using a 1 and a 0 and then averaging the two results. Finally, since equations L-4 and L-5 were developed from this identical data set, they would be expected to show a reasonably good fit; if the USBR data set were used for testing instead, or an

Table 3.7. Comparison of loss of life predictions as calculated by Lee et al. using their own data set (Lee et al., 1986, p. 68; column headings have been modified, their order has changed, and the final row represents a calculation of the RMSE based on the data presented here and found in Lee's report)

#	Location	Actual L	Lee et al. Eq. L-4	Lee et al. Eq. L-5	USBR Lower 95%	USBR Expected	USBR Upper 95%	Stanford /FEMA (IWR)
1	Teton (to Wilford)	7	3	15	45	96	205	1360
2	Teton (Rex-Amer Falls)	4	10	34	3	5	5	3910
3	Gainesville, AL	5	2	7	0	0	0	2
4	Jackson, MS	4	10	27	3	5	6	43
5	Buffalo Creek, WV	139	120	142	63	145	332	3400
6	Big Thompson, CO	139	4	18	50	109	239	1700
7	San Francisco, CA	9	47	43	173	486	1361	6375
8	Little Deer Creek, UT	1	2	3	7	10	15	43
9	Pike Co, KY	3	38	18	16	27	48	213
10	Toccoa Falls, GA	38	38	18	16	27	48	213
11	Austin, TX	13	16	21	55	122	272	128
12	Bear Wallow, NC	4	0	0	2	2	3	3
13	SW Virginia	4	2	8	0	0	0	68
14	Cheyenne, WY	11	0	2	14	24	41	68
15	Hill Country, TX	27	8	13	0	0	0	5
16	Big Country, TX	6	2	8	0	0	0	3
17	Mohegan Park, CT	6	1	4	0	0	0	2
18	Denver, CO	6	37	35	3	4	5	37
19	Millard Co, UT	1	1	4	0	0	0	2
20	Schuylkill River Basin	5	14	13	1	2	2	0
21	Potomac River, D.C. area	27	8	11	0	0	0	0
22	Wilkes Barre, PA	1	3	1	14	20	22	0
23	Harrisburg, PA	1	29	33	1	2	2	17
24	Johnstown, PA	85	49	39	224	660	1947	17000
25	S. California	18	10	11	1	1	1	0
26	Santa Barbara, CA	20	3	5	0	0	0	0
27	S. California	18	28	33	1	2	2	12
28	Kansas City, KC, MO	12	6	22	71	166	388	750
29	Old Creek Canyon, AZ	3	4	7	22	42	77	340
30	Phoenix, AZ	10	18	23	1	1	1	0
31	Tri-County area, PA	9	8	14	0	0	0	4
32	Connecticut Flood, CT	11	17	26	1	1	1	102
33	Baldwin Hills Dam, CA	5	9	30	2	3	4	140
34	Honolulu	4	7	9	32	63	126	213
35	Four Mile Run (Fairfax), VA	1	4	5	22	42	77	106
36	Tekamah Creek, NE	3	16	25	55	122	272	255
37	North Hills, PA	8	33	38	100	251	631	2125
38	Black Hills (Rapid City), SD	245	37	39	2	3	4	2040
39	Tonto Creek, AZ	23	9	13	39	80	167	319
40	James River, VA	5	9	4	7	10	11	0
41	Brushy Hill Pond, CT	0	1	4	0	0	0	10
42	Lawn Lake, CO	3	21	31	1	1	1	850
43	Northern New Jersey	2	18	13	3	5	6	0

Table 3.7 Continued

#	Location	Actual L	Lee et al. Eq. L-4	Lee et al. Eq. L-5	USBR Lower 95%	USBR Expected	USBR Upper 95%	Stanford /FEMA (IWR)
44	Phoenix, AZ	0	22	27	1	1	1	10
45	Harrison Co, WV	2	12	19	45	96	205	170
46	Lee Lake, MA	2	0	1	9	14	21	7
47	El Dorado, NV	9	16	7	10	16	25	85
Root Mean Square Error		----	22	25	47	133	374	2810
RMSE using data in table			39	39	55	127	363	2792

entirely new data set, a different equation might prove the better predictor. Significantly, the USBR equations were developed specifically for dam failures and flash floods that closely imitate dam failures; the types of flooding included by Lee et al. are broader, restricted to floods that are life-threatening but not necessarily localized or resembling a dam failure.

The final row is the root mean square error (RMSE) calculated using the data presented in the report by Lee et al. and duplicated in Table 3.7. The likely explanation for the difference between the calculated values and those reported by the authors in the preceding row is that Lee et al. inadvertently misreported one or more values. Notice, for example, that cases 9 and 10 (Pike County and Toccoa Falls) give identical estimates for every method, despite the large contrast in actual life-loss values. In any case, the relative magnitudes remain unchanged: those reported by Lee et al. will be presumed to be the correct RMSEs.

With these caveats, the RMSEs indicate that equations L-4 and L-5 make comparable predictors and both surpass the performance of the USBR equations and the Stanford/FEMA/IWR model. Interestingly, the lower bound of the USBR confidence interval made a far better predictor than the best estimate, indicating a tendency to vastly overestimate L in some cases. Without question, the Stanford/FEMA/IWR model is miscalibrated, allowing overestimation by up to three orders of magnitude.

Despite the relatively low root mean square errors, Lee et al. point out shortcomings of their own estimations. The variance in L from their equations ($\sigma = 20$) was much less than for the actual case histories ($\sigma = 45$). In their words,

> Loss of life in many of the more lethal floods, such as the Big Thompson, Colorado flood; the Johnstown, Pennsylvania flood; and the Black Hills, South Dakota flood, was significantly under-predicted by the empirical function . . . . On the other hand, the empirical function over-predicted some of the less lethal floods such as those in Denver, Colorado; Harrisburg, Pennsylvania; North Hills, Pennsylvania; Lawn Lake, Colorado; Northern New Jersey; and Phoenix, Arizona. (Lee et al., 1986, p. 71, semicolons have been added for clarity)

To these could be added several more cases of dramatic overestimation, such as San Francisco, California; Pike County, Kentucky; and Tekamah Creek, Nebraska. These were balanced by 4 cases where actual life loss was in the twenties while the estimated life loss was less than 10.

Significantly, a similar pattern emerges to that found using the logit procedure developed by DeKay and McClelland (1993b): persistent overestimation when actual loss of life is less than 10, a balance of over- and underestimation in the midranges of life loss (10 to 40) and persistent and dramatic underestimation when L is high. There are reasons for this built into the logit transformation itself, as will be explored in Chapter IV.

Finally, Lee et al. proposed three models for calculating L, two of which depend on equation L-4 or L-5, with L-4 being recommended. To support these models, they provided detailed guidance on how to model the flood waves and calculate Par, Warning time, flood depths, and the other variables used in the model. Going beyond previous guidance, they also explored evacuation modeling. An overview summary looks like this,

> receipt of evacuation warning ⇒ mobilization time ⇒ vehicular travel time and queuing delay time ⇒ time between clearance and hazard arrival

where the middle two components comprise clearance time.

The Aggregate-Empirical Model

The simplest model is the aggregate-empirical model. By way of overview, it entails:

1. Establishing flood inundation scenarios using DAMBRK;
2. Relating these to census tracts, enumeration districts, or data on individual blocks;
3. Calculating a weighted average flood depth for each reach based on the proportion of Par inhabiting each flood stage within that reach (using automated software, if possible);
4. Estimating warning time by using a rough estimate or by summing the times for hazard detection, hazard appraisal, threat determination, notification of officials, decision to warn, and completion of the first warning; and then using this sum to adjust the wave travel time (the difference in time between the peak stage at the dam and the peak stage at the centroid of the population distribution);
5. Estimating the remaining variables in equation L-4 or L-5; and
6. Applying the loss of life function of choice (either L-4 or L-5).

The distinguishing characteristics of this model are that Par is subdivided only to the level of sequential reaches along the river and variables are applied to each reach as a whole, weighted according to the population distribution within each reach.

The Empirical-Flood-Travel Model

The empirical-flood-travel model distinguishes Par_i more finely by identifying separate inundation zones within each reach based on five land elevations and defining the model variables uniquely for each. This is consistent with the divisions used in the Stanford/FEMA model. Note that unless the flood wave rises rapidly, each zone will have a different warning time. To facilitate this more detailed analysis, the model anticipated software that had not yet been written. To this author's knowledge, the software was never developed.

The Flood-Travel-Evacuation Model

The flood-travel-evacuation model also depends on proposed software. Unlike the previous approaches, this model explicitly considers evacuation rates and avoids use of the empirical life-loss equation. Instead, zones are identified by choosing representative cross sections within each reach and plotting their elevations. By outputting flood hydrographs at each cross section, the flood wave travel time to each zone can be determined for each reach. The elevation and location of each road link and origin node must also be determined by manually inspecting topographic maps. This transportation grid is entered into a traffic simulation network database, in particular the MASSVAC2 traffic evacuation simulation model. Next, the traffic simulation program is run for a short increment, say 15 minutes. Checking each hydrograph for each cross section and each zone, any roads which lie below the levels of inundated at that point in time are closed. With these closures, the traffic model is again run on an incremental basis, and the hydrographs are again checked for additional road closures. This continues until the evacuated population reaches some asymptote, implying that, due to flooding, no more individuals can escape. Some will have been trapped at the origin nodes while others will have become blocked en route. Those who remain in the flooded zones as they are inundated constitute the threatened population. Life loss is estimated subjectively by multiplying this threatened population by a reasonable fractional coefficient. The flood event in question is then compared to a reference flood to determine the incremental losses.

Since considerable guidance is provided by the authors for each of these models, the interested reader is referred to their report for more details. It is important to remember, however, that Lee et al. did not propose a single model, but three models, two of which required additional software development and one of which was independent of their regression equations.

Contributions

Overall, their contribution to the field of dam safety life-loss estimation was monumental, being solidly built on the pioneering works by McCann et al. (1985) and Brown and Graham (1988). They completed the most rigorous statistical analysis of empirical evidence to date and introduced the less commonly understood approach of using a logit transformation. They attempted to explore Par on a scale small enough to be easily understood and to which values of characterizing variables would apply with reasonable accuracy. It is likely that their method did not gain prominence primarily because it depended on undeveloped software.

Shortcomings

Despite their pioneering work, the models developed by Lee et al. (1986) had a number of shortcomings:

1. They treated the individual as the unit for regression, causing events with large populations to dominate the results.
2. Some of the floods in their database were slow-rising, widely dispersed events, atypical of dam failures, although these may be useful for estimating incremental life loss by comparing the life loss from a dam failure to the life loss from non-failure flooding.
3. Current definitions of warning time do not describe the average warning time, the extent to which a warning is propagated, the effectiveness of the message at mobilizing a timely evacuation, informal types of warnings like sensory clues and shouts from neighbors, the time required to evacuate, or the excess evacuation time above the time required to evacuate. As such, it is a point estimate that says little about a particular event.
4. Since the events were treated globally, and since the equations are nonlinear with respect to population, estimates of life loss will be different when summed over subpopulations and will depend on how the global population is divided.
5. The equations can misestimate by a large margin, even within the original data set.
6. The equations have a built in bias to underestimate when loss of life is large and to overestimate when loss of life is small (see Chapter IV).

Department of Water Affairs,

Natal, South Africa, 1988

This committee report summarized an investigation into the damage from dam breaches caused by September 1987 floods. The goal was to enable predictions regarding the probability, magnitude, damages, and life loss of a future dam failure. Among private dams, those breached included 199 shorter than 5 m and 187 taller than 5 m. Another 449 dams were damaged. Apparently, 11 breached dams and 15 damaged dams were selected as a sample to survey. "Surprisingly, no significant downstream damage or loss of life was caused by any of the breached dams observed" (Jordaan et al., 1988, p.25). The report concludes:

> The damage to be expected due to the breaching of farm earth dams, caused by flooding, up to 12 meters high is negligible and no loss of life can be expected. There can, however, expected to be sic a potential for significant damage and loss of life for a medium sized dam for the flood conditions like those encountered here. (Jordaan et al., 1988, p. 30)

In light of the small sample examined, the report concluded that the remaining cases should be reviewed when resources became available in order to form a probabilistic model for potential loss of life and damage from the failure of small dams.

Abt and Others, 1989

The Toppling Experiment

Though not strictly an effort to quantify life loss, the team of Abt, Wittler, Taylor, and Love (Abt et al., 1989) sought to define the envelope of depth*velocity relationships (called product numbers) that would topple individuals overrun by floodwaters. Since feeble individuals could not be safely tested in a flume, the lower curve of the envelope was defined using a cross-shaped, 5 ft tall, 117.5 lb, rigid-body monolith constructed of concrete-coated Styrofoam. The rectangular base was 1 ft wide and 6 in. thick, and it was placed broad-side into the current.

The upper limits and body of the envelope were defined using 20 test subjects, all healthy, ranging in age from 90 to 201 lb, in height from 5 to 6 ft, and in age from 19 to 54. Fifteen subjects were under 31 years old and only two were female. No subjects wore loose clothing likely to trap the current.

A recirculating flume was fitted with four surfaces: simulated turf, smooth concrete, steel, and a mixture of sand and pea gravel. Subjects were secured in the flume with a safety harness attached to a hoist. They were allowed to first acclimate themselves in flows of 2 to 3 feet and a depth*velocity product number of about 6. The flows were then gradually increased while the subjects periodically tried to walk upstream, face downstream, or walk crosscurrent. When they indicated a loss of stability, the experiment was terminated and repeated within 1 to 2 hours.

Conclusions, insights, and shortcomings

A wide range of product numbers defined individuals' tolerance limits: low of 7.56 and high of 22.84 for healthy adults; low of 2.32 and high of 4.21 for the monolith. Testing for a range was complicated by the fact that an infinite number of depth*velocity combinations are possible. Several conclusions from the study are presented here, along with commentary.

1. Stability was not found to be a function of surface type for the four surfaces tested, but several surfaces common to floodplains and rivers were not tested: slippery clay, tall field grass, uneven surfaces, deep mud which either traps the foot or disintegrates on contact, river cobbles or boulders, or slippery coatings like moss and algae.
2. Even in a controlled laboratory experiment, human stability in flood settings is difficult to quantify. The results from one individual to the next varied tremendously. Nevertheless, among the 20 subjects tested, there was a general trend toward larger individuals withstanding higher product numbers than those who were smaller. In an attempt to quantify this, the following regression equation was proposed:

$$P.N. = \{\exp[0.222(wt * ht/1000) + 1.088]\}$$

where wt = weight and

ht = height.

However, the R^2 value was only 0.48, indicating that the relationship explains less than half of the observed variability. There was even substantial variation when a given subject was tested two to four times within 2 hr, something the proposed equation cannot explain without considering factors such as fatigue, practice, and random moments of imbalance. As a broad generalization, it is safe to say that most subjects lost stability when flows were 4 to 5.5 fps while depths were 2.75 to 3.5 ft deep (hip deep to mid-abdomen). Higher velocities toppled individuals at lower depths—less than 2 ft for flows over 8 fps—and almost half lost stability in waist-deep water moving at 3 mph[8] or less, the speed of a leisurely walk.

3. Project bias was substantial. Seven areas were identified by the original authors. They are summarized here along with additional commentary.
   a) Subjects were willing to take higher risks in light of the safety harness.

   b) Practice improved performance.

   c) Fatigue may have negatively impacted subsequent tests.

   d) The tests did not simulate debris flows or poor lighting. Floods rich in mud would prove much denser, increasing the flood's momentum and increasing the subjects' buoyancy. Large floating debris can readily knock waders into the current.

   e) Subjects carried nothing and tended to splay their arms wide for balance as water depths rose. An adult carrying a child might not perform nearly as well. Even if the adult did not fall, the child might be washed away by depth/velocities less than needed for toppling.

   f) All tests involved water temperatures of 68 – 78°F. Performance would likely drop quickly in winter temperatures.

   g) All subjects were in good health, and most were near the age of their athletic prime. Additionally, only two subjects were women, one of which scored the lowest product number. No subjects wore clothes likely to billow.

   h) The study did not test stability for those of very short stature, especially children.

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[8] 3 mph = 4.4 fps.

Overall, it seems reasonable to conclude that this study more closely represented the outer envelope of human stability for average-sized adults than the middle. While the adrenaline that would accompany a real flood could improve performance, it is likely that the accompanying mud, debris, uneven ground, uncertain lighting, extra burdens, greater distances, and other handicaps would more than offset this effect for many individuals.

It bears repeating that this study was not intended to directly suggest conditions that would lead to loss of life, but rather the conditions that would make a flood potentially dangerous. There are numerous examples of people being swept downstream, clinging to trees, climbing upon houses or floating propane tanks, or otherwise being swept some distance without perishing. On the flip side, if one is swept under branches, caught in a deep eddy, or trapped in some other manner, even an otherwise slow and shallow flow can turn deadly.

Perhaps it is safe to say that, as a rule of thumb, a flow should not be considered life-threatening to most adults until it exceeds 2 ft deep and moves faster than a slow walk. For those of low mobility, such as the elderly, however, even this could prove dangerous: the monolith toppled in flows just under 2 ft deep when velocities ranged from 1 fps to about 2 fps. Also, none of this is meant to imply safe flows for automobile crossings—a leading hazard in flash floods.

DeKay and McClelland for the United States

Bureau of Reclamation, 1991, 1993b

The Model

Under funding by the United States Bureau of Reclamation, DeKay and McClelland[9] (1991) added the failure of Stava Dam in Italy to Brown and Graham's (1988) data set and attempted a more rigorous regression analysis similar to that employed by Lee et al. (1986). The equation they developed in 1991 for life loss was merely one component of a broader goal: determining when dam failure warnings should be issued to minimize costs when a "reasonable" dollar value is assigned to human lives (DeKay and McClelland, 1991, p. 15).[10] Since estimation of life loss (L) has value apart from warning strategies, they presented a revised life-loss equation independent of the larger model in 1993. The revision followed the same regression

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[9] To my knowledge, Duane McClelland is not immediately related to Professor Gary H. McClelland who oversaw the work of Michael L. DeKay within the Department of Psychology at the University of Colorado. At the time of this writing, Gary McClelland and Duane McClelland have never met.

[10] Recognizing that many take offense at the notion of putting a dollar value on human life (this author included), DeKay and McClelland (1991) distinguished between the immeasurable value of an identified life, and the value to society of reducing "the *probability* that any individual within the population at risk will live or die": what they termed a "statistical" life. Nevertheless, they stated that "*any* decision threshold that is established implicitly places a value on human life" (DeKay and McClelland, 1991, p. 9; italics were in the original), argued that this value should be made explicit, and went on to value a statistical human life at between $3 million and $5 million dollars.

procedures used in 1991, but four new floods[11] were added to the data set, and certain values in the original data set were updated in light of new information.[12] Until recently, this revised equation has generally been accepted as the best regression attempt to date, displacing the equations by Brown and Graham in recent practice within the USBR and overshadowing the work by Lee et al. (see, for example, Graham, 1998).

DeKay and McClelland's (1991) cost-minimization approach to warnings is not central to this study, so only their regression equations for estimating L will be presented. Chapter IV explores their model in detail, so only a brief summary is necessary at this point. Table 3.5 presents the complete data set underlying their regression, including the specific variable values assigned to each case.

As with Lee et al. (1986) a certain degree of subjectivity lies behind most variable estimates. This is most prominent with respect to warning times (Wt). When more specific estimates were not available, they modified those values reported by Brown and Graham (U.S. Bureau of Reclamation, 1989) in the following manner: when Wt was reported as less than a certain number (Wt < 1 hr), they divided the upper limit in half; when only a lower limit was reported (Wt > 2 hr), they added 50% to that lower bound; and when a range was reported, they chose the midpoint of the range. Another subjective variable was flooding lethality, renamed flooding forcefulness or *Force* in 1993. It was coded dichotomously: a 1 indicated that more than 15 – 20% of the structures that were inundated were destroyed or seriously damaged by the flood. Because damages were not always known with great precision, DeKay and McClelland (1991, 1993b) relied heavily on the expert judgement of Wayne Graham, who was most familiar with the data set.[13]

Like Lee et al. (1986), DeKay and McClelland chose a logit transformation to preclude the predicted levels of L from being negative or greater than 100%. Unlike Lee et al., however, they did not allow each individual to carry equal statistical weight.

Instead, each case was considered a single data point, as in traditional least squares regression. From this perspective, $p = L/Par$ represents the proportion of fatalities for a given failure event, rather than the probability of an individual dying in a binomial experiment.

The forms of their final 1991 and 1993 logistic equations were, respectively,

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[11] In addition to Stava Dam which was added in 1991, they added Allegheny County, PA, 1986; Austin, TX, 1981; Shadyside, OH, 1990; and Centralia, WA, 1991.

[12] The reasoning and sources underlying each revision is not included in their paper, but can be obtained upon request from the authors and is entitled "Appendix: Additions and Changes to the Bureau of Reclamation Data."

[13] It is likely that Wayne Graham has the most voluminous data files on U.S. dam failures resulting in loss of life of any individual or institution in the world. The authors' gratitude bears repeating for his willingness to allow us to copy extensively from his files. Without his cooperation, this report could not have been developed in its current form.

$$L(p) = \ln\left(\frac{p}{1-p}\right) = -1.650 - 0.513\ln(Par) - 0.822(Wt) + 4.012(lethality) - 3.016(Wt)(lethality)$$

(DM-1; 1991)

$$L(p) = \ln\left(\frac{p}{1-p}\right) = -2.586 - 0.440\ln(Par) - 0.759(Wt) + 3.790(Force) - 2.223(Wt)(Force)$$

(DM-2a; 1993b)

where L(p) = functional notation for the logit transformation of p,

p = L/Par

Par = population at risk (DeKay and McClelland used PAR and Lee et al. used P),

Wt = warning time, and

lethality = Force, as defined above (represented herein by the symbol Fd).

An effort has been made to preserve the notation chosen by DeKay and McClelland while introducing common symbols proposed later. It is later proposed that P replace p to conform to a convention in which all variables begin with a capital letter. Subsequent letters in a multi-letter symbol should be lower case so variables can rest side by side without confusion. Hence, Par has been chosen in preference over PAR; it is later suggested that Fd (dichotomous forcefulness) replace the terms *lethality* and *Force*; and Wt has replaced DeKay and McClelland's symbol WT_{Par} (DeKay and McClelland, 1991) and WT (DeKay and McClelland, 1993b). L also replaces the symbol LOL for loss of life.

Using the right-hand form of equation L-3a to accomplish the inverse transformation, and multiplying through by Par to isolate L, equation DM-2a becomes

$$\frac{L}{Par} = \frac{\exp[-2.586 - 0.440\ln(Par) - 0.759(Wt) + 3.790(Force) - 2.223(Wt)(Force)]}{1 + \exp[-2.586 - 0.440\ln(Par) - 0.759(Wt) + 3.790(Force) - 2.223(Wt)(Force)]}$$

(DM-2b)

which in turn simplifies to

$$L = \frac{Par}{1 + \exp\left[2.586 + 0.440\ln(Par) + 0.759(Wt) - 3.790(Force) + 2.223(Wt)(Force)\right]} \quad \text{(DM-2c)}$$

Choosing an alternate form, this equation can be modified by pulling the first two terms in the exponent out front as $(e^{2.586})(e^{0.440\ln(Par)})$ and simplifying to yield their final 1993 equation:

$$L = \frac{Par}{1 + 13.277(Par^{0.440})\exp\left[0.759(Wt) - 3.790(Force) + 2.223(Wt)(Force)\right]} \quad \text{(DM-2d)}$$

The corresponding equation based on the 1991 data set is

$$L = \frac{Par}{1 + 5.207(Par^{0.513})\exp\left[0.822(Wt) - 4.012(lethality) + 3.016(Wt)(lethality)\right]} \quad \text{(DM-1d)}$$

Although the 1991 equation has a higher R^2 value than the 1993 version (0.9357 vs. 0.840), equation DM-1d has been superseded by equation DM-2d since equation DM-2d is based on the same data set with four additional cases and updated values.

Finally, if desired, equation DM-2d can be expressed as the following two separate equations for a Force of 1 and 0, respectively.

$$L_{high\ Force} = \frac{Par}{1 + 13.277(Par^{0.440})\exp\left[2.982(Wt) - 3.790\right]} \quad \text{(DM-2d.1)}$$

$$L_{low\ Force} = \frac{Par}{1 + 13.277(Par^{0.440})\exp\left[0.759(Wt)\right]} \quad \text{(DM-2d.2)}$$

Equation DM-2d can also be transformed for comparison to other equations. Recognizing that 1 in the denominator is almost always small compared to the other terms in the denominator, the 1 can be dropped, allowing the following simplification:

$$L \approx 0.075(Par^{0.560})\exp\left[-0.759(Wt) + 3.790(Force) - 2.223(Wt)(Force)\right] \quad \text{(DM-2e)}$$

The main value to the approximation in equation DM-2d.1 is that it reveals the close similarity between the results obtained by confining L to positive values not greater than Par (logit procedure) and the best equation DeKay and McClelland developed for their 1991 publication using non-logit, least squares linear regression techniques, as follows:

$$L \approx 0.139(Par^{0.572})\exp\left[-0.895(Wt)+3.266(lethality)-2.404(Wt)(lethality)\right]-0.5 \quad \text{(DM-3b)}$$

This equation DM-3b was rejected because it could produce impossible estimates.

It should be noted that the underlying form of equation DM-3b is

$$\ln(L+0.5)=a+b\ln(Par)+c(Wt)+d(lethality)+e(Wt)(lethality) \quad \text{(DM-3a)}$$

The reason for adding 0.5 to the dependent logarithm is to avoid the dilemma that the logarithm is undefined when L = 0.

The significance of this logarithmic form is that the regression equation will attempt to closely match life-loss values when losses are comparatively small while allowing greater variance when life loss is large. To illustrate this, consider that ln(200) - ln(100) and ln(20) - ln(10) are identically equal to 0.7. In least squares analysis, these residuals of 100 and 10 lives, respectively, would be considered equivalent, generally leading to poor predictions whenever L is large.

Incidentally, since the logit method also involves a log transformation, similar consequences hold for it as well. The full implications of the logit transformation will be explored in Chapter IV.

To explore the relationships used by the USBR, DeKay and McClelland also developed what they felt was “the best expression for loss of life that can be derived via standard regression techniques using only population size and warning time as predictors” (DeKay and McClelland, 1991, p. C11). Like DM-3b, it was based on a log transformation of L.

$$L=1.896(Par^{0.527})\exp[-1.819(Wt)]-0.5 \quad \text{(DM-4)}$$

In their 1993 work, they derived an equation using the same variables and a logit transformation, producing what they believed to be “the best expression for L(p) that can be derived using only WT and Par as predictors” (DeKay and McClelland, 1993b, p. 198).

$$L(p)=0.146-0.478\ln(Par)-1.518(Wt) \quad \text{(DM-5a)}$$

or

$$L = \frac{Par}{1 + \exp[-0.146 + 0.478\ln(Par) + 1.518(Wt)]} \qquad \text{(DM-5b)}$$

At no time did DeKay and McClelland offer a regression equation based on using L as an untransformed dependent variable.

Contributions

DeKay and McClelland are to be commended for producing the best empirical equation to date. Since their approach makes the event the basis for regression rather than the individual, they are using variable estimates consistently with the manner in which they were measured. This is a legitimate theoretical improvement over the assignment of global variables to the individual (see Lee et al., 1986).

Although the equations by Brown and Graham (Brown and Graham 1988; U.S. Bureau of Reclamation, 1986, 1989), Lee et al. (1986), and DeKay and McClelland (1991, 1993b) were all based on global Par rather than subPar, and although they all produced exponential and/or complex forms that are nonlinear with respect to the size of Par, DeKay and McClelland were the first to caution that the application of their equation to subPar would violate the principles under which their equation was developed. Since, proportionately, fewer deaths occur as Par increases, the more Par is subdivided, the greater the sum of all lives lost will become. Also, the regression assumes a high level of heterogeneity found in large Par[14]—something lost when subPar are delineated based on homogeneous traits. These issues and others are addressed in Chapter IV.

DeKay and McClelland (1993b) recommended omitting Par with more than 3 hr of warning time and subdividing the remaining Par into a maximum of two groups if the groups can be distinguished by a significant change in flood forcefulness (i.e., changing from a canyon to a wide floodplain). They also cautioned against applying their equation to cases outside the range of the data set, such as those considered by Ayyaswamy et al. (1974).

Shortcomings

Shortcomings to the development by DeKay and McClelland will be treated in Chapter IV.

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[14] Not only is L nonlinear with respect to Par in all three formulations, but the only case in any of the three data sets that was subdivided prior to regression analysis was the Teton Dam failure. In many cases, these floods swept through many distinct communities and Par_i, causing great life loss in one area and very little in others as the warning time and nature of the flood/Par interaction changed.

The Australian National Committee on Large Dams Recommends the USBR Method, 1994

As of 1994, the Australian National Committee on Large Dams (ANCOLD) recognized that life-loss estimations are an important part of dam safety risk analysis, but that "generally the loss of life issue has been avoided" (Australian National Committee on Large Dams, 1994, p. 5). In this historic review of dam safety risk assessment, they briefly cover the methods already developed by McCann et al. (1985), the 1986 methods proposed by the U.S. Army Corps of Engineers that stopped short of predicting the number of lives lost (Lee et al., 1986), the USBR procedures (U.S. Bureau of Reclamation, 1989), and the DeKay and McClelland (1993b) improvements to the USBR procedures.

Although they recognized that DeKay and McClelland (1993b) had improved upon the USBR equations, they recommended that the 1989 USBR approach be used and they included the key portions of that report as an appendix. The basis for this inconsistency is not clear, except perhaps that DeKay and McClelland offered only an equation, while the U.S. Bureau of Reclamation's 1989 report outlined an entire set of procedures in great detail. In any case, it appears that ANCOLD would not have been opposed to substituting the logit equation developed by DeKay and McClelland for the equations suggested by the USBR.

They make no mention of the models developed by Lee et al. (1986).

B.C. Hydro, 1995

Recognizing that the current empirical developments rely on relatively small databases, Hartford and Kartha (1995) cautioned that judgment must be used in applying any equation to a specific dam that has yet to fail. This said, they recommended the use of the logit equation developed by DeKay and McClelland (1993b) using the general variable estimation methods outlined by the USBR. Following DeKay and McClelland, they would not allow more than two subPar, they subdivided Par only when there was a significant change in flood forcefulness or warning time, and they excluded from Par any individuals with more than 3 hr of warning time. They made a conservative deviation from both DeKay-McClelland and the USBR in their calculation of warning time, however, by assuming it is equal to the travel time of the flood. They also allowed further subdivision of Par in exceptional cases when they attempted more detailed risk analyses.

B.C. Hydro, 1997, 1998

The Model

The B.C. Hydro approach represents an attempt to move beyond the current regression equations and develop a model that tracks individuals in the flood via personalized probability distributions. Although “B.C. Hydro currently uses the methods of Brown and Graham and DeKay and McClelland to obtain an initial estimate” for life loss, “the existing methods of Brown and Graham and DeKay and McClelland were judged to be inadequate for B.C. Hydro’s needs.” From the authors’ perspective, “predicting how people are going to react under conditions of dam break flooding is not simply a matter of putting a few numbers into a generic equation (appealing as it might be to engineers)” (Assaf, Hartford, and Cattanach, 1998, p. 4-17). Underlying this sentiment is a desire to produce not just an average or expected value for life loss, but a probability distribution and a confidence description for that distribution.

It should be recognized that the B.C. Hydro approach is still under development, especially with respect to variable estimation, but the essential framework is in place. The method was developed under the assumption of a seismically induced dam breach, but applies to any failure mode. The following pieces of information are needed:

1. hydrographs, inundation maps, and velocities for each dam breach scenario;
2. Par;
3. approximate distribution of Par with time, distance, and elevation;
4. effectiveness of the local warning systems;
5. effectiveness of emergency response plans for industrial plants, schools, hospitals, individuals, etc.;
6. delay times due to shock or disbelief; and
7. evacuation rates by car and by foot along known evacuation routes and distances (adapted from Assaf, Hartford, and Cattanach, 1998).

Essentially, the method breaks Par down into subPar that are located in individual buildings or locations called units. Each unit is quantified using census data. Average occupancy rates can be used, but specific estimates are preferred and are required for specialized structures like hospitals and schools. Using a computer algorithm, each Par_i is then tracked based on a representative individual who experiences delay in awareness of the approaching flood, must overcome shock and confusion once informed, must mobilize and begin to evacuate, and either makes it free of flooding or encounters flood waters while en route. If free of the flood, there is a certain probability of surviving based on traffic accidents and the like; if met by flood waters, there exists a probability of being toppled, and if toppled a probability of surviving, based on the depth and velocity of flood waters at that location. Calculations continue until the flood wave reaches its peak along any given evacuation trajectory. Life loss is determined probabilistically for each Par_i and summed over Par.

Using the symbols presented by Assaf, Hartford, and Cattanach (1998) Par_i at each unit are defined by equation BC-1.

$$PAR_{UNIT} = TNR_{UNIT} * OAF_{UNIT\,/\,TDWY} \tag{BC-1}$$

The associated loss of life for each unit is defined using equations BC-2 and BC-3.

$$LOL_{UNIT} = PAR_{UNIT} * (1 - P_{SURVIVIING}) \tag{BC-2}$$

$$P_{SURVIVING} = (1 - P_T) * P_{S/E} + P_T * P_{S/C} \tag{BC-3}$$

$$P_T = 0 \qquad \text{if WD < LTD} \tag{BC-3a}$$

$$P_T = 1 \qquad \text{if WD > HSD} \tag{BC-3b}$$

$$P_T = \frac{WD - LTD}{HSD - LTD} \qquad \text{if LTD < WD < HSD} \tag{BC-3c}$$

where $\mathrm{LOL}_{\mathrm{UNIT}}$ = expected loss of life at a given unit (building or area),

$\mathrm{PAR}_{\mathrm{UNIT}}$ = number of people residing at the unit at the time of the flood,

$\mathrm{P}_{\mathrm{SURVIVING}}$ = probability of surviving the flood,

$\mathrm{TNR}_{\mathrm{UNIT}}$ = total number of residents occupying a unit,

$\mathrm{OAF}_{\mathrm{UNIT/TDWY}}$ = expected occupancy of the unit during the particular day, week, and season of the dam failure,

P_{T} = probability of being toppled by the flood,

$\mathrm{P}_{\mathrm{S/E}}$ = probability of surviving given that the individual successfully retreats to safe ground,

$\mathrm{P}_{\mathrm{S/C}}$ = probability of surviving given that the individual was caught by the flood.

WD = water depth,

LTD = lowest toppling depth, and

HSD = highest safe depth.

Currently, key variables are quantified based on distance from the dam as a surrogate for functional relationships with depth and velocity, but the modelers plan to eliminate the use of surrogates in later stages of model development. As examples of current surrogate use, the probability of toppling is defined linearly between those depths that are known to be too shallow to topple anyone ($P_T = 0$) and those which will topple everyone ($P_T = 1$). Theoretically, these depths will vary with flow velocities and the physical capabilities of the fleeing parties, both of which should be considered when selecting the highest safe depth (HSD) and the lowest toppling depth (LTD). In this early stage of model development, however, HSD and LTD are varied only with distance from the dam. They are selected with the help of human stability curves presented in U.S. Bureau of Reclamation (1989). As another example, $P_{S/C}$ theoretically describes the probability of surviving flood waters as a function of flow velocities, individual physical abilities, and the efficiency of rescue operations, but like HSD and LTD, at this stage of model development it currently increases only with distance from the dam.

Modelers simulate a unique evacuation chronology for each PAR_{UNIT} in order to dynamically track the temporal interplay between the location of individuals along their evacuation route and the presence or depth of flooding. The *Time to First Awareness of Flooding* (T_{FAF}) and any subsequent *Time Delays* (T_{DELAYS}) prior to leaving a unit are combined with the subsequent *Rate of Escape* (R_{ESCAPE}; measured as a rise in elevation) to place the PAR_{UNIT} at the appropriate depth when the flood arrives. If the representative person never leaves his or her unit ($t < T_{FAF} + \Sigma(T_{DELAYS})$), then

$$ELV_{PAR@UNIT}(t) = ELV_{UNIT} \tag{BC-4}$$

otherwise,

$$ELV_{PAR@UNIT}(t) = ELV_{UNIT} + \left[t - \left(T_{FAF} + \sum T_{DELAYS}\right)\right] * R_{ESCAPE} \tag{BC-5}$$

where t = the increment of time being considered.

$ELV_{PAR@UNIT}$ = the elevation of the unit's representative member at time t.

ELV_{UNIT} = elevation of the unit calculated from a topographic map and confirmed using GPS equipment during site visits.

The only variable needed to relate this evacuation process back to the life-loss equations presented above is the depth of water through which the representative member of PAR_{UNIT} is wading [WD(t)]. This is the difference between $ELV_{PARUNIT}(t)$ and the *River Stage Level* [RSL(t)] obtained from dam breach simulation using a program like DAMBRK.

$$WD(t) = RSL(t) - ELV_{PAR\,@\,UNIT}(t) \qquad \text{(BC-6)}$$

Running the model using discrete increments of time from t = 0 to t = *the time of peak flooding at the unit*, the river stage at a given increment of time, RSL(t), is compared to $ELEV_{PAR@UNIT}$ at each time increment. The comparisons are terminated when $ELEV_{PAR@UNIT}$ rises above the peak RSL. If the representative person never wades through water deeper than the lowest toppling depth (LTD), she is assumed to escape floodwaters and has a $P_{S/E}$ probability of surviving. If she wades through waters greater than highest safe depth (HSD), her probability of surviving ($P_{SURVIVING}$) drops to $P_{S/C}$ using the maximum depth ever encountered. However, since $P_{S/C}$ currently varies only with distance from the dam, not with depth, the maximum depth is irrelevant until the model is upgraded. If the maximum depth encountered falls between the lowest toppling depth (LTD) and the highest safe depth (HSD), depth will be considered using equation BC-3c.

Finally, the model formally recognizes the uncertainty involved in variable estimates by using a Monte Carlo simulation approach. There are two levels of uncertainty: the average value assigned to each variable and the specific value that holds true for a give unit on the day of the failure event. Assaf, Hartford, and Cattanach (1998) recommend producing either a range of possible values for each variable or a probability function for each. A probability distribution of life loss can then be produced for each type of failure event by running Monte Carlo simulations with the assigned distributions. Based on personal conversations with Assaf, he hopes to use empirical research such as that underlying the current report to provide future guidance on probability distributions to run the model.

The distributions produced for each type of failure event can be combined into a single life-loss probability function by first weighting the distribution for each type of event by its frequency of occurrence and then summing them all together. Failure events differ by time of day, week, and year, as well as by the loading magnitudes leading to breach and the subsequent nature of the failure itself. The entire procedure entails assigning individual probability distributions to each branch of a life-loss event tree, running a separate Monte Carlo simulation on each event pathway that leads to life loss, and summing these terminal life-loss probability distributions. Typically, the terminal distributions will be weighted according to their frequency of occurrence through the structure of the event tree.

Contributions

There are obvious strengths to the approach proposed by B.C. Hydro, despite the fact that it is still under development. Theoretically, the model accounts for most of the elements affecting life loss, circumventing the nonlinearity problems inherent in applying equations developed for global Par to subPar. In this case, the sum of the parts should certainly equal the whole. Also, there is a certain emotional confidence or satisfaction that can be derived from using a model that evaluates life loss on a scale approaching the individual. Although census data do not allow modelers to track individuals with their unique psyche and physical capabilities, choosing individual buildings as units is much more refined than applying regression equations to entire cities or a series of communities for which many variables represent gross averages at best. Moreover, the detail associated with the B.C. Hydro model can potentially satisfy those who share the sentiments of Assaf, Hartford, and Cattanach:

> The criticism that the model is too complex and has too many variables is, we feel, unreasonable. The logic structure is very straightforward and it has withstood expert review. We are confident that we can put the logic structure forward "with moral certainty" as the best way presently available to deal with this component of a risk analysis. . . . Dam safety is a serious business. . . . That risk management for dam safety doesn't come cheaply or easily should not come as a surprise. However, we are duty bound to do the best that we can under the circumstances and demonstrate due diligence in making decisions about public safety. (Assaf, Hartford, and Cattanach, 1998, p. 4-24, 4-25)

Shortcomings

This said, until the developers can achieve their planned model refinements, there are serious shortcomings to this approach as it exists today. The developers agree, believing that their sample predictions have lacked credibility due to the large number of variables that must be estimated subjectively. They hope that this can be overcome through more detailed studies about the important variables and through calibration with historical case studies in order to back-test the model. They also recognize that the model explicitly accounts only for drowning deaths, ignoring deaths due to heart attacks, road accidents, and convergence losses from people not originally located in one of the units under study. They discount the importance of such deaths as random occurrences but these types of deaths could possibly be accounted for in the distribution for $P_{S/E}$.

Apart from the concerns of the model's authors, there are limitations in the logic of the model itself. First, variables like the probability of surviving given that the individual was caught by the flood ($P_{S/C}$), the lowest toppling depth (LTD), and the highest safe depth (HSD) are heavily dependent on the physical capabilities of the individual. Yet, the individual is never in view, only a representative individual assigned to each PAR_{UNIT}. Is LTD based on an infant, a small child, a healthy adult; those who are more feeble or immobile due to age, illness, or disabilities; or a representative composite of these? Since life loss is not based on degrees of death, it is highly unlikely that "average" or "representative" members of PAR_{UNIT} would topple or perish at the same rate as that found by combining the fates of the smaller or less capable with those of the larger or more capable. One solution might be to distribute characteristics of age, mobility, health, and size to the unit representatives according to the proportions in the real population. This still neglects the dynamics found in families and among neighbors—for example, the more feeble are likely to receive assistance, while the more able are often slowed or handicapped by the need to carry children or to help others—but it may be possible to capture some of these dynamics by slowing the rates of evacuation for designated representatives.

Second, notice that an error in estimating a probability is different than a random error. When summed across a large number of units, an erroneous probability distribution skews every result in the same direction. When distributions are multiplied together, errors can compound exponentially. Hence, the more complex the model (the more distributions that must be considered) the greater risk there is for amplification of errors. Estimates that are based on regression using larger-scale units avoid this because the regression accounts for variance among individuals rather than assuming a skewed distribution and then summing the same error across a large number of units.

Third, it will likely prove very challenging to provide dependable estimates for many of the variables needed for the model. This is because realistic field conditions cannot ethically be duplicated in the laboratory and many distributions (i.e., velocity*depth curves) are highly specific not only to each event, but to each location within each reach.

As an example of the challenges faced by the modelers, the values Assaf, Hartford, and Cattanach (1998) used for lowest toppling depth (LTD) and highest safe depth (HSD), which lie behind P_T, were loosely based on a human-stability curve presented in U.S. Bureau of Reclamation (1989, see p. 111 – 112). This, in turn, was derived from the study conducted by Abt et al. (1989) described above. The USBR took the lowest velocity*depth product number found in that study (7.56 for a 90 lb female) and used it to plot a velocity vs. depth curve for which every coordinate pair has a product of 7.56. Presumably, this curve represents the boundary for LTD.[15] While not plotted by the USBR, the highest product number they reported ("over 22" for a 201 lb male) presumably underlies HSD. As mentioned before, these values presume ideal conditions: a uniform flume with no sudden waves, no eddies, the reassurance of safety equipment, no billowing clothing or shoes, no mud or debris, good lighting, no panic or fear, no need to carry children or precious belongings, warm water and weather conditions, no wind, solid ground with good traction that is free from dips or holes or obstacles over which one might trip, and healthy adults over 5 ft tall. Such conditions would not be expected in the field, nor would conditions be consistent across events or for every unit. One could not ethically duplicate true field conditions in a laboratory, and historical data are not likely to be sufficiently detailed or accurate to allow a refined analysis in the narrow range between the lowest toppling depth (LTD) and the highest safe depth (HSD).

Even if one could know the true toppling-death distributions for every unit, current evacuation models cannot place people in sufficiently refined estimates of depth and velocity to make the distributions useful. This level of refinement would require that the rate of escape (R_{ESCAPE}) have a unique function for each PAR_{UNIT}. If a custom equation is to be developed for each unit, the trajectory of escape must be estimated for each residence, a detailed chronology of elevations must be recorded, and a dynamic rate of progress along the path must be described. This, in turn, must be uniquely coded into a computer as a function of physical geography, human psychology, prior experiences with flooding, evacuation experience, the direction children will run and whether or not their parents will give pursuit, the paths residents know and

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[15] Although LTD is only a depth, it has been assumed that B.C. Hydro derived it based on first routing the flood to determine the depth vs. velocity relationships for the flood and then back-calculating the depth that yielded a product number of 7.56 at each cross section downstream.

travel, bottlenecks, the amount of warning time, environmental conditions, prior flooding, traffic accidents, and many other factors. If an individual must complete an evacuation by wading, a reduced rate of progress must be assumed from that point on. This also becomes a function of depth and velocities, requiring that very small time steps be used and that the evacuation function is updated with every time step. If a more generic function were developed that described only elevation changes (Assaf, Hartford, and Cattanach used a uniform rate of 50 m per hour), it completely ignores the fact that most terrain does not rise at a uniform rate, residents may have to scramble down into gullies in order to gain elevation on the other side, and the rate of evacuation will vary dramatically along the length of the floodplain.

Even if both toppling distributions and evacuation functions could be refined, current dynamic flood routing models cannot provide more than a coarse estimate of the depths and velocities at any particular location—far too coarse to target the narrow range between the lowest toppling depth (LTD) and the highest safe depth (HSD). To complicate matters further, catastrophic floods are characterized by unpredictable waves, pathways, and extreme variations in depth due to their turbulence, momentum, and debris load.

Fourth, if the third point is true with respect to the range between LTD and HSD, then equation BC-3c can be discarded, equation BC-3b can be set equal to a value less than 1 to include all depths in which people might topple, and the entire method can be reduced to the flood-travel-evacuation model proposed by Lee et al. (1986).

Assaf, Hartford, and Cattanach (1998) do depart from the flood-travel-evacuation model in one important respect. The entire B.C. Hydro model rests on the assumption that every member of Par evacuates on foot. P_T implicitly assumes an individual must be toppled to perish, and that this in turn is a function of human stability when standing in a flood. This is contrary to both intuition and history. When warning time is more than a few minutes, many individuals choose to evacuate by automobile; when warning times are so short that people do not expect to reach the hillside, they usually seek shelter inside of buildings, especially when there is an upper floor or access to the roof (insight from Appendix B). In a personal conversation with Assaf, he agreed that the assumption of universal evacuation on foot is inadequate and indicated that a future goal is to incorporate more realistic evacuation assumptions into the model. In the mean time, shortcomings five and six, below, still apply.

Fifth, fatalities involving occupants of automobiles constitute an important source of deaths in flash floods and dam failures. To recognize this, the model would have to include rate of escape (R_{ESCAPE}) for motorists and the probability that each PAR_{UNIT} would seek to evacuate by automobile. These probabilities would be specific to the circumstances of each unit. Motorists that did not clear the flood zone would be subject to a depth*velocity*$P_{TRAPPED\ IN\ AN\ AUTOMOBILE}$*$P_{S/C}$ relationship. If it were desired to calculate these types of relationships on the detailed level of LTD, HSD, and the probability of toppling (P_T), the probabilities would have to be specific to each type of vehicle and to each setting (truck, RV, bus, compact, 4-wheel drive; off-road or on-road; bridge, intersection, elevated street, etc.). All of the concerns expressed under the third shortcoming again come into play.

Sixth, while the B.C. Hydro model allows for people to be caught in buildings, it assumes they attempt to evacuate as soon as they can. When people are caught in buildings, the buildings are assumed to offer no shelter: the datum for flood depths remains the ground ($ELV_{PAR@UNIT}(t) = ELV_{UNIT}$) and the probability of surviving given that the individual was caught by the flood ($P_{S/C}$) is applied as if the representative member of PAR_{UNIT} is standing in the full force of the flow. There is no mechanism for determining whether it is safe higher in the building, whether occupants are likely to seek such havens rather than risking an open-water encounter, whether the building walls diminish the depths and velocities, or whether a building remains standing or is destroyed. Based on historical evidence, such considerations dominate life-loss dynamics in many floods, making the depth*velocity dynamics among waders a peripheral issue.

Seventh, in real floods probability of toppling (P_T) depends not only on the severity of the flood, but on the nature of the floodplain. Are there trees, telephone poles, rooftops, floating debris, or other aspects that might provide sources of refuge until emergency help can offer rescue assistance? Although P_T theoretically includes such considerations, Assaf, Hartford, and Cattanach omitted such factors when making their preliminary estimates.

Eighth, the model currently has little empirical foundation, so there is no basis for accepting it in favor of the empirical equations it attempts to replace.

Ninth, the model is likely cost-prohibitive. Expensive research would be required to estimate uncertain variables with the accuracy needed for the model. The modelers also require analysts to confirm the elevation of every unit through site visits, presumably through the use of GPS equipment. If the cost of risk assessment surpasses the costs of the most stringent, standards-based fixes, a life-loss model becomes mute.

Conclusions

Assaf, Hartford, and Cattanach (1998) can be commended for describing important details of interplay between evacuation and life loss based on first principles. Perhaps the greatest strength of the model is that it recognizes that life-loss dynamics are governed by uncertainty that is best captured through probability distributions. If the modelers can achieve their future objectives for refining the model, the model will have great promise. At the present time, however, the model proposes greater detail without regard for historical trends, without any guidance on how to develop reliable distributions, and without sufficient refinement to capture realistic evacuation patterns. It is likely the model developers would be the first to admit this, since their model is in early development. It is likely, with the mounting levels of uncertainty, that an application of the model to a portfolio of dams must either sacrifice detail or consistency.

Graham, 1999

As mentioned earlier, the recent practice of the U.S. Bureau of Reclamation was to use DeKay and McClelland's logit equation DM-2d in place of those by Brown and Graham (U.S

Bureau of Reclamation, 1989). In 1999, the U.S. Bureau of Reclamation began using a model developed by Wayne Graham (Graham, 1999). The model was formally published and is being advocated by leading dam safety risk analysts as the best dam-safety life-loss model currently available.

The Model

Graham expanded the data sets used by Brown and Graham (U.S Bureau of Reclamation, 1989) and Dekay and McClelland (1993b) to include floods of higher relative lethality or that were otherwise different than those in the original data sets. In some cases he selected subpopulations at risk (subPar) to focus on specific sets of circumstances. The mixed data set of overlapping Par and subPar represented approximately 26 dam failures, 40 floods, and 50 populations.

Graham divided the 50 populations among 15 categories based on unique combinations of three dominant factors that influenced life loss: the flood severity, the warning time, and the extent to which the population at risk understood the severity of the approaching flood. He then averaged the proportional life loss ($P_i = L_i/Par_i$) within each category and identified the lowest and highest life loss rates to provide a historic range. As a refinement, he subjectively adjusted the averages and ranges to provide a table of suggested values for use in estimating life loss when a predictive scenario matches one of the 15 categories; the categories were intended to be comprehensive.

Table 3.8 indicates the historic populations that matched each unique combination of variables, the historic fatality rates, their ranges and averages, and Graham's suggested values for use in life loss estimation. The variables and their classifications are defined below with Graham's guidelines on their use. As indicated in the notes to Table 3.8, none of Graham's historical populations fit five of the 15 categories, but he did provide suggested values (best estimates) and ranges for estimating life loss for these categories.

Graham classified flood severity as low, medium, or high. A flood has low severity when homes are flooded but not destroyed; medium severity when some homes or businesses are destroyed or knocked off their foundations, but some homes and trees remain unsubmerged; and high severity when the floodplain is swept clean with little trace of any prior existing structures or vegetation.

As guidance for choosing a classification when applying the model to hypothetical flood events, Graham suggested that flood severity should only be classified as high when a dam fails nearly instantaneously, thereby failing within seconds, and only where flood waters are close enough to the dam to be "very deep" (Graham, 1999, p. 35). To distinguish between low and medium severity, he suggested two criteria, one based on depth and one based on the parameter DV, designated destructive depth (Dv) in Chapter V. Graham defined DV as $DV = (Q_{df} - Q_{2.33})/W_{df}$, where

Q_{df} = discharge at a particular site caused by dam failure.

$Q_{2.33}$ = mean annual discharge at that site (approximately the bankfull flow rate).

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

When depths are less than 10 feet or DV is less than 50 ft^2/s (4.6 m^2/s), flood severity should be low. When depths are greater than or equal to 10 feet, or DV is greater than 50 ft^2/s (4.6 m^2/s), flood severity should be medium when not high.

Graham defined an initial warning as one that comes from the media or an official source. Based on this definition, he chose a trichotomous division of warning time:

1. None (only the sight or sound of the approaching flood serves as a warning).

2. Some (officials or the media begin warning the subpopulation 15 – 60 minutes before the flood arrives).

3. Adequate (officials or the media begin warning the subpopulation more than 60 minutes before the flood arrives).

As these categories indicate, warning time is the elapsed time between when the first official warning reaches a subPar and the flood wave reaches that subPar. As such, it is based on the distance to the subPar, the rate of flood wave travel, and the point in time when official warnings would be initiated. The rate of flood wave travel can be estimated through flood wave modeling.

Table 3.8. Graham's database and suggested values for modeling proportional life loss by category (adapted from Graham, 1999, Tables 5, 6, and 7)

Flood Severity	Warning Time (minutes)	Flood Severity Understanding	Event	Par or SubPar	Size of Par,	Life Loss (L)	Fatality Rate (P)	Historic Average P	Suggested Expected Value of P	Historic Range of P	Suggested Range of P for modeling
High	None	Not Applicable	Vega De Tera Dam	Par	500	150	0.300	0.756	0.75	0.30 to 1.00	0.30 to 1.00
			Bear Wallow Dam	Par	8	4	0.500				
			St. Francis Dam, Cal. Edison Construction Camp	SubPar	150	89	0.593				
			Armero Lahar	Par	27,000	22,000	0.815				
			Stava Dam	Par	300	270	0.900				
			Vaiont Dam	SubPar	1348	1,269	0.941				
			Malpasset Dam	SubPar	30	30	1.000				
			St. Francis Dam, imaginary	SubPar	----	----	1.000				
	15 to 60	Vague	----	----	----	----	----	----	0.75*Tpar	----	(0.3 to 1.0)*Tpar
		Precise	----	----	----	----	----	----	0.75*Tpar	----	(0.3 to 1.0)*Tpar
	> 60	Vague	----	----	----	----	----	----	0.75*Tpar	----	(0.3 to 1.0)*Tpar
		Precise	----	----	----	----	----	----	0.75*Tpar	----	(0.3 to 1.0)*Tpar
Medium	None	Not Applicable	Little Deer Dam	SubPar	50	1	0.020	0.142	0.15	0.02 to 0.43	0.03 to 0.35
			Buffalo Creek coal waste dam	Par	5,000	125	0.025				
			Shadyside flood	Par	884	24	0.027				
			Austin Dam	Par	2,000	78	0.039				
			Lawn Lake Dam, Roaring River	SubPar	25	1	0.040				
			Big Thompson flood	Par	2,500	144	0.058				
			Malpasset Dam	Par	6,000	391	0.065				
			South Fork Dam, Johnstown	SubPar	19,806	1,756	0.089				
			Mill River Dam	SubPar	750	138	0.184				
			South Fork Dam, Woodvale	SubPar	1,247	314	0.252				
			Laurel Run Dam	Par	150	40	0.267				
			Kelly Barnes Dam	Par	100	36	0.360				
			Heppner flood	Par	470	200	0.426				
	15 to 60	Vague	Black Hills flood	Par	17,000	245	0.014	0.014	0.04	0.014	0.01 to 0.08
		Precise	Teton Dam, Wilford	SubPar	600	5	0.008	0.008	0.02	0.008	0.005 to 0.040
	> 60	Vague	Arkansas River flood	Par	2,000	100	0.050	0.050	0.03	0.050	0.005 to 0.060

Table 3.8. Continued

Flood Severity	Warning Time (minutes)	Flood Severity Understanding	Event	Par or Sub Par	Size of Par	Life Loss (L)	Fatality Rate (P)	Historic Average P	Suggested Expected Value of P	Historic Range of P	Suggested Range of P for modeling
Medium	> 60	Precise	Baldwin Hills Dam, to Sanchez Drive	Sub Par	100	0	0.000	0.033	0.01	0.0 to 0.080	0.002 to 0.020
			South Fork Dam, South Fork	Sub Par	200	5	0.025				
			South Fork Dam, East Conemaugh	Sub Par	2,000	52	0.026				
			South Fork Dam, Mineral	Sub Par	200	16	0.080				
Low	None	Not Applicable	South Davis County Water Imp. Dist. #1 Dam	Par	80	0	0.0000	0.007	0.01	0.0 to 0.025	0.0 to 0.02
	15 to 60	Vague	Seminary Hill Reservoir	Par	150	0	0.0000	0.010	0.007	0.007 to 0.012	0.0 to 0.015
			Allegheny County Flood	Par	2,200	9	0.0041				
			Mohegan Park Dam	Par	1,000	7	0.0070				
			Lee Lake Dam	Par	80	2	0.0250				
			Lawn Lake Dam, Aspenglen Campground	Sub Par	275	2	0.0073				
			Brush Creek flood	Par	2,380	20	0.0084				
			Austin flood	Par	1,180	13	0.0110				
			Texas Hill Country flood	Par	2,070	25	0.0121				
		Precise	Quail Creek Dike (Dam)	Par	1,500	0	0.0000	0.0000	0.002	0.0	0.0 to 0.004
	> 60	Vague	---	---	---	---	---	---	0.0003	---	0.0 to 0.0006
		Precise	Phoenix area flood	Par	6,000	0	0.0000	0.0003	0.0002	0.0 to 0.002	0.0 to 0.0004
			Bushy Hill Pond Dam	Par	300	0	0.0000				
			Lawn Lake Dam, Downstream from National Park	Sub Par	4,000	0	0.0000				
			Prospect Dam	Par	100	0	0.0000				
			South Plate River flood	Par	10,000	1	0.0001				
			Passaic River Basin flood	Par	25,000	2	0.0001				
			flooding from Hurricane Agnes	Par	250,000	48	0.0002				
			Kansas River flood	Par	58,010	11	0.0002				
			Teton Dam (Rexburg to American Falls)	Sub Par	23,000	5	0.0002				
			Great Flood of 1993	Par	150,000	38	0.0003				
			Baldwin Hills Dam, Sanchez Drive to Coliseum	Sub Par	16,400	5	0.0003				
			DMAD Dam	Par	500	1	0.0020				

Table 3.8. Continued

SYMBOLS:

L	Life loss specific to the Par or subPar in question
Par	Population at risk
P	Proportional life loss ($P_i = L_i/Par_i$)
Tpar	Threatened population, defined as the population that remains in the floodplain when the flood wave arrives.

NOTES:

1. Column 5, “Par or SubPar,” was not included in Graham’s tables. The column was added to indicate whether the population in question represented the global population at risk or a subpopulation. In cases where an event is designated as Par in one row and a subPar in another row, the populations are nonexclusive.

2. There were no historical examples for 5 of Graham’s 15 categories: the four categories with high flood severity and warning time greater than 15 minutes and the single category with low flood severity, warning time greater than 60 minutes, and vague flood severity understanding.

3. Graham suggested approaches for estimating life loss for those five categories for which no empirical data existed (see Note 2, above). For the four categories with high flood severity and warning time greater than 15 minutes, Graham suggested that the analyst calculate the proportion of the threatened population that perishes ($Ptpar_i = L_i/Tpar_i$) instead of the proportion of the population at risk that perishes (P). He recommended applying the proportional life-loss rate (P) that is found when there is no official warning to Tpar rather than Par, but he specifically indicated that his model provides no guidance on how to estimate the size of Tpar. For the category with low flood severity, warning time greater than 60 minutes, and vague flood severity understanding, Graham suggested an expected value and range of expected proportional life loss based on judgement and patterns seen in related categories.

4. “St. Francis Dam, hypothetical,” the final data point under events with high flood severity and no warning time, is not strictly an empirical data point. Graham did not use the word hypothetical, but he wrote “How could you survive?” (Graham 1999, Table 5) and excluded estimates of population at risk and life loss to indicate he was considering the concept of the St. Francis Dam failure rather than the historical record. The historical record indicates amazing accounts of people who actually did survive, so at most locations the historical life loss was close to, but slightly less than, 100%.

5. The symbols L, Par, P, Tpar, and Ptpar were not used by Graham. They are defined in Chapter V and are consistent with the concepts Graham described.

Graham produced Table 3.9, based on his expert judgement, to provide guidance on estimating when a dam failure warning would be initiated for failure of an earthfill dam.

Flood severity understanding is a dichotomous variable classified as vague or precise. The distinction is subjectively based on the flood wave travel time and whether a warning precedes or follows the actual time of failure. The greater the flood wave travel time, the more likely subsequent warnings will accurately convey the flood severity because officials will have time to evaluate the nature of the flood. However, if a warning anticipates a dam failure, that warning is likely to have reduced credibility and result in vague flood severity understanding among recipients.

As with previous models, it is first necessary to select a dam-failure scenario to use Graham's model to predict life loss. This scenario should include:

1. Temporal considerations that are relevant to the area (day or night, seasonal variations in population, daily and weekly migration patterns for work and school, other temporal considerations).

Table 3.9. Guidance for estimating when dam failure warnings would be initiated for failure of an earthfill dam (adapted from Graham, 1999, Table 2)

			When Would Dam Failure Warning Be Initiated?	
Cause of Failure	Special Considerations	Time of Failure	Many Observers at Dam (hours before dam failure)	No Observers at Dam (hours after floodwater reaches first populated area)
Overtopping	Drainage area at dam < 100 mi^2	Day	0.25	0.25
		Night	(0.25)	1.00
	Drainage area at dam > 100 mi^2	Day	2.00	1 hr before dam failure
		Night	1.00 - 2.00	0 - 1 hr before dam failure
Piping	Full reservoir, normal weather	Day	1.00	0.25
		Night	(0.50)	1.00
Seismic	Immediate failure	Day	(0.25)	0.25
		Night	(0.50)	1.00
	Delayed failure	Day	2.00	0.50
		Night	2.00	0.50

NOTES:

1. "Many Observers at Dam" means that a dam tender lives on high ground and within sight of the dam, the dam is visible from the homes of many people, or the dam crest serves as a heavily used roadway. These dams are typically in urban areas. Negative values mean that the warning is initiated after the dam fails.

2. "No Observers at Dam" means that there is no dam tender at the dam, the dam is out of sight from nearly all homes, and there is no roadway on the dam crest. These dams are usually in remote areas.

2. An estimate of when warnings would be officially initiated and how this would be influenced by the chosen temporal considerations.

3. The area flooded and the associated flood severity.

4. An estimate of the size of each subpopulation at risk. Graham's model is intended to be applied to relatively homogeneous subPar, so the Par should be subdivided when areas differ in terms of the flood severity, warning time, or flood severity understanding. Unless a failure flood is exceptionally large, Par should extend 30 miles downstream and no further.

Once the size of each subPar is determined and its associated flood severity, warning time, and flood severity understanding, the analyst multiplies the size of each subPar by the suggested value of P from Table 3.8, estimates the range of life loss for each subPar using the suggested range of P, and sums across the subPar to determine the total estimated life loss (estimated average) and range of life loss.

<u>Contributions</u>

Graham's 1999 life-loss model has many appealing characteristics, which explains its rapid rise to prominence in dam safety risk analysis practice in Australia and North America. The more notable strengths of the model are itemized below:

1. The database on which the model relies contains a greater number of data points and a more diverse selection of event characteristics than the databases underlying previous dominant empirical models. This increases the model's credibility and range of application.

2. The life-loss equations take the form $L_i = P_i*Par_i = (\text{best estimate of } L_i/Par_i)*Par_i$. There are no inherent nonlinearities in the relationship between P or L and the size of Par, so the estimate of L is not necessarily increased when the model is applied to subPar. This allows the analyst to apply the model in ways that are most intuitively satisfying by focusing on relatively homogeneous subPar for those events where Par is clearly heterogeneous with respect to flood severity, warning time, or flood severity understanding.

3. By providing a range of estimated life loss, rather than just a best estimate, the model begins to explicitly recognize the inherent role that uncertainty plays in life-loss estimation.

4. Graham has identified three variables that empirically play dominant roles in rates of life loss: flood severity, warning time, and the relative urgency with which warning recipients feel they must evacuate.

5. The model affirms the importance of viewing life loss from the vantage point of subPar that are relatively homogeneous with respect to key predictive parameters. This is clear since 18 out of Graham's 50 data points are subPar, the model explicitly breaks life-loss estimation down on the basis of homogeneous "bins," and Graham indicates that the model should be applied to subPar rather than heterogeneous global Par.

6. Life-loss relationships were empirically grounded and refined based on the judgement of a leading life-loss expert (Wayne Graham). The suggested ranges have credible orders of magnitude, they progress in a logical sequence, and they are open to refinement as additional data becomes available.

7. A key insight incorporated into the DeKay-McClelland equation was the importance of flood severity. Graham has expanded this concept from a dichotomous variable to a trichotomous variable, refining its application.

8. The model is relatively easy to understand and easy to apply. The extent to which life-loss estimates are repeatable by independent analysts depends on the extent to which they agree on the natural division of subPar and the corresponding estimates of warning time and flood severity understanding. Graham has provided guidelines that should make agreement on these parameters relatively high.

Limitations

The primary shortcomings of Graham's model arise because the model does not go far enough in subdividing Par into subPar that are homogeneous with respect to key parameters or Graham defines key parameters in a manner that is sub-optimum. The most important limitations are explained below:

1. Although Graham's data set includes subPar that are more homogeneous than in previous data sets, both the Par and the subPar still represent high levels of heterogeneity with respect to flood severity, warning time, or flood severity understanding. It is difficult to know the extent to which historical life-loss rates apply to subPar chosen for modeling when the historical life-loss rates are based on non-homogeneous Par and subPar.

For example, the Par_i Graham used to estimate rates of life loss when the floodplain is swept clean may result in underestimates of life loss when Graham's suggested life-loss rates are applied to more homogeneous subPar. Referring to events in Table 3.8 with high flood severity, the following modifications to Graham's assigned values could be made based on research that is documented in unpublished working papers produced by Duane McClelland and that underlie Table C in the current report:

a) 125 out of 150 houses were destroyed due to the failure of Vega De Tera Dam. If a homogeneous subPar were chosen, such that Par_i was limited to people in buildings that were destroyed, Par_i would be 125/150*500 = 417 instead of 500 and the life-loss rate would be 36% instead of 30%.

b) All that is known about the Bear Wallow Par_i is that two houses were destroyed and all 4 occupants were killed in one of the two houses. It is not known how many people escaped the second house, whether anybody occupied the second house during the flood, or even whether the report of a second house was accurate. If one limited Par_i to the known occupants of the floodplain, the life loss rate would be 100% instead of 50%.

c) The California Edison Construction Camp was a tent camp located in a high meadow, so the maximum flood depths in the camp were about 10 feet. If flood severity is defined as the damages that would have occurred to solid buildings, the flood severity may have been medium instead of high.

d) It is unlikely that all 27,000 members of Par during the Amero Lahar were located in areas that were swept clean, so a life-loss rate of 0.815 may be low compared to that in the hardest-hit regions.

e) Twelve of the 300 members of Par during the Stava Dam failure were located in an undamaged portion of the Dolomiti Hotel. The homogeneous subPar with a high flood severity had a life-loss rate of 270/288 = 94% rather than 90%.

f) Nearly every survivor of the Vaiont Dam failure in Langarone, Italy, was located far up a hillside where flooding had low severity and every person survived. Of those located where the floodplain was swept clean, the fatality rate was 99%, not 94%.

g) See Note 4 under Table 3.8: The rate of life loss during the St. Francis Dam failure varied by location, but in the hardest-hit areas, the rate of life loss varied from about 71% to 100%, with a representative value of around 93%– 96%.

h) McClelland and Bowles (current report) conducted a detailed analysis of 38 subPar for which every structure was completely destroyed. Among people that failed to evacuate ($Tpar_i$), life loss averaged 86%, although in some cases the people had moved to safer locations before the flood arrived. In a subsequent analysis of 45 homogeneous subPar, the analyses were refined to consider only people who encountered the flood in areas where every house was destroyed or would have been destroyed. Under these conditions, the life loss rate increased to an average of 92%.

These contrasts between subPar that are homogeneous with respect to high flood severity and those that are merely dominated by high flood severity suggest that an expected value for P might be on the order of 0.86 or higher for homogeneous subPar experiencing high flood severity and no warning time. The range of life loss would likely also be higher. Similar analyses could be conducted for the other categories in Table 3.8. In summary, the heterogeneity in the underlying data set calls into question the extent to which the suggested values for estimating P apply to the unique characteristics of any given subPar.

2. Graham's trichotomous approach to flood severity is an improvement over Dekay and McClelland's dichotomous approach to flood forcefulness—especially because it recognizes that rates of life loss are much higher among structures that are swept away than among structures with major damage. Nevertheless, medium flood severity is inherently heterogeneous with respect to housing damages and loss of shelter (see variable Ls in Chapter V) because it includes every combination of housing damages between no houses being washed off their foundations and the floodplain being swept clean. This heterogeneity, in combination with large differences in life-loss rates between categories of flood severity, builds a form of nonlinearity

into the model that can cause life-loss estimates to vary dramatically based on how Par is subdivided into subPar.

To illustrate this point, consider the Buffalo Creek coal waste dam failure. Graham has represented the population at risk for the Buffalo Creek coal waste dam failure as a single Par with medium flood severity and no warning time (Table 3.8). Historically, there were 17 distinct mining towns spaced in regular increments along the 15-mile-long Buffalo Creek Valley. In the upper reaches, flood severity was high; in the middle reaches, flood severity was medium longitudinally and ranged from high to medium laterally; and in the lower reaches, flood severity was low. Because Graham's model is intended to be applied to subPar, there would naturally be at least 17 subPar that could be combined into three subPar based on flood severity and no warning time (with no warning, flood severity understanding does not apply, reducing 15 potential categories to three). Historically, there were 1,084 flooded houses, which results in an occupancy of 4.61 persons per house at the time of the flood based on Graham's estimate of Par = 5,000.[16]

In the upper half of the valley, the flood progressed in a manner that utterly stripped the center of the valley of every structure, wiping it clean, and that damaged or displaced structures near the edge of the valley, causing them to stack up. At least two approaches to subPar are possible using Graham's model: one that subdivides by community, and one that subdivides by lateral distance from the original stream channel. In the first case, the floodplain was swept clean for the first 35 houses, followed by a mix of obliteration and major damage for the remainder of the valley until 163 houses experienced only minor damage in the two towns at the valley mouth. Using this approach, L = (4.61 persons per house)*[(35 houses in a high flood severity subPar * 0.75) + (886 houses in a medium flood severity subPar * 0.15) + (163 houses in a low flood severity subPar * 0.01)] = 741 or 15%.

In the second approach, 546 houses were wiped away in a nearly continuous strip down the center of the valley. Adjacent to this continuous subPar were subPar that were occasionally discontinuous, depending on how the flood bounced down the valley. However, the 375 houses making up these subPar all experienced medium flood severity with a mix of damages: many houses were knocked off their foundations and piled up downstream and only 58 houses had minor damage. Finally, all 163 houses in the lowest towns experienced low severity flooding. Defining three subPar by the flood severity in the surrounding area, L = (4.61 persons per house)*[(546 houses in a high flood severity subPar * 0.75) + (375 houses in a medium flood severity subPar * 0.15) + (163 houses in a low flood severity subPar * 0.01)] = 2,155 or 43%.

If warning time was greater than 15 minutes for some subPar, the number of subPar the analyst must consider would increase, and the number of possible life-loss estimates would similarly increase, although the discrepancies would likely be less dramatic than those seen above.

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[16] Although Graham indicates that there was no official warning, our research indicates that there were official warnings by radio, by police, or by mining officials that preceded the flood arrival in most communities by more than 48 minutes. The warning time for individuals was often much less and the flood severity understanding was sometimes vague. Our research also suggests that, in contrast to a Par of 5,000, a Par of about 3,170 was more likely the case.

To the Graham Model's credit, the gross overestimation of life loss in the case of the Buffalo Creek coal waste dam failure is probably due more to a misclassification of the flood event than to a predictive weakness in the model. Based on our research, it may be more appropriate to classify the global Par as experiencing medium flood severity with an average warning time slightly less than one hour and vague flood severity understanding. Also, there are compelling reasons to assume that Par was about 3,170 people, instead of 5,000. Given these changes, and treating the population at risk as a single Par, Graham's model would estimate the life loss as 3,170*0.04 = 127. This compares favorably with Graham's historic estimate of L = 125.

3. As with flood severity, Graham's definition of warning time results in built-in heterogeneity that can potentially limit the accuracy and flexibility of the model. Limitations caused by a trichotomous definition of official warning time fall into four categories:

a) A warning time of 0 – 15 minutes is not specifically defined, but it appears that it must be treated as no warning. This is unfortunate, because, historically, the first fifteen minutes of warning time have often produced the greatest reductions in life loss. Table 3.10 provides important examples of specific, historic subPar for which short warning times dramatically reduced life loss. Table 3.10 is based on Table C in Appendix C, it is not comprehensive, and it could easily be expanded. The subPar number (#.#) refers to the event number and subPar number in the table.

b) A warning must come from a public official or the media before it can be considered in the model. This discounts the historically important role that informal warnings from neighbors and sensory clues have played. Figure 7.X, which is described in Chapter VII, suggests that, given the right circumstances, a three-minute warning from sensory clues or informal sources can reduce the expected life loss by more than 80%.

c) Figure 7.X illustrates that small changes in the average warning time can have large impacts on life loss. This is not adequately captured by the broad increments of warning time used in Graham's model.

d) It is difficult to compare events using warning time, because warning time gives no indication of the required evacuation time. A warning time of eight minutes may be more than enough time for a family to climb above the approaching flood in a narrow canyon, but it may be difficult to evacuate from a large city with a warning time of 30 or 45 minutes. Similarly, a 15-minute warning may be adequate to evacuate a hotel filled with healthy adults, but it may be possible to evacuate only a small fraction of the residents in a nursing home given the same warning time. As this illustrates, warning time without some measure of the representative evacuation time (Ret) is a poor metric for comparative life-loss estimation.

Table 3.10. Examples of low life loss due to official warnings shorter than 15 minutes

SubPar	Flood Severity (approx.)	Warning Time (minutes)	Flood Severity Understanding	Proportional Life Loss Predicted by Graham's Model (P)	Historic Proportional Life Loss (P)
12.1	High	2	n/a	0.75	0.079
29.12	Low	5	n/a	0.01	0.00
29.8	Medium	5	n/a	0.15	0.00
18.13a	High	4	n/a	0.75	0.00
18.1a	High	10	n/a	0.75	0.00
29.7	High	5	n/a	0.75	0.00
29.2	High	9	n/a	0.75	0.024
29.6	High	5	n/a	0.75	0.049
29.10	High	9	n/a	0.75	0.00
29.13	High	5	n/a	0.75	0.072
29.14	High	7	n/a	0.75	0.10

4. Graham's model is based on a data set for which the inclusion or exclusion of zero-life-loss events is subjective (see Chapter II). This is not a major concern, but it weakens the credibility of the resulting empirical life-loss rates. For example, if 20 subPar with medium flood severity, warning time in excess of 60 minutes, precise flood severity understanding, and zero life loss were added to the data set, the historic average life loss in this category would be reduced from 0.033 to 0.005.

5. Although the model recognizes the importance of uncertainty, uncertainty is not captured in probabilistic terms. One possible solution to this would be to calculate relative frequency distributions from the data points and then to use these to characterize the uncertainty. Unfortunately, there are currently too few data points in most or all of the categories to make this practical or credible.

6. The model would be strengthened if the available guidance on how to apply it were refined.

7. Currently, flood severity is based on damage to buildings. This concept should be expanded to include measurements of flood severity for other locations, such as campgrounds and among motorists (see Par type in Chapter V).

   a) Flood severity is based on depth and the variable DV. Table C in Appendix C offers many examples of subPar for which Graham's criteria of depth or DV are violated when comparing housing damages that are low or medium. Additional empirical work might refine these guidelines.

   b) The classification of subPar for which warning time falls between 0 and 15 minutes should be clarified.

   c) The current definition of flood severity understanding is subjective and difficult to standardize without more guidance.

Comparing Graham, 1999,to Previous Models

An understanding of the strengths and limitations presented above can give guidance regarding what the Graham 1999 model can and cannot do for the analyst and how to avoid its misapplication. An important second level of critique would be to compare the predictive potential of the Graham 1999 model to previous models—in particular to the DeKay-McClelland 1993 model, which it is currently replacing. The comparison, however, is not straightforward because Graham seeks to present the range of potential life loss rather than just a best estimate. Moreover, Graham's model is designed to be applicable to subPar and very high lethality events, two applications for which Equation DM-2d was not intended.

Duane McClelland and David Bowles are completing a comparison between Graham's 1999 model and Equation DM-2d, but we feel that it would be premature to publish the preliminary results. By way of generalities, Graham's 1999 model appears better suited to high lethality events, but Equation DM-2d may have some advantages in other applications. We hope to publish a full comparison in the near future.

Conclusions

In spite of what may appear to be a lengthy list of shortcomings, Graham's model also has a rather impressive list of strengths. Overall, there is an important need to continue developing and refining better life loss models, but Graham's model presents a credible and defensible approach that can be used with confidence if one understands its limitations. For example, due to its ease of use and empirical underpinnings, the model is a practical tool for making a first-cut at life-loss estimation or for making a preliminary comparison of dams in a portfolio.

If not used blindly, the model could also serve well in more detailed life-loss assessments. However, until demonstrated otherwise, it should not be assumed that Graham's model offers a predictive advantage over Equation DM-2d when applied to lumped, heterogeneous Par or heterogeneous subPar in flood settings that are not highly lethal. If, however, one were to use many small subPar, Graham's model would probably be preferable since the underlying equations do not increase the proportion of life loss as Par becomes smaller—an adverse characteristic of Equation DM-2d (see Chapter IV).

Similarly, in the narrow category of high-lethality events with zero warning time, Graham's model is preferable over Equation DM-2d because Equation DM-2d was not derived with this application in mind. Nevertheless, estimates of life loss will likely be low if they depend on Graham's model and are applied to strongly homogeneous, high-lethality events with zero warning time or warning time greater than 15 minutes. This shortcoming and similar shortcomings could be reduced if Graham's model were refined using more homogeneous subPar than found in his 1999 data set.

The section on limitations here and for Equation DM-2d, combined with limitations to Equation DM-2d presented in Chapter IV, suggest a danger inherent in both the Graham model and Equation DM-2d. Because both models are deceptively simple to apply, there is a risk that the models will be used by those who don’t understand their limitations and biases because the users lack familiarity with the underlying data sets. Graham’s model can find a valuable place in modern risk assessment, but the model should not be used as a simple solution without the results being evaluated and interpreted by a qualified expert.

Tabular Comparison

The methods for estimating loss of life have evolved not only with respect to their methodology and the level of detail considered important, but also with respect to the variables considered most influential or useful. Table 3.11 attempts to provide an overview, listing the variables identified by each set of authors, the ones they selected for use in their models, and the ones used for secondary refinement following an initial estimate. Since most of the models do not allow for subjective refinement, the latter category applies only in limited cases.

A degree of interpretation was necessary in describing each variable since authors often use different words to describe similar or identical concepts. It is also easy to overlook a variable briefly mentioned by an author but omitted from his or her model. Every effort has been made to be complete and accurate, but this list should be viewed as a representative overview that has not been confirmed by the authors themselves.

Table 3.11. Predictive variables recognized as important by the authors of existing life-loss models in dam safety

* I = identified by the author(s), M = used directly in the model, A = used to adjust the model estimation	Ayyaswamy et al. (1974)			Friedman (1975)			Petak and Atkisson (1982)			McCann et al. (1985) Stanford/ FEMA			Paté-Cornell and Tagaras (1986)			Brown and Graham (1988) U.S.B.R. (1986, 1989)			Lee et al. (1986) Corps of Engineers			DeKay and McClelland (1993b) U.S.B.R.			Assaf, Hartford, and Cattanach (1998) B.C. Hydro			Graham (1999) U.S.B.R.
Variable	I*	M*	A*	I	M	A	I	M	A	I	M	A	I	M	A	I	M	A	I	M	A	I	M	A	I	M	A	I
dam/reservoir/breach sizes	●									■	■					■	■		●	●								■
inundation mapping	●									■	■					■	■		●	●		■			●	●		■
depth of flooding	●	●		■			●	●		■	■					■		■	●	●		■			●	●		■
velocity of flow							●			■						■		■	●			■			●	●		■
peak discharge																			●									
force exerted by flow							●															■	■					
flood lethality																■		■	●			■						
damage to structures				■	■		●	●								■		■	●			■						■
types of structures							●	●								■		■	●									■
floating debris							●									■		■										
water temperatures																■		■	●									
environmental conditions																■		■										■
adjusted for flash flood				■	■																							
Par	●	●					●	●		■	■		●	●		■	■		●	●		■	■		●	●		■
subPar by time of day	●	●					●			■	■		●	●		■	■		●	●		■	■		●	●		■
subPar by time of week or year										■		■				■	■		●	●		■	■		●	●		■
subPar by distance	●	●								■	■	■							●	●					●	●		■
subPar by depth				■			●	●		■	■		●	●					●	●								■
subPar by travel time										■									●	●								
subPar by warning time																■	■		●	●		■						■
subPar by flood forcefulness																						■	■					■
subPar by unit (residence, etc.)																									●	●		
alerts																						■						
warning time							●			■		■	●		●	■	■		●	●		■	■		●	●		■
rate event threatens dam																■	■		●	●								■

Table 3.11 continued

* I = identified by the author(s), M = used directly in the model, A = used to adjust the model estimation	Ayyaswamy et al. (1974)			Friedman (1975)			Petak and Atkisson (1982)			McCann et al. (1985) Stanford/ FEMA			Paté-Cornell and Tagaras (1986)			Brown and Graham (1988) U.S.B.R. (1986, 1989)			Lee et al. (1986) Corps of Engineers			DeKay and McClelland (1993b) U.S.B.R.			Assaf, Hartford, and Cattanach (1998) B.C. Hydro			Graham (1998) U.S.B.R.
Variable	I*	M*	A*	I	M	A	I	M	A	I	M	A	I	M	A	I	M	A	I	M	A	I	M	A	I	M	A	I
monitoring capabilities																■	■		●	●								
threat recognition time																■	■		●	●								
decision process to warn																■	■		●	●					●	●		
flood warning system										■		■	●		●	■	■		●	●								
warning rate, extent, effect																■		■	●	●					●			
prior awareness							●									■		■	●									
psychological impressions							●									■		■	●									
personal mobilization time																			●	●					●	●		
vehicular travel time																			●	●								
queuing delay time																			●	●								
evacuation rate	●	●								■		■	●		●	■		■	●	●		■			●	●		
rate of elevation gain																									●	●		
ease of evacuation																■		■	●						●			■
success of rescue attempts							●												●						●			
convergence																■		■				■			●			
topography	●	●		■						■	■		●	●					●	●		■			●	●		
zoning	●			■						■	■								●	●								
# of bridges crossing river																			●	●								
future development				■	■								●	●														
urban vs. rural																			●	●		■						
demographics in floodplain	●															■		■										
age																■		■	●									
mobility																■		■	●									■
special facilities or groups																■		■	●						●	●		
experience in floods/evacuation																■		■	●	●		■						

Table 3.11. Continued

* I = identified by the author(s), M = used directly in the model, A = used to adjust the model estimation	Ayyaswamy et al. (1974)			Friedman (1975)			Petak and Atkisson (1982)			McCann et al. (1985) Stanford/ FEMA			Paté-Cornell and Tagaras (1986)			Brown and Graham (1988) U.S.B.R. (1986, 1989)			Lee et al. (1986) Corps of Engineers			DeKay and McClelland (1993b) U.S.B.R.			Assaf, Hartford, and Cattanach (1998) B.C. Hydro			Graham (1998) U.S.B.R.
Variable	I*	M*	A*	I	M	A	I	M	A	I	M	A	I	M	A	I	M	A	I	M	A	I	M	A	I	M	A	I
know-how																■		■	●			■						
information networks																■		■	●			■						
family dispersion																■		■	●									
attitudes																■		■	●									
false alarms/misinformation																■		■	●			■						
availability of sensory clues																												■
antecedent depths & velocities																												■
activities of Par																												■

Summary: Major Existing Approaches to Life Loss and Their Limitations

Stanford/FEMA model (modified by the Institute for Water Resources)

This approach uses an irregular grid to divide the inundation zone into subpopulations based on land use, warning time, and depth of flooding. Individual structures are marked on a map. A fatality rate is then assigned to each unique combination of depth, warning time, land use, warning effectiveness, and other variables.

Shortcomings can be summarized as follows:

1. Rates of life loss must be subjectively estimated without an empirical basis.
2. The number of life-loss rates that must be estimated is equal to the number of uniquely defined subPar, which grows exponentially as more characterizing variables are considered.
3. Historically, life loss has not been primarily a function of depth in isolation from velocities.

Brown and Graham (USBR)

Empirically based life-loss equations are a function of the size of the population at risk and a trichotomous division of warning time. Initial estimates can be adjusted based on subjective considerations.

Shortcomings can be summarized as follows:

1. Their trichotomous treatment of warning time risks subjective oversimplification.
2. The regression equations lack refinement.
3. The equations are intended to be applied to subpopulations but were developed using global populations. Since one of the three equations is nonlinear with respect to population size, the resulting life-loss estimates may vary depending on how a population is subdivided.
4. These equations were based on only 23 flood events, each quite unique.
5. The equations can misestimate by a large margin, even within the original data set.

Lee et al. (Corps of Engineers)

Using 47 flood events, Lee et al. (1986) developed a logit relationship in which a logit transformation of the fraction of lives lost was regressed against the warning time, the peak depth of the flood, and dichotomous treatments indicating whether or not the population was urbanized and had experience with flooding.

Shortcomings can be summarized as follows:

1. They treated the individual as the unit for regression, causing events with large populations to dominate the results.
2. Some of the floods were slow-rising, widely dispersed events, atypical of dam failures.
3. Since subpopulations were not considered separately, the peak depth of flooding did not pertain to most people in the flood.
4. Current definitions of warning time do not describe the average warning time, the extent to which a warning is propagated, the effectiveness of the message at mobilizing a timely evacuation, informal types of warnings like sensory clues and shouts from neighbors, or the time required to evacuate.
5. Since the events were treated globally, and since the equations are nonlinear with respect to population, estimates of life loss will be different when summed over subpopulations and will depend on how the global population is divided.
6. The equations can misestimate by a large margin, even within the original data set.

DeKay and McClelland (USBR)

After adding four new cases to the data set used by Brown and Graham (U.S. Bureau of Reclamation, 1989), Dekay and McClelland (1993b) developed a regression equation using a logit transformation of the fraction of lives lost against the population at risk, warning time, and a dichotomous description of high or low flood forcefulness. Until recently, this was the most widely accepted and applied equation.

For shortcomings see Chapter IV and the last three shortcomings under Lee et al. above.

B.C. Hydro (under development)

This model assigns a representative individual to every structure in the flood zone based on census data and specifies the elevation of every structure and every unique path of evacuation by foot. Using a computer algorithm and time steps, representative individuals are tracked as they try to evacuate on foot until they either encounter the flood or escape. If the flood overtakes them, probability distributions determine whether or not they are toppled and, if toppled, whether or not they drown based on the depth and velocity at each location. These probability distributions are incorporated using Monte Carlo techniques and subsequently summed across the population.

Shortcomings can be summarized as follows:

1. The model accounts only for deaths due to drowning.
2. People who do not have average physical capabilities (children, elderly, disabled, etc.) do not have the same probability distributions as a representative individual.
3. The model assumes all deaths occur by toppling while fleeing on foot. Most historical flood-related deaths do not fall in this category.
4. The model does not allow for evacuation by automobile. Inclusion of this component would only exacerbate other shortcomings of the model.
5. Buildings are treated no differently than unsheltered areas in the open floodplain, ignoring their critical historic role in providing shelter.
6. The model currently ignores the benefits of trees and other refuges in the floodplain.
7. The model potentially propagates errors exponentially by multiplying highly uncertain probability distributions and then summing across a large number of individuals, progressively increasing bias.
8. The model requires unobtainable details. One must have confidence in a unique evacuation pathway and rate curve for every residence, toppling distributions for every combination of depth and velocity, and drowning distributions for every flow pattern downstream of someone who topples. Such statistics are currently unavailable, cannot be duplicated in the laboratory, and are highly case-specific, varying with such things as the warning time, warning effectiveness, sensory clues, terrain, ground cover, turbulence, sediment load, debris load, and experience with evacuation. Moreover, the dynamics of a catastrophic flood wave are highly unpredictable, especially away from the channel center, undermining the precision assumed for toppling and drowning distributions.
9. The model does not use historic rates of life loss to validate its results.
10. The model is cost prohibitive.

Graham, 1999

The analyst is intended to divide a population at risk in to subPar, classify each according to a trichotomous division of flood severity, a trichotomous division of (official) warning time, and a dichotomous division of flood severity understanding. The model then suggests an expected (mean) value for the proportional life loss (P) for each of the 15 possible categories.

The model also suggests a range of possible values for P. The model's shortcomings arise primarily because the subPar in the underlying data set were not highly homogeneous and the criteria for the 15 subPar categories does not require that subPar be highly homogeneous. The shortcomings can be summarized as follows:

1. The heterogeneity in the underlying data set calls into question the extent to which the suggested values for modeling P apply to the unique characteristics of any given subPar.

2. Medium flood severity is inherently heterogeneous with respect to housing damages and loss of shelter (see variable Ls in Chapter V). This heterogeneity, in combination with large differences in life-loss rates between categories of flood severity, builds a form of nonlinearity into the model that can cause life-loss estimates to vary dramatically based on how Par is subdivided into subPar.

3. Graham's definition and division of warning time limits the flexibility of the model and potentially misses the most important aspects of both warning and evacuation dynamics.

4. Graham's model is biased by the necessity to subjectively decide how many zero-life-loss events to include or exclude when averaging historic fatality rates.

5. Graham's model recognizes uncertainty, but it falls short of describing uncertainty with probabilities.

6. The model would be strengthened if current guidance on how to apply the model were refined and supported through additional empirical analyses.

Global Insights from Historic Models

To date, a truly satisfying theoretical model has not been completed, primarily due to a lack of empirical underpinnings. Empirical models have evolved, growing from an effort to capture life loss through a single regression equation to an effort to divide events into smaller, more homogeneous components that can be compared to similar components. In this way, it is possible to develop historical life-loss relationships specific to each set of similar components. The summary of major existing approaches, above, provides a good global critique of current model shortcomings. As for contributions, every useful dam-failure life-loss model addresses the following components:

1. The probability of failure given assorted loadings. It is preferable to consider every conceivable loading, breaking the loadings into ranges with similar consequences.
2. Flood routing that yields credible estimates of travel times, depths, and velocities. It is preferable if these can be approximated at every point and not merely as large-scale averages.
3. Quantification of Par. It is preferable to be able to subdivide this into subPar with common attributes, describe the distribution of Par in the flood zone, and assign different values to Par according to temporal variations in the time of day, week, and year.

4. Warning time. It is preferable if this accounts for the detailed chain of events that must occur before a message can first be disseminated on a mass scale. It is also preferable if the analysis describes not only the difference in timing between the first warning and the arrival of the flood, but also the rate of warning propagation, the extent to which the warning penetrates a community, and the ability of the message to mobilize an evacuation without causing panic.
5. Evacuation. It is preferable to identify not only the number of people who escape flooding based on the warning time, but where the remainder are located when the flood arrives and whether or not those locations provide a degree of safety.
6. Loss functions that describe the rate of life loss in every unit that has been defined, whether this is on the level of Par, subPar, or locations within subPar. It is preferable for these functions to be validated empirically so that they can be used with confidence. Chapters IV and VII present desirable and undesirable characteristics of a life-loss estimation model.

CHAPTER IV

A DEEPER LOOK AT THE DEKAY-MCCLELLAND MODEL

The DeKay-McClelland Equation

Equation DM-2d is popularly referred to as the DeKay-McClelland equation, or the D-M equation, for short. It was first presented in Chapter III using a combination of symbols originally used by DeKay and McClelland (1991, 1993b) and symbols used in Chapter V. In like manner, equations L-3b and L-3a, the logit transformation and the inverse transformation, respectively, were introduced using symbols favored by DeKay and McClelland (1991, 1993b) or Lee et al. (1986). To avoid confusion and to prepare the reader for the modeling ideas presented herein, symbols described in Chapter V will now be used exclusively.

Hence,

$$L(P) = (\text{Transformation of } P) = \bar{\beta} = \ln\left(\frac{P}{1-P}\right) = \ln\left(\frac{\frac{L}{Par}}{1-\frac{L}{Par}}\right) \qquad \text{(L-3b)}$$

$$P = \frac{\exp(\bar{\beta})}{1+\exp(\bar{\beta})} = \frac{1}{1+\exp(-\bar{\beta})} \qquad \text{(L-3a)}$$

$$L = \frac{Par}{1+\exp[2.586+0.440\ln(Par)+0.759(Wt)-3.790(Fd)+2.223(Wt)(Fd)]} \qquad \text{(DM-2d)}$$

where P = proportion of lives lost among Par = L/Par,

L = number of lives lost,

Par = population at risk,

Wt = warning time, and

Fd = dichotomous forcefulness (0 or 1, with Fd = 1 meaning that 15 – 20% of the buildings in the flood zone receives major damage or is destroyed).

A Comparison Of Approaches

Table 3.5 presents the data set used by DeKay and McClelland in 1993 after they updated the variable estimates supplied by Brown and Graham (1988). Columns 7, 8 and 9 contain the life loss predicted using equations DM-2d, DM-3b, and DM-4, respectively (see Chapter III). Most of the remaining data come from DeKay and McClelland (1993b, Table I, p. 197). As a reminder, equation DM-2d is the equation DeKay and McClelland (1993b) offered to compute life loss—their final equation based on a logit transformation (equation L-3b). Equation DM-3b was the best equation DeKay and McClelland (1991) could develop using least-squares linear regression techniques without using a logit transformation. They produced the equation in 1991 before the case values were updated and before they added the final four events to the data set. Equation DM-4 was the best equation DeKay and McClelland (1991) could develop without using a logit transformation and while limiting themselves to the two independent variables used by Brown and Graham (1988)—population at risk (Par) and warning time (Wt). It was also developed using the truncated 1991 data set. The final column is the average of columns 7 and 8.

The purpose of including the final three columns is to assess the relative benefits of using a logit transformation. The root mean square error (RMSE) for each equation is reported at the bottom of the table. As can be seen, even though equation DM-2d is the only equation based on this exact set of data, its RMSE is little better than that for equation DM-3b. A casual perusal of the individual estimates also makes the equations appear comparable. Clearly the poorest equation is equation DM-4, indicating that *Force* is an important concept to include in an equation. The conclusion is that the logit transformation offers little inherent benefit apart from constraining the proportion of lives lost among Par (P) to fall between 0 and 1.0, the primary purpose for which it was chosen (DeKay and McClelland, 1991, 1993b).

Duplication of Results

As an exercise, a logit regression was performed on the data set in Table 3.5 using Excel. As expected, the same equation was obtained as was reported by DeKay and McClelland (1993b). A derivation of the equation DM-2d is presented later in this chapter.

Implications of the Predicted Life-loss Curves

To understand the trends in life loss predicted by equation DM-2d, it is helpful to graph the proportion of lives lost among Par (P) against the population at risk (Par) for dichotomous forcefulness (Fd) = 1 (Figure 4.1) and Fd = 0 (Figure 4.2) while holding warning time (Wt) constant. Graphing P against Wt while holding Par and Fd constant produces a second set of graphs (Figure 4.3 and Figure 4.4).

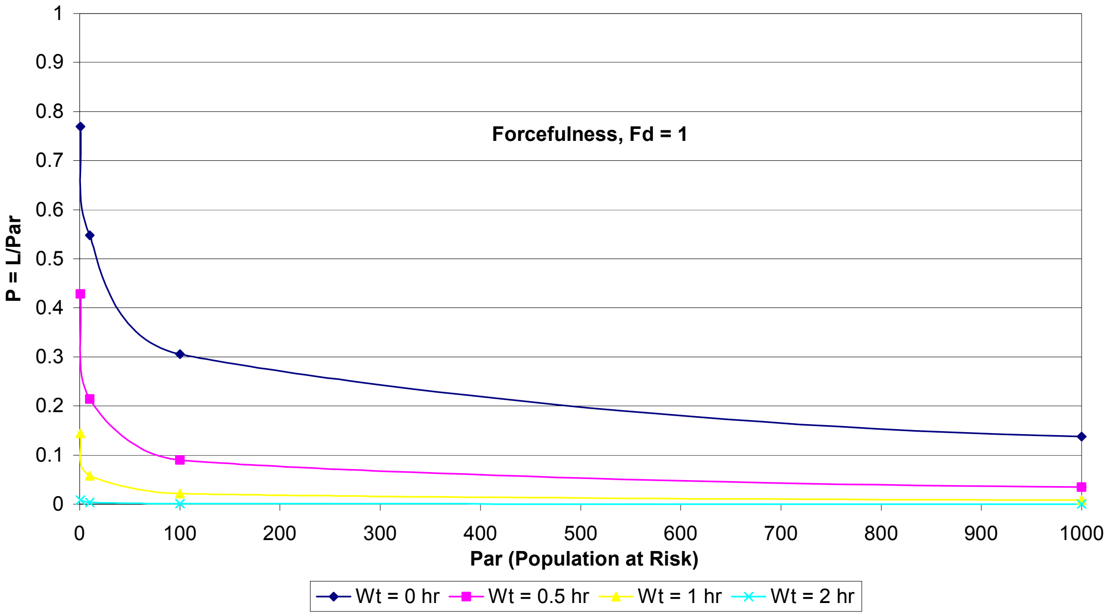

Figure 4.1. Equation DM-2d: P vs. Par with constant Wt and Fd = 1.

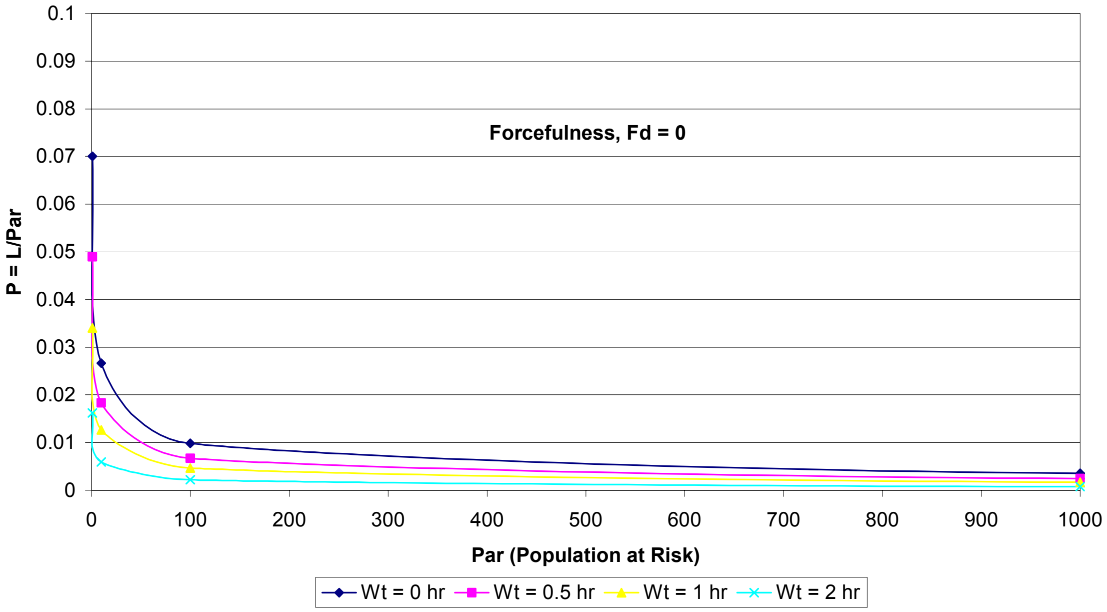

Figure 4.2. Equation DM-2d: P vs. Par with constant Wt and Fd = 0.

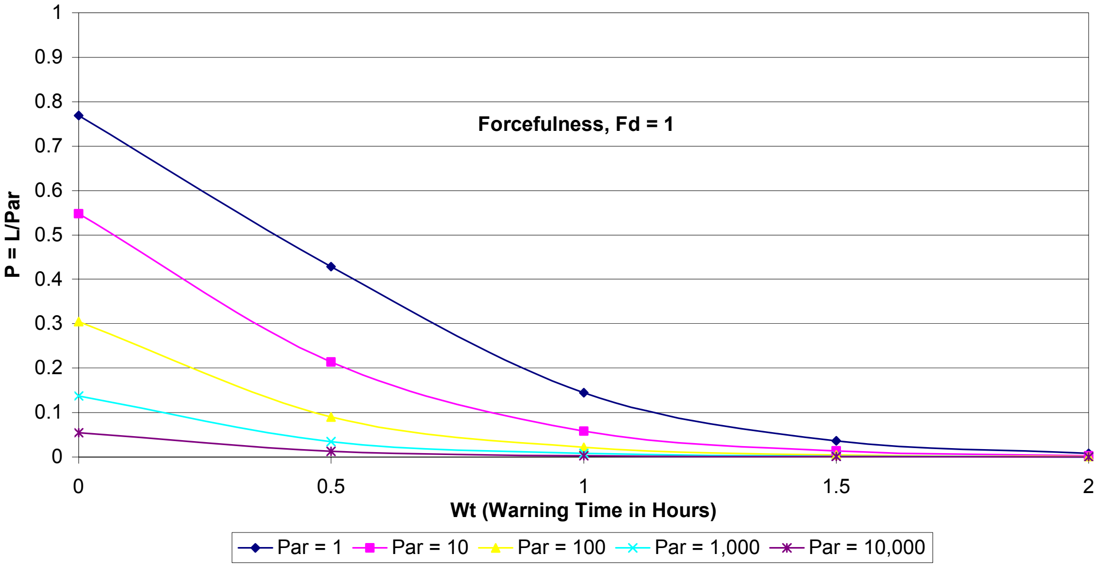

Figure 4.3. Equation DM-2d: P vs. Wt with constant Par and Fd = 1.

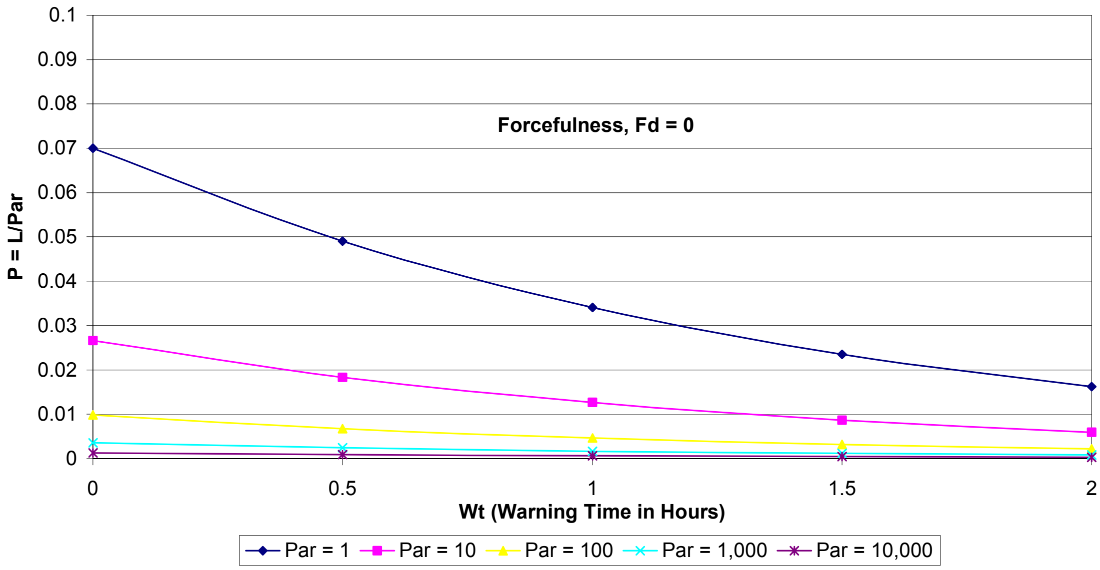

Figure 4.4. Equation DM-2d: P vs. Wt with constant Par and Fd = 0. P as a function of Par

Considering the figures sequentially, Figure 4.1 demonstrates a sharp nonlinearity of the proportion of lives lost among Par (P) with respect to the size of Par at any given value for warning time (Wt), especially when Par is less than 100. Figure 4 demonstrates the same pattern when dichotomous forcefulness (Fd) = 0, only with less than one-tenth the life loss. Conceptually, these curves suggest one or more implications:

1. Warnings are disseminated more effectively when Par is large (unlikely, since small Par are often clustered closely together and for a large Par it takes more time to knock on more doors).
2. Evacuation is more efficient when Par is large (unlikely, since small Par tend to be closer to the hillside and do not need to worry about traffic congestion).
3. The effectiveness of rescue efforts is proportionally superior in larger population centers (true, but not a dominant historical factor, as noted in Chapter VI).
4. Large Par tend to include areas that are either more distant from the river or more distant from the dam than small Par with the same dichotomous forcefulness (Fd) value, resulting in longer average warning times for a given initial warning time and lower average levels of flood forcefulness that are masked by the dichotomous treatment of Fd. This frequently takes the form of a relatively wide floodplain, where inundation is shallow and velocities are smaller, located some distance from a dam up a canyon.

Based on this analysis, the last reason appears the most reasonable and bears greater scrutiny. Essentially, it claims that the shape of the curves follows from limitations in the variables rather than from any inherent property of Par size. If a Par is small—a house, a campground, or a small canyon community—two things are likely to be true. First, the hillsides are likely to form a steep, narrow valley causing the general level of flood forcefulness to trend toward destruction over mere damage and toward the upper limits of Fd = 0 or Fd = 1. Second, the warning time is likely to closely approximate the *average* warning time (Wt_{avg}). If a Par is large—a series of small communities over many miles of narrow valley or a larger city subject to dispersed flooding across flat terrain—and the warning is disseminated more rapidly than the flood's rate of travel, opposite trends are likely from those above. Wt_{avg} will be notably greater than warning time (Wt), a higher percentage of buildings will escape destruction than for small Par, and flood forcefulness will trend toward the lower limits of Fd = 0 or Fd = 1.

The significance of these insights should not be underestimated. Among those events used to develop equation DM-2d, only the Teton failure was divided into subPar, and these subPar were still not very homogenous. In light of the extreme nonlinearity in the proportion of lives lost among Par (P) vs. Par and the method underlying development of the equation, DeKay and McClelland (1993b) cautioned that their equation should not be applied on a subPar basis (see Chapter III).

A simple illustration will demonstrate why. Assume that a dam at the head of long, narrow valley fails, destroys phone cables, prevents word from getting out for nearly an hour, and blocks access to the upper two-thirds of the valley. Wt = 0 minutes, Fd = 1, Par = 1,000 across six small communities in 10 miles, and L = 150. Deaths are concentrated in the first 3 miles because passing motorists and sensory clues propagate informal warnings down the valley, making $Wt_{avg} > 0$ minutes. Also, virtually every structure is destroyed in the first 3 miles, a larger percentage of structures are subject to only major damage in the center of the valley, and the wave has attenuated to a 100-year flood in the wider tail of the valley, causing widespread but minor damages. According to Figure 3 and equation DM-2d, P = 0.138 and L = 138 as long as at least 15 – 20% of the people live in houses that are destroyed or experience major damage and the centroid of Par is above the lowest third of the valley.

Now let us treat the six small towns as separate subPar, assuming Wt = 0 for the first four communities that are inaccessible, but Wt = 1 hr and 2 hr for the final two communities moving downstream. Fd = 1 for the first four communities and Fd = 0 for the last two.

1. If the size of the communities, moving downstream, are $Par_1 = 25$, $Par_2 = 75$, $Par_3 = 450$, $Par_4 = 50$, $Par_5 = 200$, and $Par_6 = 200$, then L = 139.
2. If, instead, $Par_1 = 50$, $Par_2 = 100$, $Par_3 = 350$, $Par_4 = 150$, $Par_5 = 150$, and $Par_6 = 200$, then L = 161.
3. If, instead, $Par_1 = 200$, $Par_2 = 200$, $Par_3 = 450$, $Par_4 = 100$, $Par_5 = 25$, and $Par_6 = 25$, then L = 212.
4. If every two communities were treated as a subPar, then life loss in the final example would be L = 172.
5. If every town in the final example were divided exactly in half based on upstream and downstream neighborhoods, then the 12 subPar would yield L = 266.

6. If the subPar were estimated based on each residence in the final example, life loss would approach 700.

7. If Par barely qualifies for Fd = 1 because 75% of the residents live downstream where damages are uniformly minor, then one distribution might be $Par_1 = 50$, $Par_2 = 100$, $Par_3 = 50$, $Par_4 = 50$, $Par_5 = 500$, and $Par_6 = 250$, resulting in L = 88.

8. If this final redistribution is analyzed as a single, global Par, the greater damage upstream still results in Fd = 1, but based on the distribution of Par, Wt = 1 hr, resulting in L = 8.

This example is telling. Depending on the size of the units to which equation DM-2d is applied and the distribution of the population, the predicted value of L can range from about 8 to about 700, or 0.8% to 70% of Par. Given the third distribution of Par presented above, the estimate of L can range from 138 to 700 (14% to 70% of Par), depending exclusively on how an analyst chooses to group Par into subPar. In the final distribution, the estimate of life loss was increased 11 fold simply by dividing Par into 6 subPar.

As these examples illustrate, the estimate of L will increase dramatically as Par is broken into smaller subPar, and L will change with identical numbers of subPar depending on how the analyst groups the population. The impact of these changes varies depending on the size of Par, on the size of the subPar (Par_i), and on the impact any divisions have on the various warning times (Wt_i) and dichotomous forcefulness values (Fd_i) associated with each Par_i. It follows that it is impossible to stipulate a standardized use of subPar that impacts every dam in a portfolio in a consistent manner; and for a single dam, estimates can clearly be grossly inaccurate.

Moreover, the equation itself cannot be used with confidence on events that do not closely resemble the dominant patterns in the original data set. Returning to our original example, equation DM-2d will estimate L = 138 when it is applied to a 1000-member subPar with Wt = 0 and Fd = 1. But what if, instead of six villages spread over 10 miles, there was a single town immediately below the dam? What if every structure was instantly destroyed, with no major damages and no minor damages? Would life loss still be 138, or would it approach 1000? Historic failures like the ones at Vaiont Dam and the Stava Dams in Italy demonstrate the latter.

DeKay and McClelland (1993b) recognized these shortcomings and suggested that Par should not be divided unless population centers are dramatically different, and then no more than 2 subPar should be adopted. They also cautioned that the equation should not be applied to situations without representation in the data set.

Returning to the initial assertion that the problem with non-linearity is an artifact of the way the variables for warning time (Wt) and dichotomous forcefulness (Fd) are defined, a model that defines subPar homogeneously with respect to concepts of warning and flood forcefulness would avoid these problems. If so, such a model could be applied to any size of subPar the analyst found convenient and to any type of failure for which representative subPar existed in the data set. This has been attempted in Chapter VII.

P as a Function of Wt

Figure 4.3 and Figure 4.4 demonstrate that equation DM-2d produces a relationship in which the proportion of lives lost among Par (P) is also nonlinear with respect to warning time (Wt) for any given size of Par and a fixed value for dichotomous forcefulness (Fd). The figures are nearly identical except that the proportion of lives lost is an order of magnitude higher when Fd = 1.

The general pattern shown in these graphs makes sense. Rates of life loss will follow the rates at which people are trapped by the flood. This rate drops as people successfully evacuate. Evacuation rates will generally begin in a semi-linear fashion and then decrease with time since those who remain are those who find evacuation most difficult.

Historically, there are often a few stragglers who refuse to evacuate, so it is appropriate that the curves converge slowly toward 0 (see Chapter VI). However, it is likely that the curves generated by equation DM-2d converge toward 0 too slowly. The basis for this assertion is historical research and recognition that DeKay and McClelland did not quantify warning time (Wt) with high precision.

As recorded in the fourth column of Table 3.5, Brown and Graham (1988) estimated Wt using half hour increments or larger ranges. These estimates were necessarily vague based on the sparseness of the historical record and the difficulty in representing Wt for spatially diverse Par. For this reason, Brown and Graham chose regression equations based on only three increments of warning time (Wt). DeKay and McClelland (1993a) modified some values of Wt based on their own research, but for the most part they mechanically subdivided the ranges provided by Brown and Graham so they could treat Wt as a continuous variable. When Wt was reported as less than a certain number (Wt < 1 hr), they divided the upper limit in half; when only a lower limit was reported (Wt > 2 hr), they added 50% to that lower bound; and when a range was reported, they chose the midpoint of the range.

An attempt has been made during the current research to refine estimates of warning time, including the average warning time (Wt_{avg}), the warning provided by sensory clues (Sc), and more precise estimates of the first official/formal warning (Wt). The results are presented in Chapters 6 and 7 and in Appendix C.

Comparing P as a Function of

Wt for Fd = 0 and Fd = 1

Figure 4.5 reminds us to distinguish between a model and the real-life situations it is attempting to predict. When Wt exceeds about 1.7 hr, equation DM-2d predicts lower rates of life loss when the flooding is more severe (Fd = 1) than when it is less severe (Fd = 0). However, the differences are minor and both curves converge to essentially the same values. If viewed from this perspective, the model implies that after 1.7 hr, evacuation approaches a standstill and fatalities occur among the holdouts, through convergence, or due to unusual circumstances that are largely unrelated to flood forcefulness.

Confidence intervals

Michael DeKay computed 95% confidence intervals for each of the data points the equation produces when applied to the underlying data set. These were reported by the ANCOLD Working Group on Risk Assessment (Australian National Committee on Large Dams, 1998) and are presented in columns 6 and 8 of Table 4.1. Figures 4.6, 4.7, and Figure 4.8 present the intervals graphically according to the size of each range. As can be seen, the intervals are extremely large and often exceed 10 times the size of the life-loss estimate itself.

These confidence intervals suggest that the predictive authority of equation DM-2d is small. In most cases, the true mean life loss for a given event has a 95% chance of falling anywhere between about 0 and a value 10 – 20 times greater than the estimate produced by the equation. The sensitivity of the proportion of lives lost among Par (P) to the size of the range is greatest when dichotomous forcefulness (Fd) = 1; i.e., when life loss is typically of greatest concern. Clearly, a model with smaller confidence limits would be desirable, but in the absence of such a model, it may be preferable to express the expected value from the DeKay-McClelland equation as a range, or as a probability distribution, rather than as a point estimate.

Table 4.1. Table of flood wave events underlying equation DM-2d, variable values, historic life loss, estimated life loss using equation DM-2d, and 95% confidence intervals for each estimate (Australian National Committee on Large Dams, 1998)

Dam Failure/Flash Flood Events	Population at Risk (Par)	Warning Time (Wt; hours)	Forcefulness (0 or 1)	Actual Loss of Life (L)	95% Confidence Interval Lower Limit	Predicted Loss of Life (Rounded Mean)	95% Confidence Interval Upper Limit
Bushy Hill Pond Dam, CT, 1982	400	2.5	0	0	0	0	6
Bear Wallow Dam, NC, 1976	8	0	1	4	0	5	8
Little Deer Creek Dam, UT, 1963	50	0	0	1	0	1	10
Centralia, WA, 1991	150	0	0	0	0	1	20
Denver, CO, 1965 (South Platte River)	10000	3.17	0	1	0	1	24
Northern NJ, 1984	25000	3	0	2	0	2	45
Mohegan Park Dam, CT, 1963	1000	0	0	6	0	4	61
Teton Dam, ID, 1976 (Rexburg to American Falls)	23000	2.25	0	4	0	4	67
Lee Lake Dam, MA, 1968	80	0	1	2	2	26	71
Swift and [Lower] Two Medicine Dams, MT, 1964	250	0.75	1	28	0	8	88
Allegheny County, PA, 1986	2200	0	0	9	0	6	100
Lawn Lake Dam, CO, 1982	5000	0.5	0	3	0	5	104
Laurel Run Dam, PA, 1977	150	0	1	40	3	40	128
Austin, TX, 1981	1180	1	1	13	1	9	137
Kelley Barnes Dam, GA, 1977	250	0.25	1	39	2	31	170
Baldwin Hills Dam, CA, 1963	16500	1.5	1	5	0	9	200
Stava Dam, Italy, 1985	300	0	1	270	5	64	243
Teton Dam, ID, 1976 (Dam through Wilford)	2000	0.75	1	7	2	25	326
Texas Hill Country, 1978	2070	0.75	1	25	2	25	333
Vega De Tera Dam, Spain, 1959	500	0	1	150	7	89	387
Kansas City, MO, 1977	2380	0.5	1	20	4	57	640
Shadyside, OH, 1990	884	0	1	24	9	127	646
Big Thompson, CO, 1976	2500	0.5	1	144	4	59	662
Buffalo Creek Coal Waste Dam, WV, 1972	5000	0.5	1	125	6	87	1074
Black Hills, SD, 1972	17000	0.5	1	245	10	174	2538
Malpasset Dam, France, 1959	6000	0	1	421	23	406	3438

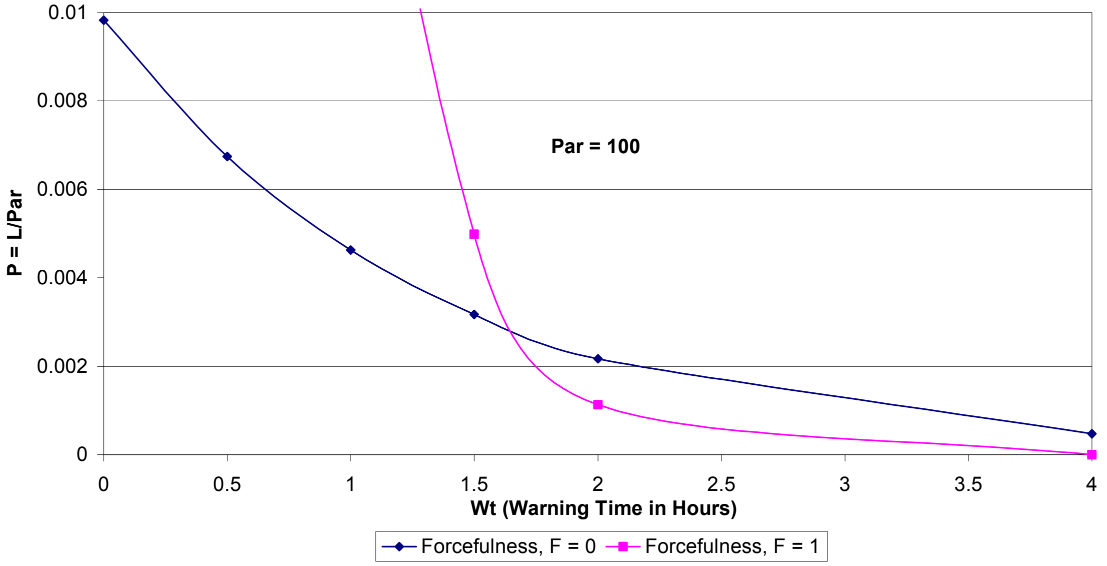

Figure 4.5. Equation DM-2d: The curves with Fd = 1 and Fd = 0 cross at about Wt = 1.7 hours.

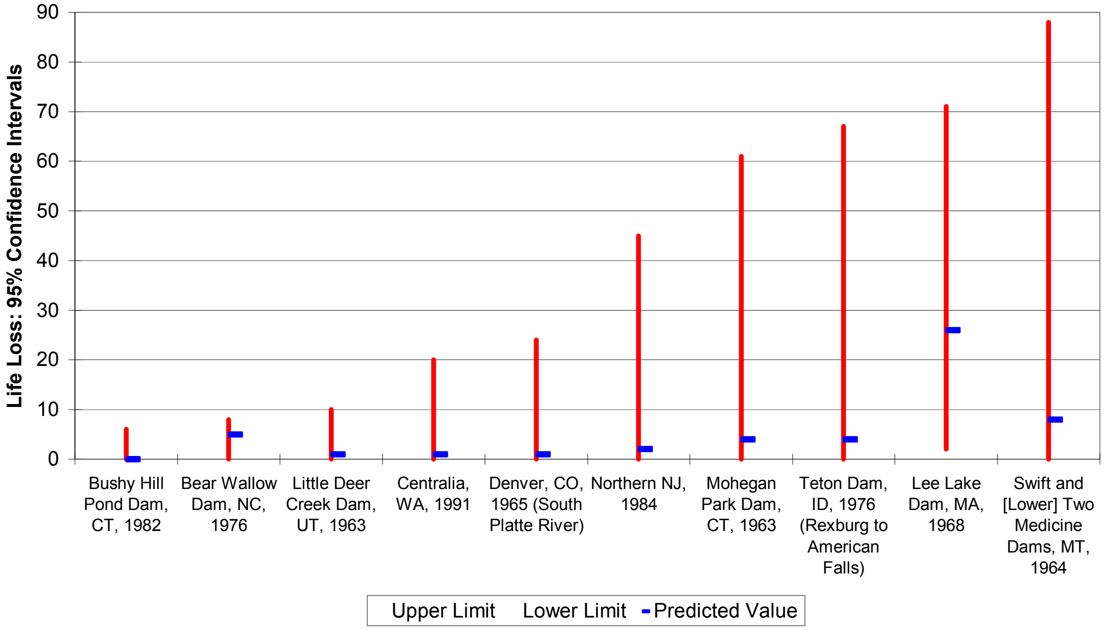

Figure 4.6. The 95% confidence intervals for data points from Table 3.5 for which the range does not exceed L = 90. The tick marks indicate the estimate produced by equation DM-2d.

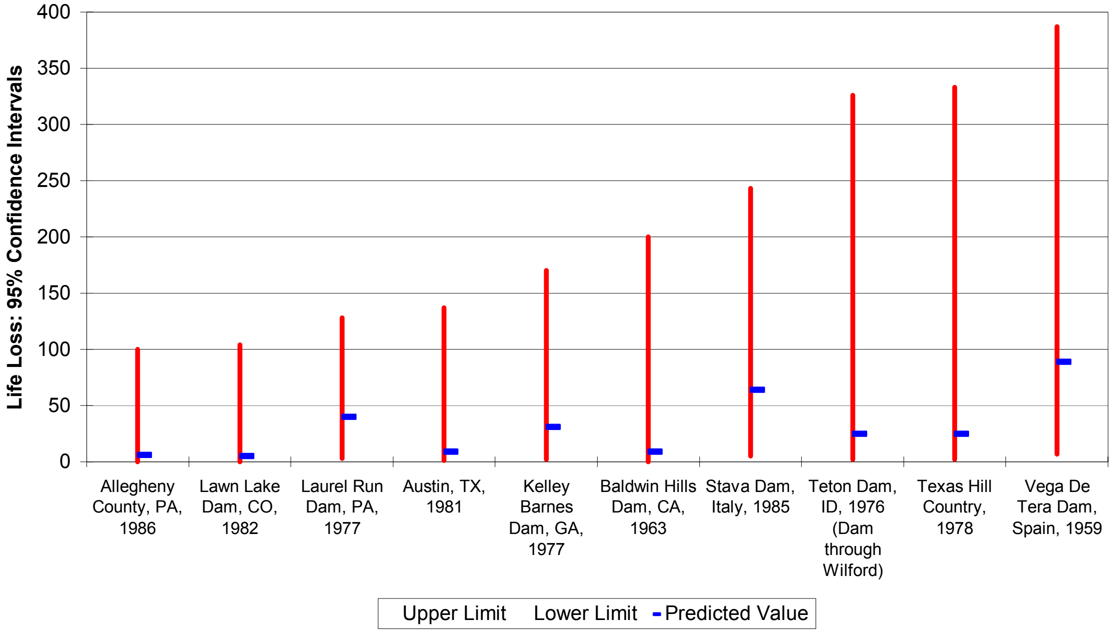

Figure 4.7. The 95% confidence interval for data points from Table 3.5 for which the range exceeds L = 100 but does not exceed L = 400. The tick marks indicate the estimate produced by equation DM-2d.

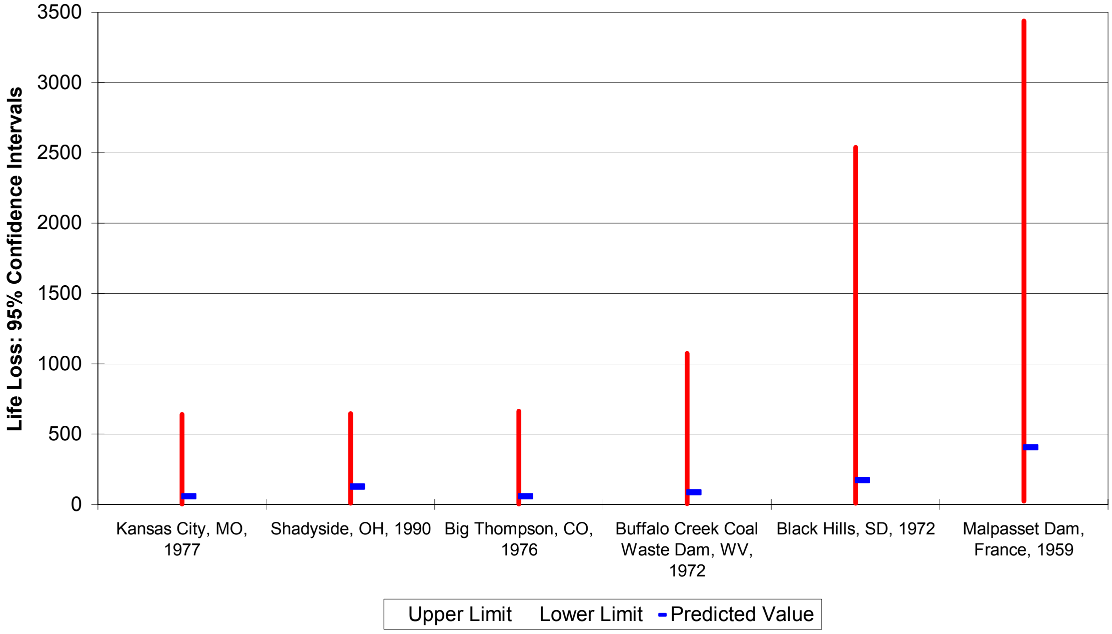

Figure 4.8. The 95% confidence interval for data points from Table 3.5 for which the range exceeds L = 600 but does not exceed L = 3,500. The tick marks indicate the estimate produced by equation DM-2d.

Implications of the DeKay-McClelland Logit Transformation

Derivation

It is helpful to review and expand upon the derivation of equation DM-2d in Chapter III. The linear form underlying this equation is

$$L(P) = \ln\left(\frac{P}{1-P}\right) = a + b\ln(Par) + c(Wt) + d(Fd) + e(Wt)(Fd) \qquad \text{(DM-2)}$$

Following a standard least squares regression on the data set used in 1993 and fitting equation DM-2 with the resulting coefficients produces equation DM-2a.

$$L(P) = \ln\left(\frac{P}{1-P}\right) = -2.586 - 0.440\ln(Par) - 0.759(Wt) + 3.790(Fd) - 2.223(Wt)(Fd) \qquad \text{(DM-2a)}$$

To isolate P, one can take the exponent of both sides,

$$\frac{P}{1-P} = \exp\left[-2.586 - 0.440\ln(Par) - 0.759(Wt) + 3.790(Fd) - 2.223(Wt)(Fd)\right]$$

multiply both sides by 1-P, isolate terms with P on one side of the equation, and factor out P to yield equation DM-2b:

$$P = \frac{L}{Par} = \frac{\exp\left[-2.586 - 0.440\ln(Par) - 0.759(Wt) + 3.790(Force) - 2.223(Wt)(Force)\right]}{1 + \exp\left[-2.586 - 0.440\ln(Par) - 0.759(Wt) + 3.790(Force) - 2.223(Wt)(Force)\right]} \qquad \text{(DM-2b)}$$

Recognizing that

$$\frac{\mathrm{A}}{1+\mathrm{A}} = \frac{1}{\frac{1}{\mathrm{A}}+1} = \frac{1}{1+\mathrm{A}^{-1}}$$

DM-2b reduces to

$$\frac{L}{Par}=\frac{1}{1+\exp\left[2.586+0.440\ln(Par)+0.759(Wt)-3.790(Force)+2.223(Wt)(Force)\right]}$$

Isolating L leads to equation DM-2c

$$L=\frac{Par}{1+\exp\left[2.586+0.440\ln(Par)+0.759(Wt)-3.790(Force)+2.223(Wt)(Force)\right]} \quad \text{(DM-2c)}$$

This equation can then be modified by pulling the first two terms in the exponent out front as $(e^{2.586})(e^{0.440\ln(Par)})$ and simplifying to yield the final equation DM-2d.

$$L=\frac{Par}{1+13.277(Par^{0.440})\exp\left[0.759(Wt)-3.790(Force)+2.223(Wt)(Force)\right]} \quad \text{(DM-2d)}$$

Logistic regression Targeting
L(P), not P or L

While the DeKay-McClelland equation has a R^2 value of 0.840[1] (DeKay and McClelland, 1993b), it is important to remember that this value measures the fraction of the variability explained by the regression equation for the transformed variable,

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[1] The R^2 value for the corresponding regression equation derived using the shorter, unmodified 1991 data set was: 0.9357 (DeKay and McClelland, 1991).

$$L(P) = \ln\left(\frac{P}{1-P}\right) \qquad \text{(L-3b)}$$

where P = L/Par. This R^2 does not address the ability of the equation to predict life loss itself or the proportion of lives lost. The implications are important because during regression, as Par grows, the equation can overestimate or underestimate the loss of life by ever greater amounts with minimal impact on the final choice of equation coefficients.

To explain this, pretend for a moment that the left-hand side of equation DM-2 is P instead of L(P). During the least-squares analysis, it is not the absolute magnitude of life loss that is considered but the ratio of life loss to population at risk. The regression algorithm seeks to minimize the sum of the squares of the residuals, which are here defined as the difference between the ratio L/Par predicted by the equation and the true value in the data set. A large residual in terms of L might be a very small residual in terms of P if Par is large. When comparing two cases, it is possible for one to have a smaller residual with respect to P while having a much larger residual in terms of L, shifting the resulting predicted value in the opposite direction than it would go if L were the dependent variable.

Using an example from the data set, consider the two cases presented in Table 4.2. Bear Wallow Dam had Par = 8 and L = 4, resulting in P = 0.5. Equation DM-2d predicts a loss of life of 4.574, resulting in P = 0.572. The residual in terms of L is 0.574 and the residual in terms of P is 0.072. Now consider the Big Thompson flash flood. Par was considered 2,500, the actual L = 144, and the predicted L = 59. The actual and predicted P-values are 0.0576 and 0.0236, respectively, producing a P-residual of –0.034. Ignoring the sign of the terms, the residual based on P is actually better than that for Bear Wallow by about half (0.034 vs. 0.072), but the residual for L is 85, or nearly 150 times that for Bear Wallow (85 vs. 0.574).

The actual regression dynamics are more complicated than this because the left side of equation DM-2 is not P but a transformation or function of P. This can potentially make the residuals with respect to L even less important.

Consider two Par of comparable size presented in Table 4.3. On paper, the failures of Lee Lake Dam and the connected dams at Stava were quite similar in the sense that Wt = 0 and Fd = 1 for both of them and their Par values were close enough for the nonlinear effects in Figure 3 to be relatively small. In reality, however, the failure at Stava was one of the worst dam disasters

Table 4.2. An example of the effect of using the ratio P as the dependent variable in the regression equation in place of L when one Par is large and another is small

Failure Event	Par	Actual L	Estimated L	Residual Using P	Residual Using L
Bear Wallow	8	4	4.574	4.574/8 – 4/8 = 0.072	0.574
Big Thompson	2500	144	59	59/2500 – 144/2500 = -0.034	-85
By what percent does the absolute value of the larger differ from the absolute value of the smaller?				112 %	14,700 %

Table 4.3. An example of the effect of using the ratio P as the dependent variable in the regression equation in place of L when Par are comparable, but L have different orders of magnitude

Failure Event	Par	Actual L	Estimated L	L(P) Residual	P Residual	L Residual
Lee Lake Dam	80	2	26	-2.933	0.30	24
Stava Dams	300	270	64	-3.503	-0.69	-206
By what percent does the absolute value of the larger differ from the absolute value of the smaller?				19%	130%	758%

on record while the failure at Lee Lake was unexceptional among floods with life loss. Hence, the actual loss of life in each case was very different from the predicted value and in opposite directions.

What is important is the impact of choosing the transformation of P, L(P), instead of P or L as the dependent variable. In order to minimize the sum of squared residuals, the regression algorithm seeks to balance high and low misestimates in a way that the majority of their absolute values tend to cluster in the same range. As indicated in the last row of Table 4.3, this has been accomplished with respect to the dependent transformation, L(P). The residuals differ in magnitude by only 19%. However, this is at the expense of balance in P, which differs by 130%, and almost total disregard for the values of L, with one residual being 7.58 times larger than the other. As a consequence, rather than a true difference of 268 fatalities between the events, the equation predicts a difference of only 38 without sacrificing a high R^2 value in the transformed domain.

Basis for Error in Ranking
Risk within a Portfolio of Dams

The logit transformation will be explored in more detail shortly, but for now it should be noted that the biases generated by the form of equation DM-2 have serious ramifications for dam safety risk analysis. The cost to save a (statistical) life is the difference between the annualized cost of a safety remediation measure and the annualized economic benefit of risk reduction to property, divided by the incremental reduction in the annualized risk of life loss brought about by the safety remediation. As such, it is a measure of the cost-effectiveness of a risk-reduction alternative that can be used to prioritize remedial measures across a portfolio of dams. Assume for a moment that the Stava Dams and Lee Lake Dam had equal probabilities of failure and that the cost of remedial measures and economic risk reduction to prevent these failures would have been identical. Furthermore, ignore for a moment alternative failure scenarios and safety measures to reduce life loss during a failure event, such as early warning systems and emergency action plans. Under these constraints, the comparative cost to save a life between these two dams would have depended solely on the number of fatalities expected from each failure. Based on the logit model as illustrated in Table 4.3, the dams at Stava might have been prioritized for safety improvement just ahead of Lee Lake Dam within a portfolio of dams: only 2.5 times as many people would have been expected to die at Stava, rather than the 135 times as many that actually perished.

One can take this a step further and consider the more realistic case where the probability of failure is different for each dam in a portfolio. If the Stava dams had a probability of failure of $2*10^{-5}$ per year, and Lee Lake Dam was just slightly more likely to fail at $6*10^{-5}$ per year, their respective annualized life-loss risks would be:

Stava dams: $(2*10^{-5}/\text{year})*(64 \text{ lives}) = 0.00128$ lives/year

Lee Lake Dam: $(6*10^{-5}/\text{year})*(26 \text{ lives}) = 0.00156$ lives/year.

Such levels of annualized life-loss risk are generally considered unacceptable, but Lee Lake would be concluded to have a higher annualized life loss than Stava even though the true annualized life-loss risk was 45 times greater, as indicated below:

Stava dams: $(2*10^{-5}/\text{year})*(270 \text{ lives}) = 0.0054$ lives/year

Lee Lake Dam: $(6*10^{-5}/\text{year})*(2 \text{ lives}) = 0.00012$ lives/year.

To show that this is not an isolated danger, consider the Shadyside[2] flash flood in 1990. As for the Stava dams and Lee Lake Dam, Wt = 0 and Fd = 1. With a Par three times larger than at Stava (Par = 884), the predicted life loss at Shadyside rises to 127, but L was actually only 24. With an L-residual over 100, this is the largest overestimation in the data set. Treating Shadyside as a dam failure, the probability of failure at the Stava dams would have to be twice as great as for Shadyside before Stava would get ranked as an equal hazard. Given twice the annualized life-loss risk of failure, the true historical annualized life-loss risk at Stava would have been 2,250% greater than at Shadyside: (2*270/24)*100%.

Significantly, given equal probabilities of failure, Shadyside would also be ranked ahead of the Buffalo Creek coal waste dam failure, the Big Thompson flash flood, and the Vega de Tera Dam failure in terms of annualized life-loss risk. In each case, the true historical annualized life-loss risk for these events was an order of magnitude greater than at Shadyside. The five cases under discussion are summarized in Table 4.4, where they have been ranked in ascending order based on predicted annualized life-loss risks. The relative historical annualized life-loss risks are presented in column 5, where the annualized risk under equal probability of failure is given as a percentage of the dam perceived to be most at risk.[3] Notice that the true annualized life-loss risk of the fifth-ranked dam would be 6 times greater than that of the first-ranked dam. The annualized risk for the fourth-ranked dam would be more than 11 times greater. Par is shown in the final column to demonstrate that this danger holds across the spectrum of population sizes.

Bias Due to the Nonlinearity of L(P) with Respect to P and L

Now that the importance of the form of the regression has been demonstrated, the mechanics of the logit transformation should be explored. Figures 4.8 and 4.9 illustrate the general behavior of the function L(P) = ln[P/(1-P)].

As illustrated in Figure 4.8, the function L(P) = ln[P/(1-P)] is symmetric about 0.0, approaching -∞ as the proportion of lives lost among Par (P) approaches 0 and ∞ as P approaches 1. This logarithmic shape grows rapidly in the tails with the result that a very small change in P will result in a very large change in the residual, $L(P_{estimated}) - L(P_{historic})$, when P is very small or very large. This is demonstrated in the relatively parabolic shape to the curve in Figure 4.9. There, the residuals of the transformations

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[2] There were actually flash floods on three watersheds that caused loss of life. Two of the rivers—Pipes Creek and Wegee Creek near the town of Shadyside, Ohio—were combined by DeKay and McClelland 1993a into a single event with a single Par.

[3] In this case, a flash flood.

Table 4.4. Selective comparison of perceived annualized risk based on estimated L and true annualized risk based on historical L

Failure Event	Rank	Estimated L	Actual L	Historical Annualized Risk Given Equal Likelihood of Dam Failure Compared to Top Ranked	Residual Using L	Par
Shadyside	1	127	24	100 %	103	884
Vega de Tera	2	89	150	625 %	-61	500
Buffalo Creek	3	87	125	521 %	-38	5,000
Stava	4	64	270	1,125 %	-206	300
Big Thompson	5	59	144	600 %	-85	2,500

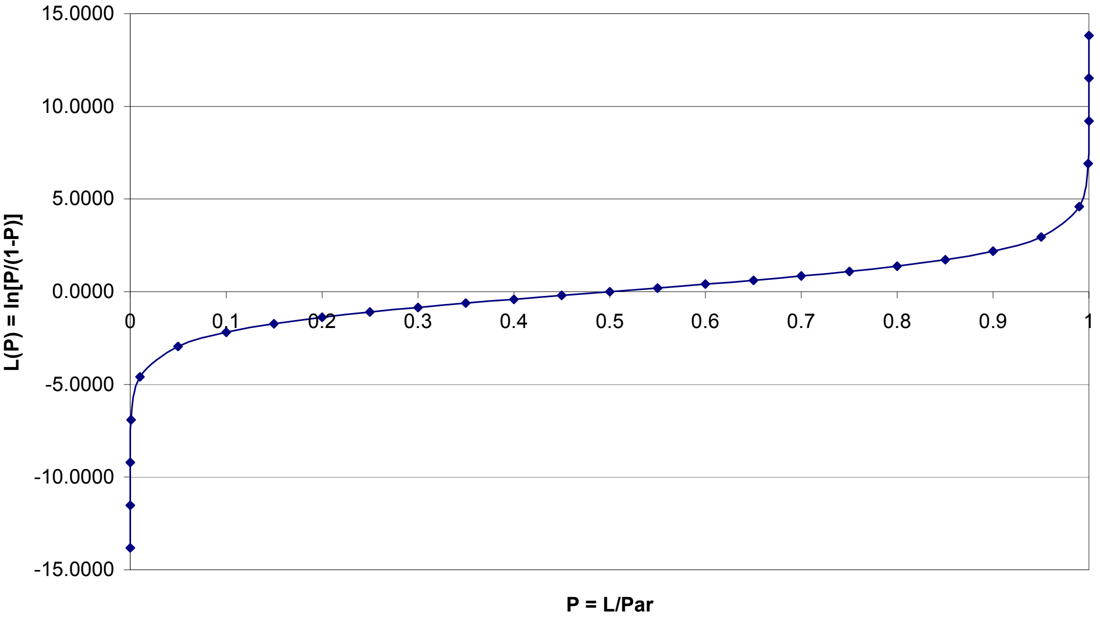

Figure 4.8. Graph of the function L(P).

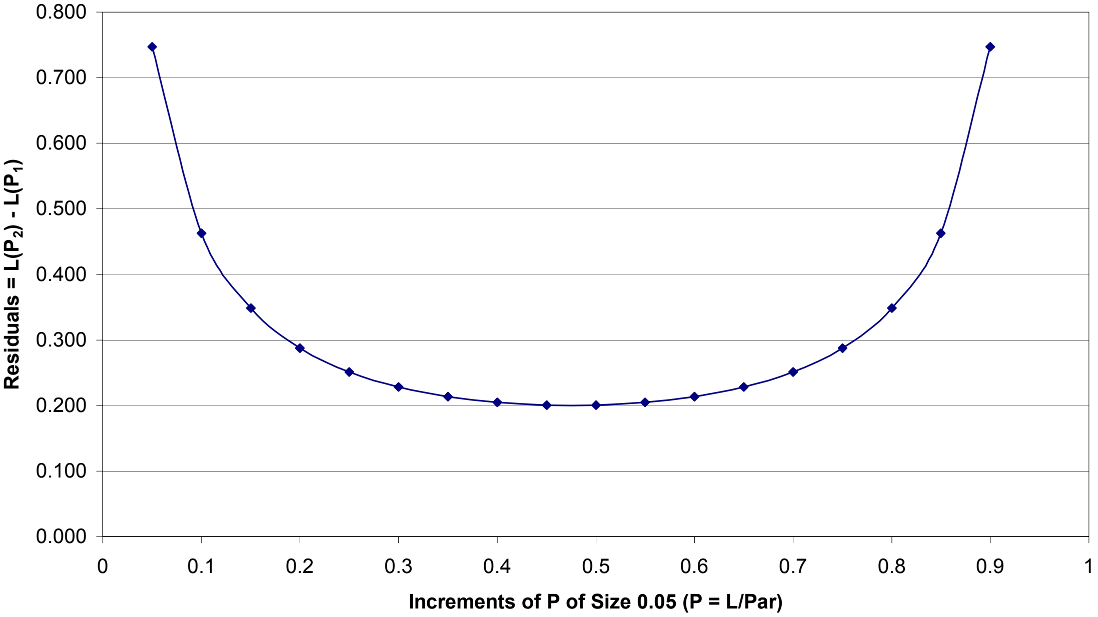

Figure 4.9. Graph demonstrating the unequal weight given to residuals $L(P_{estimate}) - L(P_{historic})$. Given evenly spaced values for P, the residuals of L(P) will be much larger when P is near 0 or 1 than near 0.5.

$L(P_2) – L(P_1)$ are graphed against the midpoint of uniform increments of $P_2 – P_1$. The arms increase arbitrarily fast depending on the size of the P-increment chosen, but for a given increment, the rate of increase steadily increases nearer P = 0 and P = 1. Thus, events for which the ratio L/Par is very small or very large dominate the regression as the algorithm seeks to minimize the sum of the squared residuals. The result is a biased regression equation.

Consider two data points with Par of 1,000. Event A had L = 2, P = 0.002, and L(P) = -6.2126; Event B had L = 150, P = 0.150, and L(P) = -1.7346. Now let us say the regression equation predicts L = 1 for Event A, resulting in P = 0.001 and L(P) = -6.9067. Thus, the residual for Event A, based on L(P), is -0.694.

Now the regression algorithm seeks to “balance” residuals—allowing some to grow in order to reduce others—to minimize the sum of their squares. In the name of balance, what predicted L value will yield the same residual of 0.694 for the second event with P = 0.15? There are two options, since squared residuals are insensitive to sign. It can underestimate the life loss by 69 or it can overestimate life loss by 111: L = 81 and L = 261. Both yield logit residuals with absolute values of 0.694.

Of course, it is unlikely that exactly balancing these two residuals will minimize the sum of squares from a larger data set, but notice two things. First, an underestimate in L of 69 has the same effect on the L(P)-residual as an overestimate of 111. As illustrated in Figure 4.9, for a given change in L(P), one will always have a larger change in P when moving toward P = 0.5

than when moving toward $P = 0$ or $P = 1$. This becomes more pronounced the closer P comes to 0 or 1. Hence, $L = 3.99$ also yields a residual of 0.694 for Event A, even though it is twice as far removed from $L = 2$ as $L = 1.00$ is from $L = 2$.

Second, the variance in L balloons as P approaches 0.5. The range $1 < L < 4$ for Event A is bounded by the same residuals as is $81 < L < 261$ for Event B.

Contrary to the independence of a single data point, when a data set is dominated by values that fall on one side of 0.5 or the other, prediction of P-values between 0.5 and this dominant set will tend to be skewed in the direction of the set. The reason for this is that near 0 or 1, a small error in P produces a very large error in L(P). Thus, to minimize the overall deviations in L(P), the regression algorithm biases the equation to predict the most extreme values of P the most accurately, even if this requires skewing less extreme estimates in the direction of the most extreme values. The extreme values, in turn, will tend to skew toward 0.5, although these deviations will be small.

It is important to remember that "extreme values" near 0 or 1 and "less extreme" values closer to 0.5 are relative concepts: It is their relative magnitudes that matter, not their absolute magnitudes. Also, the magnitude of L matters only as it relates to Par through P.

Consider events number 1, 16, and 27 in Table 4.5. Bushy Hill Pond Dam had Par = 400 and $L = 0$. Because the log of 0 is undefined, by convention L is set equal to 0.5 and $P = 1/(2*\text{Par})$. In this case, $P = 0.0013$ and equation DM-2d estimates $L = 0.32$, resulting in $P = 0.0008$ and an L(P)-residual of 0.44.

In contrast to this excellent estimate of L, equation DM-2d underestimates L by 71 people for the Black Hills flash flood. Nevertheless, the L(P)-residual is actually smaller in this case (0.35) because the P-values are an order of magnitude larger ($P_{\text{historic}} = 0.014$, $P_{\text{predicted}} = 0.010$). The absolute magnitude of the P-values is still small—despite the fact that this event had the third largest life loss in the data set—because Par is very large (17,000).

If P were a less extreme value near 0.5, L would be allowed to vary even more. Specifically, if $L = 8{,}500$ while Par = 17,000, such that $P = 0.5$, L could be estimated anywhere between 6,660 and 10,340 without exceeding the L(P)-residual of 0.44 for Bushy Hill Pond. More to the point, the algorithm treats a life-loss range of 0.32 – 0.78 when Par = 400 and $L = 0.5$ as equivalent to a life-loss range of 6,660 – 10,340 when Par = 17,000 and $L = 8{,}500$: The L(P)-residual for every endpoint has magnitude 0.44.

By contrast, when Par is very large and L is small such that P is very small, the L(P)-residuals grow rapidly with small changes in L. Equation DM-2d underestimates

Table 4.5. DeKay's and McClelland's data set, arranged in ascending order of historical L (adapted from DeKay and McClelland, 1993b, Table I, p. 197)

	1	2	3	4	5	6	7	8	9
	Event Locations	Par	Actual L When Predicted High	Actual L When Predicted Low	Actual Loss of Life	Predicted Loss of Life (Rounded)	Predicted L Eq. DM-2d	Residuals Using L	*Residuals Using L(P)= ln[P/(1-P)]
1	Bushy Hill Pond Dam, CT, 1982	400	0		0	0	0.3	0.3	-0.44
2	Centralia, WA, 1991	150	0		0	1	1.2	1.2	0.91
3	Prospect Dam, CO, 1980	100	0		0	0	0.003	0.0	-5.01
4	Denver, CO, 1965 (South Platte River)	10,000	1		1	1	1.2	0.2	0.17
5	D.M.A.D. Dam, UT, 1983	500		1	1	0	0.018	-1.0	-4.04
6	Little Deer Creek Dam, UT, 1963	50		1	1	1	0.7	-0.3	-0.42
7	Lee Lake Dam, MA, 1968	80	2		2	26	26.1	24.1	2.94
8	Northern NJ, 1984	25,000	2		2	2	2.2	0.2	0.11
9	Lawn Lake Dam, CO, 1982	5,000	3		3	5	6.1	3.1	0.70
10	Bear Wallow Dam, NC, 1976	8	4		4	5	4.6	0.6	0.29
11	Teton Dam, ID, 1976 (Rexburg to American Falls)	23,000		4	4	4	3.8	-0.2	-0.06
12	Baldwin Hills Dam, CA, 1963	16,500	5		5	9	8.7	3.7	0.56
13	Mohegan Park Dam, CT, 1963	1,000		6	6	4	3.6	-2.4	-0.52
14	Teton Dam, ID, 1976 (Dam through Wilford)	2,000	7		7	25	24.8	17.8	1.27
15	Allegheny County, PA, 1986	2,200		9	9	6	5.6	-3.4	-0.48
16	Kansas River, KS, 1951	58,000		11	11	0	0.2	-10.8	-4.00
17	Austin, TX, 1981	1,180		13	13	9	8.8	-4.2	-0.39
18	Kansas City, MO, 1977	2,380	20		20	57	57.0	37.0	1.06
19	Shadyside, OH, 1990	884	24		24	127	127.4	103.4	1.80
20	Texas Hill Country, 1978	2,070	25		25	25	25.3	0.3	0.01
21	Swift and [Lower] Two Medicine Dams, MT, 1964	250		28	28	8	7.6	-20.4	-1.39
22	Kelley Barnes Dam, GA, 1977	250		39	39	31	30.6	-8.4	-0.28
23	Laurel Run Dam, PA, 1977	150	40		40	40	40.3	0.3	0.01
24	Buffalo Creek Coal Waste Dam, WV, 1972	5,000		125	125	87	86.9	-38.1	-0.37
25	Big Thompson, CO, 1976	2,500		144	144	59	58.6	-85.4	-0.93
26	Vega De Tera Dam, Spain, 1959	500		150	150	89	89.0	-61.0	-0.68
27	Black Hills, SD, 1972	17,000		245	245	174	173.8	-71.2	-0.35
28	Stava Dam, Italy, 1985	300		270	270	64	64.0	-206.0	-3.50
29	Malpasset Dam, France, 1959	6,000		421	421	406	405.7	-15.3	-0.04
* P = 1/(2*Par) if deaths = 0 (Dekay and McClelland, 1991)			Arithmetic Mean L-Residual for L > 120: =					-79.5	
			Arithmetic Mean L-Residual for L > 25: =					-56.2	
			Arithmetic Mean L-Residual for L <= 25: =					8.5	
			Arithmetic Mean L-Residual for L < 10: =					2.2	
			Mean overestimation of L: =					13.7	
			Mean underestimation of L: =					-35.2	

life loss for the Kansas River flood by less than 11 fatalities. However, a very large Par (58,000) combined with a small number of deaths (11, estimated at 0.2) produces very small values for P ($P_{historic}$ = 0.000189, $P_{predicted}$ = 0.000003). The L(P) residual in this case is 4.00, more than 5 times greater than for Bushy Hill and the Black Hills combined.

To emphasize the previous points, the smaller P becomes, the more likely L will be overestimated. For Kansas River with Par = 58,000, L = 11, and P = 0.00019, the ranges 0.2 – 11 and 11 – 594 are both bounded by an L(P)-residual of 4.00. Also, as P becomes smaller, the regression algorithm tolerates less and less deviation in L. At P = 0.00019 and an L(P)-residual $\leq$ 4.00, Kansas River allows $0.2 < L < 594$, or a spread of nearly 600. Under identical conditions except P = 0.5, Kansas River would allow $1{,}043 < L < 56{,}956$, or a spread of nearly 56,000.

Bias Due to Trends in the Data Set

Considering the values in Table 4.5, P-values are generally less than 0.5 (only Stava Dam has a P-value greater), dam failures with low life loss tend to have very low P-values, and failures with large L-values tend to have P-values relatively closer to 0.5. Thus, based on the reasoning above, one would expect equation DM-2d to predict events with small L-values fairly accurately but with a bias towards overestimation. Events with L-values in the midrange might defy an easy trend, but events with large L-values would most likely show a clear trend toward dramatic underestimation.

One might also expect equation DM-2d to predict P more accurately when Par is large than when Par is small. This follows from the tendency in the data set for large Par to have the smallest values for P—the basis for the nonlinearity displayed in Figure 4.1 and Figure 4.2. This also leads to a tendency to put the greatest weight on those events that are least hazardous (large Par and small expected life loss). As such, equation DM-2d is least credible when applied to high-hazard events or to small Par, either of which is likely to produce relatively large values for P.

Not surprisingly, all of this describes the pattern reflected in the residuals with respect to L in the data set. Indeed, without undergoing a rigorous analysis of variance (ANOVA), clear trends are readily apparent from a perusal of Table 4.5. The events are sorted in ascending order by the number of lives that were lost, as shown in column 5. Columns 3 and 4 duplicate these values, but column 3 lists only those events for which the equation's estimates are high (P moves toward 0.5), and column 4 lists only those events for which the equation's estimates are low (P skews toward the most extreme values). Columns 6 and 7 list the estimates for L produced by equation DM-2d. Columns 8 and 9 present the residuals with respect to L and L(P), respectively. Various footnotes and mean values are found at the bottom of the table.

Columns 5, 7, and 8 indicate that prediction levels generally fall within a few lives of the true value when historic fatality rates were less than 10.[4] Of the 15 predictions in this range 67% are overestimates, skewing P toward 0.5. Of the 12 floods with $L \leq 5$, 75% are overestimated. The magnitude of prediction error in these ranges is small—often indiscernible after rounding. The arithmetic average error is 2.2 over the 15 cases that comprise the lower half the data set with respect to historic life loss.

Predictions for floods with L = 10 – 40 show a fair bit of scatter. There are eight floods in this range. L is overestimated for half and underestimated for half, though the magnitudes of the over-predictions dominate. Unlike failures with L below 10, in this mid-range the L-residuals are characterized by large variance. While the arithmetic mean L residual is 8.8, the average absolute magnitude of the residual (ignoring signs) is 23.1.

There is no way to judge the transition point between dam failures within the mid-range and high-range of life loss since no data exist for failures with $41 < L < 124$. However, the six remaining failure events all fall within the high range and L is underestimated in every case, usually by a large margin. Considering all events with actual L greater than 25, the arithmetic mean L-error is -56. This increases to -80 for the six worst catastrophes. For these six, only 59% of the actual life loss is recognized by equation DM-2d.

A quick perusal of the largest and smallest Par indicates that errors in P are generally much smaller when Par is large. Likewise, P and L are most accurate when these values are smallest, meaning the equation is least accurate in predicting L when large numbers of people are expected to die.

As a global summary of the entire data set, 14 cases overestimate loss of life by an average of 13.6 lives while 15 cases underestimate loss of life by an average of 35.2 lives. There are two cases in which an overestimation of L reflects an underestimation of the logit variable L(P). In both cases the actual L was zero and the value used for P is calculated by convention as $P = 1/(2*Par)$ (DeKay and McClelland, 1991).

All of the characteristics discussed in this chapter would be expected to hold true when the equation is used to estimate future outcomes.

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[4] A variation of at least 1-3 might be expected at all levels of life loss due to convergence deaths or other isolated fatalities which might be considered unique or random in nature.

Shortcomings of the DeKay-McClelland Model as Currently Applied

Before discussing the shortcomings in detail, it bears repeating that the DeKay-McClelland model represents the most rigorous empirical approach to date. As such, it was the preeminent life-loss method until recently and its authors should be commended for their contributions to the state of the art.

The model's most problematic shortcomings arise not from any error in statistical analysis, but from a misunderstanding of life-loss dynamics and misuse of the model by dam safety risk professionals. Neither author had a background in fields related to dam safety, hydraulics, hydrology, or emergency management. In their words, "our approach is primarily data-driven rather than theory driven. We try to be reasonable in our choice of variables and the form in which we express them, but we adhere to no particular theory regarding the causes of flood fatalities" (DeKay and McClelland, 1993b, p. 193).

The most obvious contradiction between the model and true life-loss dynamics is that the model treats an entire Par as a single entity with a single warning time and a consistent mix of damages to structures. Recognizing the logical dissonance that this causes, dam safety risk professionals have tended to apply the equation to more homogeneous subpopulations, isolating canyon communities from valley communities and those far from the dam from those close to the dam. However, the more the model is applied to homogeneous subpopulations, the more the approach violates the assumptions governing its derivation and the more suspect the results become.

This and other foundational weaknesses have been explored in great detail in the preceding sections. Hence, this section is intended only as an outline summary, with additional insights that were derived through historical analysis and reasoning. To keep the following comments brief, it is assumed that the reader is familiar with the contents of this chapter and the section on the DeKay-McClelland model in Chapter III. Support for additional insights is provided in the subsequent chapters and appendices.

Life Loss is Nonlinear
with Respect to Par

1. An application of the model to subPar increases the estimate of L.

2. Every unique division of subPar will yield a different estimate of L.

The Model was Developed Using Heterogeneous Par rather than Homogeneous Subpar

1. The current practice of applying the model to subPar applies the equation to populations unlike those in the data set. This, in turn, produces unreliable results.

2. Warning time (Wt) and dichotomous forcefulness (Fd) do not represent the average conditions experienced by individuals within a global population. As such, Wt and Fd have limited value when one compares two or more dissimilar events.

3. Wt and Fd do not represent or quantify those who are most at risk.

4. Making assumptions about evacuation rates based on the interplay between a point value like Wt and L is potentially misleading and can make it appear that evacuations proceed slowly when, in fact, the individual warning times (Wt_i) may be very small or nonexistent for those who perish.

The Model Uses Wt rather than Excess Evacuation Time (E)

1. The first official/formal warning time (Wt) is generally larger than the average warning time from any source (Wt_{avg}) and takes no account of the dissemination rate or the percentage of people reached.
2. Wt does not describe whether those who receive a warning are most at risk or least at risk.
3. Wt takes no account of the urgency or believability of the message. A NWS scrawl at the bottom of a sitcom does not have the same potential to mobilize an evacuation as a fireman at the door or the fearful sight and sound of an approaching wall of water.
4. Wt takes no account of the time of day or night, whether families are together or separated during work hours, and other factors that affect a population's response patterns.
5. Wt is independent of the time required for evacuation.
6. In summary, it is the excess evacuation time (E)—the time required to clear the flood zone minus the time available to clear the flood zone—that determines whether people are likely to escape a flood. Wt is independent of the distance to safety, the mobility of the population, the time of day or night, the urgency of the message, and other factors that determine the representative time needed for evacuation. As such, Wt, by itself, has limited usefulness when comparing dissimilar events.

Together, these factors mask the benefits of improved warning dissemination and urgency while emphasizing only the timing of the first notification.

The Model Makes No Distinction Between Day And Night

1. Darkness and sleep can dramatically hinder the ability of a population to detect sensory clues, share them with neighbors, and prepare their families to run for safety. This is most important when Wt is small. Since the data set underlying the model is a mix of day and night events, the regression equation cannot be fully trusted to apply to either.

As A Dichotomous Variable, Fd Is Too Coarse For Refined Estimates Of Life Loss

1. It is unrealistic to expect the same rate of life loss regardless of whether 20% or 100% of the buildings receive at least major damage. Indeed, life loss is likely to grow faster than the rate of damages because a higher damage rate implies a flood with greater depths and velocities at every structure.
2. Based on the events used in developing the equation, the model implicitly assumes that every Par is sufficiently heterogeneous to force the rate of housing damages toward the lower limits of Fd = 0 and Fd = 1. As such, the model "fits" only a limited type of event/population.
    a. The model does a poor job of predicting life loss for its own data set when a case falls outside of this expected range—that is, when damages are extreme.
    b. The equation is unsuited for application to Par or subPar with homogenous damages. This is in direct contradiction to the way analysts prefer to use the equation, since they tend to isolate communities closest to a dam from those downstream.
    c. The equation is unsuited for application to the most lethal flood events, such as the failure at Vaiont, Italy.

According To Fd, The Same Number Of Lives Should Be Lost When A Building Receives Major Damage As When It Is Destroyed

The model obscures the large difference in life loss when buildings are obliterated compared to when they retain a form of haven. Historically, this difference is so pronounced that this oversight may be the model's greatest shortcoming.

Sometimes Par Is Aggregated Across Many Watersheds

1. This kind of flooding is atypical of a dam failure.
2. Life loss is usually limited to the most dangerous reaches or watersheds, but because Par is expanded to include watersheds with milder flooding, housing damages tend toward the lower limits of Fd = 0 or Fd = 1 and estimates of P conform accordingly (see above).
3. Examples from the data set (see Table 4.5): Allegheny County flash floods, Black Hills flash floods, Kansas City floods, Northern New Jersey flash floods, Texas Hill Country flash floods, and Shadyside flash floods (although for Shadyside, Wegee Creek and Pipe Creek were so similar they could be combined with no dilution of Fd).

Sometimes L Has Little Relationship To Par

1. By combining subPar into a single Par, Par can be quantified in a way that has little or no relationship to the number of people who are most at risk and the nature of the flooding they experience.
2. Examples (see Table 4.5):

   a. All nine deaths in Allegheny County occurred among a small band of motorists traveling on a single stretch of road along Little Pine Creek. Nevertheless, DeKay and McClelland (1993a) quantified Par based on the number of residences that were damaged in every watershed in the county.

   b. During the Austin, Texas, flash floods in 1981, 11 out of 13 deaths occurred to motorists at low water crossings. The crossings were located in five different watersheds, they were mostly distant from areas with housing damages, the motorists were not evacuees, and in many cases the victims did not even live in the state. Nevertheless, DeKay and McClelland (1993a) quantified Par based on the number of residences that were damaged—residences that were mostly evacuated before the flooding reached lethal proportions.

    c. None of the 25 deaths during the Kansas City floods involved people trapped in buildings because the water rose slowly enough for people to walk away without hurrying. The victims were those who faced the flood after it reached dangerous proportions—motorists, pedestrians, people who came to watch the flood, and people who experienced fatal medical emergencies like heart attacks. Nevertheless, DeKay and McClelland (1993a) quantified Par based on the number of residences that were damaged across many different watersheds.

2. Examples like this argue for the importance of treating different categories of Par or subPar uniquely. That is, subPar in campgrounds, automobiles, boats, homes, or other locations may not all share the same traits with respect to warning dissemination, evacuation, flood exposure, and life loss.

Some Variables Were Assigned Values
Inconsistent With The Best Evidence

This is a matter of judgement and the availability of relevant historical documents. It is likely that future researchers will refine estimates made as part of this study, as well. However, Table 4.6 shows the most important differences between the values used by DeKay and McClelland (1993b) and those chosen as part of this study after careful research and full documentation in Appendix B.

The Logit Procedure Is Biased

1. Due to the nature of the logit transformation and the values in the data set, the regression algorithm seeks to predict P most accurately when P is smallest and least accurately when P is largest. Also, P will tend to skew high when it is smallest and skew low when P is largest.

    a. Within the data set, the model tends to predict L with high precision and a slight bias toward overestimation when $L < 10$.

    b. Within the data set, the model consistently underestimates L by wide margins (an average of 80 fatalities for the six worst cases) when $L > 125$.

    c. There is no distinct trend in underestimation or overestimation in the mid-ranges of life loss, but the precision falls in between that for (a) and (b) above.

Table 4.6. Values used by DeKay and McClelland (1993b) (D-M) and those indicated by current research (M) in which Wt was quantified only for subPar, but the symbols > and < indicate if the global value is at least 15 minutes higher or lower than the value used by DeKay and McClelland. The column for Wt in minutes reflects the subPar most representative of Par as a whole. The most significant differences are highlighted in bold

		D-M	M	D-M	M	D-M	M	M sub-Par	D-M	M
	Event	L	L	Par	Par	Wt (hr)	Wt (hr)	Wt (min)	Fd	Fd
1	Allegheny County, PA, 1986	9	9	2,200	1,700	0	0	0	0	0
2	Austin, TX, 1981	13	13	1,180	1,196	1	<	30	1	1
3	Baldwin Hills Dam, CA, 1963	5	5	16,500	16,500	1.5	>	105	1	1
4	Bear Wallow Dam, NC, 1976	4	4	8	4 – 7	0	0	0	1	1
5	Big Thompson, CO, 1976	144	145	2,500	2,500	0.5	0	0	1	1
6	Black Hills, SD, 1972 (Canyon Lake Dam)	245	237	17,000	12,375	0.5	>	45	1	1
7	Buffalo Creek Coal Waste Dam, WV, 1972	125	139	5,000	3,171	0.5	---	---	1	1
8	Bushy Hill Pond Dam, CT, 1982	0	---	400	---	2.5	---	---	0	---
9	Centralia, WA, 1991	0	---	150	---	0	---	---	0	---
10*	D.M.A.D. Dam, UT, 1983	1	---	500	---	6.5	---	---	0	---
11	Denver, CO, 1965 (South Platte River)	1	---	10,000	---	3.17	---	---	0	---
12	Kansas City, MO, 1977	20	25	2,380	3,000	0.5	<	15	1	1
13*	Kansas River, KS, 1951	11	---	58,000	---	3	---	---	1	---
14	Kelley Barnes Dam, GA, 1977	39	39	250	140	0.25	<	0.33	1	1
15	Laurel Run Dam, PA, 1977	40	---	150	---	0	---	---	1	---
16	Lawn Lake Dam, CO, 1982	3	---	5,000	---	0.75	---	---	0	---
17	Lee Lake Dam, MA, 1968	2	2	80	123	0	0	0	1	1
18	Little Deer Creek Dam, UT, 1963	1	---	50	---	0	---	---	0	---
19	Malpasset Dam, France, 1959	421	---	6,000	---	0	>	---	1	---
20	Mohegan Park Dam, CT, 1963	6	---	1,000	---	0	>	---	0	---
21	Northern NJ, 1984	2	---	25,000	---	3	---	---	0	---
22*	Prospect Dam, CO, 1980	0	---	100	---	7.5	---	---	0	---
23	Shadyside, OH, 1990	24	24	884	547	0	0	0	1	1
24	Stava dams, Italy, 1985	270	270	300	300	0	0	0	1	1
25	Swift and [Lower] Two Medicine Dams, MT,	28	---	250	---	0.75	---	---	1	---
26	Teton Dam, ID, 1976 (Dam through Wilford)	7	---	2,000	---	0.75	---	---	1	---
27	Teton Dam, ID, 1976 (Rexburg to American	4	---	23,000	---	2.25	---	---	0	---
28	Texas Hill Country, 1978	25	---	2,070	---	0.75	---	---	1	---
29	Vega De Tera Dam, Spain, 1959	150	153	500	415	0	0	0	1	1

* Not used in equation derivations (omitted as outliers).

1. These trends occur because the data set is dominated by cases in which $P < 0.5$. If it were dominated by cases in which $P > 0.5$, the direction of bias would reverse.
2. There is a tendency to predict P most accurately when Par is large because in such cases P is usually small.
3. During regression, the regression algorithm thus tends to put greater weight on those events that are least hazardous (large Par and small expected life loss). As such, equation DM-2d is least credible when applied to high-hazard events or to small Par, either of which is likely to produce relatively large values for P.

The Data Set Is Biased

1. When compared to flash flood deaths during a given year, the USBR found that their data set was biased toward the most extreme cases, thus tending to overestimate L when applied to less extreme cases (U.S. Bureau of Reclamation, 1989).
2. When compared to the most extreme historical events such as the failure at Vaiont, Italy, the data set is biased to underestimate L by assuming Fd reflects a mix of major damage, destruction, and up to 80% minor damages.
3. As long as heterogeneous Par are treated globally and in a manner for which L is nonlinear with respect to Par, there is little basis for selecting a data set free of bias. Moreover, the direction of the bias depends on the event to which the equation is applied.
4. Using the current approach, this can be avoided in only one of two ways:
    a. by reducing Par to homogeneous subPar and then developing a unique life-loss equation for each class of subPar that can be compared across events; or
    b. by dividing the existing data set into homogeneous subsets and then developing a unique life-loss equation for each class of Par that can be applied only to Par with the same traits.
5. In both cases (4a and b, above), more variables than Wt, Fd, and Par would need to be considered. That is the burden of Chapters V – VII and the Appendices.

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CHAPTER V

CHARACTERIZATION OF CASE HISTORIES

Introduction

Purpose for characterizing events

A great many variables theoretically influence life loss from a dam failure. Undoubtedly, any model which included as many of these as could be conceived (and their thousands of corresponding interaction terms) would be unwieldy in the extreme. Moreover, the number of data points necessary to calibrate such a model or for a complex statistical regression to be meaningful grows exponentially with each new variable that is considered. Due to the limited number of catastrophic floods that have occurred and the still more limited information that is available on these floods, any regression involving more than a handful of variables appears doomed from the outset.

Nevertheless, there is great value in seeking to identify as many variables as possible and to quantify them for as many historic flood events as possible when sufficient information is available. Not only does this help a researcher to identify the handful of variables that are most useful for prediction, but the process itself forces the researcher to think in new ways and to explore new kinds of information that can potentially shed light on the dynamics that affect life loss in catastrophic floods.

Several potential benefits follow:

1. As was indicated in Chapters III and IV, those variables that have been most popular in the dominant life-loss models—in particular the DeKay-McClelland (1993b) variables warning time (Wt), dichotomous forcefulness (Fd), and population at risk (Par)—have serious shortcomings when comparing dissimilar flood events. It might be possible to define new temporal relationships, exposure terms, subPar, or other variables that could prove more useful as comparative and predictive tools.
2. The use of new variables may provide insight into traditional variables. For example, Brown and Graham (U.S. Bureau of Reclamation, 1989), Lee et al. (1986), and DeKay and McClelland (1991, 1993b) all developed life-loss relationships that are nonlinear with respect to the size of the population at risk. Yet, intuitively, if every individual in a population faced threats that were identical in every way (same depth and velocity of water, identical locations, same warning time, same time needed to evacuate, identical rescue assistance, etc.) one would expect a

consistent percentage of individuals to perish, regardless of whether 10, 100, or 1,000 individuals were in that population. Granted, the threat to individuals is likely to vary with population size, both favorably (rescue resources may be more readily available) and adversely (evacuations may take longer), but it may be possible to define new variables that minimize these differences based on the size of the population alone. Likely reasons for the nonlinear trends that are nearly eliminated by focusing on homogeneous subPar are presented in Chapter V.

3. Even if variables cannot be used directly in a regression equation, perhaps because of a paucity of diverse data points, key variables or combinations of variables may help an analyst to adjust an estimate upward or downward based on reasoning and historic precedence.

4. Uncommon variables may prove useful in distinguishing among failure categories; in suggesting more than one regression equation based on these failure categories; in suggesting order-of-magnitude probabilities to use as a check against the results of a regression equation; and in suggesting a reasonable range for confidence limits.

5. By fully characterizing each event, it is possible to gain an intuitive feel for each event. This helps an analyst determine when a new event falls outside of the experience of the data set, which events a new event is most likely to resemble, and where the range of life loss is most likely to fall. This provides a reality check for an estimate produced by a regression equation. As an alternative approach, it also allows an analyst to select a handful of events that are most similar to the one in question and to customize a new regression equation based on this select group or to use the select group to craft a representative probability distribution.

6. Modern GIS, census data, and flood inundation modeling allow for increasingly refined estimates of Par and subdivision of Par by community, location, distance, depths, velocities, housing damages, and other distinctions, making many variables potentially useful. This contrasts with the problems associated with the use of global Par by Brown and Graham (1988) (U.S. Bureau of Reclamation, 1989), Lee et al. (1986), and DeKay and McClelland (1993b) (see Chapter IV).

7. Some risk analysts are more familiar with the application of an equation to hypothetical events than they are with the historical events from which the equation was derived. By presenting event characterizations with full written support, it presents an immense quantity of source material in a more readily digested package.

8. Past characterizations have not been readily accessible to future researchers, making it difficult for others to evaluate or build on their work. By fully documenting each characterization, it allows other researchers to dispute the characterizations or to refine them as they see fit.

9. Detailed characterizations may prove useful for research into aspects of catastrophic floods other than life loss and for improving the effectiveness of emergency warning and evacuation procedures.

10. Empirical approaches based on regression or calibrated parametric models are preferable to purely analytical equations because their validity is founded on historic reality and patterns of life loss are sufficiently complex that they defy uninformed intuition.

Method Of Collecting Event Histories

As indicated in the introduction to Chapter VI, source material for dam failures and flash floods is not always easy to obtain. As such, the best source of information is those who have dedicated many years to building files on such events. The majority of the documents examined in this study were copied from the personal files of Wayne Graham in the Denver office of the United States Bureau of Reclamation. Additional source material was obtained from a branch of the National Performance of Dams Program called the Center on the Performance of Dams at Stanford University. These files covered more events, but contained less material than Graham's. In some cases, information was obtained from other sources.

Every event for which at least a passing reference was obtained is listed alphabetically in Table A.1 of Appendix A. This table includes the name and location of every event, its date, an approximate magnitude of life loss, and the nature of the flood (i.e., dam failure, dyke failure, flash flood, broad flooding, sea surge, etc.).

There was not time to characterize every event for which files were gathered, so Table A.1 also indicates which events have been characterized in Appendix B, which files are lacking enough information to be useful, which files are likely to be useful for characterization in their current form, which events are likely to prove useful following additional research, and the manner in which certain events were used by DeKay and McClelland (1993a).

Since the files gathered were dominated by dam failures, and since flash floods are much more common than dam failures, flash floods remain a largely untapped direction for future research. Indeed, within a one-week period of the current composition (August 1999) news has been obtained of two flash floods. One was in Utah and one was in Switzerland that killed at least 18 people.

Characterization of events

Characterizing Variables

The first step was to define as many characterizing variables as was practical that describe a flood event or that might have a direct bearing on life loss. Initially, there were about 55. It should be emphasized that it was never intended that all of these variables would be used for prediction. Rather, it was hoped that they might provide a fuller understanding of the dynamics of life-threatening floods—especially the life-loss dynamics—and that by exploring new avenues, a narrower set of characteristics might prove useful as predictive aids.

As events were analyzed, it became apparent that those characterizing variables that might prove most useful for prediction had yet to be defined. Through an iterative process, the number of characterizing variables under consideration grew to nearly 100. The characterizing variables most relevant to loss of life were originally broken down into five broad categories:

populations at risk, flood characteristics, spatial and temporal relationships between Par and the flood, and circumstances that attend the flood. For clarity, there was value in dividing the fourth category into circumstances that are temporary, delivered by nature, and those that are human in origin and thus typically more permanent. Those variables that were late additions have been included as a sixth category since they were not fully characterized for every event. This also flags them for special consideration.

Some of the variables, like those that describe the type and dimensions of a dam, were included primarily to paint a picture of the event and to provide information on the failure itself, with their predictive potential being secondary. Such information might facilitate research into the probabilities of failure and the likelihood that such failures will be detected in a timely manner as the data set is examined and expanded over time.

The 55 variables that fill the five categories must be characterized in one of four ways: by assigning a quantitative value (such as velocity), by designating a relative rank (such as degree of urbanization), by selecting a category (such as dam type), or by recording a description (such as the location of fatalities or a description of the housing damages). The last type of variable is a means of record keeping to assist in characterizing one or more variables in the other categories.

In the language of statistics, the second and third type of variables are called *categorical* variables, with the second being known as *ordinal* variables and the third being known as *nominal* variables. Once placed in a regression equation, statisticians sometimes call the *dependent* or *Y variable* the *response* variable and the *independent* or *X variable* an *explanatory* variable (Agresti, 1996). In this text, all variables will be called *characterizing* variables or simply variables, to indicate that they characterize an event. As subsets, a variable becomes a *predictive* variable if it is later found useful for that purpose, or a dependent variable if it is the basis for regression. L(P) is an example of a dependent variable described in Chapter IV.

Nomenclature

To facilitate the unambiguous use of symbols in equations and in the text, each variable is signified using a single capital letter or a capital letter followed by one or more lower case letters. In some cases, letters or numbers can be written as subscripts if it makes a symbol easier to read. For example, Par_i refers to one or more specific subPar (Par can be singular or plural, based on context). Par_3 is the third subPar defined for a specific event.

Generally, an ordinal variable is assigned one of the following levels: N = None, L = Low, M = Medium or Moderate, H = High, V = Very High, or E = Exceptionally High. The precise nuance or meaning of each of these gradations is specific to each variable. Indeed, "low," "medium," or the other words associated with the symbols listed above are often poor grammatical companions to the variables that follow, so they are defined more thoroughly in each case. Nevertheless, to avoid the need to memorize or reference a separate set of symbols for every variable, gradations are limited to these six symbols. Most ordinal variables use only part of this range, but the sequential hierarchy of the symbols is maintained to minimize confusion.

Every nominal variable has a unique set of symbols. The reader should consult the sections that follow whenever the precise nuance, criteria, or definition of the coding of a variable is in doubt.

Comprehensive List of Characterizing Variables, Their Coding, and Their Definitions

Populations At Risk

Population at Risk (Par)

Technically, Par should identify the number of people for whom a dam failure is hazardous in the sense that their lives are truly in jeopardy. Recognizing this, the Australian National Committee on Large Dams (1994, p. 114) defined Par as “all those persons who would be *directly* exposed to floodwaters *within the dambreak* sic *affected zone* if they took no action to evacuate.” The italicized phrases were the key modifications to previous definitions. By using “directly,” they excluded those who might be safe from calm waters due to the elevation of their property or perhaps a second story. They also excluded those who might be injured by evacuating motorists after they cleared the flood zone. By including “within the dam-break affected zone” they were referring to another technical definition:

> *Dambreak Affected Zone: That zone of flooding where the changes in depth and velocity of flooding due to dambreak* sic *are such that there is potential for incremental loss of life. [They then refer to depth-velocity charts such as might be developed using study results from Abt et al. (1989) discussed in Chapter III of this thesis.] The Dambreak Affected Zone is in any case limited to those areas where dambreak causes a rise in level of floodwaters greater than 300 mm [about 1 ft]. (Australian National Committee on Large Dams, 1994, p. 110)*

As reasonable as such a definition might appear, it is impractical for several reasons. First, as any fisherman who has waded a stream soon discovers, the momentum of floodwaters has a direct bearing on his threat to life. Most healthy adults could safely wade through stagnant water several feet deep, while less than a foot of rapidly moving water can sweep a car from a road and plunge it into fatal waters downstream. Since the depth and momentum of water changes rapidly based on local variations in slope, contour maps are inadequate tools to define hazardous regions on this scale. Second, the hazard posed by water varies among individuals. Small children or infants, the elderly, those who are disabled or physically disadvantaged, those who cannot swim, or those with fear of water might perish in situations posing little threat to others.

In light of these uncertain factors, the term Population at Risk becomes somewhat misleading and challenging to define. In order to include all hazardous regions, the population must be defined so expansively that only a portion of the Par would truly be at risk of death in most cases; given sufficient warning and evacuation, none of the Par would risk death apart from the dangers inherent in emotionally charged situations and the evacuation itself. Traditionally, Par has been defined as broadly as possible to include all those who, given no warning and without moving, would get their feet wet from the flood (i.e., Dekay and McClelland, 1993b; U.S. Bureau of Reclamation, 1989[1]; Lee et al., 1986[2]).

"Get their feet wet" has usually neglected any increase in elevation provided by buildings (Lee et al., 1986, made this explicit; see footnote). If such elevations are included, one can face dilemmas: A woman who is gardening is swept away by 2 or 3 ft of water while her husband remains dry cooking dinner in the elevated kitchen and her 5-year-old daughter scrambles to escape the torrent of water pouring through the open basement window. If such elevations are neglected, there is still the risk that people will enter the flood zone from outside or while crossing it from an island inside. Moreover, dam break studies cannot fully account for the effects of channel scour, debris dams, variations in channel geometry, bridge failures, road and berm washouts, dispersion, or other vagaries on the direction and pattern of a dynamic flood wave, making even the most refined analysis lacking.

Identifying historic Par is no easier. Without the aid of GIS or detailed census data, Par must often be estimated using evacuation figures, statistics on housing damages, by viewing aerial photographs, by counting dots that represent structures on maps, or by other forms of approximation. However, for historical floods these methods generally rely on the actual dimensions or affects of the flood and so they may provide better estimates than a computer simulation of inundation.

What we want is a definition of Par that when used predictively is most likely to match the definitions implicitly used for historic events. DeKay and McClelland (1993b, p. 196) defined this as "the number of people that were evacuated or the number of people that would have been evacuated had there been any warning." However, this is highly subjective and may include areas much larger or much smaller than the flood itself. Also, Par has seldom been quantified in this manner; most of the Par in Appendix B are quantified based on the number of buildings with at least minor damage. Such damage is a function of the depth and velocity of a flood near its peripheries.

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[1] "All individuals who, if they took no action to evacuate, would be exposed to flooding of any depth" (U.S. Bureau of Reclamation, 1989, p. III-25).

[2] "A person is at risk if he or she would be touched by the flood water at peak stage if he or she were to stand outside" (Lee et al., 1986, p. 6).

By way of a solution, Par can be defined using a trichotomous approach to flooding and a modification to the ANCOLD definition. The three categories recognize the diverse nature of flooding, defining it in a manner that reflects the likely patterns underlying the calculations of Par in the case studies. In general terms, the definition by Lee et al. (1986) should be adopted for Par inhabiting terrain that is steep or close to the dam: "A person is at risk if he or she would be touched by the flood water at peak stage if he or she were to stand outside" (Lee et al., 1986, p. 6). At the other extreme, in areas where a flood consists of a nearly stagnant backwater, Par should include only those who would be exposed to flooding greater than or equal to 1.5 ft in depth. When flood characteristics fall between these extremes, Par should include only those exposed to flooding greater than 6 – 12 inches deep, based on a convenient contour. The depths surrounding a single Par should vary according to all three of these criteria as the area's topography and relationship to the river change.

To standardize these criteria and give them justification, the divisions can be refined with the help of depth-velocity curves that indicate the conditions needed to sweep away humans and automobiles; and with assumptions regarding the depths likely to mobilize a voluntary evacuation. The sections that follow convert the three general guidelines in the preceding paragraph to three standardized rules, each followed by supportive reasoning.

In flooded areas where the lateral slope exceeds 0.01 and the velocity at depths of 1 ft exceeds 3 fps, a person is a member of the Par if they would be touched by the flood while standing outdoors on the ground prior to evacuation. If the lateral slope is greater than 0.01, a one foot rise in flood depths will not encompass a new row of houses, but those houses within the flood will extend to depths of 1 ft. At velocities of 3 fps, these depths would likely inspire evacuations and cause minor housing damage.

For perspective on these relationships, as water nears 2 ft deep, a monolith simulating a feeble adult can be consistently toppled in flow velocities ranging from 1.18 to 2.16 fps (less than half of walking speeds). At the other extreme, wearing safety harnesses in a laboratory flume, very healthy adults can be toppled in water between 1.6 and 2.0 ft deep with velocities ranging throughout the 4.5 to 8.5 fps range (see Abt et al., 1989, or Chapter III). Including all ages and all levels of health, it is likely that many people—especially children—could be toppled between these extremes in the far less ideal conditions of a sudden flood surge. Once toppled, people can be swept toward the center of the channel. Thus, flows as shallow as 1 ft deep can be dangerous if they approach 10 fps and flows that are 2 ft deep are potentially lethal to an important fraction of the population even when velocities are moderate.

Safety officials who do not know how high a flood will rise would probably include all such areas in an evacuation plan.[3] Moreover, depths in this range will pile mud and debris in

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[3] Remember that Par includes far more people than are likely to die, except in the most extreme events. In order for a regression equation to apply to future estimates of life loss, current definitions of Par must be as expansive as historic definitions. Evacuation plans would be particularly expansive for fast, violent floods, probably extending to the limits of flooding or beyond.

yards and possibly flood ground floors, causing minor housing damages. In both cases, such areas would likely be included in historic Par.

> *In flooded areas where velocities are less than 1 fps at depths of 2 ft, a person is a member of the Par if they would stand in water greater than 1.5 feet deep while standing outdoors on the ground prior to evacuation. In contrast to the high velocity, narrow flood anticipated above, a leisurely flood crossing a wide floodplain will form backwaters that pose little hazard to life. Two questions arise: At what depth are lives endangered and at what depth are houses damaged?*

The answer to the second question might be the point when an automobile can be carried toward treacherous water. The U.S. Bureau Reclamation (1989) presents a graph derived from a study conducted by Simons, Li, and Associates, Inc. (1984) for the City of Boulder Colorado. The study attempted to determine the depth-velocity combinations necessary to move an automobile downstream. Interestingly, the graph of such a relationship is almost vertical: at a depth of 1.25 ft, a flood must travel at 10 fps to move a car, while at a depth of 1.9 ft, a car can be moved by the slightest current. At walking speeds (4 – 5 fps), the depth is close to 1.5 ft.

Even where average depths and velocities are low, a flood can generate an unexpected current across low spots that funnel the water. Motorists who are swept away while attempting to cross a road with seemingly minor flooding is a leading cause of death in flash floods. Thus, quiescent floods with depths of about 1.5 ft have the potential to endanger lives in select locations. At these same depths, houses would be damaged even in stagnant water. Hence, Par should always extend to depths of 1.5 ft, no matter how calm the flood.

In flooded areas where velocities fall between the extremes of the two previous rules, a person is a member of the Par if they would stand in water greater than 1 foot deep while standing outdoors on the ground prior to evacuation. These floods fall between the extremes of a quiescent backwater and a raging torrent. Many people would not evacuate if water did not enter their homes or rage swiftly across their yard. Nor would they be at measurable risk. As such, only those who have water lapping at their door should be considered—somewhere between about 12 – 18 inches. Based on the scale of most flood maps, any contour that sets flooding close to 1 ft would be satisfactory.

Summary. When the lateral slope exceeds 0.01 and the velocity at depths of 1 ft exceeds 3 fps, the geographic boundaries of the Par extend to the edge of the flood. When velocities are less than 1 fps at depths of 2 ft, the geographic boundaries of the Par extend inland to points where the flood drops below 1.5 ft. In all other flood conditions, the geographic boundaries of the Par extend inland to points where the flood drops below 6 to 18 inches, or 1 ft for convenience. Par includes all those present in the geographic boundary after the dam fails and prior to the arrival of a warning.

Although these rules are intended to standardize analysts' approaches and conform them to the definitions most likely to underlie the quantification of Par in the present study, they can be violated if such violation will more closely conform to the patterns in this present study. For example, if a long, public building had a second or third story entrance high above a flood, but the first floor was far down slope where it faced high-velocity flooding, the analyst might want to exclude those on the second or third floors from the Par if the structural integrity of the building was not expected to be threatened.

Threatened Population (Tpar)

Recognizing that population at risk (Par) includes many individuals who will never be threatened by flood waters due to evacuation—and conversely that convergence of curiosity seekers and safety workers on a floodplain can increase counts beyond the members of Par—the threatened population is defined as all those present in the flood inundation area when the flood wave arrives.

The same depth and velocity relationships apply for Tpar as for Par. That is, in general, once flooding exceeds about a foot, anyone trapped in a building or wading across the floodplain becomes part of Tpar, but the first 6 – 12 inches of flooding can be ignored.

SubPar (Par_i)

Population at risk (Par) should be subdivided whenever there is a clear change in a major characterizing variable and there exists sufficient historical evidence to characterize Par_i individually. The exact information required will depend on the components of any proposed model, but information regarding the size of the subPar, the life loss within that subPar, some measure of the warning time applicable to that subPar, and a description of the flooding characteristics or damage characteristics within that subPar are essential. It is also highly desirable to know how many people successfully evacuated prior to the flood's arrival, the average time required for evacuation, and the circumstances or locations where individuals either perished or survived the flood. Most variables must be characterized anew for every subPar and may be subscripted for ease of reference. The goal is to produce subPar that are as homogenous as possible and that can then be grouped with like populations from diverse events to obtain a historic frequency distributions for key variables like life loss (L).

Threatened SubPar ($Tpar_i$)

$Tpar_i$ is the same as Tpar, but it is specific to a subPar (Par_i).

Life Loss (L)

Life loss (also commonly called loss of life) refers to the number of deaths of any kind and at any location that can be attributed directly or indirectly to flooding, without regard to whether or not the deaths would have occurred had the dam not failed under the same loading.

In some cases, flood victims are never recovered and are listed as missing rather than dead. When victims remain on the list of missing in the most recent reports, they are included in L under the assumption that they most likely perished; if not confirmed fatalities, they perished in the minds of all who knew them, with comparable local effect.

Expected Life Loss (Le) and Historic Life Loss (Lh)

In predictive applications, L refers to the expected life loss (mean life loss) as generated by a predictive model, without adjustment. When predictive models are applied to historic case studies, the historic L can be distinguished from the expected L by using Lh and Le, respectively. In such cases, Lh or Le should be substituted for L in the definitions below (Lha, Len, etc.). When the context is clear, L alone should be used, as it is throughout the rest of this report.

Adjusted Life Loss (La)

When making an estimate, if the investigator finds reason to adjust the expected value of L, this adjusted value can be distinguished from L by using the symbol La. The symbol La is unnecessary if the context makes the meaning of L clear.

Natural Channel (never a dam) Life Loss (Ln)

This is the expected life loss (L) given that the dam had never been built and the same loading (earthquake, storm) occurs. Unless the dam that fails is relatively new, Ln generally assumes less flood plain development and different recreational patterns than after a dam has been in place for many years. Ln is a construct that is counter-historical, except in the case of flash floods on dam-free rivers.

Life Loss given Dam Removal (Ldr)

Dam removal is often considered as a risk mitigation option. This variable assumes the dam is removed, sediment issues are resolved, and the channel through the reservoir is restored shortly before the failure loading occurs, using the then-current level of flood plain development and channel geomorphology.

No Failure Life Loss (Lnf)

The number of deaths that would have occurred had the dam not failed given the same initiating conditions. In the event of internal failures with no unusual loading conditions, Lnf is always zero. In other types of failures, it may be difficult to quantify Lnf from the case descriptions themselves, so it must be estimated in some other manner. In some instances, case studies or established methods involving flash floods or earthquakes may prove useful.

Incremental Life Loss ($Li = Li_n$ or Li_{dr} or Li_{nf})

Various symbols for life loss (L, Ln, Ldr, Lnf) and the subtleties of each are defined above.

Despite our best flood mitigation efforts, floods claim many lives every year. In some cases, such as where a downstream channel constriction creates an elevated tailwater, a dam failure may add little height to the ensuing flood wave, thus contributing little to the ensuing life loss.[4] The incremental loss of life (Li) is limited to those deaths that would not have occurred without the failure.

Even after a failure determining the incremental life loss is often challenging and sometimes impossible, since it is difficult to know how many lives would have been lost without a failure. There are, however, several possible baseline cases against which to compare.

If $Li_n = L - Ln$, Li_n discounts the fact that the existence of a dam, historically, probably led to increased recreational activity and its flood control benefits likely promoted flood plain development. Indeed, it may be the irrigation benefits that allowed a community to develop in the region at all. Such a comparison contrasts quite dissimilar scenarios, making the dam owner responsible for the growth in downstream population, but ignoring both the many benefits the dam provides and the lives the dam potentially saved during previous flooding events. When comparing developed nations with dams to less developed nations without dams, one could even argue that the relative prosperity that dams have helped bring about has saved lives by reducing poverty and disease.

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[4] For example, when Rapid City in the Black Hills of South Dakota flooded in 1972, flooding was so severe that when Canyon Lake Dam failed, the reservoir pool was only about a foot higher than the tailwater. It has been suggested that of the 245 fatalities, perhaps only 33 can be directly attributed to the extra flooding caused by failure of the dam (Graham, 1998).

On the other hand, if a dam has not yet been built, comparing L to Ln seems to be the most natural approach to a dam's hazard potential.

For existing dams, if Li_{dr} = L - Ldr (U.S. Bureau of Reclamation, 1989), comparisons are more direct, since standards of living, past benefits, and levels of development are the same in each case. One has a useful measure to help determine whether the dam should be kept or removed. It should be noted that the number of fatalities might actually be lower given a dam failure over against the same event rushing through the valley without a dam in place. While a dam failure will unleash a wave of larger volume, if the failure does not progress rapidly, the peak may be dampened compared to a natural flash flood. Also, if monitoring of the dam may allow adequate warning time and the dam delays the onslaught of flooding, lives can potentially be saved through evacuation.

One drawback to this definition of Li is that it ignores the future affects on recreation and flood plain development caused by removing the dam. Even if Ldr were redefined to be a current removal with a future population at risk, there is no way of knowing how far into the future a failure might occur, making it difficult to adequately define any growing disparities between L and Ldr in terms of Par. Also, like Li_n, comparing L and Ldr for a future event ignores the lives potentially saved through flood abatement and economic development due to keeping the dam prior to failure.

The third possible definition is Li_{nf} = L - Lnf. This definition is useful in comparing the status quo against various versions of the dam following proposed improvements; or in comparing various designs of a dam yet to be built. This comparison may be used to guide future decisions or to evaluate past decisions. Like Li_{dr}, Li_{nf} cancels the shared historical benefits or harms of the two scenarios, focusing attention on the isolated event of interest. It has the advantage that any differences in flood protection or floodplain development are likely to be minor. A tremendous practical benefit is that the two scenarios depend on similar hydrologic data.

None of these definitions prove adequate for every purpose. Clearly, if rehabilitation alternatives are being considered, the Li_{nf} has many advantages for existing dams, but in any risk assessment or liability investigation, removal of the dam must be included as one of the policy alternatives. In that case, the Li_{dr} seems imperative. If a dam has yet to be constructed, Li_n is the only increment that gives due consideration to not constructing the dam at all. For some dam owners, the choice of analysis may hinge on legal liability considerations, in which case any or all three may prove important.

Proportion of Lives Lost (P)

The proportion of lives lost (P) refers to lives lost among a population at risk (Par) as opposed to lives lost among a threatened population (Tpar) or other subdivision of Par. Like the other variables, it can be specific to a global population at risk (Par) or to a subPar, with the latter relationship designated by a subscript: P = L/Par and $P_i = L_i/Par_i$.

Fatality Type (Ft)

Fatality type helps define the manner in which a flood proves lethal. It categorizes the dominant types of death according to their nature or locality. Ideally, the associated number of deaths should accompany each symbol.

N = none.

C = campers, including recreationists hiking/walking/standing *near* the river

W = those *in* the river when the flood wave appears: waders and swimmers.

B = those *on* the river when the flood wave appears: rafters and boaters.

L = those in or on a lake when the flood wave appears: boaters and swimmers.

E = employees of the dam owner who are at the dam for construction, repairs, monitoring, failure prevention, etc. Note that this category will overlap with some of the others.

Af = automobile occupants killed by flood waters.

Aa = those killed in an automobile accident during evacuation.

D = general drowning deaths in areas with buildings. Note that it may be impossible to distinguish deaths in buildings, automobiles, and on the floodplain here.

Sf = slope failure at or very near the dam itself.

O = other = non-drowning deaths other than auto-related or slope failure near the dam: mudslide associated with the flooding and not the dam failure itself, suicide, heart attack, exposure, disease, etc.

U = Unknown mix.

Locations of Deaths

The location of a death is generally considered the place where an individual was overcome by flood waters, in contrast to the location where the body was recovered. In general, it associates the death with a particular Par$_i$. When more detail is available, it locates the victims in buildings, in automobiles, in the open, etc.

Flood characteristics

Flood Type (Flt)

This is the source of the flood. In some cases, more than one source is involved.

D = dam failure.

Dy = failure of a dyke—whether it be a sea dyke or a levee—thus being similar in some respects to a long dam.

Ff = a flash flood, meaning the flood wave is sudden and fast rising or a wall of water.

F = flood, meaning a widespread event that cannot be described according to the other categories in this list.

Ts = a tsunami or tidal wave.

S = a sea surge.

H = flooding caused by a hurricane and distinguished from F or Ff in that the deaths are not necessarily a result of the flooding.

Gb = a glacier burst.

O = other types of flooding difficult to categorize, such as when a storage tank or water tower bursts.

Peak Velocity (V)

V is the peak velocity for a given Par$_i$. It may require an approximation based on eyewitness accounts of the approaching flood wave or an average value based on post-failure flood routing or known travel times.

Maximum Depth (D)

Since rivers vary greatly in depth, the maximum depth in the center of the channel has little comparative value from one case to another. D is thus the maximum depth on land for a given Par$_i$. D should be the greatest flooding depth that could have been witnessed by any member of Par$_i$, whether or not they were present or survived. This would generally be estimated using high water marks on buildings or trees, or the height of a wall of water (Ww). The datum will be somewhat subjective, but should be the lowest point at which a member of Par$_i$ might have originally occupied.

Peak Volumetric Flow Rate (Qp)

Qp is the maximum volumetric flow rate experienced at the location of a specified Par or subPar during the duration of the flood.

Bankfull Volumetric Flow Rate (Qb)

It is desirable to quantify the magnitude of a flood in a way that discounts the flow in the main channel to quantify the rate at which water actually flows across the floodplain. A flow of 30,000 cfs in a very large river might never top the banks, while such a flow in a tiny mountain creek would likely cause considerable damage to bordering communities. This normalized measurement is found by subtracting the bankfull flow rate from the peak discharge (Qp – Qb).

While a simple concept, Qb is not so easily defined. Floodplains are rarely flat with a clear channel rim. Superelevation can cause the outer bank to flood before the inner bank. Quite often, communities are constructed on surrounding hills, terraces, or a higher floodplain created during an earlier flow regime, which can make the narrow floodplain directly next to the river difficult to discern. In mountainous areas, V-shaped valleys can obscure the floodplain altogether. Compounding this, there can be natural levees or low spots produced by previous channels that crisscross a river valley (Leopold, 1997).

Physically, the geomorphology of streams are governed by their flow regimes. Hence, "nearly all stream channels, whether large or small, will contain without overflow approximately that discharge that occurs about once a year. Higher flows" occurring once every 2 to 5 years, will overflow onto the floodplain (Leopold, 1997, p. 64). Generally speaking, Qb is equaled or exceeded 2 to 4 days per year, with a return period of about 1.5 years. This holds true whether the high flows are from rainstorms or spring snowmelt (Leopold, 1997).

This suggests several methods for estimating Qb. The ideal method is to use a known stage-discharge relationship at a low point within the subPar. Short of this, a reasonable estimate for Qb can be made by interpolating the 1.5-year return flow off a flood-frequency diagram for the area in question. Since the mean annual flood has an average recurrence interval of 2.3 years (Leopold, 1997), the mean annual flood would provide a reasonable approximation. If flows for only a few specific return periods are already known—say the 5 and 10 year floods—these place a boundary on Qb from which reasonable estimates may be possible. Similarly, a few stage-discharge values may suggest a reasonable range for Qb. Even typical or average flows for a river suggests something about its size, pointing toward an order of magnitude for Qb.

The preceding discussion highlights that it is generally not critical to calculate Qb with high precision. This holds true because there is already great uncertainty as to what multiple of Qb is needed to reach the first person, there is great variation between subPar as to the general steepness of slopes beyond the riverbank, and, most importantly, since Qb is often one or two orders of magnitude smaller than Qp, a rough estimate is all that is needed to refine Qp – Qb. In light of this, Qb can usually be estimated without extensive hydrologic calculations.

Maximum Width (W or W_{max}) and Derivatives (W_{min}, W_{avg})

The peak flow rate (Qp), the bankfull flow rate (Qb), and the maximum width of a flood at a given subPar (W), are necessary to compute the magnitude of the destructive velocity (Dv) for a given Par_i. An alternative to W, also designated W_{max}, is to use the minimum width (W_{min}) or some representative average width (W_{avg}). When W alone is used, it is assumed that it is W_{max}.

Destructive Velocity (Dv)

The variable Dv was first proposed by Graham (1998).[5] Graham did not provide a name for the variable, but the symbol was derived from the relationship depth*velocity. By definition, Dv = (Discharge above bankfull)/(width of flooded region) = ($Q_{peak} - Q_{bankfull}$)/width. This has units of $(distance)^2$/time or depth*velocity.

Since velocity alone tells little about the potential of a flood wave to cause destruction, the flow's depth is a critical component. By using the entire volumetric flow rate and dividing it by the flood width, the resulting variable automatically averages across variations in depth and velocity, providing a description not only of the entire flood wave, but also of its interaction with Par_i. In general, since populations tend to spread further from the river as a valley widens, the more dispersed Par_i, the wider the flood and the smaller Dv becomes compared to the same flow rate in a narrow canyon. If one were to use (maximum depth)*(velocity) instead, it would provide only a point estimate at the center of the channel, describing little about the flood's total magnitude and how it interacts with Par_i.

Since no temporal variation is included in this variable, it should be quantified using maximum values, whether or not the maximum width corresponds with maximum flow. Since depth and velocity are indirectly included in this variable, they need not be treated separately, except as they vary with time. This is the purpose of rise rate (R) and wall of water (Ww) below. Nevertheless, the maximum depth within reach of Par_i (D) and the peak velocity within reach of Par_i (V) are included in case Dv cannot be adequately quantified.

Since one could use W_{max}, W_{min}, or W_{avg} (defined above) to quantify Dv, Dv_{min} corresponds to W_{max} (because maximum W minimizes Dv), Dv_{max} corresponds to W_{min}, and Dv_{avg} corresponds to W_{avg}.

Maximum Rise Rate (R)

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[5] Graham's symbol was DV, meaning depth*velocity, as explained in the text. The name "destructive velocity" was chosen here because the variable combines an average depth with an average velocity to describe the destructive potential of the flood wave and this preserves Grahams general symbol.

Flood waves that cause common sorts of fatalities must generally rise fast enough to trap people unawares or overtake them as they seek to flee.[6] The maximum rise rate refers to the steepest portion of the rising edge of the outflow hydrograph.

Quite often, floods resulting from dam failures or severe flash floods rise instantaneously as a *wall* of water. Since this peak rise rate is infinitely fast and thus not quantifiable in the same way, "Ww" should be entered to indicate that the next variable applies instead.

R should also be treated as an ordinal variable as follows:

M = moderate (can walk away from the flood waters if not lingering).
H = high = rapid (requires immediate, rapid action to avoid being trapped).
V = very rapid (difficult or impossible to outpace waters, even with immediate evacuation on foot or by automobile).
Ww = wall of water (indicates the rise rate is instantaneous and can only be quantified by measuring the height of the wall of water).

Wall of Water (height of) (Ww)

The height of a wall of water is usually based on eyewitness accounts and/or flood routing. When more than one value is suggested, those figures which are deemed most credible should be averaged. In cases where the flood wave does not pile up in a wall, one should enter a "0," indicating that it must be described using the rise rate (R) above.

Often, eyewitness accounts of Ww are based on the in-channel depth of Ww, which may exceed the peak depth on the bank (D). Hence, $Ww \leq D$.

Damage and Destruction (Dd)

The number of structures destroyed, seriously damaged and damaged to any extent should be recorded by category of structure and degree of damage, when available. Note that this variable is essentially a detailed record for quantifying forcefulness (F) and loss of shelter (Ls).

Forcefulness ($F = Fp, Fd, F_5,$ or $Fpar$)

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[6] An exception to this might be when water crossing a road appears safe, but subsequently sweeps an unsuspecting motorist downstream. Even in this case, however, fatalities are more likely when the water rises unexpectedly during the crossing.

Dekay and McClelland (1991, 1993b) developed this variable. Originally, it was intended to represent the proportion of Par actually subjected to potentially lethal flooding[7] by dividing the number of residences destroyed or seriously damaged by the sum total of all residences experiencing any damage at all. This is defined here as Fp for proportional forcefulness.

As reasonable as Fp may at first appear, it is not easy to define in a consistently meaningful way. The force required to damage or destroy shacks, mobile homes, frame dwellings, brick houses, and large commercial buildings is quite different. Even within a given category, it will vary across centuries and countries depending on the building codes.

In contrast to the forcefulness of a flood, its potential lethality may be better captured by including all occupied structures,[8] since a structure that experiences little harm generally provides a safer haven than one that is damaged.

The importance of each structural category varies with occupational cycles and with the relative proportion of each type of structure in the flood zone. This point becomes critical when considering Par_i located at a campground or along a stretch of river frequented by rafters or fishermen; in such cases, there may be virtually no significant structures at all!

For consistency, this study will follow Dekay and McClelland (1991, 1993b), focusing exclusively on residences. Not surprisingly, Dekay and McClelland found Fp difficult to quantify using historic data, so they turned to Fd.

Fd is *dichotomous forcefulness* wherein forcefulness is high (1) or low (0). To fill in historical gaps, Dekay and McClelland (1991, 1993b) relied heavily on the expert judgment of Wayne Graham. Fd is conceptually identical to Fp, with the dichotomous dividing line between about 0.15 – 0.2. To update the Dekay and McClelland definition, Fd = 1 is definitively set at Fp ≥ 0.2 based on all available evidence and, in the case of Par_i without buildings, the destruction that would have been likely if frame residences were physically present.

F_5 goes a step further, subjectively dividing Fp into five even ranges:

L = low (0 – 0.2).

M = medium (0.2 – 0.4).

H = high (0.4 – 0.6).

V = very high (0.6 – 0.8).

E = exceptionally high (0.8 – 1.0).

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[7] Forcefulness was originally called Flooding Lethality or lethality for short (DeKay and McClelland, 1991). Presumably, since the variable measures the force of the flood on buildings and does not take account of the temporal considerations that influence lethality, the more accurate term was adopted in 1993 (DeKay and McClelland, 1993b).

[8] i.e., excluding barns, outhouses, chicken-coops and the like, but including RVs in campgrounds, mills, businesses, power plants, and other structures occupied for many hours each day.

Fpar is the number of habitable structures of any type that are damaged severely or destroyed, divided by Par_i.

Height of the Dam (H)

Ideally, the height of the dam is measured from the streambed and not the bottom of the foundation.

Height of the Reservoir Pool at Failure (Hp)

Ideally, the height of the reservoir pool at failure would be measured from the tail water of the dam, but this is unlikely to be available historically, so it is defined in relation to the dam height. Sedimentation within the reservoir is ignored, since it is the distance of fall that is of most interest. Given overtopping, the depth of overtopping is added to the height of the dam. In the absence of overtopping, the distance to the reservoir pool below the dam crest is subtracted from the height of the dam.

Breadth of the Dam (B)

The breadth of the dam is the distance between abutments at the dam crest.

Volume of Release (Vol)

The volume of release is the volume of impounded water at the time of failure that is subsequently released during the failure event. It does not include additional inflows into the reservoir after failure has begun in earnest.

Rate of Failure (Rf)

Not strictly a rate, Rf is the number of minutes it takes until at least 80% of the breach has developed from the time failure begins in earnest. The reason 80% is used is to distinguish the main breach from the residual erosion which may continue throughout the failure event and the minor erosion which precedes catastrophic failure. Rf may be thought of as the “most rapid” 80% of the failure.

To help standardize eyewitness accounts, when a failure is described as nearly instantaneous (i.e., “as an explosion”, “quicker than you can write these words”), Rf should be assigned a value of 0.5 minutes. If the failure is a very rapid erosion or slope failure but falls short of near-instantaneous, it should be assigned 5 minutes unless evidence suggests a more precise value.

Area of Final Breach (A)

The area of the final breach is measured perpendicular to the direction of flow when the breach is fully developed. For consistency, it is measured to the top of the original dam crest unless the breach does not extend to the top.

Spatial and Temporal Relationships between Par_i and the Flood

Summary of Month/Day/Year, Hour, and Day of the Week (T)

The variable T is simply a designation for the complete textual record of the time of failure. Aspects of T are coded symbolically to facilitate analysis using time of day (Td), time of week (Tw), time of year (Ty), and time of season (Ts) described in the subsequent sections.

Time of Day (Td)

Code Td as follows:

N = night (most people are asleep; 11:30 PM – 6:00 AM).
S = separation (most families are separated by school or work; 8:00 AM – 6:00 PM on weekdays).
H = home (most families are together; 6:00 – 8:00 AM, 6:00 – 11:30 PM; weekends, holidays, and when Par_i is dominated by recreationists and it is not night).

Notice that this variable says something about the lighting conditions, the ease of warning notification, the time required to begin an evacuation, and whether or not families are together.

Time of the Week (Tw)

Tw is coded dichotomously:

Wend = weekend

Wday = weekday.

Time of the Year (Ty)

Ty is simply the month, coded as 1 – 12, beginning with January and ending with December.

Time of the Season (Ts)

Ts indicates the season of the failure. It has relevance to environmental conditions such as the temperature of the air and water, the lighting conditions, and the willingness of people to leave their homes. Here, the variable is coded dichotomously:

S = summer (May – October).

W = winter (November – April).

Warning Time (Wt)

Warning time (also known as the initial warning time) is defined as the difference in time from when the first warning is given of a dam break or of an impending dam break and the time when the leading edge of potentially lethal flood waters first arrive at the leading edge of Par_i from the failure. "Potentially lethal flood waters" are described under Par, above. A flood is generally considered potentially lethal once it exceeds 1 – 2 ft in depth. "First warning" is the warning that first reaches a member of Par_i, is intended for dissemination, and encourages evacuation. As such, contrary to previous definitions of warning time (i.e., U.S. Bureau of Reclamation, 1989), Wt does not necessarily begin with a public safety official.

Individual Warning Time (Wt_i)

Wt_i is the increment of time from when an individual first receives news that the condition of the dam warrants evacuation and the floodwaters gain lethal potential at the location where the individual was when the news was received. The news can come from any source, official or otherwise, human or environmental.

Note that the symbol Wt_i can also indicate the value of Wt for a particular Par_i. Since warning time (Wt) and individual warning time have different definitions, with individual warnings able to come from more types of sources, it is important to note the contextual use of Wt_i. Individual warning time (Wt_i) is the same as individual escape time (Wt_e) below, except Wt_e can be extended as one tries to outrun the flood.

Individual Escape Time
(warning time for escape) (Wt_e)

Wt_e is the increment of time from when an individual first receives news that the condition of the dam warrants evacuation and the floodwaters reach lethal potential at the place to where the individual has fled or the location where the individual exits the flood zone. This is the most meaningful definition of warning time because it is the only one that measures the full time it takes to be overrun by the flood wave. Unfortunately, unless it can be accurately estimated on a case-by-case basis, it has little practical value.

Average Warning Time (Wt_{avg})

Ideally, the average warning time would rely on the individual escape time (Wt_e) in place of the individual warning time (Wt_i), each defined above; but realistically the average warning time (Wt_{avg}) must be the lesser of Wt_i and the warning provided by sensory clues (Sc) averaged across the population. In practice, Wt_{avg} will be an approximate estimate of the average interval members of Par_i have from the time they first become aware of the danger until the time the flood waters reach the ground above which they occupied at the time of awareness.

Wt_{avg} is based on warnings from any source, including sensory clues (Sc), and so Wt_{avg} is never less than Sc, but it can be more than the warning time based on the first formal warning (Wt). Wt_{avg} includes informal warnings from passing motorists or neighbors, but it considers warnings only after they are clearly understood and viewed by the general population as credible. For example, motorists honking their horns might alert people that something is happening, but it would not be a warning until shouts or sensory clues made the danger comprehensible. Likewise, officials might advise a population that a dam is in danger of failing (making Wt long) but if there has been a history of false alarms, the population might not mobilize until a more credible warning is initiated (making Wt_{avg} much shorter).

Building Types by Percent (Bt)

Bt represents a community profile within the flood zone. It is coded as follows:

N = none.

T = tents.

Sh = shacks or flimsy buildings.

M = mobile homes or RVs.

R = residential homes.

C = one story commercial or commercial of unknown height.

H = commercial over one story.

Lm = structures with less mobile populations (hospitals, nursing homes, schools).

Development (Dev)

Along with building type (B)t and goodness of fit (Gf), development (Dev) helps profile a community. Dev measures the degree of urbanization, and is coded as follows:

N = none (rural, communities under 100).

L = low = small town.

M = medium = suburban.

H = highly urbanized; large city, densely populated, potentially tall buildings.

Goodness of Fit (Gf)

Gf is a spatial variable that describes the variance in exposure faced by members of Par_i by indicating their spatial homogeneity or heterogeneity with respect to the river. It is called goodness of fit because it suggests the degree to which other variables accurately represent individual members of Par_i. A low (poor) Gf implies that many individuals are exposed to a lower degree than group variables imply and a high (good) Gf implies that the entire Par_i is well represented. Note that Gf provides a measure of development/urbanization, proximity to the river, and uniformity within a community—issues also addressed by excess evacuation time (E), warning effectiveness (We), development (Dev), and striking characteristics and valuable quotations (Schvq). Gf is coded as follows:

L = low = poor (a large, urban area; multiple communities over a long reach of river; wide flood plain; mix of canyon and open plain; variable values would suggest excessive danger more often than not if applied on the individual level).

M = moderate = satisfactory (a typical small town or mountain community with some residences near the river and some on higher ground or in the hills; a series of small communities with similar warning time; a wide flood plain with urban/suburban development among which the flood rises slowly).

H = high = good (all of Par_i reside within a narrow flood path; small canyon community clustered along the river; campgrounds; very small Par in a similar location, such as a few cars at a flooded road).

V = very high = very good (a huge wave which submerges an entire community without warning; a wave which annihilates virtually every structure within the area of Par_i; no basis for saying some members of Par_i are less exposed or safer than others and no time to escape before the flood arrives).

Outdoors (O)

Outdoors is a dichotomous variable, defining whether or not at least a significant minority of persons are outdoors. This has bearing on when sensory clues might be picked up, the rate at which people are likely to run for high ground, the rate a short warning might spread, and the level of protection available if escape cannot quickly be obtained. Tents are considered outdoors. A fairly subjective variable, guidelines would suggest:

I = indoors (winter, work hours, night).

O = outdoors (summer, recreationists, campgrounds).

One would expect this variable only to have relevance when warning time is extremely short.

Sensory Clues (Sc)

Even without an official warning, individuals might have several minutes notice of an approaching flood wave if there are visual or auditory clues, such as breaking trees or the sound of thundering water. Using testimony of survivors, the average length of this warning should be quantified in minutes, using zero when virtually everyone was surrounded before the flood was detected (this is more likely at night).

Preparedness (Pr)

Pr defines the degree to which a Par_i is prepared to evacuate at least half an hour before the technical definition of warning time (Wt) officially begins. The scale ranges as follows:

N = none (not aware of the potential for danger 0.5 hr before Wt begins).

L = low (aware the safety of the dam is in question, but it is not considered serious).

M = moderate (alert to the potential for evacuation or experienced in evacuation).

H = high (expecting to evacuate and concrete steps toward that eventuality).

This variable considers qualitative factors like previous news reports regarding the dam, false alarms, evacuation rehearsals, alerts that fall short of warnings, experience of the community with flooding, and other aspects of testimony to define how quickly a community would likely respond to an official warning.

Warning Effectiveness (We)

Warning effectiveness describes how effectively a warning campaign mobilizes a community for evacuation. Ideally, it would include the percentage of Par_i receiving a warning, the rate the warning propagates, and the effectiveness of the warning in initiating prompt evacuation (its believability and urgency). However, since these aspects are not readily quantifiable, We often resembles a categorical form of Tpar:

N = no official warning.
L = low (fewer than 50% receiving or believing a timely warning).
M = moderate (up to 90% receiving and believing a timely warning).
H = high (virtually complete evacuation before the flood wave arrives).

Evacuation SubPar ($Epar_j$)

$Epar_j$ are subsets of Par_i in which the subsets are characterized by the same representative evacuation time (Ret, defined next). These $Epar_j$ need not have equal numbers, and the number of groups can be one or more depending on the degree of heterogeneity within a given subPar.

Representative Evacuation Time (Ret_j)

Defined for use in calculating E (below), Ret_j is a categorical variable used to typify the number of minutes it would take to evacuate each $Epar_j$ without the evacuation being interrupted by the arrival of the flood. It does, however, take into account the degree of urgency felt by the evacuees. Ret_j does not include warning delays as a warning propagates through a community, but it does include the time required for a warning to propagate through a given building. For example, if a mother is awakened by the sound of an approaching flood or an official knocking at her door, Ret_j includes the time required for her to recognize the danger, awaken her husband, throw on minimal clothing, gather her sleeping children, decide what possessions to grab and where to go, warn a neighbor or two if she feels there is time, and run with her family across the floodplain to the safety of the hillside. Since excess evacuation time (E) is based on the average warning time (Wt_{avg}), each building leader in $Epar_j$ theoretically receives a warning at the same moment.

Ret_j are based on the likely choices of individuals, even if those choices are not the most expedient. For historic events, Ret_j considers actual evacuation times and delays among the threatened population (Tpar). Ret_j extends when individuals reenter the flood zone to retrieve a belonging, to reach their family, or to help others. Important considerations include the time of day (Td) (whether people are asleep or awake and whether families are together or separated), the distance of buildings from the edge of the flood zone, barriers such as fences or streams, the travel distance to safety by road, the likelihood of congestion or transportation bottlenecks, whether prior flooding has blocked roads or bridges, the availability of personal or mass transportation, the time individuals will take to gather important possessions and warn others, the urgency of the warning and the perceived threat of the approaching flood, the anticipated time remaining before the flood arrives, and the general mobility of the $Epar_j$. Are there nursing homes, hospitals, schools, retirement communities, populations with language barriers or high levels of distrust, or other populations in the flood path that might need extra time to evacuate?

The section on evacuation rates in Chapter VI provides many insights regarding the factors that have influenced Ret_j during the events characterized in the unpublished working documents. Still greater detail is provided in the unpublished working documents themselves under Ret_j for each of the characterized subPar. Table 5.1 provides a starting point for estimating Ret_j.

Excess Evacuation Time (E)
(ease of evacuation)

When an individual's evacuation time is less than her individual escape time (Wt_e), he or she escapes the flood. If an individual's evacuation time is greater than Wt_e, he or she must find a refuge or fight the flood to survive. The margin of safety reflecting the *average* excess evacuation time is the ease with which a *population* can evacuate. It can be positive or negative. Hence, excess evacuation time (E) is the difference between the time needed for evacuation (Ret_j) and the time available (Wt_{avg}), both of which are averages. For practical reasons, E should be defined using a larger scale than the individual. It can be normalized as follows:

$$E_i = \frac{\sum_{j=1}^{n} Epar_j * (Wt_{avg} - \mathrm{Re}t_j)}{Par_i}$$

The representative evacuation time (Ret_j) and evacuation subPar ($Epar_j$) were previously defined. When $Epar_j$ is equivalent to a homogeneous subPar, the equation reduces to the average warning time minus the representative evacuation time ($Wt_{avg} - Ret_j$). When E is negative, it means the average evacuation time needed was greater than the time available.

Table 5.1. Representative evacuation times (Ret_j) for a single household on foot, neglecting the effects of barriers like fences and streams

Width of the Flood (ft)	Outdoor Distance to Safety (ft)	Dev (N, L, M, H)	Sense of Urgency	Mobility (L, H)*	Range of Evacuation Times for a Family (minutes)		Ret_i (minutes)	
					Day	Night	Day	Night
1,000	300	N – M	High	H	0.5 – 3	1 – 6	1	2
1,000	300	N – M	High	L	2 – 10	4 – 15	4	6
2,500	1,000	N – L	High	H	3 – 6	4 – 10	4	7
2,500	1,000	M – H	High	H	3 – 10	4 – 15	6	8
2,500	1,000	N – H	High	L	3 – 10	5 – 15	6	8
5,500	2,500	M	High	H	5 – 20	5 – 30	10	15
5,500	2,500	N – M	High	L	10 – 30	10 – 30	15	20
5,500	2,500	M – H	High	L-group home	20 – 180	30 – 180	45	60

*L implies one person with limited mobility living with one or more others with normal (H) mobility. The final row is an exception, where a nursing home or similar facility is in view.

Natural Circumstances that Attend the Flood

Failure Mode (Fm)

Fm can be coded using the following symbols:

I = internal.

Ip = piping.

Ie = embankment failure: sliding, overturning, foundation failure, or blowout with normal water levels.

F = flooding.

F = flooding (dam failure not present or not relevant).

Ff = flash flood (no dam failure).

Ff/D= dam failure contributes little volume to a dominant flash flood

Fo = failure due to overtopping or spillway washout.

Fe = embankment failure: slumping, sliding, overturning, foundation failure, or blowout during overtopping or reservoir elevations significantly higher than those for which the dam was designed to ordinarily operate.

S = seismic failure.

Sp = piping or other gradual development following an earthquake.

Se = a rapid embankment failure during or shortly after an earthquake.

G = gate failure <u>not</u> leading to dam breach.

L = landslide <u>not</u> leading to dam breach.

Attendant Circumstances (Ac)

Ac refers to conditions that attend a flood, the presence of which can increase the fatality rate of the event. Examples include an earthquake, extreme weather conditions such as snow or ice, hurricane-force winds, extreme prior flooding, or a downed radio tower.

It should be noted that power failures, darkness at night (Td = N), and rain are common features of many floods, and the latter two are already noted in the variables time of day (Td) and local magnitude of loading (Ml). As such, they should only be included under Ac if their impact was exceptional.

Attendant circumstances should first be described, then corporately assigned a subjective rank based on the impact the circumstances had on variables like warning time (Wt), excess evacuation time (E), and rise rate (R). These ranks are:

N = none.
L = low impact.
M = moderate impact.
H = heavy impact.

Magnitude of Loading (M)

M is a description of a storm over the watershed, the magnitude of an earthquake as experienced at the dam site, the size of a flood wave from an upstream dam failure, or some other narrative description of the loading which leads to dam failure. Descriptions including peak rainfall rates and depths and their return period would be typical. Although most hydrologic failures are likely to be coded as very large (V), internal failures during fair weather are more likely to fall in one of the other categories. Also, one purpose of M is to provide a baseline against which the local magnitude of loading (Ml) can be compared to determine whether local residents experienced the severity of rainfall that led to a hydrologic failure. M should then be coded as follows:

N = no external loading (i.e., an internal failure).
L = low = small (loading is common; could be expected every few years).
M = moderate (loading is infrequent; once every 5 – 15 years).
H = high = large (loading is uncommon; could be expected once every 15 – 50 years).
V = very large (loading is quite rare; could be expected once every 50 – 100 years).
E = exceptionally large (loading is difficult to imagine; more rare than 1/100 years).

Magnitude of Local Loading (Ml)

Ml is coded in the same manner as magnitude of loading (M), but it pertains to the local conditions experienced by Par prior to the flood wave arrival.

Human Circumstances that Attend the Flood

Dam Type (Dt)

It is possible that Dt can be combined with variables like height of the dam (H), peak velocity (V), failure mode (Fm), and rate of failure (Rf) to categorize the potential lethality of a reservoir or to facilitate future studies into the likelihood that a particular type of dam will fail. Dt should be identified as follows:

N = none (i.e., a flash flood or other Flt).

E = earthen.

R = rock fill.

M = masonry.

C = concrete gravity.

A = concrete gravity arch.

Rescue Resources (Rr)

Rescue resources include such things as rescue helicopters, the availability of the National Guard or another branch of the military, paid or volunteer firefighters or police officers located close to the Par_i, emergency management and evacuation personnel, communication systems not dependent on utilities susceptible to damage or network overload, earth-moving equipment, utility vehicles, and boats.

Sometimes a community can prove extra heroic, with volunteer rescuers either increasing or decreasing the rate of life loss. Due to its mixed implications and difficulty of measurement, heroism should not be included as a separate rescue resource. However, rescues often involve simple tools like garden hoses and human chains, and these should be recognized as rescue resources. Rr provides a way of normalizing failures, whether they were in remote or readily accessible areas, and whether they occurred before or during the modern era.

This variable is probably most relevant when floods are expansive in large, metropolitan areas. It is significant that the evacuation plan for the City of Sacramento, California, which is below Folsom Dam, indicates some areas as “evacuation areas” and others as “rescue areas.”

R can be categorized as follows:

N = none (rescuers are prevented from assisting until the next day; victims are overwhelmed so quickly that no rescue attempts are feasible).

L = low = limited (rescuers are able to help some people, but they are mostly limited to hand tools: ropes, rowboats, floating debris, human chains, etc.).

M = medium = modern (modern communication, transportation, and rescue resources are available locally, at least in moderate supply; generally reflects the state of development present in urban areas of the USA after 1950).

H = high = exceptional (large numbers of military or rescue workers stationed nearby, immediate access to many local helicopters, an abundance of boats in the community; plenty of floating debris, trees, tall buildings, or hills to sustain victims until they can be rescued; modern wireless communication systems; state-of-the art early-warning and evacuation system).

Detectability (Det)

Det ranks the extent to which there are signs of imminent failure more than 3 hr before the dam begins to breach or the degree to which the breach could be predicted by monitors at the dam.

N = no signs of trouble.

L = low (one or more minor changes at the dam, but would not lead the typical dam monitor to anticipate failure).

M = moderate (sufficient changes to consider altering the reservoir operation as a precaution, but would not lead a typical monitor to expect failure within the year).

H = high (evidence demanding immediate attention, as it suggests a dam failure is not unlikely if no action is taken).

V = very high (dam failure appears probable or imminent and can not be readily avoided).

Striking Characteristics and Valuable Quotations (Schvq)

Schvq is a narrative summarizing those aspects of the failure which stand out, might be fairly unique, or are not adequately described in the variables above. This might include eyewitness descriptions of the event.

To code this variable, it should be viewed as a general description of how well the overall set of variables describes the event:

L = low = poor (existing variables do a poor job of fully capturing the unique attributes of this flood event).

H = high = good (existing variables do a good job of fully capturing the nature of this flood event).

Important Variables Brought to Light During Characterization of Events

Pre-failure Warning Time (Wtpf) and Post-failure Warning Time (Wtpof)

Wtpf and Wtpof provide a means of differentiating between the length of potentially urgent post-failure warnings and the total length of warnings that may begin with less urgency or credibility before a dam actually fails. Wtpf indicates the full length of warning time (Wt) when it begins prior to failure. Wtpof does not start until failure begins. Hence, if Wt begins an hour before failure and the flood travels for 30 minutes, Wtpf = Wt = 90 minutes and Wtpof = 30 minutes.

Wall of Water Weighted by the Rise Rate (Wwr)

In order to combine events with and without a wall of water, the depth can be weighted according to the rise rate. Hence, Wwr = the value of wall of water (Ww) or, if Ww = 0:

a) Wwr = a*D (the peak flood depth (D) multiplied by coefficient a) when the rise rate (R) = very fast (V).

b) Wwr = b*D (the peak flood depth (D) multiplied by coefficient b) when R = H.

c) Wwr = 1 ft when the rise rate is moderate (R = M).

In these equations, a and b are constants less then 1 that reduce D appropriately to account for extra evacuation time during slower rise rates. Their values should be specified, but they may be adjusted if it improves the usefulness of Wwr.

Basis of Par (Bpar)

When warnings proceed failure, or people anticipate a failure, evacuation can proceed in two distinct phases: part of Par evacuates as a precaution and part of Par remains behind to see what happens. In such cases it is sometimes convenient to treat those who remain behind as Par, since more is known about this group, and to characterize every variable accordingly. For example, the average warning time (Wt_{avg}) would be based on the warnings that the second group takes seriously and the representative evacuation time (Ret_j) would measure the time needed to evacuate once they chose to do so. Bpar indicates whether the true subpopulation at risk (Par_I) is in view, or whether Par_i is redefined to include only the remnant who delay to see what will happen. Bpar is coded as follows:

Pre = pre-evacuation, meaning before any evacuations have begun.

Post = post-evacuation, meaning Par is based on those left behind after the first group leaves and the threatened population (Tpar) is the number who become trapped in the flood.

Par Type (Pt)

Pt refers to the physical environment surrounding a given subPar or fraction of a subPar. When recording the codes for Pt, each symbol should be listed separately and, when possible, tagged based on its percent of Par_i. When the components of Par are not known, Pt should be designated U.

C = campers, including recreationists hiking/walking/standing near the river.

W = those in the river: wade fishermen, swimmers, rescue workers, etc.

B = those on the river: boaters and rafters.

L = those in or on a lake: boaters and swimmers.

E = employees who are at the dam for construction, repairs, monitoring, failure prevention, etc. Note, it may be desirable to reclassify this Pt as D, W, or another overlapping category for purposes of analysis.

Af = automobile drivers or passengers.

T = people occupying a train.

D = those who, prior to evacuation, are in or near buildings. This corresponds to general drowning deaths in town. These people might encounter the flood while indoors, while evacuating on foot, or while evacuating in a vehicle, but generally speaking, they were quantified based on structural damages and the mode or place of death may not be known.

U = unknown mix. Whenever possible, subPar should be broken down into pure Pt (C, W, B, L, Af, or D) to facilitate characterization and analysis.

Proportion of the Threatened Population (Ptpar)

Ptpar is similar to the proportion of lives lost among the Par (P = L/Par), except that Ptpar is the proportion of lives lost among the threatened population: Ptpar = L/Tpar.

Evacuation Nonsuccess Factor (Ef)

Ef is the proportion of Par remaining in the flood zone when the flood arrives: Ef = Tpar/Par. Tpar and "flood arrival" are defined in such a way as to ignore trivial flooding that does not greatly hinder free movement (generally 6 – 12 inches for waders close to the hillside and lesser depths for those evacuating by automobile).

Havens: Safe Havens (Sh), Chance Havens (Ch), Pseudo-safe Havens (Psh), Aerated Havens (Ah), and Compromised Havens (Coh)

Havens are discussed at length in Chapter VI based on historical insights. Each variable is described below.

Safe havens (Sh). Safe havens may or may not be flooded, but they represent places of shelter in which deaths have historically been extremely rare. When deaths occur, they generally involve young children or persons of limited mobility who cannot swim and are trapped in an area without another person of average ability to assist them. Safe havens include the following:

1. An upper story with sufficiently shallow flooding that occupants are not washed out a window and can float on a bed or stand freely. These conditions are generally maintained when the flow does not rise more than one foot above the windowsills in the highest story (about 3 ft above the floor) and the building is not destroyed.
2. Quiescent flooding that does not trap people without air. When flooding is relatively quiescent, people readily keep their heads above water by treading water, standing on stationary platforms such as counters, floating on beds, or by clinging to floating furniture. If such flooding does not persist to the point where it would lead to extreme hypothermia or exhaustion, a relatively safe haven is maintained even when waters come within 1 ft of a flat ceiling or 2 ft of the peak of a sloped ceiling, whether or not the ceiling is elevated.
3. An attic that is accessible from within a house or trailer home.
4. A rooftop: The important point is not that safe havens in buildings are equally easy to reach, but that if some people can reach them, they preserve a means of shelter that is likely to reduce life loss across a subPar compared to situations in which every building is obliterated. Means of access might include an internal or external fire escape, a roof door, or a dormer window. During 19th century floods, there were many examples of people using a bedpost or other sturdy object to poke a hole in a ceiling or wall to reach shelter. Similar access to a roof might be possible through many attics today. People have also been known to climb objects like drainpipes or trellises, or to intentionally use the current to float up to the roof while they cling to such objects. However, when rooftops must be accessed through highly unreliable means and people must apparently rely on chance to be successful, they should be treated as chance havens.

5. A stout tree that is easy to climb, taller than the flood, and not toppled.
6. Any island or region that experiences shallow flooding during the peak of the flood, such that depths are easy to resist while standing or clinging to convenient anchors like telephone poles or lampposts (depths of 1 – 5 ft, depending on the velocity).
7. The hillside beyond the flood if a member of the threatened subpopulation ($Tpar_i$) can readily drive or wade to it while the flood is still shallow, or if they can reach it directly from the roof or an upper story.

Chance havens (Ch). If debris does not crush or fatally wound flood victims, it can provide a means of floatation that has saved many lives. Debris is defined as a chance haven rather than a safe haven because its availability and pathway cannot be readily predicted, its benefits are unreliable, and it can directly cause life loss when not a benefit.

Chance havens are refuges in the flood, including other types of havens, that are reached primarily by chance or whose benefits are highly unreliable. As such, they contribute significantly to the variance in fatality rates across similar events.

Chance havens fall into at least five categories:

1. Rafts and floatation aids: severed rooftops, mattresses, propane tanks, logs, etc.
2. The roofs of floating buildings: Because it is both more difficult and more dangerous to reach and remain on a rooftop after a building begins to drift, lurch, spin, or sink, rooftops should be treated as chance havens whenever a building drifts more than 100 yards. Although somewhat arbitrary, choosing 100 yards seeks to standardize the approach of analysts in a way that seems to reflect the trends in the historic events analyzed in this study. Based on historic damage patterns and life loss, buildings that drift less than 100 yards are more appropriately considered pseudo-safe havens most of the time. This is explored more in Chapter VI.
3. Stationary structures: any immobile refuge that is reached while drifting, including rooftops, upper-story windows, aerated havens, treetops, overhanging branches, debris dams at bridges that allow victims to walk to dry land, and the shore itself. If people must rely heavily on chance to reach a largely inaccessible roof, this would also constitute a chance haven.
4. Aquatic havens: any location from which shore can be easily reached, such as a lake or a quiescent backwater, without fighting high velocities.
5. Wading havens: These are rare, falling in the narrow range of depths and velocities that are too high to be considered safe havens and too low to consistently sweep people away. Due to debris, waves, and unpredictable turbulence, such chance havens would not typically last long (see Figure 13 shown later).

Pseudo-safe havens (Psh). Pseudo-safe havens are safe havens on or in buildings that become reclassified once the building begins to drift. They are a hybrid between safe havens, which are static and predictable, and chance havens, which depend on the whims of the current and the debris load. They exist only among a subset of buildings with major damage (see Loss of

Shelter, Ls). As indicated above and in Chapter VI, rooftops are considered chance havens (Ch) rather than pseudo-safe havens when a building drifts more than 300 ft.

Aerated havens (Ah). Aerated havens are typically found only when parts of stationary buildings are torn away (the upper end of Ls = M). They are those pockets of protection formed by the remaining walls, floor, counters, etc., that provide a place for survival if the occupants are fortunate enough to have been located in that portion of the building. They are not safe havens because their locations depend in part on chance, and great strength, stamina, and good fortune may be required to resist being swept away in the face of increased exposure. However, they are not chance havens because they are most likely to form in locations where people are most likely to seek shelter—that is, in the most protected sections of temporary safe havens. For those who occupy an aerated haven (Ah), survival would generally be more likely than for those already in the open current and less likely than for those in a safe haven.

Compromised havens (Coh). This simply places pseudo-safe havens and aerated havens in a single category. These two havens are likely to be highly variable with respect to life loss, with rates similar to safe havens when the haven is modestly compromised and with rates approaching that in the open flood when the haven is severely compromised.

Loss of Shelter (Ls)

Loss of shelter apportions Par_i based on the loss of safe havens (Sh), pseudo-safe havens (Psh), and aerated havens (Ah) in or on buildings. As such, it is a refinement of forcefulness (F) and similarly relies on damage and destruction (Dd) for guidance. However, unlike F or Dd, Ls records the proportion of Par_i associated with four levels of shelter loss:

L = low loss of shelter = no structural damage or minor structural damage limited to flooding on the first floor.

M = major loss of shelter = major structural damage.

H = high (complete) loss of shelter = total destruction.

Mh = highly uncertain whether Ls = M or H.

To expound on each of these categories, it is important to realize that Ls is not the same as economic damages. Lives are lost within buildings when occupants fall into water in which they cannot swim; become trapped underwater as a room fills to the ceiling; get struck by large, external debris penetrating from outside; get struck or trapped underwater as the building breaks apart; or get washed through a wall or out a door or window into open water. As such, the critical question is not the degree of economic damages or whether a building should later be condemned, but whether or not a structure maintains an accessible safe haven, pseudo-safe haven, or aerated haven for the duration of a flood.

It follows, that loss of shelter is not synonymous with the definitions used by the American Red Cross or other agencies to define housing damages. Ls = L implies relatively safe havens on every floor, Ls = M implies complete loss of a safe haven on the first floor, and Ls = H implies complete loss of all safe havens, pseudo-safe havens, and aerated havens, including any accessible rooftop. Since loss of a safe haven is generally accompanied by structural damage, traditional categories of minor and major damage generally agree with Ls = L and Ls = M when they are based on structural damages and not mere water damage. By contrast, Ls = H only if no accessible, aerated pockets of protection remain, regardless of whether a building floats off its foundation or is later condemned.

The following refinements, based on historical observations, should be kept in mind (largely copied from Chapter VI):

1. Ls = L. Almost every room has a counter, desk, couch, table, chair, bookcase, bed, dresser, piano, or other piece of furniture that can provide an elevated platform or a floatation device during a flood. When a flood is relatively quiescent, with few exceptions, these objects and a little swimming allow people to keep their heads above the water surface even when the flood nears the ceiling. While elevated ceilings could pose a special problem, a flood reaching such depths without causing major damage would necessarily be very calm, making it easier to cling to floating furniture, tread water, or hang onto rafters. This has been demonstrated in commercial buildings. Hence, Ls = L when there is minor structural damage and the flood does not encroach within a foot of the first-floor ceiling or within 2 ft of the peak of a sloped ceiling.
2. Ls = M. If the highest accessible floor (including an accessible attic) is filled with water beyond 1 ft of the ceiling, but the flood does not crest an accessible roof, Ls = M rather than H because an accessible safe haven remains. If walls are ripped off but portions of walls and floors or counters remain to shelter occupants from the main current or to provide something to which they might cling, the loss of shelter is major; but if only trivial structural members remain such that all shelter is lost, the dwelling is destroyed.

   A building is destroyed any time it is torn apart and submerged in the flood. However, if a building floats off its foundation and maintains an accessible pseudo-safe haven for the duration of the flood, Ls = M.
3. Ls = H. If a rooftop is inaccessible, a building is destroyed when the top floor or accessible attic is completely submerged. If a rooftop is accessible, the building is considered destroyed only if the flood or flood waves wash across the crest of the roof to an extent likely to wash people into the flood. Since the momentum of the flood riding the slant of the roof will cause waves to run up, this elevation is generally on the order of a foot or two below the roof's crest.
4. Ls = Mh. Ls = Mh means that, based on uncertainty, analysts view Ls = M and Ls = H as having roughly equal probabilities. It is a category that applies primarily when estimating Ls for hypothetical floods. Based on the current state of the art, it is unlikely that analysts will be able to predict the boundary between Ls = M and Ls = H with great precision. Ls = Mh is a subset of the pseudo-chance zone defined below.

Weighted Loss of Shelter (Lsw)

Historical analysis is greatly facilitated when loss of shelter (Ls) is homogeneous—that is, when Ls = H100%, M100%, or L100%. When Ls is mixed, however, life-loss trends can still be explored by placing the overall mix of damages on a scale from 0 to 1. The scaled value is called the weighted loss of shelter. The weights assigned to each type of damage (L, M, and H) should correspond to the relative historical lethality observed among structures with each category of damage. These relationships can be determined from cases for which Ls was homogeneous.

Theoretically, proportion of the threatened population that perishes ($Ptpar_i = L_i/Tpar_i$) should tend to increase as safe havens are removed by the flood. Thus, when every structure is swept away and destroyed, $Ptpar_i$ should be greatest and such structures should be given full weight ($W_H = 1$). If one relies on average values across homogenous subPar, the correct weight for Ls = M would be W_M = (avg. $Ptpar_i$ for Ls = M100%)/(avg. $Ptpar_i$ for Ls = H100%). In the same way, the correct weight for Ls = L would be W_L = (avg. $Ptpar_i$ for Ls = L100%)/(avg. $Ptpar_i$ for Ls = H100%). A weight of zero applies if the average ratio of life loss is zero.

$Lsw = 1*(Ls = H) + W_M*(Ls = M) + W_L*(Ls = L)$ where Ls = H, Ls = M, and Ls = L each represent the percentage of $Tpar_i$ (or Par_i if the distribution of $Tpar_i$ is unknown) associated with structures in the respective damage categories.

Flood Zones: Safe Zones (Sz), Compromised Zones (Coz), Chance Zones (Cz), And Pseudo-Chance Zones (Pcz)

When one includes the open current and depths in which successful wading is highly dependent on chance, a flood can be divided into four zones with unique life-loss distributions. Each zone is described below.

1. Safe zones (Sz). This includes all safe havens. These provide a high degree of safety and a consistently low rate of life loss. Havens that have been only mildly compromised have similar life-loss characteristics and so should be included. The proportional life-loss distributions in safe zones should closely approximate that for loss of shelter (Ls) = L.

2. Compromised zones (Coz). That central portion of compromised havens that have not been purposely classified as safe zones or pseudo-chance zones. Because the tails are accounted for under pseudo-chance zones and safe zones, the proportional life-loss distribution should closely resemble that when the severity of structural damage for loss of shelter (Ls) = M is in the central 60% – 80%.

3. Chance zones (Cz). The places where people are submerged or face the open flood, and all chance havens that might be reached while drifting. The proportional life-loss distribution in chance zones should closely approximate that for loss of shelter (Ls) = H.

4. Pseudo-chance zones (Pcz). There is a range of depths*velocities, unique to each type of building, for which it is unclear whether a structure is most likely to be destroyed, float far downstream, or experience severe damage that leaves only aerated havens. In such cases, life loss (L) = Mh, meaning L = M or L = H. Similarly, there is a range of depths*velocity for which it is highly uncertain whether people will topple or be able to wade. Combined, these locations comprise the pseudo-chance zones. The proportional life-loss distribution for pseudo-chance zones should closely approximate a combination of the relevant portions of the proportional life-loss distributions for Ls = H and Ls = M.

Zone Densities (Zd): Safe Zone Density (Szd),
Compromised Zone Density (Cozd),
Chance Zone Density (Czd), and
Pseudo-Chance Zone Density (Pczd)

Density represents the distribution of the threatened population ($Tpar_i$) among flood zones based on topographic, structural, and hydraulic considerations as they interface with flood routing and the rise rate of the flood. The word "density" refers to the number of people who have access to a category rather than to the physical dimensions of flood zones themselves. Access includes the physical ability to move to a location and sufficient time to get there before being cut off by the flood.

Density is predicated on the historic pattern that most members of $Tpar_i$ will seek out the safest haven they can reach in the time available. A more expansive list of insights and justifications can be found in Chapter VI. The result of these insights is that we can apportion $Tpar_i$ among the flood zones its members are most likely to occupy by apportioning the accessible physical havens and by associating them with the average number of $Tpar_i$ likely to be nearby based on census data. Accessibility is cut off if the flood rises too quickly, but this is rarely a concern when loss of shelter (Ls) = M, the usual case in which densities are widely distributed.

Thus, *Szd, Cozd, Pczd,* and *Czd* each represent the number of people expected to be in each of the corresponding flood zones. People can be expected to choose Sz, Coz, Pcz, and Cz in that order, as they are available. People should be assigned to the highest level that persists for the duration of the flood, with the understanding that they are only assigned to Cz if the haven they previously reached ceases to exist.

Life Loss Zones (Lsz, Lcoz, Lpcz, Lcz)

Zones of life loss are analogous to the life loss specific to a subPar (L_i), except that they are specific to the safe zone (sz), compromised zone (coz), pseudo-chance zone (pcz), and the chance zone (cz).

Proportion of Lives Lost in Zones (Prsz, Prcoz, Prpcz, and Prcz)

The proportion of lives lost in each zone is analogous to the proportion of the threatened population that perishes (Ptpar_I), except that it is specific to one of the zones sz, coz, pcz, or cz (defined above). Note that “proportion” is designated with Pr instead of the traditional P in order to avoid confusion between the pseudo-chance zone (Pcz) and the proportion of lives lost in the chance zone (Prcz).

Tools For Researchers

Appendix D contains several tools that can help readers and researchers keep track of the many variables presented above and some of their subtleties. Table D.1 is an alphabetical list of every variable in Chapter V. Table D.2 is a summary table of every variable, their names, their symbols, the codes used for nominal and ordinal variables, a brief description of each code, and the units. An abbreviated version of Chapter V and a copy of the template used when characterizing events for Appendix B follow in Appendix D.

CHAPTER VI

INSIGHTS FROM HISTORIC FLOOD EVENTS

Modes of Death and Means of Survival

According to a thorough study of the unpublished subPar characterizations, deaths have historically occurred in the overlapping contexts presented in Table 6.1. People have survived catastrophic floods through the means presented in Table 6.1.

Pieces of the Life-Loss Puzzle

This section lists qualitative insights from historic case studies that have sufficient support that they were evaluated to be highly reliable. Many but not all of the case studies are thoroughly characterized in working documents that underlie the summary in Appendix B. In those working documents, the observations are carefully supported by reference to several hundred source documents, subsets of which are listed at the end of each event to which they pertain.

Only a modest effort has been made to index these insights to the events underlying Appendix B for the following reasons:

1. Dozens of statements from survivors, eyewitnesses, and researchers from many different events support most of the observations.
2. While the working documents underlying Appendix B include careful records of source materials, such statements were often not critical in characterizing the cases and so they were only summarized or not recorded.
3. The most pertinent information was discovered iteratively as more and more events were characterized.
4. While reading through events to identify those most easily characterized, insights were gleaned or reinforced from events not found in Appendix B.
5. When an insight was recorded under Schvq or another variable because it was considered significant, new, or particularly cogent, it was generally not repeated under subsequent subPar for the sake of efficiency.
6. This section is intended only as a summary and not as a substitute for the unpublished subPar characterizations and the hundreds of source documents underlying them.
7. The volume and complexity of the presentation in the unpublished event characterizations would make full indexing a daunting task.

Table 6.1. Means by which people die in a catastrophic flood

	Buildings/ Damages			Other Locations				* Relative Frequency
Mode of Death	Destroyed	Major	Minor	Floodplain	Vehicle	Boat	Dry Land	
1. Lethal blow when struck by or crushed between large/sharp debris.	●	●		●				H
2. Trapped underwater within a stationary structure. Water pressure often seals doors.	●	●	●		●			H
3. Pulled underwater by an undertow or sinking raft while riding a mobilized house, vehicle, boat, roof, mattress, or other floating refuge.	●			●	●			H
4. Mobilized home drifts, then disintegrates through collisions, exposing occupants.	●							H
5. Pinned underwater after drifting against a tree, pole, house, fence, rock, etc.				●				H
6. Held underwater by swift and violent undercurrents.				●				H
7. Insufficient strength to swim across swift and violent currents before tiring.				●				H
8. Buried in sediment carried by the flood.	●			●	●			H
9. Overtaken by a wall of water while driving out of a canyon instead of climbing the slope.					●			H
10. Water-born plagues in countries lacking modern water-treatment facilities.	●	●	●	●	●		●	H
11. Lethal blow from a collapsing structure.	●	●						M
12. Lethal blow when driven violently into a pole or other obstacle.				●	●			M
13. Baby or young child swept out of adult's arms while adult wading.								M
14. Fall off a raft (usually a roof, vehicle, or mattress) and unable to swim adequately.	●	●	●	●	●			M
15. Motorists attempt to cross a flooded road/bridge and wash into deeper water, where trapped.					●			M
16. Unexpected wall of water washes vehicle off a road or bridge.					●			M
17. Climb on top of a vehicle, only to be washed away as the water rises.					●			M
18. After evacuating, return to the flood zone for a belonging and swept away.	●	●		●			●	M
19. Enter flood to try to rescue or warn family, friends, or strangers.				●			●	M
20. Firefighters or other evacuation officials caught by the flood.							●	M
21. Delay evacuation to grab money, boots, pet, or other valuable.	●	●		●				M
22. Struck by debris while clinging to a pole, causing injury and knocking loose.				●				L
23. Wading through shallow flood and step into a submerged creek, culvert, etc.				●				L
24. Buried by a slope failure at/near the dam following drawdown.							●	L

Table 6.1. Continued

	Buildings/ Damages			Other Locations				* Relative Frequency
Mode of Death	Destroyed	Major	Minor	Floodplain	Vehicle	Boat	Dry Land	
25. Undercutting causes roadway to collapse as vehicle passes overtop.					•			L
26. Due to poor visibility (night, rain, fog, sharp curve), drive into a washout.					•			L
27. Weight of train causes bridge to collapse during flood conditions.					•			L
28. Vehicle is moved down a street in shallow water, then washed into a deep, water-filled pit.					•			L
29. Come to watch flood, then surrounded and swept away.							•	L
30. Trapped, lacerated, or strangled by flood-borne barbed wire, power lines, etc.				•				L
31. Hypothermia.		•	•	•	•		•	L
32. Explosions caused by boilers, transformers, smelters, etc.	•	•	•					L
33. Burned in fire caused by natural gas, broken power lines, lanterns, etc.		•	•					L
34. Fall from a high window during evacuation.			•				•	L
35. Electrocution when live power lines break.			•	•			•	L
36. Swimmer pulled under by an unexpected undertow in a reservoir following a flood.							•	L
37. A boat on a reservoir is capsized and pulled under at the mouth of a tributary.						•		L
38. Boaters are washed downstream at great velocity until they crash or capsize.						•		L
39. Heart attack or other fatal condition caused by fear and exertion during the flood.	•	•		•	•			L
40. Lethal shock after the flood due to lost family, community, or financial security.							•	L
41. The depression associated with losses or the guilt associated with “undeserved” survival causes a loss in the will to live and death within days, months, or years. This includes suicides, but also marked changes in activity levels, rapid deterioration (especially among elderly), and behavioral diseases like alcoholism, drug addiction, and patterns of self-destruction.							•	L

* Relative Frequency is coded as follows: L = low (would expect only in an atypical or extreme event), M = medium (common, but probably not a dominant mode if many died), H = high (one of the dominant modes if many died). These are subjective categories based on historical accounts of fatalities.

Table 6.2. Means by which people survive when faced with a catastrophic flood

	Buildings/ Damages			Other Locations			* Relative Frequency
Mode of Survival	Destroyed	Major	Minor	Floodplain	Vehicle	Dry Land	
1. Run up nearby hillside, keeping dry or splashing through early flooding.	●	●	●	●	●	●	H
2. Run upstairs to a second or third story.	●	●	●	●			H
3. Stand on a couch, counter, piano, refrigerator, table, dresser, or cupboard.		●	●				H
4. Climb a tree before or after being swept downstream.				●			H
5. Washed into calm or shallow water, where can climb onto shore.				●			H
6. Grab an overhanging tree branch near shore and pull self to safety.				●			H
7. Ride a floating house until it lodges against the ground or another structure.		●					H
8. Drive laterally out of the flood zone.					●		H
9. Outpace an advancing flood, driving down a narrow canyon.					●		H
10. Wash out into the relatively calm waters of a lake or reservoir and then swim to shore.	●	●		●	●		H
11. Climb onto roof (via upstairs window or by poking hole through from below).		●					M
12. Swim to a roof or drift there on a mattress, log, board, or propane tank.	●	●		●			M
13. Float indoors on a mattress or buoyant furniture, or stabilize someone less capable on such a raft.		●	●				M
14. Cling to a telephone pole, lamppost, fence, etc. in water 6-ft deep or less.				●			M
15. Baby or small child thrown to someone on shore by wader who can't move.				●			M
16. Ride a floating house, roof, or other raft until it piles up in a debris dam behind a bridge, then walk across roofs and debris to dry land.	●	●					M
17. Rescued by a helicopter while on a roof, second story, tree, car top, or island.		●		●	●		M
18. Rescued by boat.		●	●	●	●		M
19. Pulled/carried to safety by a human chain, rope, or larger/stronger person.		●	●	●	●		M
20. Pulled inside a second-story window after drifting near there.				●			L
21. Baby or child passed or thrown out a window to someone in a safer location.	●	●					L
22. Dug out of mud after wave passes, with help of dogs and rescue crews.				●			L

* Relative Frequency is coded as follows: L = low (would expect only in an atypical or extreme event), M = medium (common, but probably not a dominant mode if many survived), H = high (one of the dominant modes if many survived). These are subjective categories based on historical accounts of survivors.

When indexed to indicate a useful example, the citations take the form (#.#). The first number indicates the number of the event and the second number indicates the number of the subPar associated with that event. If only the first number is given, it refers to a pattern found in more than one subPar during that event, or to notes recorded in an introductory summary to the event as a whole. If an event rather than a number is indicated (i.e., South Fork Dam, Johnstown, 1889), it simply means that the applicable event was reviewed in detail, but was not formally characterized with a written record.

Each index number refers to a specific subPar named in Appendices B and C. Appendix C provides a summary table of the values assigned to every characterizing variable for every event formally characterized. Appendix B provides an alphabetical list of those events. A common numeric code (#.#) accompanies the subPar names in both appendices for easy cross-referencing. The remainder of Appendix B provides examples, excerpts, and bibliographic information from the formal characterization of each subPar, focusing primarily on insights recorded under the category "Striking Characteristics and Valuable Quotations (Schvq)."

Given that a life-threatening event has occurred, pieces to the life-loss puzzle can generally be stored in one of the puzzle boxes presented in the first column of Table 6.3. The second column in Table 6.3 indicates important questions or descriptions pertaining to these topical puzzle boxes, and the third column indicates the variables from Chapter V that are most relevant to each box. Chapter VI opens each puzzle box in turn, lays the puzzle pieces out in detail, and attempts to fit most of the pieces together using qualitative and historically based observations. Because one of the goals for this chapter is to help researchers understand which variables play the most crucial roles and how these variables interact in complex ways, each section heading includes relevant variables in parentheses from column three of Table 6.3.

Type of failure (Fm, M, Dt, Ty, Ts)

Flash Floods

Modern radar, combined with flood-prediction algorithms, are still imperfect in consistently predicting major flash flood events before they occur, although significant improvements have been made. Human operators are also prone to error or misjudgment. In some cases, there is a reluctance to issue a warning because the computers frequently detect false anomalies (1.1).

Table 6.3. Issues influencing the rate of life loss

Category	Description or Governing Question(s)	Variables
1. Type of Failure	a) Breach = hydrologic, seismic, or internal b) Uncontrolled Release = mechanical or human error c) Drawdown = upstream slope failure d) Displacement = landslide displacing the reservoir	Fm, M, Dt, Ty, Ts
2. Detectability	Do people detect the likelihood of a failure?	Det, Dt
3. Warning Times and Effectiveness	How much time does each person have to evacuate after becoming aware of the danger, and how mobilizing is the message?	Wt, Sc, O, We, Td, Wt_{avg}, Pt, Ft, Flt
4. Evacuation Rates	What proportion of people can clear the flood zone before they are endangered or trapped?	Ef, Pr, Td, Tw, Ts, Ml, Pt, Dev, Ret
5. Excess Evac. Times	How much extra time do people have to evacuate before they are endangered or trapped?	E, Ef
6. SubPar Type and Evacuation Modes	Where are people located? What is significant about each location and people's associated behavior?	Pt, Ft
7. Homogeneity of SubPar	Have the subPar been defined in such a way categories 5 – 10 apply homogeneously to each?	Par_i, Pt, Gf, Ls, Fp, F_5, Schvq
8. Flood Dynamics	What are the hydraulic characteristics of the flood among $Tpar_i$?	Flt, V, D, Qp, Qb, W, Dv, R, Ww; Dt; H, Hp, B, Vol, Rf, A
9. Loss of Shelter	What are the structural damages and to what extent do these expose $Tpar_i$ to the flood dynamics?	Bt, Ls, Dd, Sh, Psh, Fp, Fd, F_5, Fpar, Pt
10. Safe Havens, Chance Havens, Pseudo-Safe Havens, and Aerated Havens	Safe Havens: How accessible are refuges in which $Tpar_i$ can seek protection? Chance Havens: How likely is it that debris and obstacles will save lives rather than cause deaths? Pseudo-Safe Havens: If buildings float, are they likely to stay intact or be destroyed? Aerated Havens: When a building has major damage, do accessible pockets remain that are more dangerous than safe havens, but that nonetheless facilitate survival?	Sh, Ch, Psh, Ah, Coh, Pt, Bt, R, Ww, D_{local}, V_{local}, Sc, Wt_{avg}, E, Schvq
11. Flood Zones and Zone Density	Is there time to reach a safe zone? If so, what is the distribution of $Tpar_i$ among flood zones that have unique historic distributions of life loss?	Sz, Cz, Pcz, Coz, Szd, Czd, Pczd, Cozd
12. Lethality Rate Outside Safe Havens	When not protected, how many people can float to safety on debris, wash to shore, walk across a debris dam, or otherwise escape the flood?	$Ptpar_i$, Ls, Pt, Ft; L_i, P_i, $Tpar_i$; Ln, Lnf, Li_n, Li_{nf}
13. Lethality Rate in Safe Havens	Can this be equated with the lethality rate on land, where damages are minor, or to some other function?	Ls, Pt, $Ptpar_i$ Sh, Psh
14. Lethality Rate on Dry Land	This would include stress-related deaths of evacuees and the relatives of victims.	Ft, Schvq
15. Life-Saving Interventions	How many members of $Tpar_i$ can be rescued? How does this affect the rate of life loss?	Rr, Sh, Psh, Ch, $Ptpar_I$
16. Complications or Aberrations	Are there unique circumstances that increase or decrease the life loss in this particular event?	Ml, Ac, Td, Ts

Table 6.3. Continued

Category	Description or Governing Question(s)	Variables
17. Post-flood psychological trauma	Does the loss of friends, family, jobs, financial attainment, or emotional peace of mind hinder the ability of people to live life in a healthy manner or cause premature death?	Schvq
18. Applicability of Historic Events to Future Events: Logic Behind a Proposed Model		

In many areas, flash floods and hydrologic failures due to intense thunderstorms are much more likely during the summer. This is also when tourists are most likely to be present—especially outdoor recreationists in or near streams.

Sabotage

Sabotage has not been common outside of wartime, but it has occurred often enough to be an important source of failure. Dams breached through sabotage or war-time bombing include the following: Eastover Mining Company Sludge Pond, Kentucky, 1981 (20); Mohne Dam, Germany, 1943 (killed 1,200); Eder Dam, Germany, 1943; and the Dnjeprostroj Dam, Soviet Union, 1941 (U.S. Bureau of Reclamation, 1983). Unsuccessful attempts at bombing or sabotage include the Peruca Dam in Croatia, blasted by retreating Serbian forces, 1993 (Engineering News Record, 1993); and the Ordunte dam during the Spanish Civil War. German forces visited the Aswan dam with the intention of studying how to destroy it, but this was never accomplished (Gruner, 1963). The most destructive intentional breach occurred in 1938 when Chiang Kaishek tried to stop the Japanese army that was invading China. He dynamited a hole in the southern levee of the Hwang-Ho River. The effect on the Japanese is not reported, but the flood destroyed thousands of villages, half a million Chinese peasants drowned, and several million more died through famine following the destruction of agriculture (Kovach, 1995).

Earthquake

Historically, there have been virtually no lives lost due to a dam failure caused by an earthquake. Interestingly, failure by sabotage is usually ignored in dam safety risk assessments (although it is sometimes included in a relative vulnerability assessment, it is impossible to estimate the likelihood of initiation of sabotage) and failure by an earthquake is often considered one of the greatest hazards, especially if a sudden failure mode is plausible.

Importance of Type of Failure

The nature of a dam failure is irrelevant to life loss, except as it influences the nature of the resulting wave, season, and the warning characteristics. There are two exceptions to this:

1. When people are killed by the failure of the slope itself (11). A dam can threaten workers following a sudden drawdown if the drawdown results in a failure of the embankment while workers are present (11.1).
2. When the loading is also local. Examples include an earthquake that blocks evacuation routes and traps people in buildings; and a severe storm that blocks evacuation routes (South Fork Dam, Johnstown) or hinders the awareness of sensory clues (29).

Detectability (Det, Dt)

Several insights are worth noting: In many cases, the Par near a dam has been aware that the dam was unsafe (17). When a safety concern has been detected, there has generally been a reluctance to issue a warning until failure is viewed as highly likely or inevitable. Based on modern improvements in dam engineering, monitoring, and safety awareness, many clues that were not properly interpreted in the past would be recognized as serious safety concerns if they manifested today, but still reluctance by public officials and owners might result in delays.

Warning Times and Effectiveness (Wt, Sc, O, We, Td, Wt_{avg}, Pt, Ft, Flt)

As the number of variables listed in the heading indicates, there are a large number of possible perspectives one can take regarding the timing and effectiveness of warnings. It is useful to examine historical insights for a number of these in detail.

Warning Time

The following insights are worth noting:

1. The initial warning time (Wt), whether restricted to official sources or defined to include any human source, says nothing about the percentage of people warned, the urgency or effectiveness of the warning, the rate of warning propagation, the average time available for evacuation, or the time needed to evacuate. As such, it is informative regarding the response rate of officials, but it provides little information regarding the reduction of Par_i to the threatened population ($Tpar_i$). As an extreme example, Wt for the Bangladesh storm surge of 1970 was 3 days, but 225,000 people died because dissemination of the warning was limited and even willfully blocked by officials (Smith and Handmer, 1986).
2. Researchers have defined Wt such that it must come from a human, and in some cases that human must be a public official or a member of the media. As such, the average warning time from any source (Wt_{avg}) is generally longer than Wt when no official warning is given. Under such circumstances, Wt_{avg} will generally equal the average warning provided by sensory clues (Sc).

3. Before the magnitude of an approaching flood is clearly understood, officials can be reluctant to broadcast a warning over mass media for fear that it will clog the streets with curiosity seekers (16.1).
4. The possibility of communication bottlenecks should not be underestimated. For example, in one case the National Weather Service (NWS) had an unlisted phone number and routinely left its National Air Raid loud speaker turned off (16.1).

Warning Effectiveness

The following insights regarding warning effectiveness (We) are worth noting:

1. When warnings precede a failure and thus reflect only the possibility or likelihood of a flood of unknown magnitude, large segments of the population may postpone evacuation to "wait and see," or may go to extreme lengths to avoid evacuation altogether (35.5).
2. A history of false alarms can hinder the credibility of evacuation warnings, especially if the warnings are begun prior to failure (17).
3. Those who have prior experience with extreme flooding, other natural disasters like tornadoes, or who have participated in evacuation drills, are more likely to evacuate promptly and via a safe route (15.1)
4. When the magnitude of an approaching flood is greater than officials or residents expect, it can be difficult to get people to believe the seriousness of the danger and to evacuate. This is especially true when the most severe events in memory caused only nuisance flooding or when a flash flood is preceded by mild local weather (15.1, 16.1).
5. The likelihood that people will evacuate increases with the number of warnings they receive and the number of different sources from which they receive them (15.1).
6. Even though a county or dam owner has an emergency action plan, few may be familiar with it, fewer still may be able to relate it to the real-life dynamics of a catastrophic flood, officials may be ill-prepared to actually put it into practice in a timely manner, and the names and telephone numbers of key contacts may not have been kept up-to-date. In some cases, a plan may depend on a single person or a small set of persons who are unavailable or incapable of responding at the time of the disaster (16.1, 34.1).
7. Those most difficult to warn are usually motorists and outdoor recreationists.
8. Historically, NWS flash flood warnings appear to have had a limited ability to mobilize evacuations when presented as a crawl across the bottom of the TV screen or a brief auditory message. There are several reasons:
    a) Warnings often lack urgency or cover a sufficiently broad area that listeners figure it pertains to other locations.

    b) Readers of a crawl figure if a serious danger was imminent, it would not be presented as a crawl.

    c) Recipients figure that if a true emergency existed, warnings would be confirmed by other sources.

    d) Not everyone is watching TV or listening to the radio.

Sensory Clues

All of the following sensory clues have alerted people to danger:

1. A loud roar, resembling an amplified version of thunder, ocean waves, an earthquake, or a crashing airplane.
2. The sight of an approaching wall of water, which can often resemble fire, smoke, or fog from a distance because of the way light reflects off the spray that rises. This is usually covered in front and above by debris, including houses, logs, trees, and a thick mat of earth. In some cases, the debris is so dense that it completely hides the water from view.
3. The sound of cracking trees and telephone poles.
4. The sound of logs, trees, and boulders bouncing off the canyon walls.
5. The sound of houses exploding into a shower of boards as they are ripped from their foundations and smashed one against another.
6. The sound of a creek growing louder and louder when a flood rises slowly.
7. The sight and sound of exploding power stations or transformers.
8. The buzz of electricity from snapping power lines.
9. Power lines swinging violently from upstream disturbances.
10. Railroad tracks snaking violently.
11. An advance, fast-rising flood, filled with debris, that precedes a wall of water by 2 – 30 minutes. The first warning might be shallow flooding in the house.
12. The sight of neighbors moving vehicles to high ground or congregating on the hillside.
13. The obscure warning of motorists racing by while honking their horns.
14. Pets becoming agitated.
15. Power outages.
16. Dead phone lines.

The following conditions can mask sensory clues:

1. Heavy rain and hail tend to drive people indoors and mask both visual and auditory clues (22, 29).
2. A strong wind.
3. No wall of water, but a fast-rising flood at night that rises with little sound (18).
4. The darkness of night can hinder visual clues and obscure auditory clues, but floods are often loud enough to wake people at night. Nevertheless, even when there is a loud wall of water, a fast-rising leading wave can surround a home before the greater wave is perceived (16.2).

Average Warning Time

Individual warnings (Wt_i) provide a basis for an average warning time (Wt_{avg}). These individual warnings can arrive by any of the following modes:

a. sensory clues,

b. telephone calls from neighbors or authorities before a flood nears the area (i.e., before the phone lines go dead),

c. passing motorists honking their horns and shouting warnings out the window,

d. shouts from fleeing neighbors,

e. family or friends who stop by on foot or in an automobile,

f. the radio,

g. the TV,

h. CB radios,

i. fire fighters or police officers who drive through neighborhoods with bullhorns or who go door to door, and

j. a self-appointed Paul Revere who races from door-to-door or business to business delivering a quick warning with the intention that it be passed along.

The following insights and subtleties regarding the average warning time (Wt_{avg}) should be noted:

1. In a long, narrow river valley, when a wall of water progresses slower than people can drive, there will typically be motorists or residents who detect the flood through sensory clues and who flee downstream in an automobile. If they can gain distance, these motorists may stop along the way to warn residents or to pick up family and friends. At the least, they will typically turn on their lights, honk their horns, and possibly shout quick warnings out their windows. Such warnings do not always communicate the approaching danger effectively, but they generally prompt a curiosity that alerts other residents to sensory clues or alternate forms of warning. This allows many to run up a nearby hillside or to evacuate by automobile. Such actions generate a chain reaction, as more vehicles evacuate, people warn their neighbors, or people notice the swarm of unusual activity outside their windows. This contagious process can mobilize the better part of a community, saving countless lives, even in the absence of warnings by public officials. However, it is by nature much more random than a formal evacuation plan implemented by trained public officials. As such, when many houses are rapidly destroyed, the chances that at least some people will remain ignorant of the approaching danger and fall victim to the flood remains high (30). The Buffalo Creek dam failure provides an excellent example of this process as it worked itself out over 15 miles (see Wt, Wt_{avg}, and Sc in the unpublished working documents for event 17).

2. Wired telephone service is quickly lost in virtually every catastrophic flood and so should not be counted on to propagate a warning at the last minute.

3. Power is quickly lost or intentionally turned off in virtually every catastrophic flood, eliminating the usefulness of most last-minute radio or TV broadcasts.

4. No cases provided information on the use of wireless telephones in disseminating a warning, but during disasters wireless exchanges can quickly become overloaded, blocking communication traffic.

5. Although the average warning time (Wt_{avg}) characterizes individual warning times (Wt_i) more closely than does the warning time based on the first official warning (Wt), Wt_{avg} does not characterize those with the shortest Wt_i. As such, Wt_{avg} may appear large even though a significant percentage of the subPar receives little or no warning. This is especially true when Par type are mixed: i.e., a river reach that includes residents watching the evening news and those who are sleeping in isolated campsites (16.2).

6. Wt_{avg}, like Wt and the average warning time provided by sensory clues (Sc), lasts only until the flood reaches a level of potential lethality. This is defined conservatively such that only trivial flooding is permitted. Once a house is surrounded by water or people in the floodplain have to wade, the stopwatch on warning time is read. Evacuation after this point is defined as reaching a safe haven.

Evacuation Rates (Ef, Pr, Td, Tw, Ts, Ml, Pt, Dev, Ret)

The following list provides important historical observations and insights regarding evacuation rates:

1. When the inundated area is not more than about 1,000 ft wide, most houses have a back door within 300 ft of safety. If the danger is clearly understood, it generally takes 0.5 – 3 minutes for a family to evacuate during the day, and 1 – 6 minutes at night, depending on how many people must be gathered, how quickly they expect the flood to arrive, how extreme the weather is outside, and whether or not they linger, get dressed, grab possessions, or warn neighbors. These ranges must be extended slightly when the danger does not immediately register (6.1). Average values (the representative evacuation time, Ret) are on the order of 1 – 2 minutes during the day and 2 – 4 minutes at night. During the day, a large wall of water can provide an average warning time (Wt_{avg}) of 1 – 4 minutes based on sensory clues, which explains why some very destructive floods have killed a small percentage of Par when Wt = 0 minutes (30).

2. Frequently, healthy individuals slow their evacuation to help others—neighbors, strangers, aged parents, a disabled relative, babies, children. In some cases, they all perish together (6.1).

3. It is not uncommon for people to delay or turn back to grab a pocket book, pair of boots, coat, clean clothes for a child, or some other valuable of minor importance. Sometimes people will return after reaching high ground. They can also delay to grab a pet or to release pigs or horses (17, 18, 18.25, 29). Many people have died due to such delays.

4. Strong rains, bitter cold, and other extreme weather conditions can slow an evacuation, but people will quickly run outside if they expect a towering wall of water to crash into their house at any moment.

5. Spouses who work outside the flood zone may run or drive into the flood zone to try to reach their families before the flood arrives, even if there is insufficient time to reach home or to evacuate once there. This increases the representative evacuation time (Ret) and can greatly increase life loss (29).

6. When workers are concentrated in a factory, warnings can often be propagated within seconds or minutes with a high degree of credibility and urgency (29).

7. Fences can prove formidable barriers to evacuation on foot, slowing escape or preventing it altogether. In some cases, elderly adults have thrown children over fences while they were forced to face the flood (6.1).

8. There is a small percentage of people who refuse to evacuate, even in the face of clear, urgent, door-to-door warnings (8.1, 18.3a).

9. Evacuation warnings are generally less effective prior to dam failure since the magnitude of the flood is not known and it is uncertain when or if a flood wave will actually appear. Hence, the evacuation rate prior to failure can be much slower than after failure (17, 23.1, 35).

10. Sometimes people believe a dam might fail, or even has failed, but believe the flood will do no more than nuisance flooding at their home. Under such misapprehensions, even the sensory clues of a leading, fast-rising, debris-filled flood may not produce a rapid evacuation (15, 17.12, 22, 29.9).

11. Evacuation rates will vary with the expected travel time of the flood. That is, people who can evacuate in seconds or minutes may take much longer if they think they have half an hour or an hour.

12. The last four points limit the effectiveness of many evacuations, causing the trend line of the evacuation nonsuccess factor versus the excess warning time Ef = Tpar/Par vs. E = Wt_{avg} - Ret) to approach an asymptotic value slightly above zero as E increases (see Figure 7.1 for an historic example).

13. Most people who evacuate on foot in narrow valleys choose a reasonably direct route toward safety, moving laterally toward the nearby hillside.

14. When evacuees panic, they can freeze in their tracks, jump out of upper story windows, or overlook the closest hillside and run parallel to the river, sometimes toward the flood (17, 18, 26.2, 29).

Some panicked individuals have run toward the river to cross a bridge to run up the hillside on the opposite side. While cases of panic are uncommon, they can infect an entire group, resulting in great, unnecessary life loss (29).

Excess Evacuation Times (E, Ef)

Because the representative evacuation time (Ret) is based on escaping the flood zone, and since individual warning times (Wt_i) underlying the average warning time (Wt_{avg}) stop increasing once 6 – 12 inches of water crosses the floodplain, the excess evacuation time ($E = Wt_{avg} - Ret$) says something about the likely size of the threatened population ($Tpar_i$) but it says nothing about the ability of people to reach safe havens (18). Likewise, E says little about the ability of people to wade to safety or escape with the help of rescuers during the early stages of flooding (18.21).

When E is small or negative, safe havens provide the best alternative to evacuation. For example, when people dwell on an island that is submerged by a flood, there may be patches of relatively high ground that allow people to safely stand in shallow water (a safe haven) while their houses are washed away. The same can hold true for any location cut off from the edge of the flood by bridges, barriers, or distance. In such cases, because people may seek shelter outside of buildings on higher ground, high loss of shelter does not reflect the nature of the flood experienced by the residents. Expecting the proportion of the threatened population to perish ($Ptpar_i$) to approach 1.0, one might be surprised to find the life loss approaching zero (18.21).

E is the only measure of time that describes the likelihood that people will successfully evacuate. The initial or official warning time (Wt), the average warning time from any source (Wt_{avg}), and the average warning time provided by sensory clues (Sc) say something about the time available for evacuation; and the representative evacuation time (Ret) describes the time needed to evacuate; but only $E = Wt_{avg} - Ret$ describes the difference between the two. In the same way, Sc and Wt_{avg} indicate whether people are likely to reach a safe haven only when these values are compared to the time required to get there.

SubPar Type and Evacuation Modes (Pt, Ft)

The rate of life loss varies significantly among Par type (Pt) since it is a function of where people are located when the flood reaches lethal proportions. Apart from where people are located when they learn about a failure, the excess evacuation time (E), people's modes of evacuation, and the local loss of shelter (Ls) influence where people are located at the flood's peak. Issues affecting lethality are presented or expanded upon toward the end of this chapter. The subsections below present insights specific to each Par type.

Residential vs. Commercial vs. Seasonal

Each of these words defines a type of community with unique temporal characteristics.

Residential neighborhoods. During school, work, and commuting hours, the population in residential areas should not be based on the average occupancy, since a large percentage of both adults and children will not be home. The same holds true during camping holidays, weekends in the summer when people are likely to be away from home, and popular shopping times.

Commercial districts. Depending on the nature of the local businesses, commercial districts can be largely vacant outside of work hours and especially at night, on Sundays, and on holidays.

Seasonal areas. In some cases, a subPar will consist almost exclusively of tourists or recreationists. Examples by region include campgrounds (3), areas frequented by fishermen (2), and resort communities (32). In such cases, the subPar will fluctuate in size based on the season and whether it is a weekend or holiday, so the likelihood of a dam failure should also be estimated on a seasonal basis.

Buildings

Those who are caught while running from a building toward the hillside benefit from being among buildings only if the buildings shield them or provide a chance haven as they are washed downstream.

Automobiles

The likelihood of people being in a vehicle rather than at home or at work is much higher during regular commuting hours and much lower at night.

People often choose to evacuate by vehicle when it is safer, shorter, and quicker to run up the hillside. There are several reasons for this:

A vehicle may have great monetary value, so there is a desire to remove the vehicle from the flood zone. This is apparent when people risk their lives to drive a vehicle a short distance up a hillside (17.14) or when they refuse to abandon a stalled vehicle while it is still safe to wade (1).

1. A vehicle is associated with speed, which is desirable during an evacuation.
2. A vehicle provides a means by which a family can reach food and shelter once their house is flooded.
3. Many people are conditioned by habit to drive rather than to walk or run.
4. A vehicle helps transport those with limited mobility.

Additional historical insights pertaining to motorists and their passengers are enumerated below:

1. Motorists who become stalled in water are usually reluctant to leave their vehicles. While flooding is minor or moderate, they may decide to climb on top of the vehicle or remain inside while it drifts. Thus, slow-rising floods that provide ample time for evacuation can prove lethal: the window for evacuation is lost and the flood continues to rise or a sudden wall of water sweeps through (1.1, 25.2).

2. Water through which people can wade is often capable of washing a vehicle downstream (9.3, 23.1). As sediment coats a road surface and the weight of a vehicle is reduced through buoyancy, friction between the tires and the road is reduced considerably.

3. Many automotive fatalities are a result of motorists choosing to cross a flooded bridge or roadway, either because the flood appears shallow or because the motorist does not realize what a small depth/velocity combination is needed to move an automobile into deeper/swifter water (8). In the common scenario where a motorist hesitates and then chooses to venture across a flooded roadway, the resulting subPar is a form of convergence. In such cases, variables like the warning time (Wt), the average warning time (Wt_{avg}), and the excess evacuation time (E) have little or no relevance (23.1).

One does not see a steady stream of vehicles swept away at the same river crossing because after the first vehicle begins to float, other drivers stay clear. However, the same crossing can sweep more than one car away if it is isolated and the first automobile disappears from view before a later motorist arrives (8.3).

1. Variables like the destructive velocity (Dv) and the peak flow rate (Qp) only apply at bridges after a vehicle is swept into the channel, since most of the water passes beneath the bridge.
2. A unique danger exists to motorists who might plunge dozens of feet when a section of roadway that has washed away is hidden by darkness, rain, fog, or a blind corner (27.1).
3. Excavations, ditches, canals, and other topographic depressions can turn an otherwise shallow flood into a death trap by slowly washing motorists into a place from which they cannot escape (9.3).

Campgrounds

The size of subPar in campgrounds varies dramatically with the season, generally swelling in the summer and peaking on summer holidays and weekends, so the comments under seasonal subPar apply here. Campgrounds are somewhat unique in that official warnings are especially difficult to deliver to outdoor recreationists and recreationists may have fewer opportunities to find shelter than those in other surroundings may. See the section on the lethality rate outside of safe havens.

In the River (waders and swimmers)

Few people wade or swim more than an hour after dark, so this type of subPar can be ignored at such times.

See the section on the lethality rate outside of safe havens.

Along Shore (hikers and the curious)

Few people hike or watch floods more than an hour after dark, so this type of subPar can be ignored at such times.

See the section on the lethality rate outside of safe havens.

Boats

When on a river, boaters face increased risks due to the difficulty of delivering an official warning and the increased evacuation time most boaters would require. See the section on the lethality rate outside of safe havens.

Trains

Depending on the depth of flooding and whether or not a train is moving, a train is most similar to either a mobile home (as was the case near Johnstown when South Fork Dam failed in 1889) or an automobile, though in both cases less buoyant. The impact of a crash can cause deaths even when people stay dry (19).

Homogeneity of SubPar (Par_i, Pt, (Gf, Ls, Fp, F_5, Schvq)

Descriptive variables are generally point estimates [i.e., maximum depth (D), maximum velocity (V), destructive velocity (Dv), and initial warning time (Wt)] or descriptive variables are based on a representative average across a subPar [i.e., sensory clues (Sc), average warning time (Wt_{avg}), and excess evacuation time (E)]. The more homogeneously each subPar is defined [i.e, with respect to Par type (Pt), loss of shelter (Ls), location, warning times, etc.], the more closely a point estimate or average value can characterize every member of Par. That is, homogeneous subPar reduce the variance if characterizing variables were applied to each individual.

Although each flood is highly unique, it is possible to compare statistically dissimilar Par using statistically similar subPar when those subPar are defined homogeneously and one focuses on the threatened population ($Tpar_i$) to reduce temporal variations. These two steps—reducing Par to homogeneous subPar and Par_i to $Tpar_i$—allows one to characterize the hazard to a population primarily by variables like loss of shelter (Ls), maximum depth (D), and maximum velocity (V).

Flood Dynamics (Flt, V, D, Qp, Qb, W, Dv, R, Ww; Dt; H, Hp, B, Vol, Rf, A)

It is possible to make a large number of generalizations regarding the dynamics of extreme floods. The following list enumerates those aspects of flood dynamics that are most important:

1. Catastrophic floods are violently turbulent. They often strip the clothing off both those who perish and those who survive. Victims can be so mangled and caked with mud that friends and relatives do not recognize them. Sometimes bodies are dismembered or so disfigured that it is impossible to tell the victim's sex (32.1). The main current generally makes normal swimming difficult or impossible. Many people die because the current pulls them under or prevents them from reaching the surface. If a person is driven into an object such as a house, tree, rock, fence, or telephone pole, the current has sufficient force to pin the person underwater and even bury them in sediment.
2. In open currents, people who die usually do so because they are held underwater, tire trying to fight turbulence, or are injured through a violent collision with stationary or mobilized objects—all functions of high velocities.
3. The peak flow rate of a dam break flood wave typically follows the leading edge by at least a minute, and floods often rise in progressive surges or waves. It follows that fatal depths are often less than the peak depths and the depths encountered while people seek out safe havens, including wading to shore, are usually much less than the peak depths. It also means that those farther from the river may have precious extra seconds to evacuate compared to those closer to the river (22.2).
4. Depth is principally important as it works with velocities to provide the needed moment and momentum to topple people and buildings, to allow high velocities and turbulence to develop, and to trap people underwater by crashing down from above. Thus, if people are able to swim, the velocity of a flood is more important to life loss than its depth; velocity is the killer and the depth is the accomplice (18.13). As an example, over 50% of the campers died when 3 ft of water raced across the Arás alluvial fan (3), but all those who drifted free of currents in the depths of Lake Mohave were amazed at how easy it was to swim to shore (22.4, Eldorado Canyon). In the same way, it is likely that over half of the town of Rivadelago survived the total destruction of their homes, without warning, at night, because the Vega de Tera flood was immediately dissipated in the deep, quiescent waters of the lake just downstream (36).
5. The ratio of serious injuries to deaths varies greatly by event, making generalizations difficult. In some events, people either die or escape relatively unharmed (22). In other events, the number of people admitted to emergency rooms might be several times greater than the number of deaths (17). As a rule, if a flood is extremely lethal, destroying all safe havens, there are few injuries because people either evacuate or die (35).
6. Extreme scour and deposition—on the order of a few feet to over 10 ft—is common in extreme floods. In some cases, the river channel may permanently shift to flow where buildings once stood (3, 15, 18.3a, 36).
7. In some cases, the flow forms vortexes that can drill deep holes into the ground (18.3a, 12 ft deep).

8. Catastrophic floods are characterized by an unusually large debris load: Earth from the failed embankment and canyon walls, cobbles and boulders, forest litter, felled trees, roofs and sharp boards from shattered houses, floating mobile homes, vehicles of all shapes and sizes, barbed wire and boards from fences, telephone poles, propane tanks, railroad cars, railroad ties, etc.

Consider the following examples:

a) The Eldorado Canyon Flash Flood picked up enough dirt and gravel from bare canyon walls that its leading edge sprayed out gravel and appeared to have a viscosity comparable to freshly mixed concrete (22.7).

1. The Stava embankments had sufficient volume in relation to the reservoirs that the resulting flood contained approximately 50% sediment (32.1). Extremely high sediment loads are common when tailings dams fail (17).

b) When the Bayless Pulp & Paper Company Dam failed, it picked up 700,000 cords of logs from the pulp mill, completely blanketing the floodwater to the point that some observers high on the hillside could not see the water when the flood passed through Austin, Texas (8).

c) The Buffalo Creek flood was typical of a wall of water passing through sequential communities. It was characterized by every conceivable item on the floodplain, but it was dominated by automobiles, splintered boards, shattered houses, and houses that were still intact, riding high above the flood and being pushed before it by a wall of water that was black with mud from the embankment (17).

d) The Mill River Dam failure provided an example of a flood that passed through forested valleys between communities. Consider the following quote from a young boy:

> A great mass of brush, trees, and trash was rolling rapidly toward me. I have tried many times to describe how this appeared; perhaps the best simile is that of hay rolling over and over as a hayrake moves along the field, only this roll seemed twenty feet high, and the spears of grass in the hayrake enlarged to limbs and trunks of trees mixed with boards and timbers; at this time I saw no water. (Sharpe, 1995, p. 97)

1. If the flood is not slow rising and it passes through a canyon or narrow valley, debris tends to concentrate at the leading edge of the flood, slowing the wave and causing it to pile up as a wall behind a loose, mobile debris dam.

2. A narrow constriction can also cause a surging wave to mount up into a wall of water (22.1).

3. A wall of water will tend to ride a winding canyon like a bobsled, sloshing up one side and then another. Often it is described like a snake riding the canyon walls (6.1, 17). Superelevation differences of 10 – 20 ft have been observed, representing roughly 30% – 80% of the flood's peak depth (17, 22.2). When a tributary enters another river at a sharp angle, the flood can wash far up the opposite shore before moving downstream (17, 35). The turbulent nature of

these behaviors can send a finger of water out to snatch one house away from between two others or leave houses untouched at an elevation below houses that are destroyed (17, 22).

4. Because a wave must generally be slowed to pile into a wall of water and debris, such a wall will often sweep a fast-rising, debris-filled flood before it as the mobile wall leaks and sections break away to travel at unhindered velocities. This can provide an important sensory clue, giving residents precious seconds or minutes to run or wade to safety before the wall of water arrives (17.6).

5. Debris dams tend to form behind bridges, reversing attenuation and causing the wave to rise in height. If the bridge or dam fails catastrophically, the renewed wall of water will be higher and the peak flow rate will be greater than if the temporary dam had not formed. As debris dams form and fail, a flood wave can be slowed and renewed over and over as it moves through many miles of canyon or narrow valley (17).

6. When a series of small dams dot a river (common when mills are plentiful and factories depend on water power), the sequential dam failures increase the volume of the flood and compensate for attenuation through valley storage.

7. When a wave is renewed, valley storage forces the peak flow rate to follow an exponential decay pattern, approaching a limiting value (16, 18, 26, 29, 31, 35). As the flow rate decreases, average depths and/or velocities will also decrease. Since the peak flow rate (Qp) is a function of the product of average depths and velocities, depths and velocities decay much more slowly than Qp. Of course depths and velocities can increase at the expense of the other if the average slope or cross-sectional area changes (26, 22.1).

8. Obstacles like train cars, buildings, and sturdy trees that support a debris dam can divert a flood and protect regions behind them (17.7, 18.8, 29.1). When the terrain is reasonably flat, a debris dam or building can also turn a flood and send it in an unexpected direction, such as down a side street between a row of buildings.

9. In a row of buildings or connected apartments roughly parallel to the direction of flow, the leading units can buffer those downstream, resulting in progressively less damage (18.5).

10. A row of buildings will buffer buildings inland (18.8).

11. Parameters like destructive velocity (Dv) and peak flow rate (Qp) characterize areas near the channel far better than areas near the flood's fringe (18.3b). Dv and Qp grossly misrepresent a subPar when the subPar is located in a finger of the flood or a quiescent backwater (16.6, 18.13).

12. As Par_i grow in size, the maximum flood width (W) and hence the destructive velocity, Dv = [the peak flow rate (Qp) – bankful flow rate (Qb)]/[maximum flood width], become less representative.

13. When Par_i is heterogeneous, point values like maximum depth (D) and maximum velocity (V) generally approximate the flood conditions only in those areas near the original channel, even if those areas are a small fraction of Par_i.

14. Dam type (Dt), the height of the dam (H), the height of the reservoir pool at failure (Hp), the breadth of the dam (B), the volume of the reservoir released (Vol), the rate of dam

failure (Rf), and the cross-sectional area of the breach (A) are relevant to life loss only insofar as they influence variables like the detectability of the ensuing failure (Det), the average warning time (Wt_{avg}), the rise rate of the flood (R), the height of a wall of water (Ww), the maximum velocity (V), the maximum depth (D) and the underlying probability that a structure will fail. As such, they are at best surrogates in a life-loss equation and should largely be ignored. They do, however, offer the possibility for checking or calibrating the accuracy of flood inundation modeling.

15. When the excess evacuation time (E) is very small or negative, the rise rate (R) is a critical factor that determines whether people are likely to be trapped or washed away. Slow-rising floods do not generally pose a threat to people in their homes since occupants can readily evacuate, but motorists reluctant to leave a parked or stalled vehicle can linger to the point that evacuation becomes impossible (25). An extremely fast-rising flood that does not pile into a wall can trap more people than a wall of water if the former provides fewer sensory clues (18). However, once the flood has arrived, a wall of water is impossible to avoid, but a fast-rising flood may provide the few seconds or minutes necessary to wade to shore before it prevents wading.

16. Current definitions of forcefulness ($F = Fp, Fd, F_5$) mask the most important factor differentiating rates of life loss by combining structures with major damage and total destruction into a single category. When buildings are destroyed, most people remaining in those buildings die, but when buildings have major damage, the fatality rate varies widely depending on the frequency with which safe havens remain. On average, the historical fatality rate in buildings with major damage has been closer to that observed in buildings with minor damage (the proportion of the threatened population that perishes, $Ptpar \cong 0$) than to that in buildings that have been destroyed ($Ptpar \approx 0.8 - 1.0$).

As an example of how forcefulness (F) masks this distinction, consider the contiguous subPar 18.12a and 18.12b. Every building in 18.12a was destroyed and every building in 18.12b had major damage, making proportional forcefulness (Fp) = dichotomous forcefulness (Fd) = 1.0 in both cases. The fatality rates diverged significantly, however, as expected, with the proportion of the subpopulations at risk that perished being $P_{18.12a} = 1.0$ and $P_{18.12b} = 0.013$.

17. The following real-life behaviors of flood waves are difficult to model with current software:

a) The effects of debris dams in creating and renewing the depths of a wall of water (17).

b) The effects of debris dams in protecting areas from damage (29.5).

c) The effects of debris dams and buildings in changing the direction of flow.

d) The selective inundation of a crashing flood as it ricochets off alternating sides of a canyon with superelevation differences exceeding 10 ft (17, 22).

e) The ability of a wave's momentum to carry it out of the channel and along a new course when it encounters a bend.

f) The ability of a wave to rocket out of a constriction like water from a fire hose and miss adjacent areas that would be flooded if the flood had less momentum (6.1, 26).

g) The reduction in velocity caused by mobile and stationary debris (17).

h) Differences in depth, velocity, and arrival time between a wall of water and its leading fast-rising flood (17).

18. The force of the current makes it extremely difficult to regain one's footing after being swept off one's feet. Consider the words of a rescue worker who fell while wading under a safety rope: "I have a new respect for water. It was an incredible force. Words can't describe it. . . . Your foot leaves the ground and you're gone." (Kaiser, 1995, p. A1). Fortunately, his fellow firefighters grabbed him before he drifted away.

19. The type of failure (Ft) is relevant only insofar as it affects aspects of warning and the dynamics of the flood wave itself. For example, the Vaiont failure (35) was extremely unique. The dam itself did not fail, but a large portion of the mountain slid into the reservoir and sent a massive wave 325 ft over the top of the dam. Despite the source of the wave, a flood with similar hydraulic characteristics might be expected half a mile below a tall, concrete gravity or arch dam that suddenly burst (31), or below an earthen, rockfill, or mine-waste dam perched high on a very steep slope (32).

20. Given identical volumes and no warning, an expansive flood is safer than a narrow flood for two primary reasons. First, as a flood spreads laterally, three factors combine to greatly reduce the flood's local velocities: a) Depths decrease through volume spreading so that a wall of water cannot be sustained. b) A wide floodplain implies a relatively flat downstream slope. As momentum carries the flood laterally, the slope becomes even smaller. c) Buildings near the river absorb the flood's energy, buffering each successive row of buildings. Second, as velocities and depths drop, loss of shelter shifts from high (H) to medium/major (M), and then to low (L). This greatly increases the number of safe havens, chance havens, and the survival rate (18).

Loss of Shelter (Bt, Ls, Dd, Sh, Psh, Fp, Fd, F_5, Fpar, Pt)

Loss of Shelter vs. Economic Damages

It is important to realize that loss of shelter (Ls) is not the same as economic damages. Lives are lost within buildings when occupants fall into water in which they cannot swim; become trapped underwater as a room fills to the ceiling; get struck by large, external debris penetrating from outside; get struck or trapped underwater as the building breaks apart; or get washed through a wall or out a door or window into open water. As such, the critical question is not the degree of economic damages or whether a building should later be condemned, but whether or not a structure maintains an accessible safe haven or pseudo-safe haven for the duration of a flood.

It follows that loss of shelter is not synonymous with the definitions used by the American Red Cross or other agencies to define housing damages. Instead:

1. Ls = L implies relatively safe havens on every floor.

2. Ls = M implies complete loss of a safe haven on the first floor.

3. Since loss of a safe haven is generally accompanied by structural damage, traditional categories of minor and major damage generally agree with Ls = L and Ls = M when they exclude damage to furniture from water and mud.

4. Ls = H implies complete loss of all safe havens (including accessible rooftops) and loss of every aerated pocket of protection. If an aerated pocket of protection remains, Ls = M even if a building floats off its foundation or is later condemned.

An anchored house may be torn apart, so a house that is securely anchored to a chimney or foundation can provide a more dangerous refuge than one that is free to float (17).

When a house floats off its foundation and is mobilized downstream, several things can happen to it. It can sink or be sucked underwater by an undertow; waves can break it to pieces; it can collide with a stationary object like a tree or the jutting end of a house and break apart; the roof can sever off and form a raft; it can collide with another floating house or a debris dam and explode in a shower of boards; it can jam in a debris dam and form part of a bridge to safety, or it can drift a short distance and run aground.

It is useful to examine the three classifications of Loss of Shelter (Ls) individually.

Ls = H: total destruction

A house can be destroyed in many ways. It can:

1. be slowly battered to pieces by waves and debris,
2. be obliterated in an instant by a towering wall of water,
3. collapse on itself, especially if it is made of stone or brick,
4. pop up like a cork and float off its foundation, then disintegrate through collisions downstream, or
5. float a while and then sink.

A building can be destroyed even if the water surface elevation is well below the elevation of the top story (18.7, 29.2, 29.7). However, a house is destroyed only when all safe havens, pseudo-safe havens, and aerated pockets of protection disappear during the flood. During or after destruction, any of the structural members, especially a severed rooftop, can provide a chance haven.

If a rooftop is inaccessible, a building is destroyed when the top floor or accessible attic is completely submerged. If a roof is accessible, the building is considered destroyed only if the flood or flood waves wash across the crest of the roof to an extent likely to wash people into the flood. Since the momentum of the flood riding the slant of the roof will cause waves to run up, this elevation is generally on the order of a foot or two below the roof's crest (18.10).

Ls = M: major damage

If the highest accessible floor (including an accessible attic) is filled with water beyond 1 ft of the ceiling, but the flood does not crest an accessible roof, Ls = M rather than H because an accessible safe haven remains (18.15).

People have survived by huddling in a back corner, sitting on a counter, or hiding in a cupboard when two walls and most of the floor have been washed away (18). Hence, if walls are torn off but portions of the structure remain to shelter occupants from the main current or to provide something to which they might cling, the loss of shelter is major; but if only trivial structural members remain such that all shelter is lost, the dwelling is destroyed.

A building is destroyed any time it is torn apart and submerged in the flood. However, if a building floats off its foundation and maintains an accessible pseudo-safe haven for the duration of the flood, Ls = M.

A building just inside the edge of the flood can experience major damage when a leading wall of water or sudden surge tosses large debris such as logs or millstones through the walls. These, in turn, can injure or kill those that are inside (6:1).

Ls = L: minor damage

Almost any room has a counter, desk, couch, table, chair, bookcase, bed, dresser, piano, or other piece of furniture that can provide an elevated platform or a floatation device during a flood. When a flood is relatively quiescent, with few exceptions, these objects and a little swimming allow people to keep their heads above the water surface even when the flood nears the ceiling. While elevated ceilings pose a special problem, a flood reaching such depths without causing major damage is necessarily very calm, making it easier to cling to floating furniture, tread water, or hang onto rafters. This has been demonstrated in commercial buildings with two-story ceilings (18). Hence, Ls = L when there is minor structural damage and the flood does not encroach within a foot of the first-floor ceiling or within 2 ft of the peak of a sloped ceiling.

Safe havens, Chance Havens, Pseudo-safe Havens, and Aerated Havens (Sh, Ch, Psh, Ah, Coh, Pt, Bt, R, Ww, D_{local}, V_{local}, Sc, Wt_{avg}, E, Schvq)

Safe Havens

Havens that are safe for most people under most circumstances can be predicted based on flood mapping, a survey of building heights, and estimates of which trees and buildings will remain standing. Safe havens include the following:

1. An upper story with sufficiently shallow flooding that occupants are not washed out a window and can float on a bed or stand freely. These conditions are generally maintained when the flow does not rise more than one foot above the windowsills in the highest story (about 3 ft above the floor) and the building is not destroyed (18.23, 18.24).
2. Quiescent flooding that does not trap people without air. When flooding is relatively quiescent, people readily keep their heads above water by treading water, standing on stationary platforms such as counters, floating on beds, or by clinging to floating furniture. If such flooding does not persist to the point where it would lead to extreme hypothermia or exhaustion, a relatively safe haven is maintained even when waters come within 1 ft of a flat ceiling or 2 ft of the peak of a sloped ceiling, whether or not the ceiling is elevated. Although it would be highly variable by context, the safe haven would be lost after the flood remained at such high elevations for more than 0.25 – 2 hr, the general range in the historical record (18).
3. An attic that is accessible from within the house or trailer (26).
4. A stationary rooftop, if it is accessible from the house and waves do not wash over the top (18).
5. A stout tree that is easy to climb, taller than the flood, and is not toppled.
6. Any island or region that experiences shallow flooding during the flood's peak, such that depths are easy to resist while standing or clinging to convenient anchors such as telephone poles or lampposts (depths of 1 – 5 ft, depending on the velocity; 18.21, 18.25).
7. The hillside beyond the flood if a member of $Tpar_i$ can readily drive or wade to it while the flood is still shallow, or if they can reach it directly from the roof or a window (18.2, 18.13, 18.21).

Chance Havens

If debris does not crush or fatally wound flood victims, it can provide a means of floatation that has saved many lives. Debris is defined as a chance haven rather than a safe haven because it cannot be readily predicted, its benefits are unreliable, and it can directly cause death by wounding flood victims or trapping them underwater. Chance havens can contribute significantly to the variance in fatality rates across similar events.

Beyond floating debris, given the right circumstances, chance havens also include safe havens, pseudo-safe havens, aerated havens, and areas of low velocity within swimming distance of shore. Chance havens thus fall into four categories:

Rafts and floatation aids: Severed rooftops, mattresses, propane tanks, and logs are the most commonly mentioned in stories about survivors (18.7).

The roofs of floating buildings: Because it is both more difficult and more dangerous to reach and remain on a rooftop after a building begins to drift, lurch, spin, or sink, rooftops should be treated as chance havens whenever a building drifts more than 100 yards. As indicated above, if people must rely heavily on chance to reach a largely inaccessible roof, this would also constitute a chance haven.

Stationary havens: Any immobile haven that is reached while drifting, including rooftops, upper-story windows, treetops, overhanging branches, debris dams at bridges that allow victims to walk to dry land, and the shore itself.

Aquatic havens: Any location where shore can be easily reached without fighting high velocities, such as a lake or a quiescent backwater.

Pseudo-safe Havens

Pseudo-safe havens are safe havens on or in buildings that become reclassified once the building begins to drift. They are a hybrid between safe havens, which are static and predictable, and chance havens, which depend on the whims of the current and the debris load. They exist only among a subset of buildings with major damage (see Loss of Shelter).

As indicated above, rooftops are considered chance havens (Ch) when a building drifts more than the length of a football field. Predicting whether a floating structure will maintain a pseudo-safe haven or be destroyed requires an estimate of its trajectory, the duration over which it can float, and the likelihood of a high-velocity collision. While these apparently depend in part on chance, some useful historic patterns generally hold true. Since pseudo-safe havens only apply in the narrow range of depths and velocities between the lower-end of major damages and the point where buildings are destroyed by the currents themselves, the following scenarios are comprehensive:

1. Currents capable of destroying anchored houses have usually destroyed floating houses or eliminated the safety of their havens. Very few people have survived by riding a house more than a short distance.
2. Mobile homes tend to float in modest depths and velocities, but being single story, a pseudo-safe haven is maintained inside only until water rises more than a foot above the windowsills. In swift water or depths over 6 ft, this condition will generally not last long as the water pressure bursts open windows and doors and waves and debris batter holes in the walls.
3. Houses and mobile homes near the edge of a flood that float only a foot or two off the bottom tend to travel less than 300 ft before they run aground or stack up against other

houses, trees, or barriers. In such cases, the safety of the haven is generally preserved and the survival rate is comparable to that for stationary safe havens.

4. Those who have survived after riding a house or mobile home more than a few hundred yards have usually scrambled onto the roof or lodged in a debris dam where they could walk across the shattered roofs of former houses to dry land. In both cases, the pattern required chance havens and should be treated as such.

5. Concrete, stone, and brick structures do not generally float, at least for long. The same would hold true of most large, commercial buildings.

Rooftops as Havens

To reiterate and to clarify, rooftops fall into one of the following three categories, depending on circumstances.

<u>Safe havens</u>. When accessible and dry, rooftops are safe havens. The important point is not that safe havens in buildings are equally easy to reach, but that if some people can reach them, they preserve a means of shelter that is likely to reduce life loss compared to situations in which every building is obliterated. Means of access might include an internal or external fire escape, a door to the roof, or a dormer window. During 19th century floods, there were many examples of people using a bedpost or other sturdy object to poke a hole through a ceiling or wall to reach shelter (18). Similar access to a roof might be possible through many attics today. People have also been known to climb objects like drainpipes or trellises, or to intentionally use the current to float them up to the roof while they cling to such objects. However, when rooftops are generally inaccessible and people must rely on chance to reach them, they should be treated as chance havens.

<u>Chance havens</u>. A rooftop is a chance haven any time a person washes there from upstream, access depends largely on chance, the rooftop severs from the underlying building, or the building drifts more than 300 ft downstream.

<u>Pseudo-safe havens</u>. A rooftop is a pseudo-safe haven if a person reaches the roof through an access largely free of chance and the building floats off its foundation and travels less than 300 ft without being overtopped.

Aerated Havens

An aerated haven can remain when part of a stationary building is torn away and the flood does not rise more than a few feet above the floor or the highest counter (Ls = M). The following types of events can reduce safe havens to aerated havens:

1. when another building floats past and tears of an ell or smashes a wall (29).
2. when a log or trees crashes through a wall (6.1).
3. when a house at the edge of a flood is cut in half by a wall of water (17, 35.1)
4. when a house is well-anchored and progressive waves break apart the walls most upstream or closest to the channel (18).

5. when a central chimney or other anchor supports an attached portion of the floor (18).

Aerated havens are not safe havens for the following reasons: Their locations depend in part on chance, making them more difficult to target in advance by building occupants. Great strength, stamina, or good fortune may be required to overcome the pull of the current. Since they are open to the current, people must cling to fixed objects like counters and doorframes rather than floating furniture.

Aerated havens are more dependable than chance havens because building occupants are likely to gravitate toward them before the building is torn apart. That is, aerated havens are most likely to form where temporary safe havens appear safest—downstream or inland from the battering currents and debris.

For those who occupy an aerated haven, survival would be more likely than if they were trapped underwater or swept downstream, but less likely than if the safe haven had not been torn apart.

Flood Zones and Zone Densities (Sz, Cz, Pcz, Coz, Zd, Szd, Czd, Pczd, Cozd)

Flood Zones

Recalling that dry land is considered a safe haven or a chance haven after the flood arrives, there are three types of havens in which members of $Tpar_i$ survive floods: safe havens, compromised havens (pseudo-safe havens and aerated havens), and chance havens. People have also been known to survive after being buried in mud (32.1), but such cases are rare and can probably be neglected. When one includes the open current and depths in which successful wading is highly dependent on chance, a flood can be divided into four zones for the purposes of life-loss estimation: safe zones (Sz), chance zones (Cz), pseudo-chance zones (Pcz), and compromised zones (Coz). Each of these is discussed below.

Safe zones include all safe havens. These provide a high degree of safety and a consistently low rate of life loss that approaches or equals zero. The distribution of life loss should closely approximate that for loss of shelter (Ls) = low (L).

Such locations should be relatively easy to predict based on flood mapping except in the uncertain range where safe havens may become compromised havens. Fortunately, havens that have been only mildly compromised have similar life-loss characteristics to safe havens (one is still on the far left of a curve like Figure 6.1 shown later), so one need not be overly conservative when making estimates. For example, if one is not sure whether a building will float or not, but it is reasonably certain that it will at least maintain a pseudo-safe haven by quickly running aground, it should be treated as a safe zone.

Chance zones include the places where people are submerged or face the open flood, and all chance havens that might be reached while drifting. This set includes places where loss of shelter (Ls) = high (H), campgrounds, and the floodplain when it is not a safe haven. The distribution of life loss should closely approximate that for Ls = H.

Like safe zones, chance zones should be relatively easy to predict, except in the narrow range where buildings might be severely damaged or drift far down stream without being destroyed. These are dealt with next.

Pseudo-chance zones fall in that narrow range of depths*velocities for which it is unclear whether a building is likely to be destroyed, float far downstream, or maintain aerated havens.

One approach to estimating life loss in pseudo-chance zones would be to combine the most relevant portions of the life-loss distributions for Ls = H and Ls = major (M). Thus, the inherent uncertainty underlying the zone prediction is recognized by using a distribution that incorporates that uncertainty into its formulation.

Compromised zones are that central portion of compromised havens that have not been intentionally classified as safe zones or pseudo-chance zones. Thus, omitting the portions likely to be classified elsewhere, the life-loss distribution should closely resemble the central 60% – 80% of the distribution for Ls = M.

Zone Densities

Zone density (Zd) represents the distribution of $Tpar_i$ among zones based on topographic, structural, and hydraulic considerations as they interface with flood routing, the rise rate of the flood, and the propensity of people to relocate to a safer zone if there is time to do so. The word "density" refers to either the number of people or the fraction of $Tpar_i$ per zone based on access rather than the relative concentration of zones in an area. Access includes the physical ability to move to a location and sufficient time to get there.

While it is not possible to predict the exact pathway of an individual, history suggests that most members of the threatened population ($Tpar_i$) will seek out the safest haven they can reach in the time allowed. While some will reject a safe haven in a building only to be swept away while crossing the floodplain, this occurs primarily when the excess evacuation time (E) is positive and the vast majority of buildings are destroyed (29). That is, those fleeing must believe that their building will be destroyed and that there is enough time to reach the hillside when, in fact, there is not enough time. This is a very specific set of circumstances that inherently limits the number of such cases. More importantly, the cases are most likely when a wall of water is large enough to destroy most buildings, making them a small fraction of the total life loss in the event. As such, it is not critical to treat them separately.

Generally, it takes far less time to reach an upper floor than to evacuate the flood zone for several reasons: there is little need to get dressed or to grab belongings, the route is a matter of habit requiring little planning, one can avoid extreme weather conditions, one can continue moving after flooding blocks escape outside, people most often sleep upstairs, and the trip takes only about 5 – 30 seconds to complete for an entire family. Even when a flood is rising in the first floor, the walls often provide adequate shelter to allow people to wade, swim, or ride the current to the top of the stairs (18). As an indirect example, although the trailer homes in subPar 26.3 were swept off their foundations and often destroyed within minutes of the flood's onslaught, the numerous descriptions by survivors indicate that there was a short window of time when families gathered together and sought shelter before the trailer walls were destroyed.

The result is that most people reach the safest zone that is accessible and temporal considerations apply primarily to reducing Par_i to $Tpar_i$. These authors are aware of only four historic contexts in which people have not reached a safe haven when it existed on an upper floor of the house they occupied:

1. They chose to attempt to evacuate and were washed away in the open floodplain (29).
2. They were asleep or awake while downstairs at night. Without any sensory warning, the flood burst through the windows, walls, or doors with such turbulence that it made it impossible to wade or swim to the stairway before they were swept away or the room was flooded to the ceiling (18.20).
3. A flood similar to the one just described but with slightly less violence and speed overcame someone with limited mobility, such as an invalid, a young child, or a baby that was swept out of its parent's arms. It should be noted that adults and children with limited mobility are more likely to sleep downstairs, placing the most vulnerable in the place of greatest danger (18.18).
4. The ground floor had no ready access to the floors above (18.23).

In some cases, people open a door, begin to run or wade for the hillside, or try to climb into a car in an attempt to evacuate. When they realize the flood is rising or approaching too quickly to make it, they turn around and run upstairs (17, 18.1).

We can apportion $Tpar_i$ among the flood zones its members are most likely to occupy by apportioning the physical havens that are accessible. As indicated above, access to a haven is rarely limited by temporal consideration when the haven is in the building that people are occupying, so temporal considerations can often be ignored. When a region includes buildings, the subPar should be defined homogeneously with respect to evacuation times so that $Tpar_i$ can be distributed according to the average occupancy rate in each type of structure present. Each flood zone is exclusive of the others such that, when treated as a fraction of $Tpar_i$, the safe zone density (Szd) + the compromised zone density (Cozd) + the pseudo-chance zone density (Pczd) + the chance zone density (Czd) = 1.0.

As an example of the assignment of zone densities, if a subPar consists entirely of two-story buildings that will sustain major damage or be destroyed and half of those buildings are on ground high enough to maintain a safe haven, then the safe zone density (Szd) ≈ 0.5. This value might increase if an additional row of mobile homes was located in a buffered backwater where they were expected to float a short distance inland. This value would decrease if the flood was expected to rise so quickly and with so little sensory warning that a portion of $Tpar_i$ would be unable to reach the second story. If some of the buildings were frame houses and 30% of the buildings were expected to either float more than 300 ft downstream, lose second-story walls, or flood 4 – 6 ft deep in the second stories with high velocity currents, the compromised zone density (Cozd) ≈ 0.3. If it was thought that half of this 30% might be destroyed, then Cozd ≈ 0.15 and the pseudo-chance zone density (Pczd) ≈ 0.15. That leaves a chance zone density (Czd) ≈ 0.2 for buildings that are almost certain to be destroyed.

Since rooftops are much less accessible than upper floors, one would want to treat them accordingly in a model. One way to do this is to first estimate how many rooftops are accessible using emergency means, then estimate the times needed to reach the rooftops and eliminate any rooftops that cannot be reached before wading is prohibitive on the highest floor. As a simplified approach, any rooftops that cannot be reached within 2 minutes from the ground floor or within 5 minutes from an upper floor should be eliminated. Those eliminated but not flooded become chance havens instead.

Attics should be treated as described above for rooftops, except that they do not generally provide chance havens.

When safe havens consist of high ground, they provide a convenient alternative to pre-flood evacuation when the excess evacuation time (E) is small or negative. For example, when people dwell on an island that is submerged by a flood, E may be quite negative due to the length of time required to get off the island. However, there may be patches of relatively high ground that allow people to safely stand in shallow water (a safe haven) while their houses are washed away nearby. The same can hold true for any location cut off from the edge of the flood by bridges, barriers, or distance. In such cases, the loss of shelter does not reflect the nature of the flood experienced by the residents, since the residents are not located among the structures(18.21). It should only be assumed that residents evacuate to such locations when E is small or negative, the representative evacuation time (Ret) is greater than a couple minutes, and houses have more than minor damage or are single story.

Trees are probably the most difficult safe haven to predict. However, people do not generally climb trees unless they are in the open and there is insufficient time to reach a building or the hillside. As such, trees generally play a significant role only in campgrounds and other outdoor settings, where their concentration should be given due consideration (3). People occasionally climb trees when a flood overtakes them while they are running across a floodplain, but the flood must rise in the very narrow range that prevents wading but does not cause toppling. Hence, more often than not, trees play an important role among dwellings only as chance havens, as people are swept off the floodplain or out of buildings and they pull themselves into trees as they are swept underneath.

The value of trees as chance havens depends on their density in an area, their ability to withstand the flood, and the velocity of the current. As the depth and velocity of a flood increases, trees are more likely to topple, provide a dangerous object against which people are killed, or become impossible to grasp and hold onto without being submerged or torn away. Generally speaking, if houses are destroyed, trees provide no refuge except where they overhang near shore. Where housing damage is minor, trees are not needed for shelter. Where houses have major damage and upper-stories are not plentiful, trees can play an important role along with rooftops and other floating debris.

Lethality Rate Outside Safe Havens
($Ptpar_i$, Ls, Pt, Ft; L_i, P_i, $Tpar_i$; Ln, Lnf, Li_n, Li_{nf})

Life loss is a function of distance from a dam only as it is affected by warning times, depths, velocities, widths, loss of shelter, or other variables that are themselves indirect functions of distance from the dam. As the original wave increases in depth and magnitude when the average warning time (Wt_{avg}) = 0, life loss can be extended indefinitely downstream until the wave itself loses lethal potential.

As testimony to the high lethal potential outside of safe havens, whole families often perish together when houses are destroyed or they are overcome while crossing the floodplain (17.1). Atypical events that cost lives and atypical events that save lives are both common (6, 17). This is due in part to the dual nature of chance havens: they can either kill or save. The following sections examine the lethality rate outside of safe havens on a location-specific basis.

In Wading Depths

Waders in catastrophic floods are much more likely to be swept away than waders in a laboratory channel exposed to the same average depth/velocity combination. The following historic examples indicate why:

1. Real floods often generate surges or waves that greatly exceed the average flow conditions, sweeping people into deeper water.
2. Real floods hide holes, logs, curbs, ditches, side stream channels, bushes, and other obstacles that cause waders to fall into deeper water or trip unexpectedly.
3. Real floods contain up to 50% sediment, increasing the flood's momentum and increasing a wader's buoyancy, both of which promote toppling. In extreme cases, the sediment can also trap a wader's feet or legs, hindering or preventing movement and possibly burying him or her.
4. Catastrophic floods often arrive as a wall or a sudden surge against which it is difficult to brace, especially while running.
5. Real floods are highly turbulent, making bracing and balancing much more difficult.
6. Real floods typically carry a lot of large debris, which can easily knock down a wading adult.
7. Real floods often increase in depth over time, so any delays such as stumbling can eliminate the opportunity to complete a crossing.

8. In real floods, a wader may not be wearing shoes and natural surfaces or mud may hinder traction.

9. An adult may be able to wade, but it is common for babies and young children to be swept out of their arms by the rising current, by a sudden wave or surge, when struck by debris, or when the adult falls.

10. Among waders, strength and stamina are key factors, so size, age, gender, and general health are all important variables.

11. If the individual is wearing boots or waders, these tend to fill with water and catch the current, pulling the person downstream and toward the stream bottom. Modern, tight-fitting neoprene waders, however, are less susceptible to this and increase a person's buoyancy.

Imagine an experiment in which 100 identical individuals are placed on a floodplain, the depth or velocity is held constant at each location, and the other variable (depth or velocity) is varied over many repetitions of the experiment. The flood is allowed to behave like a typical, historic, catastrophic flood. Now plot the parameter that is allowed to vary (depth or velocity) against the average lethality rate.

The resulting plot, a cumulative distribution function, is likely to follow a steep S-curve resembling a graduated step-function. When flooding is minor, the proportion of the threatened population that perishes (Ptpar) approaches zero: virtually everyone manages to wade to dry land or a safe haven. When flooding becomes challenging to the point that movement is slow and the chance of falling and regaining one's footing is high, shorter or weaker individuals risk being swept away. If the waders are carrying babies, young children, or helping those with limited mobility, many of those being carried or assisted will be swept away. If there is an abundance of large debris, it will knock the weak and the strong alike into the flood. As conditions worsen, approaching the limits of wading, the number swept away will rise exponentially as they teeter, slip, get hit by waves, step into depressions, get hit by debris, get temporarily released by someone carrying them, or otherwise stumble. The fatality rate for those swept away will be high, because momentum will make it difficult or impossible to regain their footing and they will be swept into deeper and swifter water with greater turbulence. Survival will depend to a large extent on chance. The currents must keep them at the surface, preferably sweep them near a large floating object, steer them clear of fatal collisions, and ultimately deliver them to a place where they can exit the flood—overhanging tree branches, the roof of a stationary building, a backwater near shore, etc.

The likelihood of a flood providing the conditions needed for survival decreases exponentially as the flood increases in velocity and depth since both of these conditions are accompanied by an increase in turbulence. This turbulence pulls people and debris underwater, renders swimming ineffective, forces air out of peoples' lungs, and causes direct physical harm.

Historically, the vast majority of people who have been swept away have died. Among the cases studies, the lowest characteristic depth for a high-velocity flood passed through the campground on the Arás Alluvial Fan in Spain. The maximum depth was about 3.3 ft, with a characteristic depth around 3 ft. Of the 150 campers present, 58% perished. Most of the survivors climbed trees or found shelter in buildings, so 80 – 100% of those swept into the current drowned. In events with greater depths, nearly everyone has drowned who has been swept away.

These dynamics suggest the pattern of life loss found in Figure 6.1 for those in the flood zone without shelter. The flat portion to the left represents flooding through which it is easy to wade. The initial gradual rise accounts for mishaps, followed by less capable waders and babies or young children swept out of adult's arms. Life loss then increases rapidly as healthy adults of various strengths and sizes begin to be swept away. Survivors are primarily limited to those who do not lose their footing or who manage to cling to a pole, wall, roof, tree, or other anchor. As the force of the flood makes it impossible to hold onto stationary objects, people in open water are at the mercy of the flood and life loss rapidly approaches 100%. The ones who survive are those that are immediately carried by a wave toward shore, manage to use debris for flotation, or are washed to a tree or rooftop. At some point, a flood becomes sufficiently violent to pull even large debris beneath the surface, making survival extremely improbable (29, 31, 32.1, 35). In such cases, the only survivors are those who are tossed onto land or into buildings at the edge of the flood where depth*velocity values are smaller (35.1), and those dug out of mud when a flood passes in less than 5 minutes (32.1).

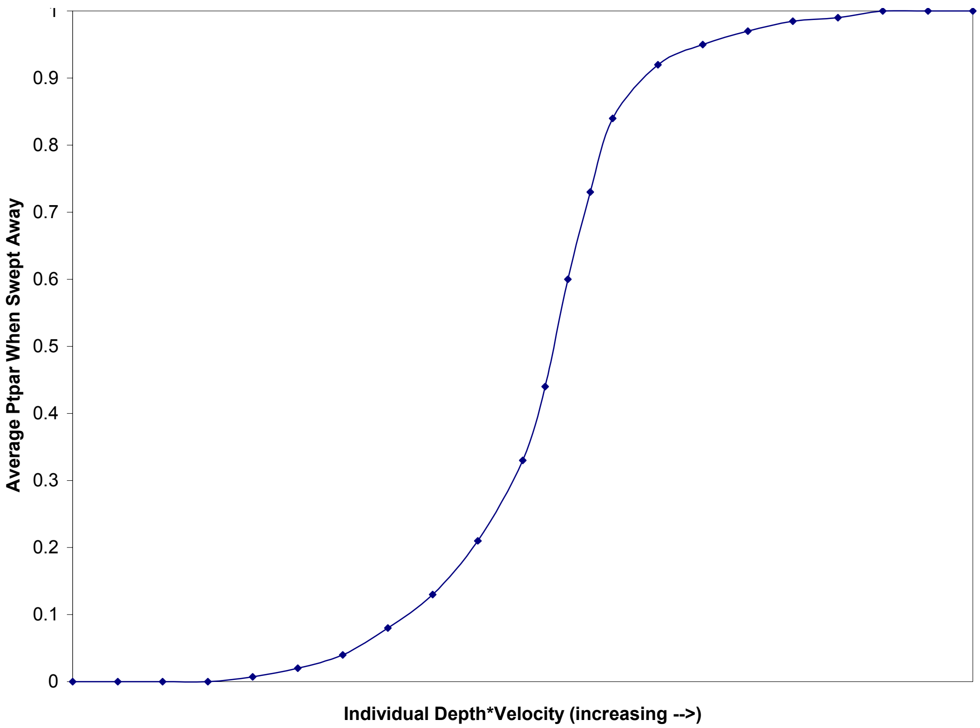

Figure 6.1. An illustrative distribution of average fatality rate based on the peak depth*velocity a heterogeneous group of people encountered above an open floodplain. This graph applies to wade fishermen, those camping in tents, those overtaken while evacuating on foot, and those swept out of a building or other refuge into the flood.

In Drifting Depths

Catastrophic flood waves are violently turbulent (see the previous section on flood dynamics). As such, even strong swimmers are tossed about like debris. Where velocities are high and depths prohibit wading, most of those swept away drown or experience lethal injuries, with some experiencing dismemberment or extreme disfigurement. When velocities are high and depths exceed an event-specific cutoff of about 6 to 20 ft, the fatality rate generally approaches 100%.

In light of how difficult it is to reach or stay at the surface in a turbulent flood, it is generally safer to be swept off a roof or out an upper-story window than to be overtopped by a wave while on the floodplain or in a lower story. Those who reach the surface can survive if they can reach a permanent chance haven, such as a rooftop or a tree top; or if they reach a drifting chance haven that they can ride until they are rescued, they wash to shore, or they climb to safety across a debris dam.

In Buildings

Death in a building typically involves one or more of the following: 1) being trapped underwater when the flood rises to the ceiling, 2) being struck by debris driven through the wall, 3) being struck as the structure collapses, or 4) being washed out of the building to perish downstream.

Because structural members are more buoyant in water than in air, the risk of being killed by falling members appears to be greatest on floors where the flood is least deep. When a structure is rapidly torn apart by a flood wave, the occupants are often driven into the open current while still alive (17.3, 26).

<u>In buildings with major damage (Ls = M)</u>. When structural damages are major [loss of shelter (Ls) = major (M)], the internal environment in the building is usually a mix of areas that are highly lethal and relatively safe. As in buildings that are destroyed, lives are lost when occupants are injured by the building itself or by passing debris; when they are washed through a window, door, or wall; and when they are trapped underwater. As in buildings with minor damage, flooding on an upper story or on the roof can be sufficiently shallow or quiescent to make survival virtually certain (18.10). Hence, the elevation of the top story in relation to the peak elevation reached by the flood is the single most important determinant of the rate of life loss in buildings with major damage.

The rate of life loss will follow a sharp S-curve resembling a step function when graphed against depth*velocity (see Figure 6.1). The dynamics are similar to those for waders, except that people are wading on an elevated floor instead of the floodplain and there are more items on which to float, stand, or cling. This will shift the graph toward the right and flatten the curve.

When water rises behind a door, the pressure can make it difficult or impossible for an average person to overcome the pressure and open it (17, 18). Survival for an occupant of a building who is not swept into the current occurs in only three places: Safe havens, pseudo-safe havens, and aerated havens. Every other location is completely submerged or destroyed.

Conditions in safe havens and pseudo-safe havens are comparable to when loss of shelter (Ls) = low (L). The historic rates of life loss have approached zero when the safe haven or pseudo-safe haven was not eliminated.

In aerated havens, occupants require more strength, stamina, and good fortune to survive than in a safe haven since the occupants have a higher degree of exposure to the flood. Nevertheless, there is a higher survival rate than in the open current. Chance plays a large role in whether or not an aerated haven remains or is destroyed.

<u>In buildings that are destroyed (Ls = H)</u>. Life loss approaches 100% for the threatened population (Tpar) occupying buildings that are destroyed. Survival largely depends on chance havens (18:7).

In Automobiles

If a flood sweeps a passenger vehicle into water more than 4 ft deep, those inside the vehicle are virtually guaranteed to drown unless they are rescued while the vehicle is still floating (9.3, 17.4). There were no exceptions in the historical events that were examined. Consider the following obstacles: External water pressure makes it difficult or impossible to open a car door or a car window while underwater. If a window is opened or broken, the flow of water and confining nature of the vehicle make it very difficult to exit the vehicle until it is completely filled with water. By then, the occupants will be disoriented and nearly drowned. If someone escapes the vehicle, the turbulence of the water will make it extremely difficult to reach the surface. Throughout, the flood will be dark with sediment, making it nearly impossible to see once submerged. Combined, these factors make it extremely difficult for passengers of a vehicle to survive after being submerged.

The following are all contexts in which occupants of vehicles can die during a flood:

1. When a flood undermines a section of road or weakens a bridge, causing it to collapse as an unsuspecting motorist passes overhead. Similarly, the road can collapse at a distance too short for stopping (14).
2. When a motorist drives onto a flooded bridge or stretch of road before they see the danger. Drivers are most vulnerable to this at night during driving rain or fog (34.2).
3. When a section of roadway (perhaps across the dam crest) erodes away at a blind spot (due to darkness, mist, rain, a sharp corner, etc.) and motorists subsequently drive off the cliff and crash into the ground or stream (27.1).
4. When people attempt to drive out of a long canyon instead of climbing the hillside and the flood overtakes them (15).

5. When a road follows a stream and a wall of water catches motorists by surprise or travels faster than the vehicles (31.6).

6. When a road follows a stream and motorists become stalled in incipient flooding, remain with their vehicles too long, and are swept away as the flood rises or suddenly surges (1).

7. When a sudden surge of water sideswipes a vehicle on a dry or mildly flooded road or bridge (23.1, Nix Lake Dam failure).

8. When a motorist decides to cross a submerged river crossing or a flooded intersection near a canal, gully, or flooded drainage ditch, and the flood sweeps the vehicle into swifter and deeper water (8).

9. When an evacuee attempts to move a parked vehicle out of harms way and the flood rises too quickly (there have been many close calls of this nature in driveways).

10. When an expanse of city streets is inundated slowly or quickly (16.1, 25.2).

11. When a driver has a fatal accident while evacuating (we found no historical examples).

12. When an employee is driving on a dam while it fails, either to examine it or attempt repair work while driving heavy equipment (we found no deaths but, but several close calls).

See automobiles under the section on subPar type and evacuation modes for additional insights that pertain to motorists and their passengers.

In Trains

Depending on the depth of flooding and whether or not a train is moving, a train is most similar to either a mobile home (as was the case outside Johnstown when South Fork Dam failed in 1889) or an automobile, though in both cases a train is less buoyant. The impact of a crash can cause deaths even when people stay dry (19).

In Campgrounds

Campsites are often located near a river where valleys are steep and narrow so recreationists can readily be exposed to any combination of high velocities, great depths, and a wall of water (3). Survival largely depends on evacuating, climbing a tree, or reaching a sturdy outbuilding (3). Safe havens persist only if the flood does not topple the trees and buildings. If there is not time to climb a tree before the flood arrives, the flood must have sufficiently low velocities that someone can grab a tree while in motion without being torn away.

Unfortunately, campgrounds can be one of the most difficult areas to reach with an official warning (16.2). Many campsites are informal and isolated, away from established campgrounds; established campgrounds often have no telephone or ranger on-site; it may take a long time to drive to a campground; and campers are less likely to listen to mass media reports than those in residential areas or automobiles (16.2, 16.3).

While sensory clues often give a warning in the quiet of a campground (Little Deer Creek Dam, Utah, 1963), the warning may be very short if there is no wall of water to cause trees to crash (3). Even with a wall of water, if the flood travels quickly, is of great depth, or people are asleep, the average warning time (Wt_{avg}) may be less than the time needed to evacuate (16.2, 16.3, 31.4, 31.5). This said, there are two factors that make evacuation easier:

1. The representative evacuation time (Ret) is often quite short if the valley has steep hillsides—on the order of 0.25 – 2 minutes during the day and slightly longer at night.
2. Due to proximity, shouting can be readily heard, and so a warning can propagate very rapidly through a campground, even at night.

In Rivers (waders and swimmers)

Waders and swimmers are more vulnerable than recreationists on the bank are because their evacuation is slowed and they are more likely to be caught in deeper water without a refuge. Due to the popularity of tailwater fisheries below dams, it is dangerous when a gate fails, a gate is opened very quickly (2), or when water levels rise during hydropower peaking or startup. Few people wade or swim more than an hour after dark, so this type of subPar can be ignored at such times.

Along Shore (hikers and the curious)

Although there were no subPar in the data set consisting of hikers, reasoning suggests that this subPar would be nearly identical to campgrounds except for the following:

1. There is little chance of delivering an official warning, unless Wt is more than 2 – 3 hr.
2. Hikers may climb canyon walls or reach other places from which a rapid evacuation is impossible.
3. This subPar can be largely ignored more than an hour after dark.

There have been several examples of onlookers watching a flood who were subsequently trapped or killed (25.2, 29.18). This can be a form of convergence.

In Boats

Due to its density, a flood wave entering a lake will generally plunge toward the bottom, creating a powerful, choppy undertow near shore. By contrast, it may cause only a small swell at the surface more than a few hundred feet from shore. The exact dynamics depend on the depth, size, density, and orientation of the reservoir in relation to the incoming flood. Where the described pattern holds, boaters are likely to be capsized and pulled underwater near the mouth of the river, but not greatly endangered elsewhere.

Boaters in a reservoir above a dam that fails are also in danger, especially if they are near the dam.

Regardless of their location, boaters increase their chances for survival dramatically when they wear life jackets (22.5).

In high velocities, boaters on a river risk capsizing or colliding with an object in a violent manner. A craft's high profile and streamlined shape can cause it to become airborne in ways that are less likely among those riding rooftops or logs. Consider the following eyewitness account (16.1):

> There was [this] boat [that] came down the creek with three or four people in it, moving at a tremendous speed, totally out of control and about the time it got to where the water fountain was, the boat shot 30 or 40 feet straight in the air. This was the last time we saw the boat or the people. (Natural Disaster Institute, 1976, p. 371)

As with hikers, this subPar would be very difficult to warn. The evacuation rate would almost always be longer than for any other recreational category. Fortunately, this subPar is not likely to exist when a single dam fails by overtopping as the result of a flood, since boating is uncommon during extreme weather. Sunny-day dam failures would, however, pose a particular risk to boaters. The popularity of guided fishing trips, river rafting, kayaking, and personal drift boats has increased dramatically over time. Many rivers experience boats year round. As such, this type of subPar may become more relevant to future failures than to historic ones.

In the Cold

During failures in the western world, where flooding usually passes within 5 minutes to 3 hr and people reach shelter within 0.25 – 8 hr, deaths attributed solely to exposure are rare, but they have happened (6.1, 18). However, it would be difficult for researchers to distinguish deaths due to drowning and deaths due to hypothermia when both sets of bodies are found in the flood and detailed causes of death are not listed. In theory, if a flood were at extreme winter temperatures, one might expect those unable to escape the water and find warmth to become unconscious or perish within 5 – 20 minutes. For some, the immediate shock would make breathing difficult and drowning much more likely.

Lethality Rate Inside Safe Havens (Ls, Pt, Ptpar$_i$)

Since most safe havens are found in buildings, this discussion is limited to that context.

In Buildings with Minor Damage (Ls = L)

Life-loss rates are essentially zero when loss of shelter (Ls) = low (L). Death can result when the first floor is flooded to the ceiling, but regardless of the structural damages, such cases should be considered major damage in light of the loss of shelter.

When buildings experience minor damage, debris and high velocities do not endanger the occupants. Generally, a safe haven remains on the ground floor. If depths are shallow, the flood has little lethal potential. If depths exceed 4 or 5 ft, the water must have low velocities to avoid causing major damage. In such situations, deaths are quite rare. They result when someone is trapped on the ground floor and the water rises to the ceiling or when a child who cannot swim falls off a bed or other perch while no adult is in the room. Those who have limited mobility usually survive if someone is present to balance them on a floating mattress or other elevated surface. Even when a safe haven is lost and water comes within a foot of the ceiling, the water is sufficiently quiescent to allow most people to survive by treading water or by standing on furniture. As such, deaths are usually caused by limited mobility, an inability to swim, or other anomalies like electrocution.

Death by exposure, disease, or starvation is possible if the flood traps people for prolonged periods or the flood contaminates food and water supplies in less developed regions. Such was the case when the Banqiao and Shimantan Dam failures stranded people for many days amid very expansive flooding, although these deaths were excluded to make the subPar more pertinent to the west (10).

In Buildings with Major Damage (Ls = M)

The most consistent factor governing the death rate among occupants of buildings is whether or not there is a safe haven on the highest floor. This follows from the historic pattern that very few people die in safe havens and most people die when exposed to the full force of the flood (see the section on lethality rates outside of safe havens).

When a building has one or more upper stories and major damages are limited to the lower stories, those in the upper stories remain dry or experience the flood as if it causes only minor damage. When velocities are not high enough to sweep people out of a room, 3 – 4 ft of flooding above the highest floor produces a death rate comparable to that in buildings with only minor damage. This rate is usually zero, except in anomalous cases, such as when young children are trapped alone in a room and one or more falls into the water off a floating bed.

If velocities are low, people can survive even when flooding is nearly two-stories deep by staying near a second-story ceiling for air, either by treading water or by standing on furniture (18.9, 18.10). Such flooding exceeds the cut off for a safe haven, but it is still more sheltered and much safer than the open current.

A wooden house will most likely float away before the water reaches the second-story ceiling, maintaining a pseudo-safe haven until the building sinks or is torn apart. When houses have more than one story, the bedrooms are usually on the upper floors. This can significantly reduce life loss at night when a flood may fill the lower floor before the occupants are aware of the danger (18).

Lethality Rate Outside of the Flood Zone (Ft, Schvq)

Deaths outside of the flood zone fall into five categories:

1. Those who are injured in the flood, but who wash to shore while still alive and die within hours or days from inhaling water and mud, exposure, internal bleeding, or other traumatic injuries (6.1, 17.6), or appear to have injuries from which they can recover, but die days later from a brain hemorrhage or other complication of an injury (17.3).
2. Those who die of a heart attack, stroke, or other complication brought on by fear for one's personal safety.
3. Those who die of a heart attack, stroke, or other complication shortly after learning that their loved ones have perished (17).
4. Those who commit suicide during or after the flood (Teton Dam, 1976).
5. Those who lose the will to live and rapidly deteriorate or die in their sleep within a few days, weeks, months, or years (17).

The percentages of deaths in categories 2 and 3 are small to the point of being negligible, especially since deaths of this nature are most likely when a large number of people die in a flood from other causes. Heart attacks while drowning or being swept downstream would be difficult to identify and should be considered general drowning deaths.

Note that many of these deaths are omitted from the official lists of flood-related fatalities. In some cases the individuals may not have been a part of Par or the surrounding community.

Life-saving Interventions (Rr, Sh, Ch, Psh, Ptpar$_i$)

For many, rescuers must reach them by helicopter, crane, or other extraordinary means within minutes if they are to be saved. Consider the helplessness of an eyewitness firefighter (16.1):

> The water was chest high and the front of the truck was floating from time to time. From the rear of the fire truck we could see with the aid of large spotlights . . . ; people were clinging to anything that would float. Roofs and walls from damaged homes all had people clinging to them, floating refrigerators, cars and propane tanks. People were hanging in trees, the roar of the water was terrible and the sounds of screams [for] help were even louder than that. People floated by just out of reach and we couldn't get to them . . . . The screams died down as people fell from the trees and rooftops and were swept away. (Natural Disaster Institute, 1976, p. 30)

The floods with the greatest life loss have generally claimed their victims before professional rescuers were able to arrive. The task of the professionals was to search for the dead and injured after the flood had receded.

When people can reach treetops, housetops that are not moving, or islands, hundreds or thousands of people can be rescued by helicopter or boat over several hours, but in such cases most of the individuals are not at high risk of drowning and could survive while waiting for the flood to pass (9).

People have rescued flood victims by forming human chains to reach stranded motorists, waders, or those already adrift; by pulling a drifting swimmer through a second-story window; or by holding them on a floating mattress while waiting for the water to subside inside a building. Overall, however, the most common rescues have involved those who risk their lives to provide early warnings or to assist weaker individuals to shore while it is still possible to wade.

When a flood passes quickly, lives can sometimes be saved by digging victims out of the mud and by rushing those with serious injuries to nearby hospitals (17, 32). Since such quick floods are uncommon, however, those in the most danger are least likely to be rescued because they are swept out of reach or they are submerged. Thus, often those who are rescued could have survived had they not been rescued, or if they had been rescued after the flood had passed, and the rate of life loss is reduced less than (number rescued)/$Tpar_i$.

As a sidebar related to the relative ineffectiveness of modern rescue resources at reducing life loss, one should not assume that modernity in general necessarily decreases fatalities during flooding. Consider that automobiles do not necessarily enhance survival, for the following reasons:

1. Horses and buggies could transport people quite quickly.
2. A horse can be a superior means of evacuation to a car since it is not dependent on roads and can run up steep hillsides.
3. Historic evacuees were less likely to get stuck in traffic gridlock.
4. It is the modern addiction to automobiles that often leads to fatalities. A high percentage of deaths during flash floods accrue to motorists who voluntarily try to cross flooded roadways or bridges. During the Big Thompson flash flood, those at greatest risk were those who attempted to drive out of the canyon, and those least at risk were those who chose to climb the canyon walls on foot (Gruntfest, 1977).

Other considerations include the following: In narrow floods, the fastest way to evacuate is on foot. It can even be quickest for those with limited mobility, since family or neighbors are usually willing to assist them. Even in wide floods, evacuation on foot can be fairly rapid. The average adult walks 3 miles per hour and can jog much faster. A healthy adult empowered with adrenaline should be able to clear even a very wide floodplain in 30 or 40 minutes. Finally, evacuation warnings do not necessarily propagate more rapidly today. People were more familiar with their neighbors in the past and shouting readily penetrated into poorly insulated buildings.

There are, however, modern advantages: Warnings can be delivered via loudspeakers on police cars or helicopters. Modern rescue equipment, especially helicopters and trucks with cranes, provide distinct advantages. Modern building codes preserve havens more readily. Wireless communication has the potential to facilitate warnings even when wired systems are destroyed, although cellular phone systems can quickly become overwhelmed during emergencies. Detailed census and GIS databases and trends toward registration at campgrounds and wilderness areas may improve our ability to warn and to identify missing persons.

Overall, increased casualty rates prior to the modern era can probably be attributed to these main causes:

1. The 100-year floodplains were often developed.
2. High hazard dams were more likely to fail.
3. Warning time was often less due to limitations in monitoring and detection systems, and limitations in communication pathways over long distances.
4. Dam owners were reluctant to issue timely warnings.
5. Mass communication was not possible.

It follows that older cases of dam failure can be studied alongside modern cases, so long as these difference are kept in mind.

Complications or Aberrations
(Ml, Ac, Td, Ts)

What follows is a list of historic or readily conceivable complications that could be repeated in future events to increase the likelihood of life loss:

1. As suggested in Chapter II, if an earthquake impacts a community as well as a dam, it can conceivably block evacuation routes, start fires, trap people in buildings, and disrupt communications before a flood arrives, all of which could increase life loss.

2. The nature and concentration of a debris load influences the likelihood that someone can drift to safety while avoiding being crushed or pierced. Examples of particularly lethal debris loads include 700,000 cords of logs from a paper mill (6) and miles of barbed wire.

3. An irony of floods is that they sometimes start fires when lanterns are tipped, gas mains rupture, power lines break, transformers or electric substations explode, or furnaces are damaged. If floating debris such as a house catches fire, the fire can spread to other houses or to a debris dam. This greatly increases the danger to the occupants of the houses and to victims who are still alive but who have been swept to the debris dam (15, 16.1, 18.25; and South Fork Dam, in Johnstown, Pennsylvania, in 1889).

4. Although power companies typically shut off the power to flooded neighborhoods to protect victims and rescue workers, while broken wires are live they pose a threat of electrocution to waders or those who come in contact. Deaths of this nature are rare.

5. Lives can be lost in hospitals when flooding does not impact the patients or personnel directly if the flood prevents essential medical professionals from reaching the building or eliminates critical power sources. Natural gas lines and electric power lines are generally shut off to flooded regions to prevent leaks, fires, and electrocutions. Propane and gas tanks can readily float away. Combined, this can render both the main power and all backup generators inoperable. Such was the case in subPar 16:1, but there is no historical record of actual deaths due to this type of event in the sources examined.

6. Invalids are dependent on others for evacuation. When individual warning times (Wt_i) are short, increased life loss can result as more mobile individuals linger to try to help the less mobile evacuate (16.1).

7. Both summer and winter floods sweep snakes out of riverside haunts, adding them to the hazards in the water and leaving them behind in inhabited areas. This increases the likelihood of poisonous snakebites during and after the flood, although the frequency and fatality rate of such bites is still low (17, 22).

8. Apart from drowning, prolonged floods or floods in winter can cause fatal hypothermia (18.28), but deaths specifically identified as such have been rare.

9. Convergence deaths result when onlookers come to watch the flood and inadvertently become trapped and swept away (25.2).

10. Certain characteristics of floods can make an accurate accounting of the death toll difficult or impossible:

   a) Often, whole families perish together, sometimes with their neighbors, so no one remains who can identify them or tell how many people were in the home at the time of the flood.

   b) Floods can so mangle bodies as to make identification impossible.

   c) Floods can wash victims dozens of miles downstream or bury them in mud, making recovery difficult.

   d) It is difficult to dig for the dead using power equipment, since there is a reluctance to tear bodies apart.

   e) It is difficult to know how many tourists, transients, motorists, or visitors were in an area.

   f) When homes are destroyed, people can scatter all over the country to stay with relatives. This makes it difficult to equate a list of missing with people who died.

   g) Usually no records are kept of those who die weeks or months after the flood due to indirect causes.

   h) Death records can be county-specific with no master list.

   i) In many cases, companies and foreign governments have not been eager to fully account for the dead and missing due to issues of culpability and liability.

j) When a flood enters the center of a reservoir at an orthogonal angle, the dense, sediment-laden flow will sink, generating strong, spiraling currents near shore. This can create or enhance dangerous undertows many miles away that persist for some time. In this manner a flood can kill an unsuspecting swimmer the following day without being attributed to the flood (22.7).

Post-flood Psychological Trauma (Schvq)

When homes are obliterated, people die, and people are relocated, it destroys social networks and a highly valued sense of community and belonging. This can generate and prolong extreme and debilitating psychological scarring (17).

The trauma of a flood with large life loss includes seeing a large number of naked, muddied, and mutilated corpses, including friends and relatives. They are first seen floating by, sticking out of the mud, tangled in debris piles, or washed into homes. They are then viewed again as people search rows of bodies in temporary morgues, searching for familiar faces, hoping for the best and fearing the worst.

Traumatic symptoms include an irrational fear of storms, even when relocated far above a river; recurring nightmares; a desire to withdraw from social contact; an inability to return to work; lethargy; drug or alcohol abuse; suicidal tendencies; chronic depression and apathy; marital conflict or divorce, including blame for warning one set of relatives over another or failure to save a child; guilt for surviving when others died; guilt for failing to save others or viewing oneself as a coward; and early death after giving up the will to live (16.1, 17). Disillusionment and a sense of personal violation can also follow, as there is almost always widespread looting following a destructive flood (17).

The tendency of floods to kill people in clusters increases the emotional trauma and life-style disruptions. As an extreme example, only one woman survived from a family group of 55 (35). A strong faith in God, His sovereignty, and in heaven, can help people cope with the death of loved ones and move forward with healthy living patterns (26).

Applicability of Historic Events to Future Events: Logic Behind a Proposed Model

Logic Behind a Proposed Model

A flood is like a chemical element. While highly unique, each element is composed of a small set of subatomic particles that are indistinguishable from the basic building blocks of every other element. In isolation, the behavior of a single particle is impossible to predict: The behavior of electrons is governed by their own motion—constrained by preferences for certain energy levels and orbital configurations—and the random motion of other particles. However, while one cannot predict the behavior of any individual particle, elements behave predictably on a macroscale.

In the same way, every flood is startlingly unique, but by progressively breaking each Par down into more and more fundamental units, homogeneous base units can be defined that share remarkably similar traits. Similar to the random motion of electrons, the outcome for each base unit (a homogeneous group of one or more persons) depends on human motion and the random motion of the flood. While one cannot know the outcome of any one base unit, it is possible to describe its probability distribution. One can then sum across the base units using a Monte Carlo simulation or the statistical means, in conjunction with their deviations, to estimate the likelihood of various rates of life loss for a specific event.

Fundamental base units are homogeneous with respect to the larger environment, temporal considerations, and the hydraulic characteristics to which they are exposed. Delineating subPar according to Par type (Pt) neutralizes differences in the environment. Reducing like subPar to like threatened populations ($Tpar_i$) neutralizes temporal variations. Dividing each $Tpar_i$ into homogeneous bins based on degrees of exposure neutralizes hydraulic differences. Among buildings, this can be done by classifying $Tpar_i$ according to the loss of shelter (Ls). When Ls = major (M), $Tpar_i$ should be further distributed among flood zones [safe zone density (Szd), compromised zone density (Cozd), pseudo-chance zone density (Pczd), and chance zone density (Czd)]. Since some of these zones share the same homogeneous characteristics as when Ls = low (L) or Ls = high (H), they are truly base units.

Role of Historic Events

Historic events are used to determine the probability distributions for each type of fundamental base unit. Naturally, these distributions can be refined as more and more homogeneous subPar are analyzed.

Since fundamental base units are homogeneous with respect to the surrounding environment, temporal considerations, and the nature of the hydraulic exposure; it is not surprising that their distributions during 19th and 20th century floods appear comparable (26). This suggests two important insights. First, if modern rescue equipment is not immediately available, loss of shelter is based on historic reality rather than a uniform construction standard; modern dam safety standards are mute by assuming a failure; and the benefits of modern warning technologies and transportation systems are neutralized by focusing on threatened populations ($Tpar_i$) and actual excess evacuation times (E); life-loss patterns should be consistent across the centuries. Second, one can similarly mix ancient and modern failures when comparing the evacuation nonsuccess factor (Ef_i) = $Tpar_i/Par_i$ to E in one of three ways: 1) exclude expansive floods for which automobiles or horses provide a distinct advantage, 2) include only floods for which the average warning time (Wt_{avg}) is sufficiently short that only evacuation on foot is possible, or 3) adjust the representative evacuation time (Ret_i) to account for the forms of transportation that are/were available. One or more of these conditions is met for every event characterized in the unpublished working documents and summarized in Appendix C, so the current study can be used to predict future outcomes.

Since life-loss distributions can be expected to be consistent across time, they can be used to predict statistical life loss in dam safety risk assessment.

Limitations to Historic Events

While the death rate in a given level of hydraulic exposure is not likely to change across the centuries, several things are likely to change and must be explored separately from the current mix of events: 1) Since warning effectiveness (We) is improved with advancements in communication equipment, monitoring equipment, monitoring procedures, early warning systems, and emergency action plans, the warning time provided by the first official warning (Wt) will not produce a uniform value for the average warning time (Wt_{avg}) across the centuries. 2) Since building codes change with time and country, loss of shelter (Ls) is specific to the structures at a site. The likelihood that a flood will cause Ls = low (L), major (M), or high (H) can only be explored coarsely using the present database. 3) If one explores the detectability of a failure or the likelihood of a particular failure mode, the present database should be used with great caution since dam safety engineering is an evolving science.

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CHAPTER VII

GOALS FOR A MODEL AND EXPLORATORY DATA ANALYSIS

A Brief Review

It is useful to review the topics that have been covered in previous chapters. Chapters 1 and 7 present the nature of dam safety risk assessment, the important role life-loss estimates play within that field, theoretical considerations relevant to model development, and the difficulty of selecting an unbiased data set for regression analyses.

Chapter III presents every important, flood-related life-loss model that had been developed or proposed up to 1998. The chapter describes the contributions and shortcomings of each model in detail and concludes with a summary of essential model components and considerations for representing those components.

Until recently, the DeKay-McClelland regression equation DM-2d was the dominant life-loss equation in use. However, it has often been used in a manner inconsistent with its development and in violation of the assumptions that must be satisfied for its estimates to be considered reliable. Hence, Chapter IV explores this equation at length, raising important questions about its credibility and its usefulness.

Chapter V provides an extensive list of variables that pertain in some way to life loss associated with dam failures or catastrophic flood waves. Although many of these variables were identified in some form by previous researchers (see Table 3.11 in Chapter III), this is the first time that most of them have been given specific names, symbols, definitions, and categories by which they can be coded. Other variables, especially those that show the greatest promise for estimating life loss, have been defined for the first time. All the variables are summarized in easy-to-use reference guides in Appendix D.

Chapter VI provides the historical and theoretical foundations on which one or more new models can be developed. Table 6.1 details the ways in which people perish during floods and Table 6.2 details ways in which people survive floods. Table 6.3 then offers a way to break issues that affect the rate of life loss into 18 logical categories. The remainder of the chapter catalogues numerous historical insights that are useful for gaining a good understanding of the real-world dynamics within each category. These insights are supported by event characterizations fully recorded in unpublished working documents that underlie the examples and summaries in Appendix B and the master chart of characterized values in Appendix C; as well as by other failure events that have been studied but not yet characterized.

The final category in Chapter VI describes the relevance of historical research to predicting life loss in future or hypothetical events. This should be reviewed carefully, since it presents the logic behind a conceptual model proposed in a companion working document entitled, *Working Paper Draft Report: A Proposed Life-Loss Model Under Development*.

An Overview of the Problem

On the scale of large populations spread across the length and breadth of a flood, every catastrophic flood event is startlingly unique. When one considers that Chapter V and Appendix D present over 90 characterizing variables that affect life loss in interdependent ways, and that most of these variables can be described using four to six different ranks, up to 14 different categories, or any number of different quantitative values, it is difficult to conclude that any three or four variables can reasonably account for the variance in life loss across events. This is highlighted by the fact that Brown and Graham (1988) and DeKay and McClelland (1993b) both chose to omit certain cases as "outliers" even though those cases represent historical reality and not experimental error.

Moreover, given the relatively small number of available data points—one for each historical flood event—the statistical significance of a regression involving numerous variables is necessarily unsatisfactory. Even with only three independent variables, the very broad confidence limits displayed in Table 4.1 and Figures 4.1 – 4.4 illustrate this problem.

Generally, analysts have felt uneasy assuming that point estimates like warning time (Wt) and dichotomous forcefulness (Fd) could fully capture the uniqueness of a large, heterogeneous population. It is hard not to feel uneasy if the population at risk (Par) includes a small canyon community just below a dam, campgrounds along the river, popular fishing holes or reaches for rafting, bridges or stretches of highway that follow the river, a metropolitan community on the open plain, and perhaps a marina in the reservoir below. To reduce the level of cognitive dissonance, analysts have often attempted to select values for warning time (Wt_i) and dichotomous forcefulness (Fd_i) that are specific to more homogeneous subPar (Par_i) and then to apply equations on that basis. Unfortunately, as described in detail in Chapter IV, the more homogeneous Par or subPar become, the less they resemble the original data set, the more the nonlinear relationships distort the results, and the less credible the results become in many cases.

More fundamental than questions about statistical validity are questions about human confidence. Unless human decision-makers can have confidence in the reasonableness of an approach to life-loss estimation, the results of any dam safety risk assessment will be viewed as suspect. Indeed, in the absence of confidence, statistical risk assessments will be forgone altogether. Chapters 3 and 4 have raised some serious questions that should give any risk assessor pause before continuing with the current models, at least without making some attempt to factor in the wide uncertainty in predictions.

Goals for a Solution

Shortcomings in current models suggest traits that would be desirable for the next generation of models and the accompanying benefits of these traits:

1. A model should be intuitively transparent and logically satisfying to engender confidence in its use and acceptance of its results.
2. A model should be empirically tested or empirically grounded to validate its predictions.

3. A model should focus on homogeneous subPar or smaller units that maintain similar characteristics across events. There are at least four reasons for this. First, the use of subPar increases the number of data points in a data set. This in turn allows more variables to be considered in a model, primarily through the separation of data points into distinct bins. Second, life loss within homogeneous units is less dependent on the uniqueness of a given event than are global Par; homogeneous units should provide a more consistent basis for prediction and comparison across events. Third, by focusing on homogeneous subPar, events are broken down into their most basic, shared components. These components could then, theoretically, be recombined to represent events that are quite different on a macroscale. As such, a limited data set can be used to make predictions regarding hypothetical events that are unlike those in the data set. Fourth, as noted in Chapters 2 and 4, it is difficult to select a data set free from bias, especially when life loss (L) is nonlinear with respect to Par; however, by basing regression on homogeneous units, each equation or probability distribution becomes relatively free from bias. Moreover, events with greater life loss can still reveal the conditions (homogeneous units) under which life loss is expected to be small or zero.

4. A model should first reduce subpopulations at risk (Par_i) to threatened subpopulations ($Tpar_i$) before applying life-loss relationships so that these relationships are independent of warning times. This allows one to eliminate warning time (Wt) from a regression equation and to apply life-loss functions derived from events with an average warning time (Wt_{avg}) approximately equal to zero or known values for the threatened subpopulation ($Tpar_i$) to events with different warning times.

5. Ideally, to reduce variance based on levels of exposure, members of a threatened subpopulation ($Tpar_i$) should first be distributed among approximately homogeneous flood zones before applying life-loss functions. These flood zones are aptly called homogeneous units.

6. A model should rely on a variable like excess evacuation time (E) that describes the interaction between warning time and evacuation time, rather than one in isolation from the other.

7. In its simplest form, excess evacuation time (E) = the average warning time (Wt_{avg}) – the representative evacuation time (Ret). Wt_{avg} is estimated subjectively based on historic descriptions. It accounts for the source of warnings (human and environmental), the time remaining before flood arrival, and the fraction of a population that gets warned. It produces an average value, considering both representative values [sensory clues (Sc), time of day (Td), time of week (Tw), time of season (Ts)] and point estimates [detectability (Det), warning time (Wt), warning time for evacuation (Wt_e), individual warning time (Wt_i)].

8. Although the average warning time (Wt_{avg}) has been assigned a single value for each historic subPar in Appendix C, the value of Wt_{avg} will likely be known with less precision when attempting to predict its value for a hypothetical, future event. To capture this uncertainty, it is desirable to express Wt_{avg} as an estimated probability distribution, specific to the event under consideration.

9. The representative evacuation time (Ret) is a subjective estimate based on historic accounts of individual evacuation times under various conditions and logical assumptions about the rate at which people can move in an emergency. As such, Ret considers important psychological variables (the urgency of individual warnings, prior flood experience, the tendency of a message

to cause or prevent panic), important physical limitations (the mobility of a population, physical barriers like streams and fences, the distance to safety, the available modes of transportation), whether families are together and their general preparedness to evacuate [preparedness (Pr), time of day (Td), time of week (Tw)], climatic hindrances [time of season (Ts), attendant circumstances (Ac), magnitude of local loading (Ml)], and the nature of the population under consideration [Par type (Pt)]. Like the average warning time (Wt_{avg}), the representative evacuation time (Ret) can be expressed as an event-specific probability distribution.

10. Whether warning time is described as a point estimate like Wt or an average value like Wt_{avg}, it transcends a single event only when related to the width of the floodplain, the mobility of the occupants, the urgency of the warning, the time of day or night, and other factors that affect the amount of time required to successfully complete an evacuation. The excess evacuation time (E) captures this interplay. Also, by quantifying E based on subjective, logical, and empirical factors, E is able to represent a complex function of dozens of other variables that could not readily be analyzed using traditional statistical methods without an extensive data set. To explicitly capture the uncertainty there is in knowing the true value of E before an event occurs, it can be expressed as an event-specific probability distribution to reflect the distributions of average warning time ($Wt_{avg)}$ and representative evacuation time (Ret).

11. A model should be linear with respect to the population at risk (Par) so that differences in the proportion of lives lost do not vary with size but with the value of the variables that characterize each homogeneous unit. In that way, the model can be applied to any size Par or to any size subPar (Par_i) without skewing the estimated life loss. Analysts who assess the same hypothetical event should obtain similar estimates, regardless of how they divide Par into subPar. The model would also make comparisons between dams in a portfolio more reliable. To assist in this process, explicit guidelines should be prepared for model users.

12. A model should use average values for homogeneous subPar—preferably probability distributions of average values for homogeneous subPar—rather than point estimates for heterogeneous Par. Average values, while harder to quantify, more closely represent the experience of each individual. This is more closely assured when subPar are relatively homogeneous with respect to the characterizing variable under consideration. Conversely, point estimates, like warning time (Wt), maximum depth (D), and peak velocity (V), do not necessarily represent more than a tiny fraction of a subPar, making comparisons across events problematic.

13. One should be able to upgrade a model by refining past event characterizations, by completing new event characterizations, or by performing experiments to improve estimated distributions.

14. A model should either be simple to use or have the potential to be automated so that results can be produced in an efficient and cost-effective manner.

15. A model should be versatile, able to produce a quick estimate for preliminary analyses or a refined estimate for more detailed analyses. It should also be able to yield the expected life loss (an estimate of the mean) or a range of possible lives lost in the form of a probability distribution.

16. A proposed model may be under development and thus depend on distributions or data that are not adequately known at this time, but only if there is some reasonable hope of estimating the needed information in the near future.

Important Empirical Distributions, Exploratory Data Analysis, and Potential Trends

Introductory comments

Appendix C presents a table containing dozens of characterized variables for 179 subPar and 163 non-overlapping subPar. To date, only the first stages of analysis have been possible. As new data points are added to the data set, ever-richer avenues can be explored.

A caution should be noted, however. From the perspective of life-loss dynamics in flood zones, every subPar is independent of every other subPar once they are reduced to the threatened subpopulations ($Tpar_i$) and fully characterized. That is, life loss is person-specific and location-specific and not event-specific. Other variables, however, are event-specific [i.e., time of day (Td), failure mode (Fm), height of the reservoir pool at failure (Hp), dam type (Dt), M, etc.] and can appear to have statistical significance if some events are broken down into more subPar than other events. The current data set includes 38 events, but some events like Dale Dyke (56 subPar), Mill River (19 subPar), and Buffalo Creek (16 subPar) dominate. The reason for this dominance is because these floods passed through many communities and sources recounted the events on a personalized scale that made it possible to identify both subPar and threatened subpopulations ($Tpar_i$). Fortunately, all of these events included subPar with loss of shelter (Ls) = L, Ls = M, and Ls = H, so this greatly reduced event-specific biases.

For now, four tracks have been explored: 1) temporal relationships that provide a reasonable estimate of the evacuation nonsuccess factor ($Ef_i = Tpar_i/Par_i$); 2) probability distributions of the proportion of the threatened population that dies ($Ptpar_i$) based on subPar that are homogeneous with respect to loss of shelter (Ls); 3) exploration of variables that, in isolation, might skew the proportion of the threatened population that perishes ($Ptpar_i$) toward the upper tail, lower tail, or central portions of distributions specific to levels of loss of shelter (Ls); and 4) probability distributions for flood zones. In a sense, the third track was an early attempt to reduce Ls to flood zones without defining flood zones directly or determining their densities.

An Expert System

The companion report, *A Working Paper Draft Report: A Proposed Life-Loss Model Under Development*, describes a detailed conceptual model that relies, in part, on the data analyses that follow in the remainder of this chapter. Apart from that conceptual model, the subPar characterized in unpublished working documents form a database that can inform an expert system. Given an expert system, the analyst can then select whatever criterion or criteria he or she feels is most important for a particular subPar. For example, in the Vaiont failure, the depth of the 325-ft flood was critical; in the Arás Alluvial Fan flash flood, the velocity of the 3-ft flood was critical, in combination with high levels of exposure; and in the failure of the Banqiao and Shimantan Dams, the sheer expanse of the flood and the poor quality of the peasants' shacks was critical. Responding with the number of subPar the analyst requests, the expert system would select the subPar that most closely matched the analyst's criteria, produce their names for reference, and produce customized life-loss distributions based on criteria selected by the analyst.

Analysis

Overview of the Data Set

Although there were 163 non-overlapping subPar in the data set from 38 separate flood events, threatened subpopulations ($Tpar_i$) could be accurately quantified for only a fraction of them. The reason is simple: the threatened population (Tpar) is seldom known or reported for historic floods. The exceptions are when $Wt_{avg} = 0$ and Tpar = Par, or when an author recounts a flood on a house-by-house basis.

Such floods are invaluable, not only because they portray the evacuation dynamics, the flood dynamics, and the life-loss dynamics in great detail, but also because they often can be broken down into subPar with known values for loss of shelter (Ls) and zone densities (Zd). In all, there were 92 subPar for which both Par_i and $Tpar_i$ could be quantified. There were 122 subPar for which loss of shelter (Ls) was known, but not all of these were homogeneous with respect to Ls. Among subPar with $Tpar_i > 0$, there were 38 subPar with Ls = H100%, 22 with Ls = M100%, and 19 with Ls = L100%. When these subPar were further divided into zones, it was possible to identify 45 isolated chance zones, three pseudo-chance zones, 11 compromised zones, and 47 safe zones.

Reducing Par_i to $Tpar_i$ (E vs. Ef)

It might prove useful in a model to estimate life loss based on the threatened population (Tpar or $Tpar_i$) rather than the population at risk (Par or Par_i). If Par_i can be reduced to $Tpar_i$, many aspects of warning time can be eliminated from subsequent consideration. An empirical relationship between the excess evacuation time (E) and the evacuation nonsuccess factor (Ef) provides a potential means of moving from Par_i to $Tpar_i$. This relationship is presented in Figure 7.1 and Figure 7.2.

Figure 7.1 illustrates the relationship between the evacuation nonsuccess factor (Ef) and excess evacuation time (E) derived for those characterizations in the working documents for which both the threatened subpopulation ($Tpar_i$) and Par_i were known. The uncertainty resulting from historic variability can be maintained by expressing the evacuation nonsuccess factor (Ef) as a probability distribution. Alternatively, one can draw a smooth S-curve through the figure and treat the evacuation nonsuccess factor (Ef) as a point estimate. The choice depends on whether life-loss functions are expressed as mean values or as distributions.

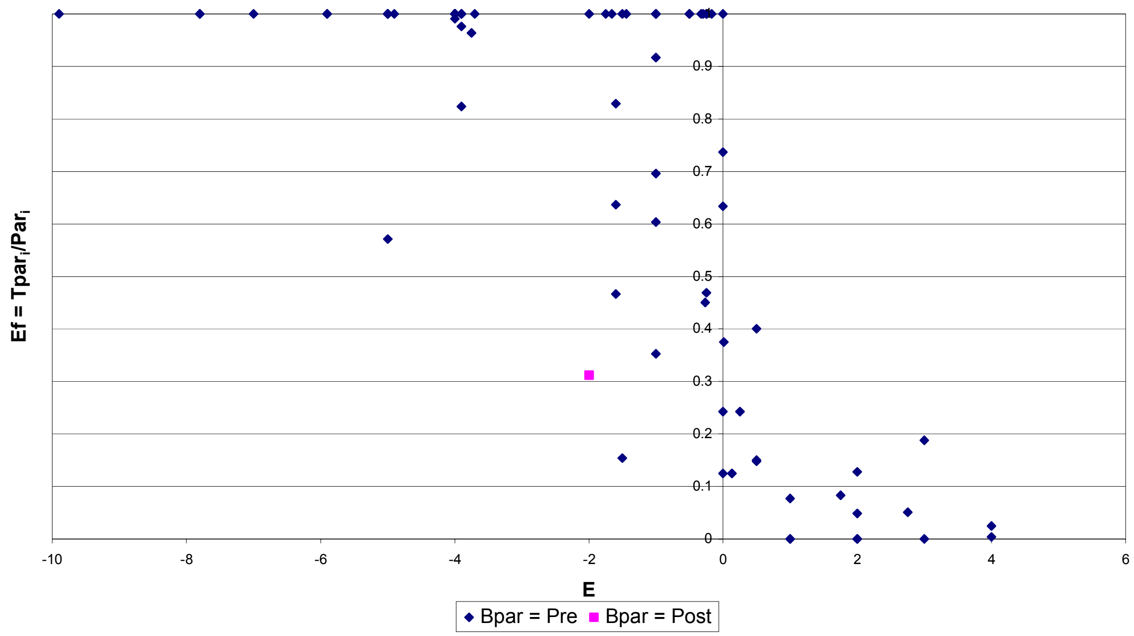

Figure 7.1. The evacuation nonsuccess factor (Ef) vs. the excess evacuation time (E) when E is close to zero.

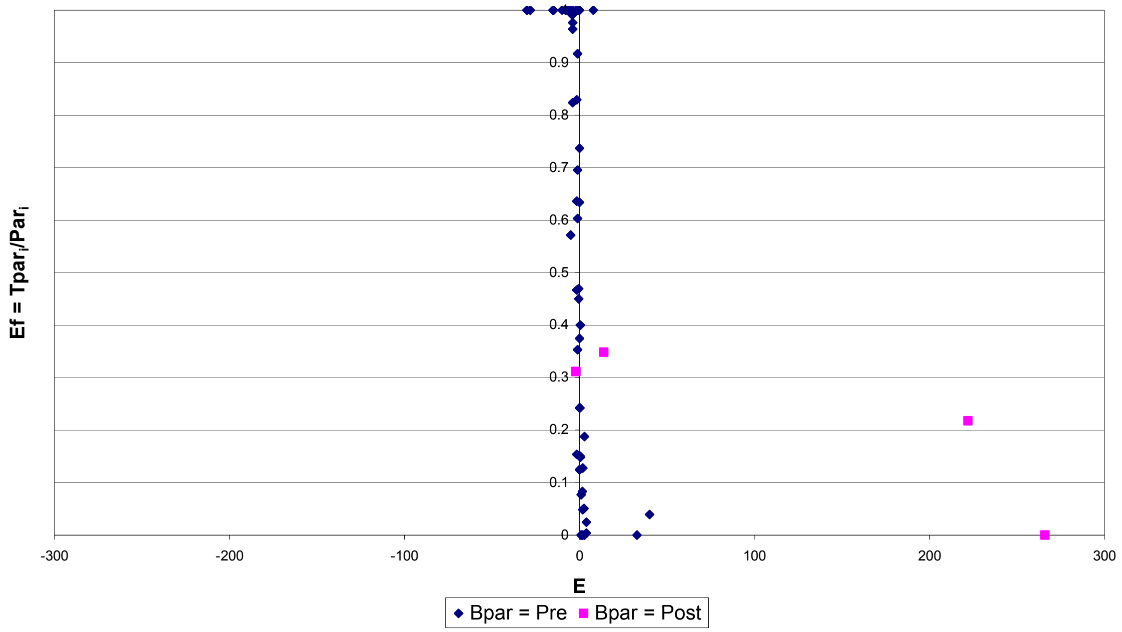

Figure 7.2. The evacuation nonsuccess factor vs. the excess evacuation time (E) when the basis of par (Bpar) is pre-evacuation (Pre) and post-evacuation (Post).

The first figure indicates that three out of the five largest values of E occurred because an official warning was delivered before the dams failed. In two of these three cases, the evacuation nonsuccess factor (Ef) was substantially higher than one would expect from the general trend in the graph (more visible in Figure 7.1). To these could be added subPar 35.5, the shore side communities around Vaiont Lake. Those people had more than a day's warning and were forcibly evacuated by the police—in some cases twice—yet 158 people ($Ef \approx 0.15$) evaded evacuation and died. That data point reflects a value for E of –5 minutes and an Ef value of 1.0 because Par was quantified based on those who evaded evacuation. The significance of these three events is that warnings prior to failure often carry less urgency or credibility than warnings during or after failure, and should not be treated in the same way. Additional evidence comes from events that could not be included in the figure. For example, warnings were disseminated from many sources, official and unofficial, up and down the Buffalo Creek Valley hours before the dams failed. Despite these efforts, the warnings were generally disregarded due to the history of false alarms in the region. Deaths occurred for about 12 miles.

Figure 7.1 narrows the scale to show the large number of E-values close to zero. The fact that most E-values were close to zero is a byproduct of several factors: 1) The most common type of flood event that leads to many fatalities is one with short warnings in a steep, narrow valley and total destruction of buildings, 2) events through long, narrow valleys are most readily broken up into many subPar, and 3) writers are more likely to chronicle an event on a house-by-house basis—helpful in quantifying threatened subpopulations ($Tpar_i$)—when communities are small and sequential than when they are large and dispersed.

Although it is not immediately apparent, a close comparison between Figure 7.1, Figure 7.2, and Appendix C will reveal that negative E-values continue out to -30 minutes and beyond with no departure from evacuation nonsuccess factor (Ef) = 1.0. There were no historical examples of $Tpar_i < Par_i$ when $E < -5$ minutes. Values of $E < -10$ minutes reflect expansive, urban neighborhoods or island communities with little or no warning time. As such, this graph represents all types of communities, large and small, canyon and plain, when the average warning time (Wt_{avg}) is short; and should accurately reflect the pattern of activity within the final, urgent minutes before the arrival of any catastrophic flood. It fits especially well for those who live within 1,000 ft of the hillside.

The strong and extended trend line at the evacuation nonsuccess factor (Ef) = 1.0 shows that it would be unrealistic to expect any evacuation of a homogeneous subPar when $E < -6$ minutes. However, most people can run far and fast when their life depends on it, so between $E = -4$ minutes and $E = +4$ minutes, Ef drops from about 0.98 to 0.02 in an S-pattern with an inflection point at $Ef = 0.5$ and y-intercept at 0.25. There is, of course, wide scatter around this trend line.

The right tail of the graph can be extended indirectly through events like Buffalo Creek that provide especially good studies in life loss with incremental increases in E. The subPar can not be used directly because the values for $Tpar_i$ are not known. However, every fatality was a member of $Tpar_i$ and the approximate value of $Tpar_i$ can be guessed via the life-loss distributions presented in Table 7.1 (illustrated graphically later in Figures 7.9 and 7.10). The results are displayed using new scales in Figure 7.3. The new data points were calculated by distributing life loss (L) within each subPar proportionately to the number of dwellings at each level of loss of shelter (Ls) within that subPar, then dividing each subdivision of life loss (L_{ij}) by the appropriate average proportion of lives lost recorded in the bottom row of Table 7.1. Potential threatened subpopulations ($Tpar_i$) among houses with Ls = L were neglected since they would have grossly distorted the results.

While it might be preferable to display confidence limits, it is gratifying to see that the general pattern produced is exactly what one would have expected. That is, the new data points fit well with the original pattern close to zero and they continue to approach zero asymptotically with time. Note that while most people evacuate within the first 5 – 10 excess minutes, even when the warning time exceeds the evacuation time by 40 and 55 minutes, there can still be stragglers that do not evacuate for one reason or another.

Table 7.1. Proportion of lives lost within threatened subpopulations ($Ptpar_i$) with homogeneous loss of shelter (Ls) when values were available

Homogeneous Loss of Shelter							
Ls = H100%				Ls = M100%		Ls = L100%	
1.00	1.00	0.93	0.57	0.88	0.020	0.013	0
1.00	1.00	0.93	0.50	0.80	0.013	0.0025	0
1.00	1.00	0.89	0.40	0.56	0	0.0016	0
1.00	1.00	0.86	0.38	0.50	0	0	0
1.00	0.99	0.84	0	0.43	0	0	0
1.00	0.99	0.83		0.43	0	0	0
1.00	0.98	0.80		0.33	0	0	0
1.00	0.98	0.78		0.28	0	0	0
1.00	0.98	0.71		0.13	0	0	0
1.00	0.97	0.66		0.037	0	0	
1.00	0.94	0.64		0.036	0		
Average = 0.857				Average = 0.202		Average = 0.000914	
H = 0.857				M/H = 0.236		L/H = 0.00107	

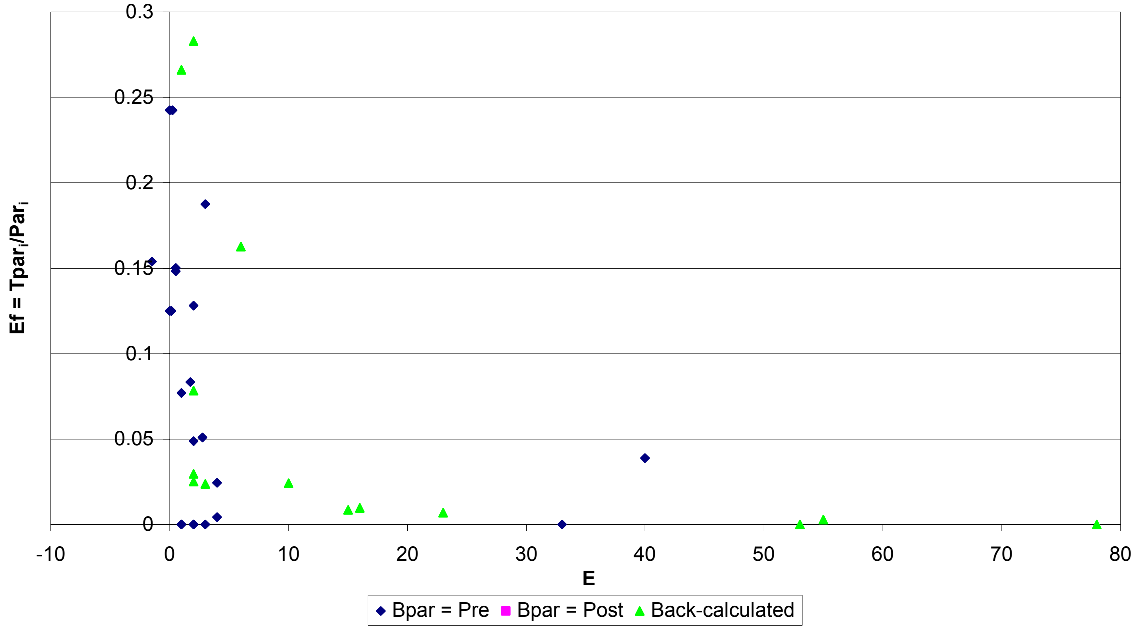

Figure 7.3. The evacuation nonsuccess factor (Ef) vs. the excess evacuation time (E), including points back-calculated from subdivisions of life loss (L_{ij}) and the average life loss for associated categories of loss of shelter (Ls).

There are two ways these figures might be used. One way would be to draw a smooth S-curve through the center of the data points and then to read point estimates off this curve. Another approach would be to sketch upper and lower bounds around the data points and then to determine the distribution of the evacuation nonsuccess factor (Ef) within small increments of excess warning time (E). The distributions can be produced directly using the data points in Appendix C of *Estimating Life Loss*. As a general trend, the skewness in this distribution shifts from positive to negative as E changes from negative to positive values. Any prediction of life loss that intends to capture real-world dynamics needs to incorporate this intrinsic variability.

Using E and Ret to Define SubPar

The excess evacuation time (E) depends on the value of the representative evacuation time (Ret) and the average warning time (Wt_{avg}): $E = Ret - Wt_{avg}$. If E is a useful variable for a potential life loss model, it follows that Ret is similarly important. Thus, Ret might prove one of many useful criteria by which Par could be divided into subPar—historically as well as predictively. Table 7.2 offers one set of criteria by which Ret might be used to designate subPar. The data in the table is not based on a detailed statistical analysis, but it is based on expert judgement after the author characterized the events and subPar in the unpublished working documents.

Reducing Par_i to $Tpar_i$ (shortcomings of Wt, Wt_{avg}, and Sc)

Warning time (Wt), average warning time (Wt_{avg}), and sensory clues (Sc) are much less useful than the excess evacuation time (E) in predicting the evacuation nonsuccess factor (Ef).

Table 7.2. Possible criteria by which changes in Ret_i indicate a region should be subdivided into two or more subPar

When $Wt_{avg} \le X$ and $Ret_i \le 150\%$ of Wt_{avg}, then when moving across Ret_i, if the smallest Ret_i differs from the largest Ret_i by 20% of X or more, a new Par_i begins. Use the smallest value of X, below, for which $Wt_{avg} \le X$.
X (minutes)
5
10
15
20
50
100
200
Any number > 200

Figure 7.4 shows a slight reduction in Ef as Wt increases beyond 45 minutes, but Figure 7.5 is essentially trendless when Wt is less than 15 minutes. Figure 7.4, does, however, reinforce the notion that pre-failure warnings are ineffective. The data point at the extreme upper right corner represents the communities around Vaiont Lake, discussed above. Overall, when Wt began prior to failure, less than 80% of the population evacuated in six out of seven cases. The triangles represent these same seven data points, only Wt is limited to the time subsequent to failure. Notice that under these constraints, the evacuation rates were in keeping with other events, suggesting Wt was not taken seriously until the dams actually failed.

The average warning time (Wt_{avg}) shows a stronger trend in Figure 7.6 and its corresponding close-up in Figure 7.7 than did Wt, while sensory clues (Sc) in Figure 7.8 shows simultaneous trends in opposite directions. Such illogical results are possible because, fundamentally, any measure of warning that is independent of the required evacuation

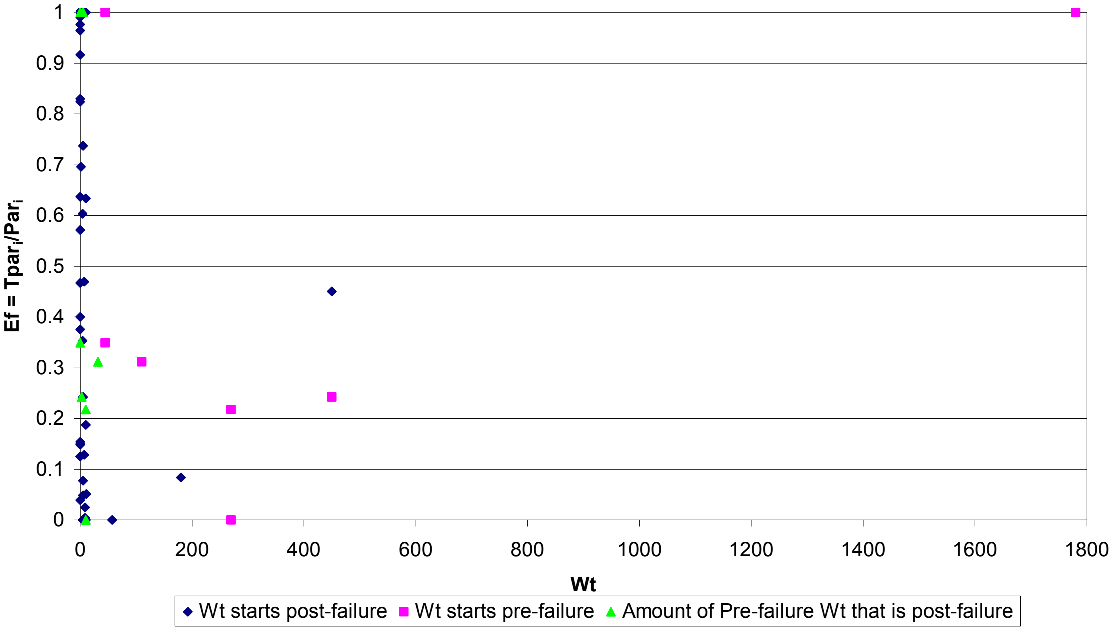

Figure 7.4 The evacuation nonsuccess factor (Ef) vs. the warning time (Wt) for the full data set.

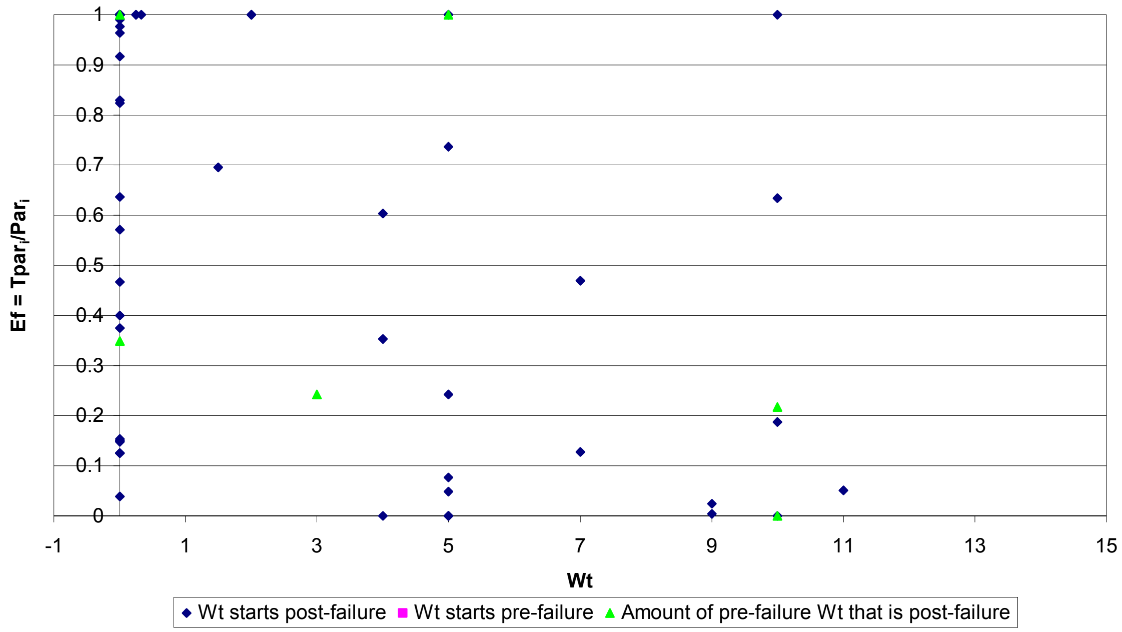

Figure 7.5. The evacuation nonsuccess factor (Ef) vs. the warning time (Wt) when Wt is short.

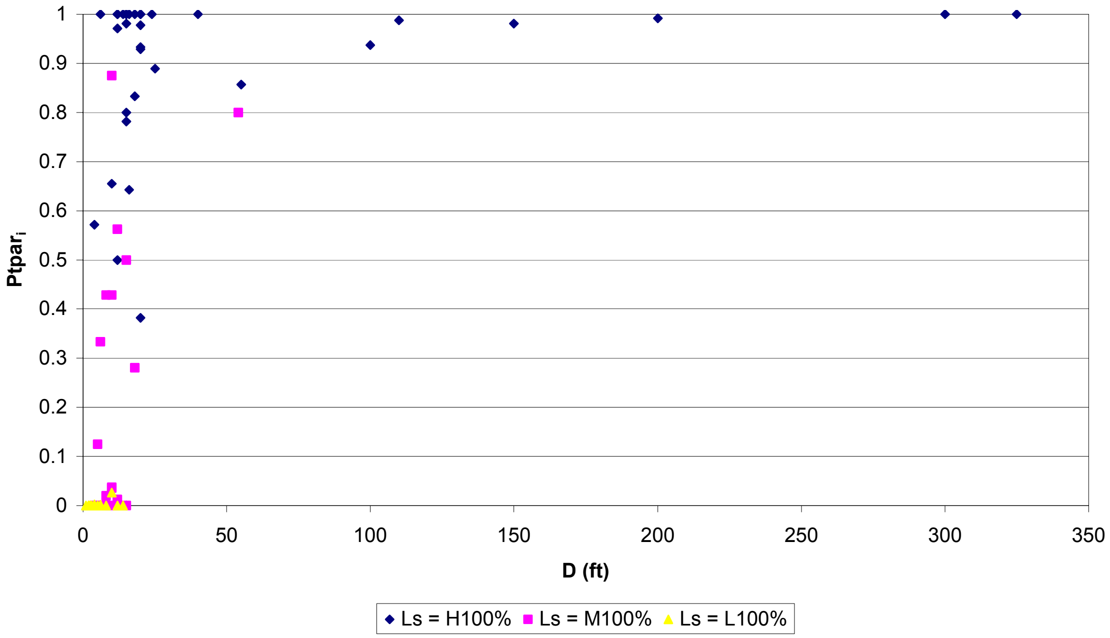

Figure 7.6. The evacuation nonsuccess factor (Ef) vs. the average individual warning time from any source (Wt_{avg}) for the full data set.

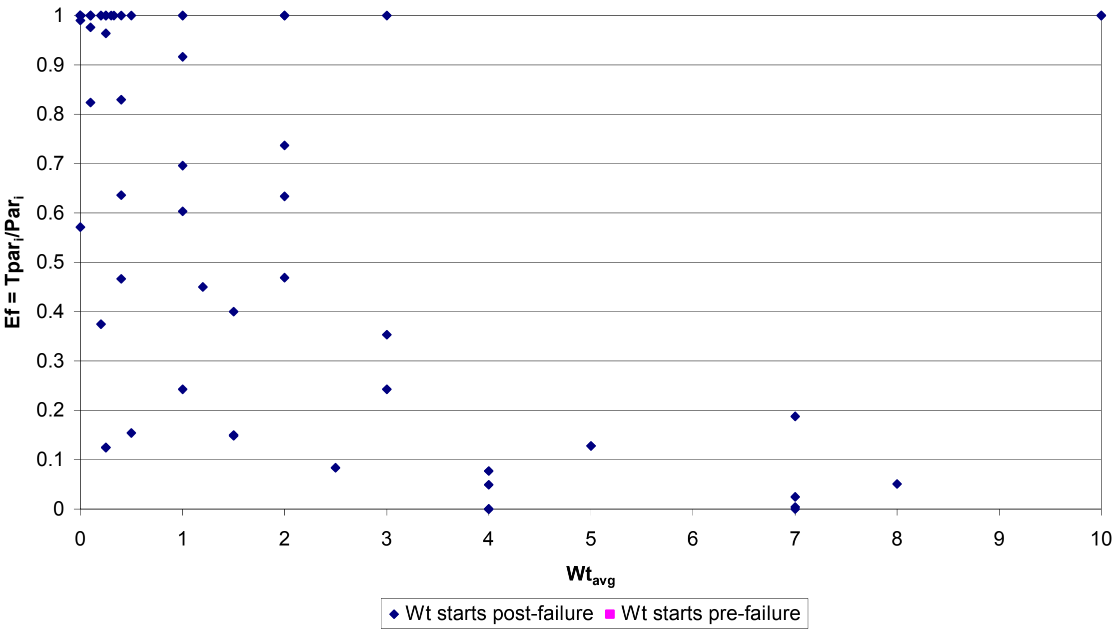

Figure 7.7. The evacuation nonsuccess factor (Ef) vs. the average individual warning time from any source (Wt_{avg}) when Wt_{avg} is short.

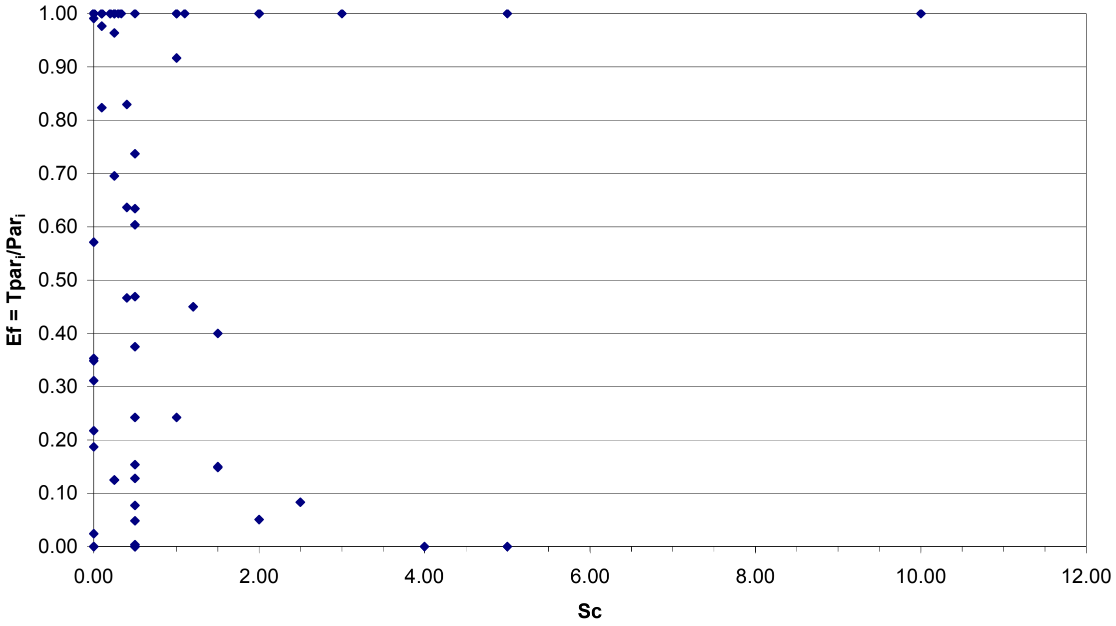

Figure 7.8. The evacuation nonsuccess factor (Ef) vs. the average warning time provided by sensory clues (Sc) for the full data set.

time is only half of the puzzle. In and of themselves, warning times mumble when they try to declare who can and who cannot escape the flood zone.

Applying Loss Functions to Homogeneous Units Based on Ls

Conceptually, if one could reduce subPar (Par_i) to threatened subpopulations ($Tpar_i$), it would be desirable to be able to predict the extent of the threat each member of $Tpar_i$ faced—that is, their likelihood of perishing. One possible way to distinguish various levels of threat is to identify flood conditions that define hierarchical zones of life-loss. An early effort to do this focused on grouping uniform housing damages under one of three levels of loss of shelter (Ls): Ls = H100%, Ls = M100%, and Ls = L100%. Figures 7.9 – 7.11 present histograms of the proportion of lives lost for each $subPar_i$ that was completely homogeneous

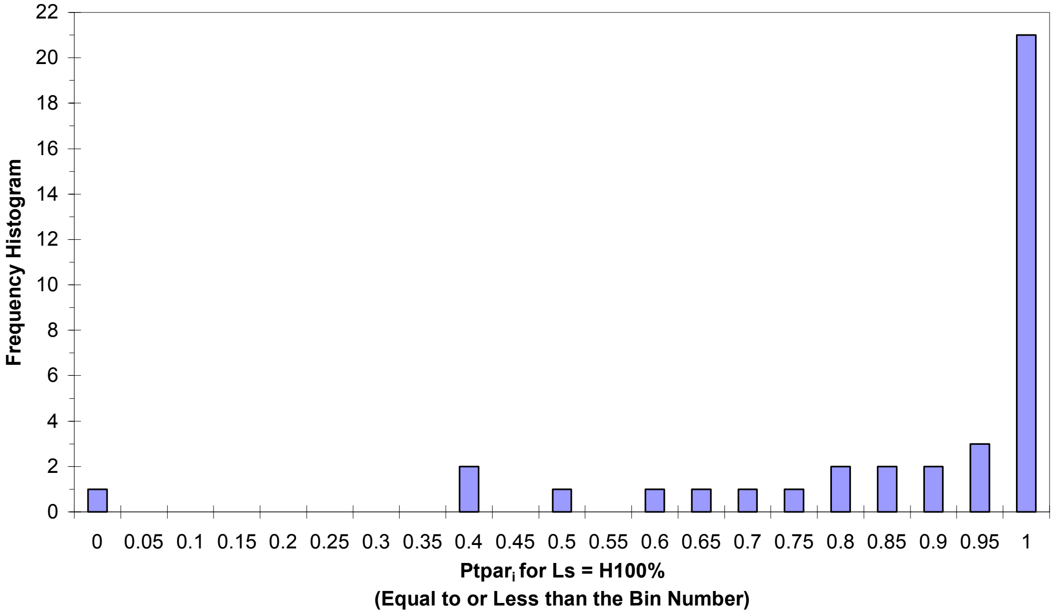

Figure 7.8. Histogram of the proportion of the threatened subpopulation that perishes ($Ptpar_i$) for loss of shelter (Ls) = H100%.

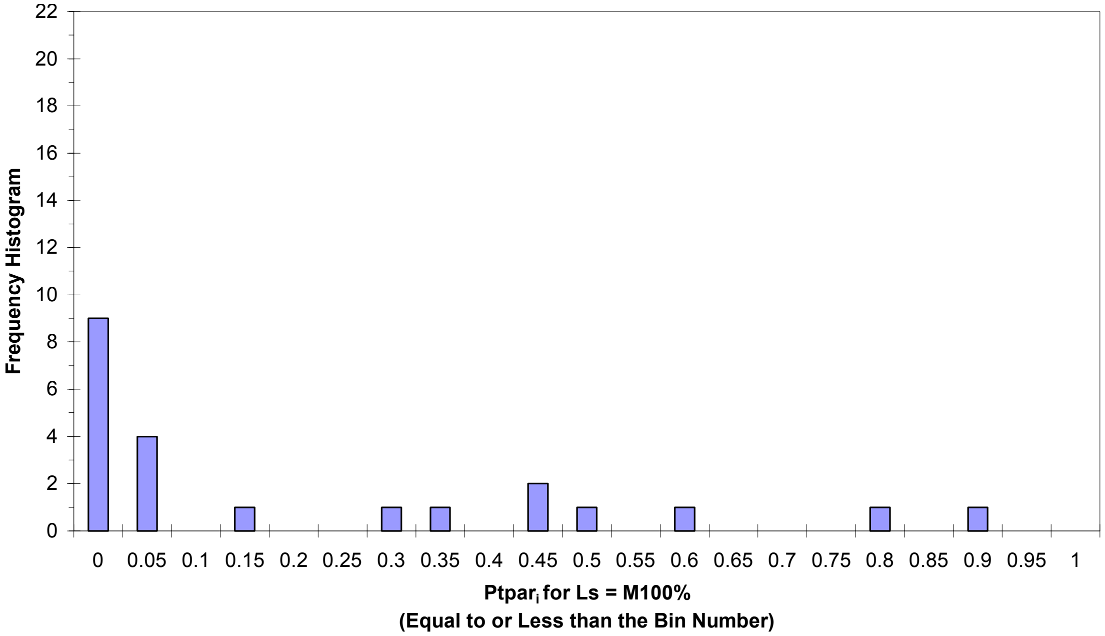

Figure 7.10. Histogram of the proportion of the threatened subpopulation that perishes (Ptpar$_i$) for loss of shelter (Ls) = M100%.

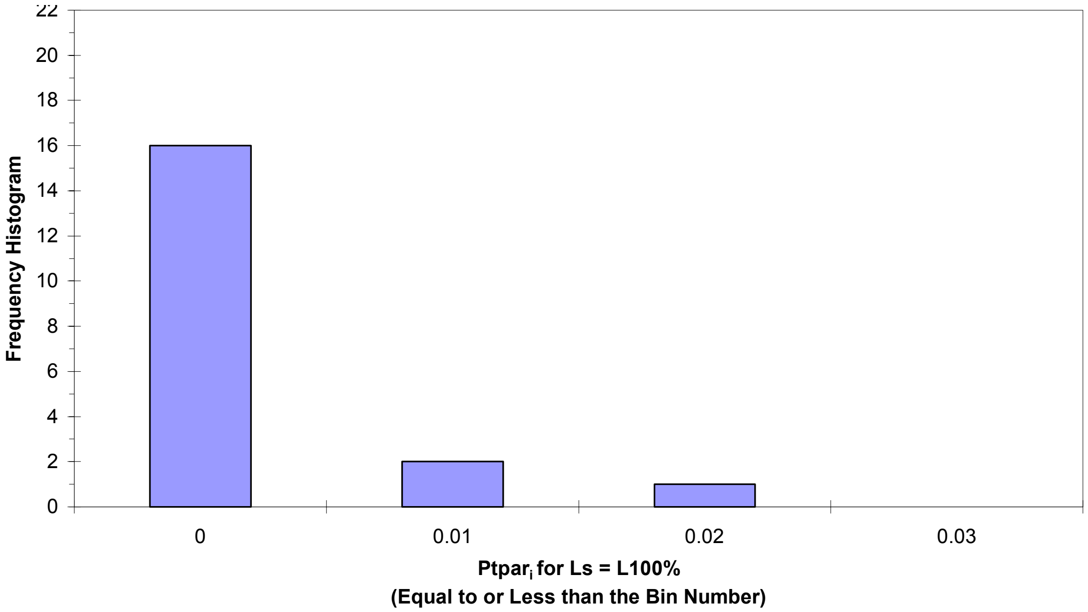

Figure 7.11. Histogram of the proportion of the threatened subpopulation that perishes (Ptpar$_i$) for loss of shelter (Ls) = L100%.

with respect to a category of loss of shelter (Ls). The underlying values can be found in Table 7.1 and in Appendix C.

Notice the strong trends when Ls = H and Ls = L. When Ls = H, the most likely value for the proportion of lives lost among Tpar_i (Ptpar_i) is 1.0, and the average death rate is 85.7%. When Ls = L, however, deaths are a rare exception, so one would generally expect zero deaths and, on average, only 1 out of 1,000 people left stranded in the flood zone would die (see the averages at the bottom of Table 7.1).

When Ls = M, the flood conditions could approximate Ls = L or Ls = H, depending on the height of the building and the nature of the damages. Not surprisingly, the proportion of the threatened population that dies (Ptpar_i) ranges across the spectrum when loss of shelter (Ls) falls between Ls = L and Ls = H. Losses appear to be clumped into three separate distributions. Most likely, the distribution near zero reflects cases for which upper stories or other safe havens provide flood conditions most similar to Ls = L. The distribution on the far right reflects tenuous conditions in which people are more likely to be submerged or swept away than to find adequate shelter. The distribution in the middle likely represents subPar with a range of major damages, some very severe and others rather mild, producing a mixed distribution.

Figure 7.12 ignores the frequency of occurrence within each Ptpar_i range, but it demonstrates the diversity of values and the overall spread. The plot is based on the weighted loss of shelter (Lsw), which is a weighted, linear combination of Ls-values for which the average Ptpar_i when Ls = H is the reference. The equation is shown at the bottom of the graph and it is explained in Chapter V. The importance of the graph is that life loss falls within the expected ranges for subPar with a mixture of Ls values: it increases as the weighted loss of shelter (Lsw) approaches loss of shelter (Ls) = H.

Refining Loss Functions with Predictive Variables

While these Ptpar_i distributions are satisfying, the wide range of possible values in Figures 7.9, 7.10, and 7.12 suggest that loss of shelter, alone, does not describe all of the variability in life loss. Does it make sense that life loss can range between 0% and 100% when loss of shelter (Ls) = H? Does Figure 7.10 represent three distributions or only one?

To try to narrow the range of each distribution that might apply in a given context, Ptpar_i was graphed against a number of possible predictive variables with the data points broken out separately for each category of loss of shelter (Ls) = X100%. The most likely candidates for predictors were various approaches to depth and velocity.

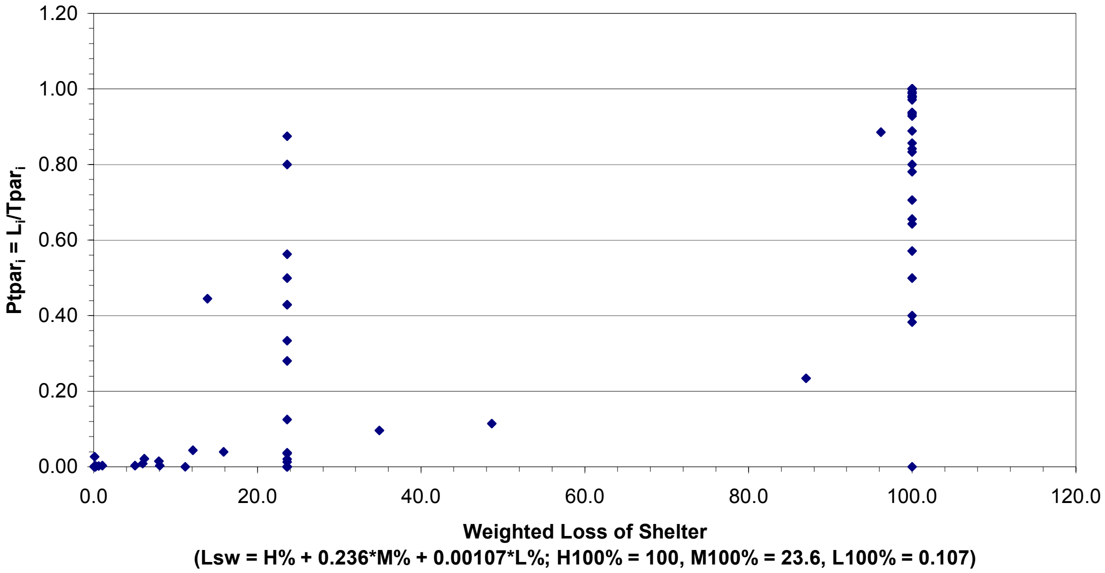

Figure 7.12. Scatter plot of the proportion of the threatened population that dies ($Ptpar_i$) vs. the weighted loss of shelter (Lsw).

Figure 7.13 shows the proportion of the threatened population that dies ($Ptpar_i$) vs. the maximum depth (D), with $Ptpar_i$ broken out by categories of loss of shelter (Ls). Figure 7.14 duplicates this graph when $D < 30$ ft. It is important to remember that D is a maximum value and not necessarily representative of a subPar as a whole. However, together, these figures suggest several valuable insights.

When $D > 100$ ft, one can reasonably expect Ls = H100% and $Ptpar_i$ will fall within that range of the Ls = 100% distribution for which $Ptpar_i > 0.94$. This roughly corresponds with the upper 40th percentile of the $Ptpar_i$ distribution.

Although the graph implies that when $D \leq 3$ ft one would expect only minor damages, this is not necessarily the case. For example, with $D \approx 3$ ft, velocities were sufficiently high across the Arás Alluvial Fan that had it been a neighborhood instead of a campground, damage would most likely have been major. The roads were washed away in places and erosion was pronounced. At 4 ft, the flood through Eldorado Canyon caused residential trailers to float and move into deeper water where they were destroyed. $Ptpar_i = 0.57$ instead of 1.0 for this data point because three people were able to reach shore before the trailers were swept away. At 6 ft of depth, frame houses below Lee Lake Dam were destroyed, killing those who could not evacuate.

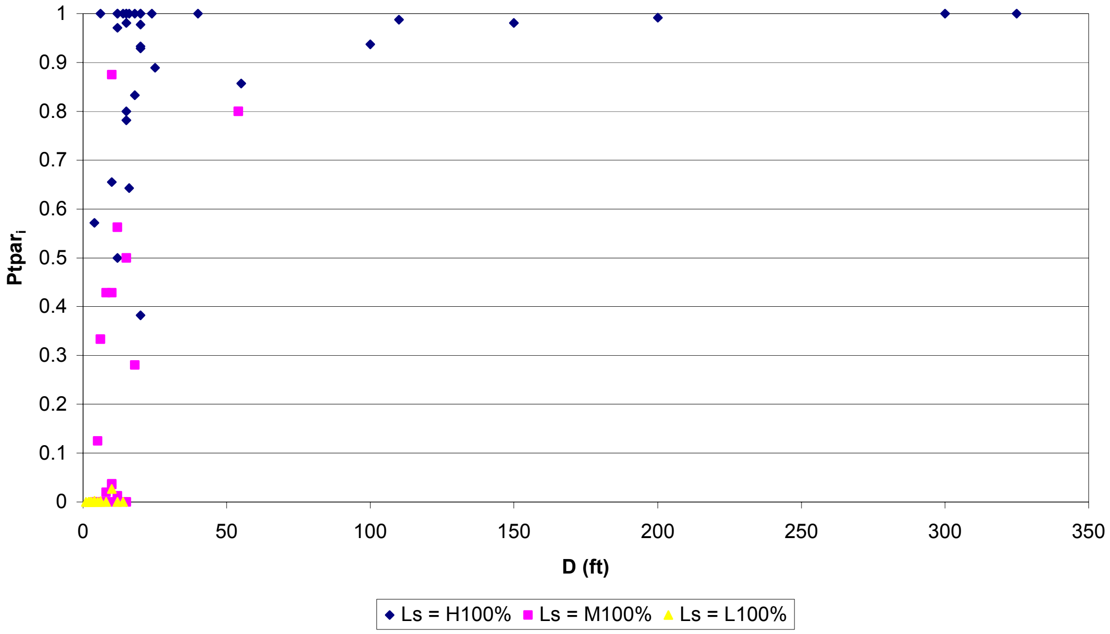

Figure 7.13. The proportion of the threatened subpopulation that perishes (Ptpar$_i$) vs. the peak depth (D) for the full data set.

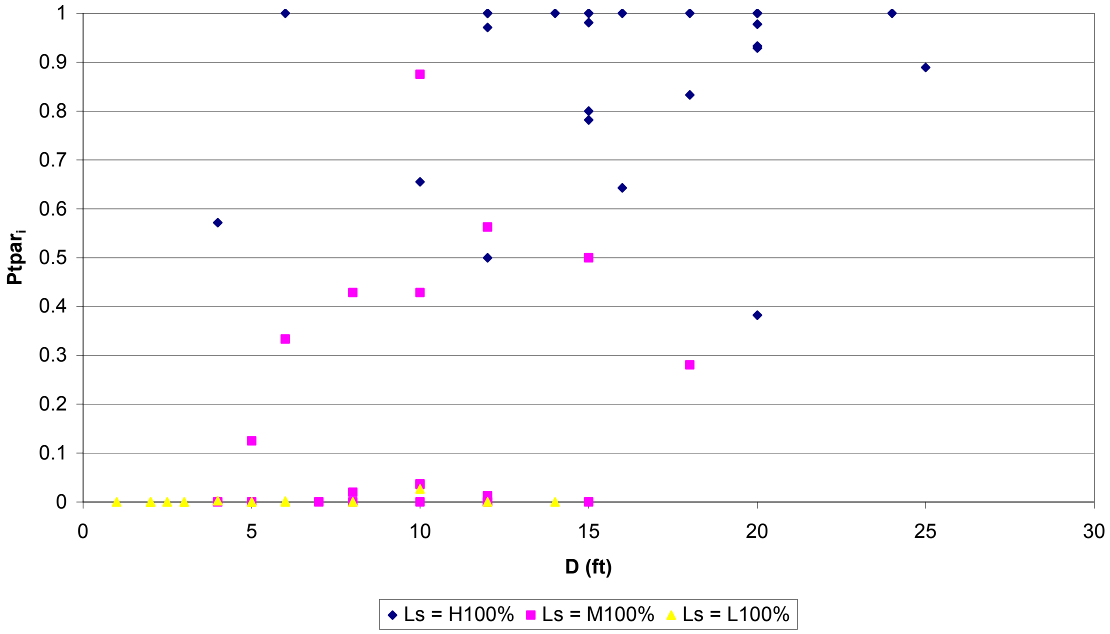

Figure 7.14. The proportion of the threatened subpopulation that perishes (Ptpar$_i$) vs. the peak depth (D) when D < 30 ft.

Taking each category of loss of shelter (Ls) in isolation, there are no clear trends when depth (D) < 30 ft that would allow one to focus on one part of a distribution of the proportion of the threatened population that dies ($Ptpar_i$) over another. More severe damage can be expected as D increases, but the graph does not provide a reliable distribution for prediction since damages are highly dependent on velocities. However, when $D \geq 20$ ft, Ls = H100% unless buildings are very tall and sturdy (such as some commercial structures) or some buildings are in water less than 20 ft deep.

Figure 7.15 is almost identical to Figure 7.14, except that the variable Wwr is used in place of depth. Wwr represents the height of a wall of water (Ww) or the comparable height of a fast-rising flood, taken as 0.8*D when the maximum rise rate (R) = V, 0.3*D when R = H, and 1 ft when R = L. These weightings are subjective, but they seek to capture the depths that are most likely to impact people if they are caught while evacuating. Since most events in the data set had walls of water, and since these walls were usually equivalent in height to the peak flood depth (D), little new information is provided. However, note that key data points for Ls = H100% and Ls = M100% are shifted toward smaller values, reinforcing the point made earlier that floods less than 4 ft in depth can still cause considerable damage and life loss if velocities are high.

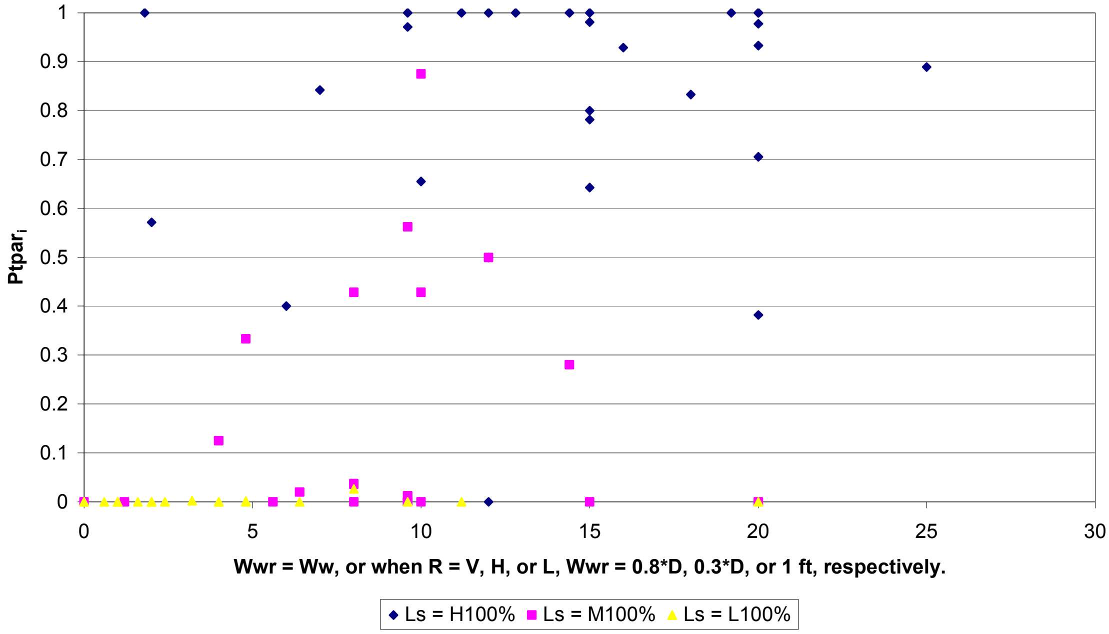

Figure 7.15. The proportion of the threatened subpopulation that perishes ($Ptpar_i$) vs. the height of a wall of water or the equivalent height of a rising flood (Wwr).

Figure 7.16 indicates the relationship between the proportion of the threatened population that dies ($Ptpar_i$) and peak velocity (V). As is true for depth (D), V is not necessarily representative of Par_i as a whole. When Ls = H100% or L100%, no apparent trends exist that would allow one to refine the $Ptpar_i$ distributions in Figures 7.9 and 7.11. It is possible to postulate that when V < 10 fps among buildings, $Ptpar_i$ will not exceed 0.15, but this should be verified through additional research and one would not expect this to hold true if buildings were submerged.

Theoretically maximum depth (D) and peak velocity (V) should have greater predictive potential when their separate influences are combined. Figures 7.17 and 7.18 explore this for the product of V*D, which, again, is not necessarily representative of Par_i as a whole. One can be reasonably confident that when D*V > 600 ft^2/s, a relatively homogeneous, residential subPar

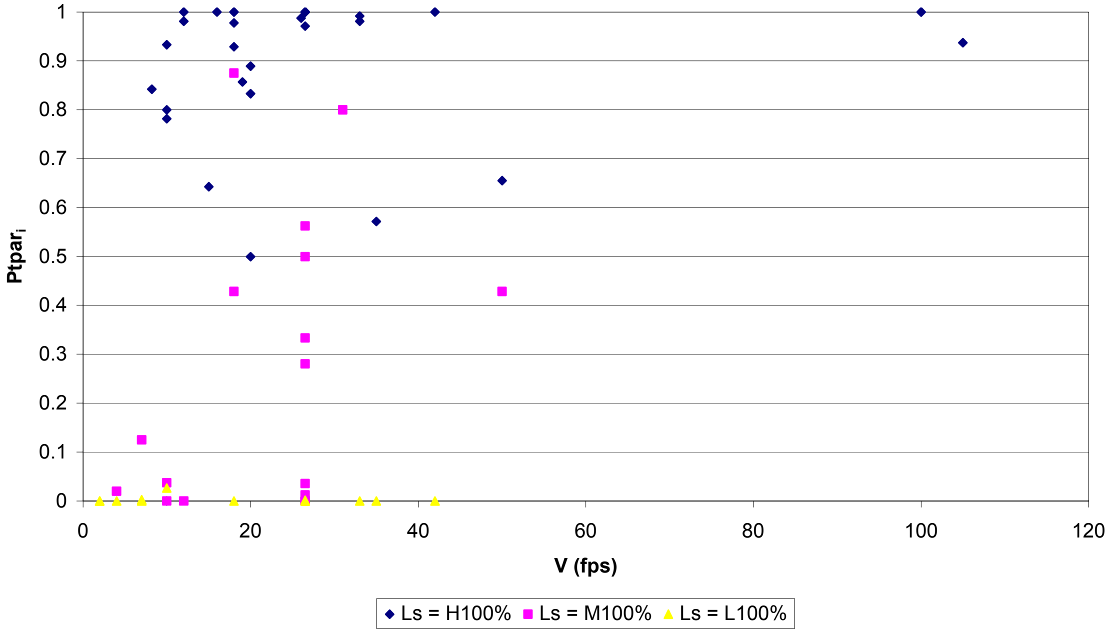

Figure 7.16. The proportion of the threatened subpopulation that perishes ($Ptpar_i$) vs. the peak velocity (V).

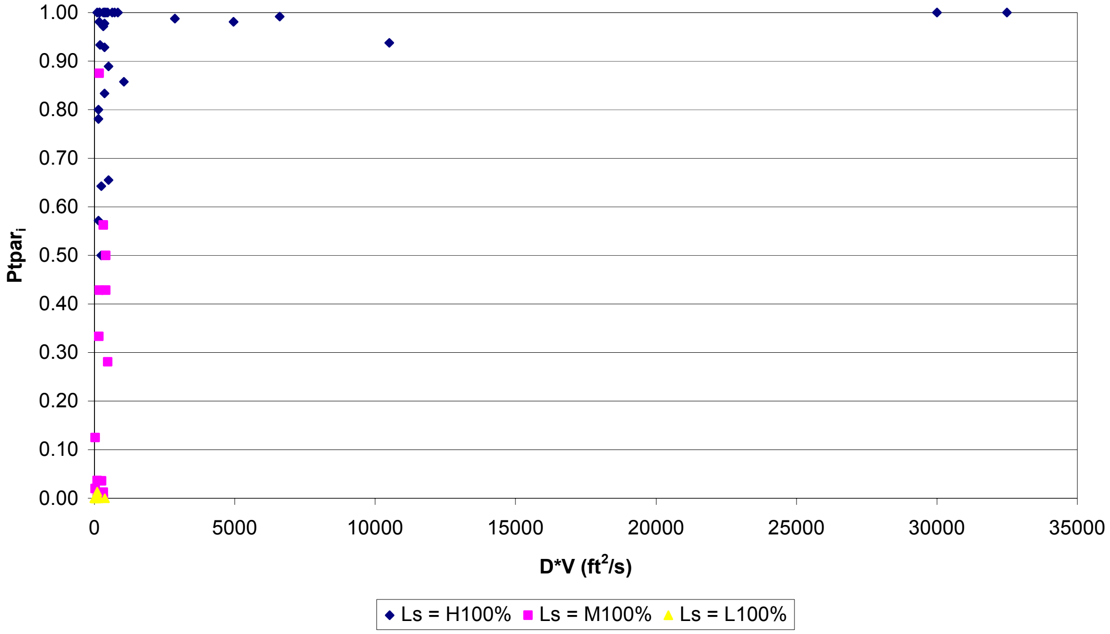

Figure 7.17. The proportion of the threatened subpopulation that perishes (Ptpar$_i$) vs. the product of peak depth and peak velocity (D*V).

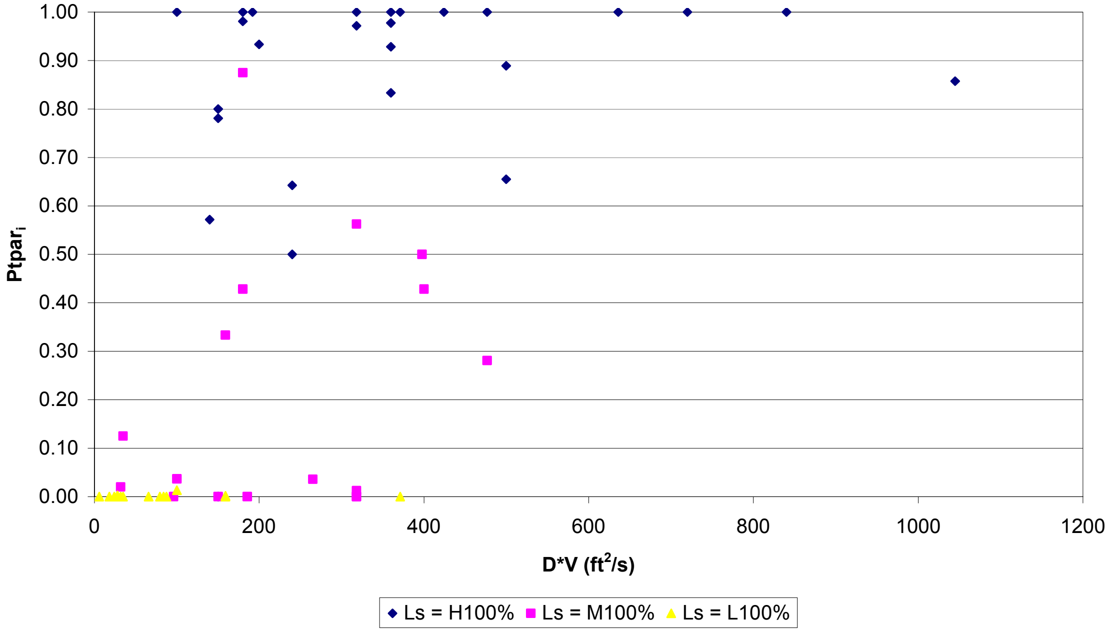

Figure 7.18. The proportion of the threatened subpopulation that perishes (Ptpar$_i$) vs. the product of peak depth and peak velocity (D*V) when D*V < 1,200.

will have Ls = H100% and $Ptpar_i > 0.8$. Above D*V = 2,500 ft^2/s, one would generally expect $Ptpar_i \geq 0.94$. At the other extreme, when D*V < 40 ft^2/s, one would most often expect $Ptpar_i < 0.15$, but this can be violated as suggested by a $Ptpar_i$ value of 1.0 when D*V = 50 ft^2/s. In between these extremes, D*V offers little help in distinguishing levels of damage or life loss. That is not to say that it is impossible to predict levels of damage in this range, but only that the point values peak depth (D) and peak velocity (V) offer little help without knowing what D and V are at each structure and the relative durability of the structures involved (whether structures are mobile homes, unbolted frame houses, bolted frame houses, brick houses, commercial structures, etc.).

The destructive velocity (Dv) seeks to represent an entire reach more uniformly than D*V since it relies on W and the peak volumetric flow rate (Qp). However, there is still the dilemma that Dv does not represent the fringes of a flood zone well or those segments of a reach wider or more narrow than W. For the most part, only the maximum width was available, so Figures 7.19 and 7.20 display only Dv_{min} (Dv is minimized when W is maximized). There are no apparent trends when Dv is small, but Ls = H appears to stop about Dv = 600 ft^2/s and Ls = M appears to stop about Dv = 1,000 ft^2/s in homogeneous, residential communities. Researchers would want to confirm this with additional data points, however. Beyond Dv = 1,000 ft^2/s, one would also expect $Ptpar_i$ to fall above 0.95.

Figure 7.21 explores the impact that day and night have on $Ptpar_i$. The data are inconclusive. Because time of day (Td) usually remains the same for every subPar associated with a given event, there is great potential to detect false trends. In particular, the Dale Dyke Dam failure occurred at night, as do many lethal flood events, so there are more subPar with Td = N than with Td = H or S. It should be noted, however, that Td is already incorporated into the model in that it profoundly affects excess evacuation time (E) by shortening the average warning time (Wt_{avg}) and lengthening the representative evacuation time (Ret). Once people are trapped in a flood, the effects of Td should be less pronounced.

In the same way, the general preparedness of people to evacuate prior to failure should influence the value of E through both Wt_{avg} and Ret, but it should have little bearing on life loss after the flood arrives. Figure 7.22 demonstrates no clear trend except that preparedness (Pr) tends to be low among events with life loss.

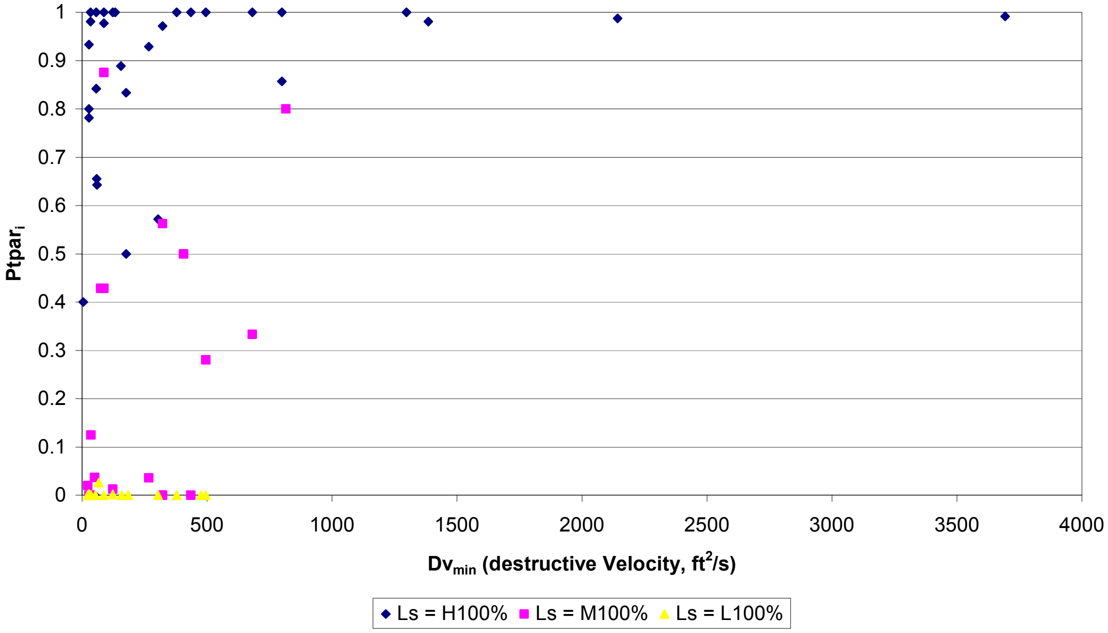

Figure 7.19. The proportion of the threatened subpopulation that perishes (Ptpar$_i$) vs. the destructive velocity (Dv), based on the maximum width (W$_{max}$) to produce Dv$_{min}$.

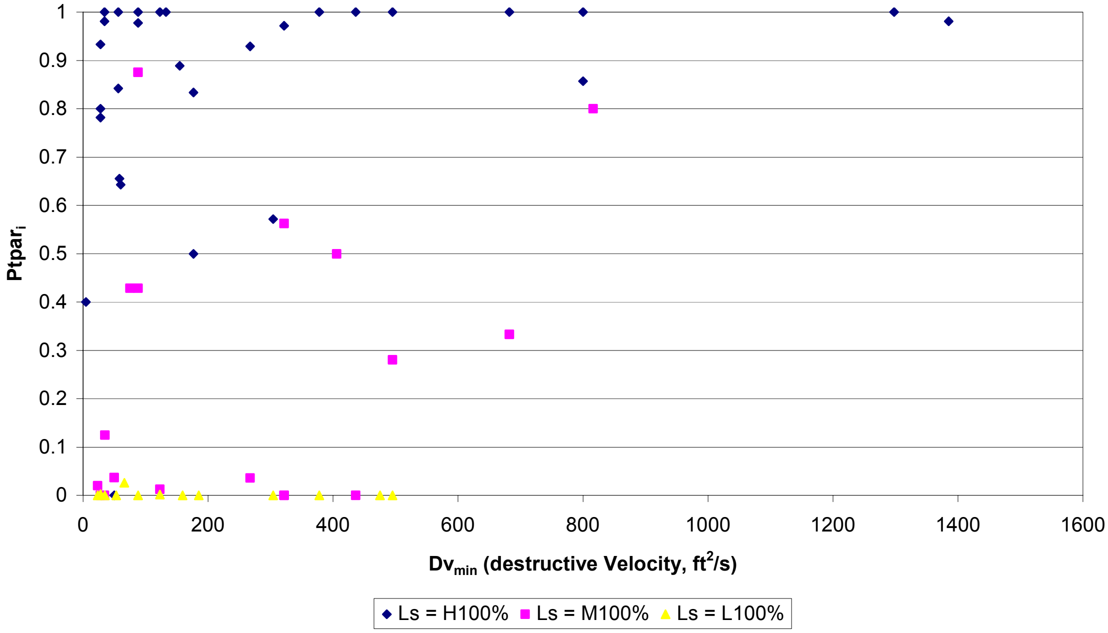

Figure 7.20. The proportion of the threatened subpopulation that perishes (Ptpar$_i$) vs. the destructive velocity (Dv), based on the maximum width (W$_{max}$) to produce Dv$_{min}$ when Dv$_{min}$ < 1,400 ft^2/s.

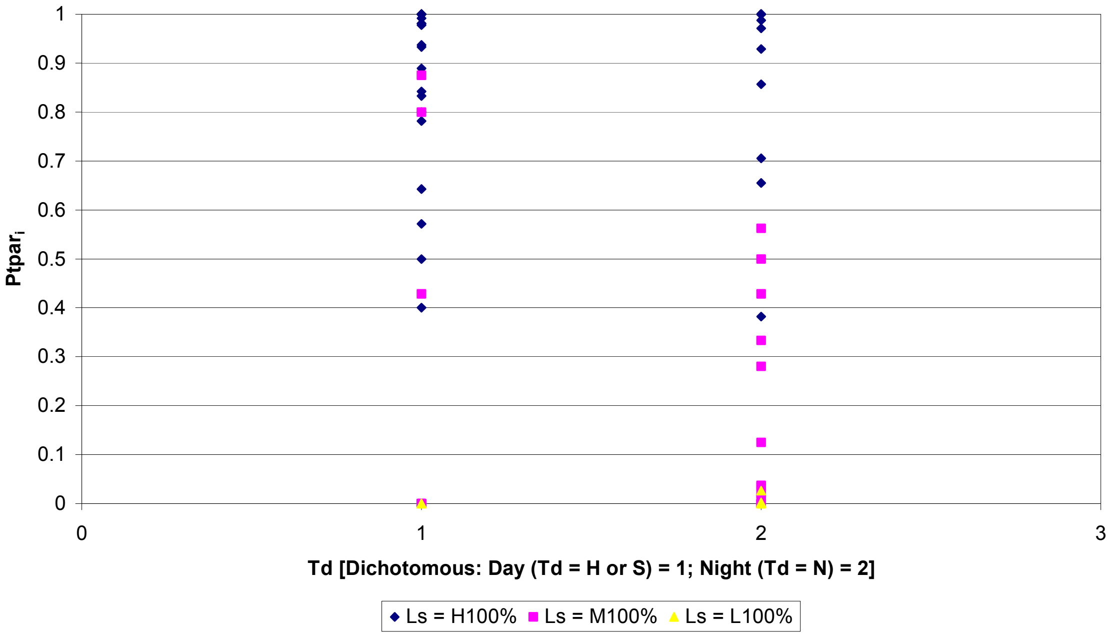

Figure 7.21. Range of the proportion of the threatened population that dies (Ptpar$_i$) for a dichotomous treatment of day and night (time of day, Td).

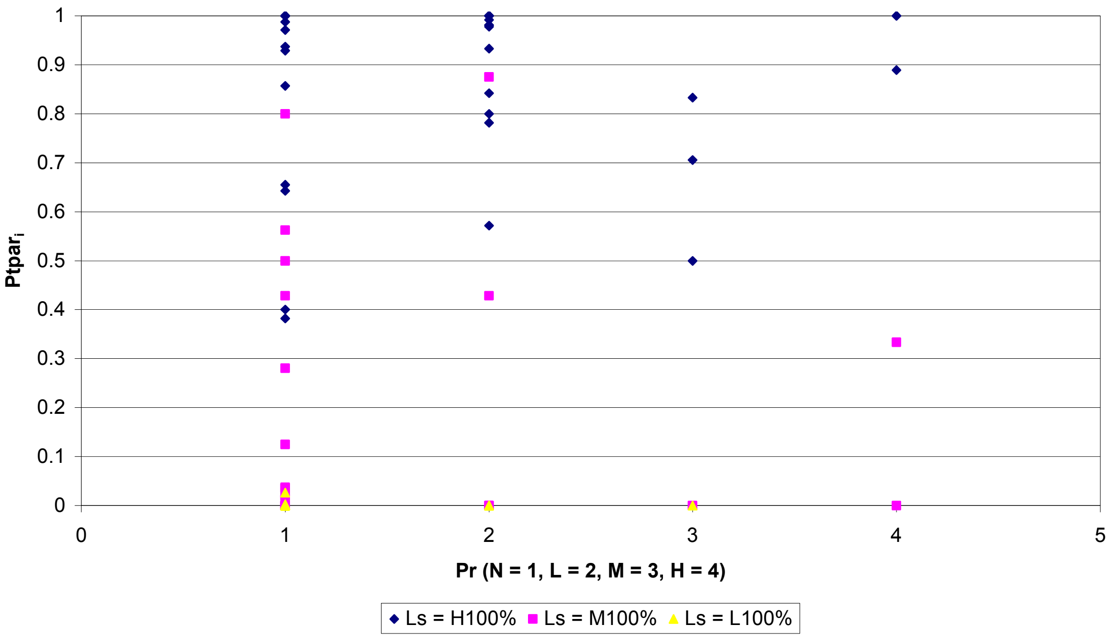

Figure 7.22. Range of the proportion of the threatened population that perishes (Ptpar$_i$) for a categorical treatment of people's preparedness to evacuate prior to failure (Pr).

As for both time of day (Td) and preparedness (Pr), the level of development (Dev) in a region suggests something about the rate at which a warning can propagate and the length of time it might take to evacuate (affecting E). Development (Dev) should only affect the proportion of the threatened population that dies ($Ptpar_i$), however, to the extent that it reflects the shape of the floodplain, the likely damages present, and the nature of chance havens (or lethal walls of housing debris). Thus, Figure 7.23 does not reveal reliable trends, but it does show that the data set is dominated by events in relatively narrow valleys as opposed to urban reaches. Only heavily urbanized areas, including tall buildings, qualify for development (Dev) = 4, and none of these were in the data set.

There is no obvious reason to expect excess evacuation time (E) to influence the proportion of the threatened population that dies ($Ptpar_i$) after the flood arrives, and Figure 7.24 shows no clear trends.

Figure 7.25 shows a trend opposite to what might be expected: $Ptpar_i$ is higher when adverse attendant circumstances (Ac) contributed essentially nothing to life loss (L_i) and lower when Ac had a profound effect on L_i. There may have been isolated cases in which Ac was coded inconsistently, but overall the graph simply reflects two facts: events with high rates of life loss are not dependent on Ac to kill people, and the data set was dominated by events for which life loss was largely independent of Ac.

The same can be said for rescue resources (Rr). Among the floods studied, most had low levels of rescue resources available in the first critical minutes when rescues are most likely to reduce life loss. Generally, advanced rescue resources can help only those who survive a flood's

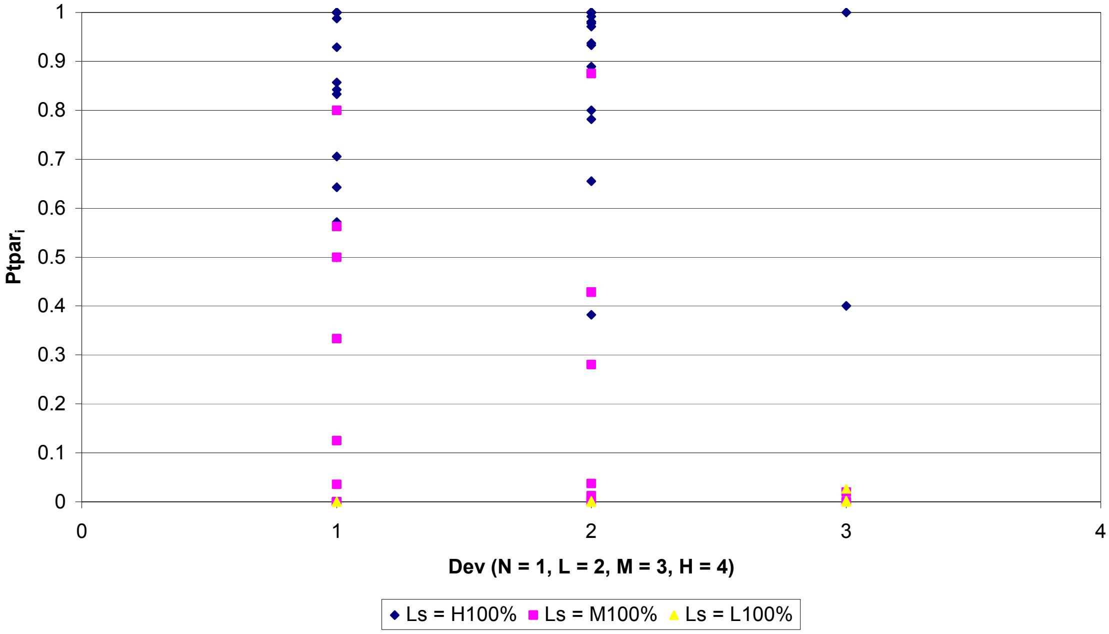

Figure 7.23. Range of the proportion of the threatened population that perishes ($Ptpar_i$) for a categorical treatment of the level of development (Dev) surrounding and including the subPar in question.

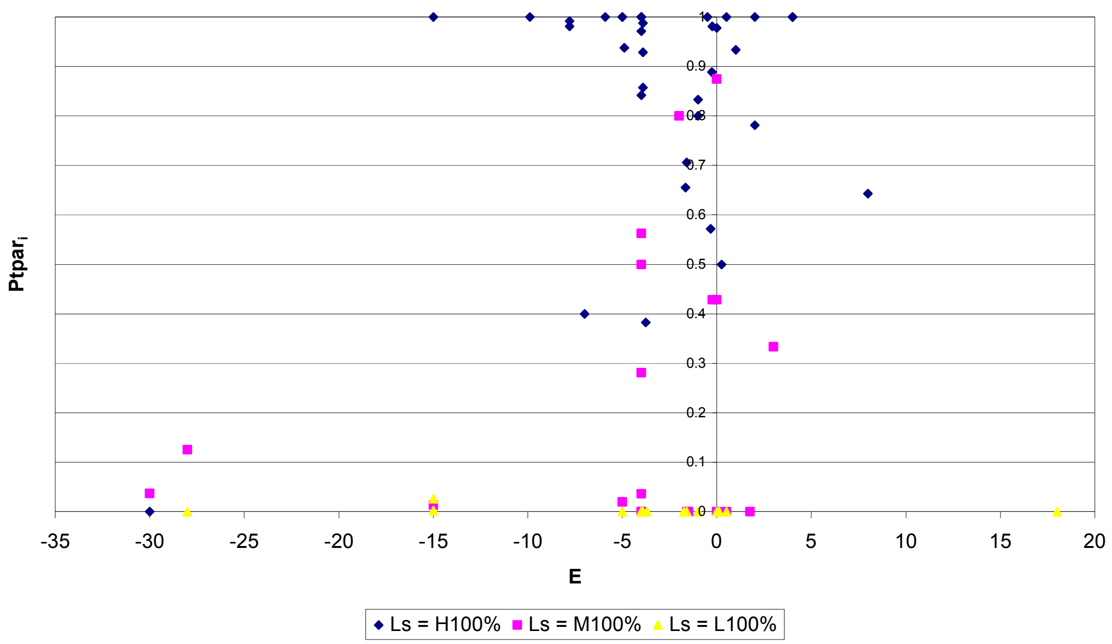

Figure 7.24. The proportion of the threatened subpopulation that perishes (Ptpar$_i$) vs. the excess evacuation time (E).

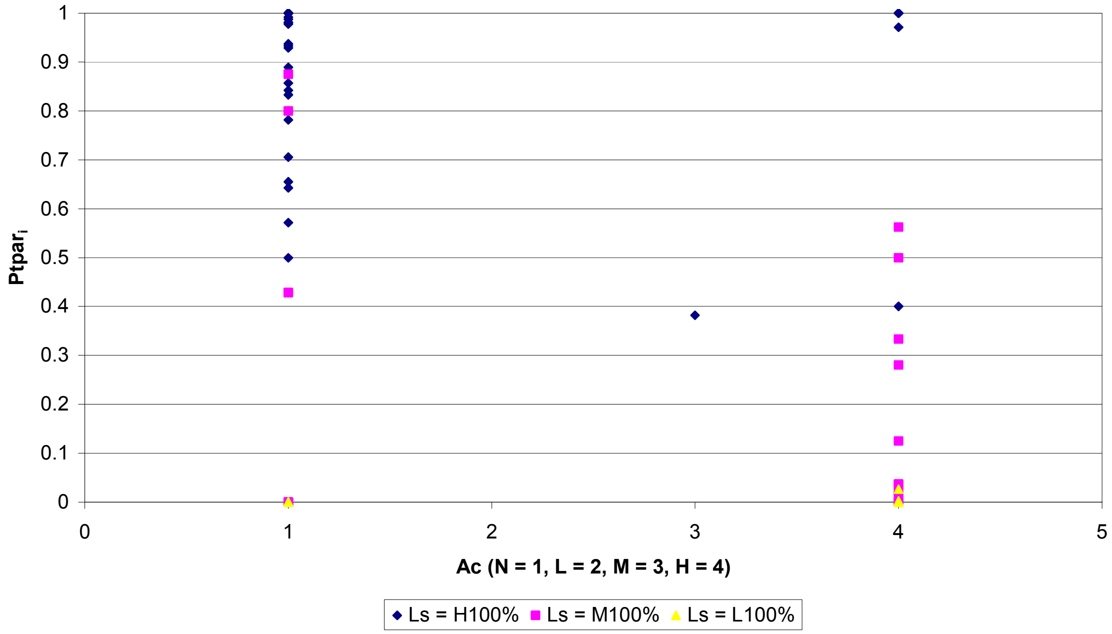

Figure 7.25. Range of the proportion of the threatened population that perishes (Ptpar$_i$) for a categorical treatment of any attendant circumstances (Ac) that might accompany a flood wave.

first onslaught, after which their survival is much more likely. An example of the latter would be a large, urban area that floods and traps people on rooftops, treetops, and in upper stories. In such cases, people are available for rescue simply because they have already reached a flood zone with a relatively low rate of life loss. Of course lives can be saved when people who are injured are rushed to area hospitals. In any case, Figure 7.26 suggests no reliable trend in rescue resources (Rr) vs. the proportion of the threatened population that perishes ($Ptpar_i$) for any category of loss of shelter (Ls). Each category reflects a V-pattern centered at Rr = 2, which simply indicates that the data set was dominated by events with Rr = 2, increasing the likelihood of greater spread in $Ptpar_i$ at this value.

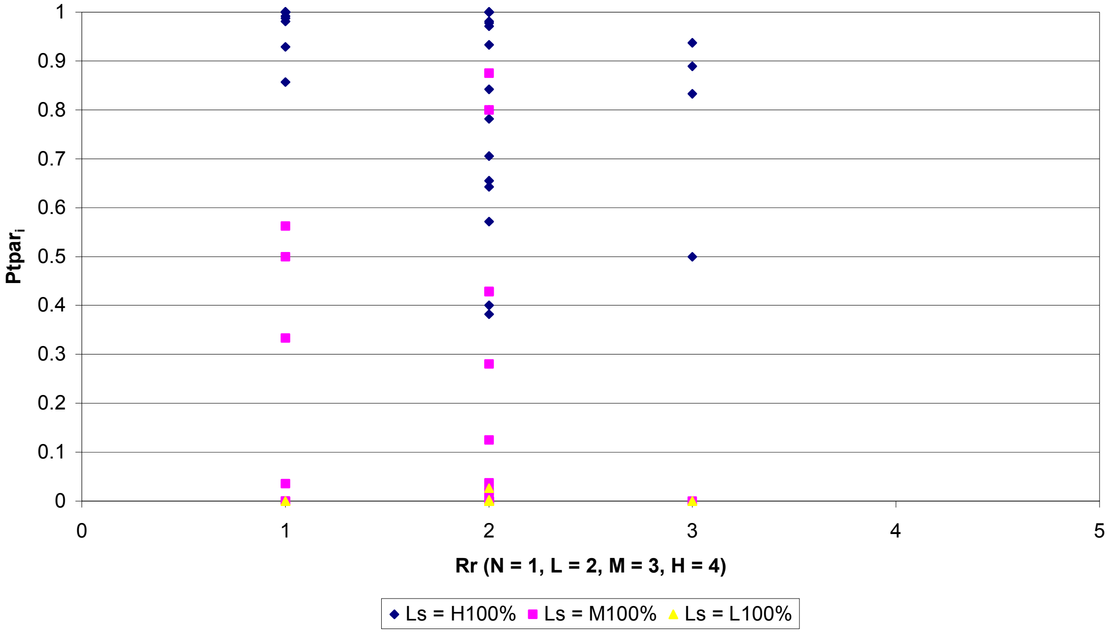

Figure 7.26. Range of the proportion of the threatened population that perishes ($Ptpar_i$) for a categorical treatment of the extent to which rescue resources are modern and available (Rr).

Summary of Predictive Variables

The following variables were not found useful in identifying subsets of the distributions in Figures 7.9 – 7.11: time of day (Td), preparedness (Pr), development (Dev), excess evacuation time (E), attendant circumstances (Ac), and rescue resources (Rr). The first three, however, have a profound impact on the estimate of life loss (L) through their influence on the average warning time (Wt_{avg}), the representative evacuation time (Ret), and excess evacuation time (E).

The most promising variables appear to be depth and velocity or functions that describe the nature of the flooding people experience. This is not surprising, since it is the flood dynamics that cause fatalities. Depth (D), wall of water adjusted for D using R (Wwr), peak velocity (V), D*V, and Dv_{min} all have the shortcoming that they are either extreme point values or extreme averages that do not necessarily describe the flooding unique to a threatened subpopulation ($Tpar_i$). Moreover, if people are in havens, they will not experience the full force of the flood.

Nevertheless, the following trends can be considered reliable under normal circumstances, with the idea that efforts should be made to confirm them through additional historical characterizations.

1. Depth (D) in isolation:
   a) If $D > 100$ ft, Ls = H100% and $Ptpar_i$ is represented by that portion of Figure 7.9 for which $Ptpar_i \geq 0.94$ or possibly $Ptpar_i \geq 0.9$.
   b) When every building has $D_{ij} \geq 20$ ft, Ls = H100%.
   c) When $D < 30$ ft, Ls will determine which $Ptpar_i$ distribution applies, but in each case, the entire distribution applies.
   d) Wwr offers no clear predictive advantage over D.

2. Peak velocity (V) in isolation:
   a) The entire $Ptpar_i$ distributions apply when Ls = H100% or Ls = L100%.
   b) It is possible that when $V < 10$ fps in residential areas, $Ptpar_i \leq 0.15$.

3. V*D in isolation:
   a) When $D*V > 600$ ft^2/s accurately represents a residential area, Ls = H100% and $Ptpar_i \geq 0.8$.
   b) When $D*V > 2{,}500$ ft^2/s accurately represents a residential area, Ls = H100% and $Ptpar_i \geq 0.94$.
   c) When $D*V < 40$ ft^2/s, Ls = L or M and $Ptpar_i$ is almost always ≤ 0.15, which eliminates most of the variance within the $Ptpar_i$ distribution for Ls = M100%.
   d) Ls-values are heavily dependent on the durability and buoyancy of the buildings.

4. Dv_{min} in isolation:

   a) Above $Dv_{min} = 600$ ft^2/s, it would be rare for Ls = L.
   b) Above $Dv_{min} = 1{,}000$ ft^2/s, it would be rare for Ls = M. Also, $Ptpar_i \geq 0.95$ on the $Ptpar_i$ distribution for Ls = H100%.

Notice that depth/velocity relationships provide guidance on Ls as well as $Ptpar_i$.

Applying Loss Functions to Homogeneous Units Based on Zd

The fundamental problem with most potential predictive variables is that they are point estimates and may or may not describe the conditions in the immediate vicinity of each member of Par_i. It is incongruous to reduce a subPar to a fairly homogeneous unit and then to attempt to refine the predictions further by including less homogeneous variables. Instead, it is desirable to refine the units further and then to develop new distributions for the next greater degree of homogeneity. This is the goal of flood zones.

Each subPar for which sufficient information was available was divided further among one or more flood zones, regardless of whether or not loss of shelter (Ls) was homogeneous for a particular subPar. As was done with loss of shelter (Ls), each historic example of a zone was gathered together with other examples of the same zone to determine the distribution of the proportion of lives lost under that level of flood exposure.

Table 7.3 lists the data points that were obtained. Flood zone densities replace the designation threatened subpopulation ($Tpar_i$), and preparedness (Pr) is used as the prefix for "proportion" to avoid confusion between pseudo-chance zones (Pcz) and the proportion of lives lost in the chance zone (Prcz).

The average value for each zone's proportion is listed in the second-to-last row. Confirmation that these zones are more homogeneous than are categories of loss of shelter (Ls) is evidenced by the fact that the average proportion of lives lost in the chance zone (Prcz) value (0.918) is higher than the average $Ptpar_i$ value for Ls = H100% (0.857); and the average proportion of lives lost in safe zone (Prsz) value (0.000345) is an order of magnitude less than the average $Ptpar_i$ value for Ls = L100% (0.00107). The high end of the $Ptpar_i$ distribution for Ls = M was eliminated for the proportion of lives lost in the compromised zone (Prcoz) because those lives were lost in chance zones. Similarly, the single data point at $Ptpar_i = 0$ for Ls = H100% represented a threatened population that found haven in the safe zone.

The pseudo-chance zone closely resembles the chance zone rather than a combination of the chance zone and compromised zone, although there were only three data points to evaluate. Until this zone can be refined, it is probably appropriate to apply the proportion of lives lost in the chance zone (Prcz) distribution to pseudo-chance zone density (Pczd), although one could add the nonzero values from the proportion of lives lost in the compromised zone (Prcoz) distribution or, alternatively, the values that overlap with the proportion of lives lost in the chance zone (Prcz) distribution, with little effect.

Table 7.3. Proportion of lives lost in each flood zone for which values were available

Proportion of Lives Lost in the . . .					
Chance Zone		Pseudo-Chance Zone	Compromised Zone	Safe Zone	
Prcz		Prpcz	Prcoz	Prsz	
1.000	0.988	1.000	0.500	0.013	0
1.000	0.981	0.900	0.500	0.002	0
1.000	0.981	0.900	0.241	0	0
1.000	0.978		0.222	0	0
1.000	0.971		0.036	0	0
1.000	0.938		0	0	0
1.000	0.933		0	0	0
1.000	0.933		0	0	0
1.000	0.929		0	0	0
1.000	0.915		0	0	0
1.000	0.889		0	0	0
1.000	0.857			0	0
1.000	0.857			0	0
1.000	0.842			0	0
1.000	0.833			0	0
1.000	0.806			0	0
1.000	0.800			0	0
1.000	0.706			0	0
1.000	0.655			0	0
1.000	0.643			0	0
1.000	0.500			0	0
1.000	0.383			0	0
0.991				0	0
				0	
average = 0.918		average = 0.933	average = 0.136	average = 0.000	
Prcz = 0.918		Prpcz/Prcz = 1.016	Prcoz/Prcz = 0.148	Prsz/Prcz = 0.000	

Figure 7.27 presents the distribution of the proportion of lives lost in the chance zone (Prcz) in the form of a histogram and is directly analogous to Figure 7.9. Figures 7.28 and 7.29 present the distributions of the proportion of lives lost in the compromised zone (Prcoz) and the proportion of lives lost in the safe zone (Prsz), respectively, and should be compared to Figures 7.10 and 7.11. Figure 7.30 illustrates the dramatic difference in fatality rates between chance zones and safe zones. Each of the 45 points across the bottom represents a unique homogeneous unit with its own value for the proportion of lives lost in the chance zone (Prcz) and for the proportion of lives lost the in the safe zone (Prsz). As such, the rectangular graph represents the entire population in every chance zone or every safe zone, and the shaded regions represent the respective percentage of lives lost in each zone. Numerically, if the chance zone had 3,000 members, 2,754 would die, but if the safe zone had 3,000 members, one or fewer people would be expected to die.

Limitations to Refining Loss Functions with D, V, or Dv

Conceptually, point estimates of peak depth (D), peak velocity (V), or destructive velocity (Dv) are especially ill suited to characterize the specialized environment within each flood zone. For example, by definition, peak velocity (V) only represents the velocity in a safe zone when an entire subPar is characterized by shallow wading depths in the open. Compromised zones are characterized by great variability in life loss, as reflected in the distribution of the proportion of lives lost in the compromised zone (Prcoz), so there can be no one-to-one relationship between compromised zones and D, peak velocity (V), or Dv. Only the chance zone is likely to be well-characterized by these predictors. In this case, the chance zone is nearly identical with loss of shelter (Ls) = H100%, minus $Ptpar_i = 0$.

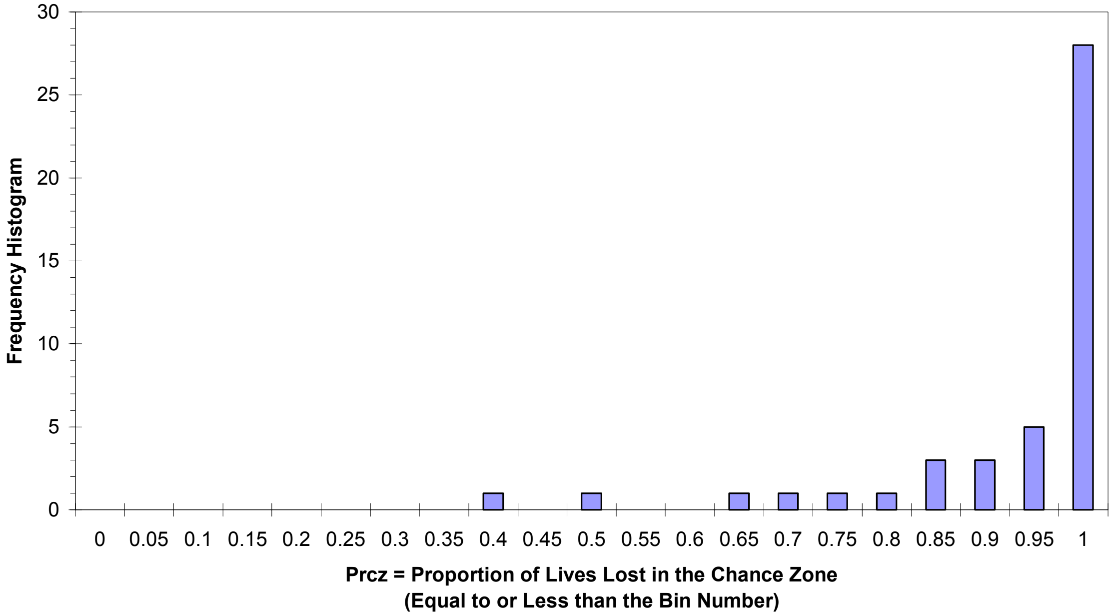

Figure 7.27. Histogram of proportion of lives lost in chance zones.

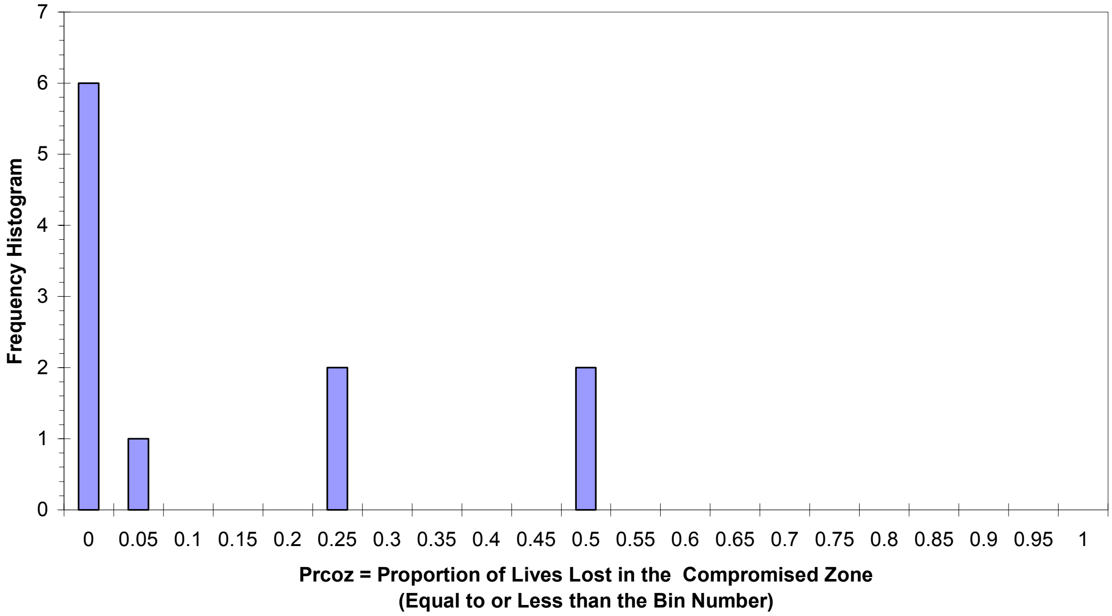

Figure 7.28. Histogram of proportion of lives lost in compromised zones.

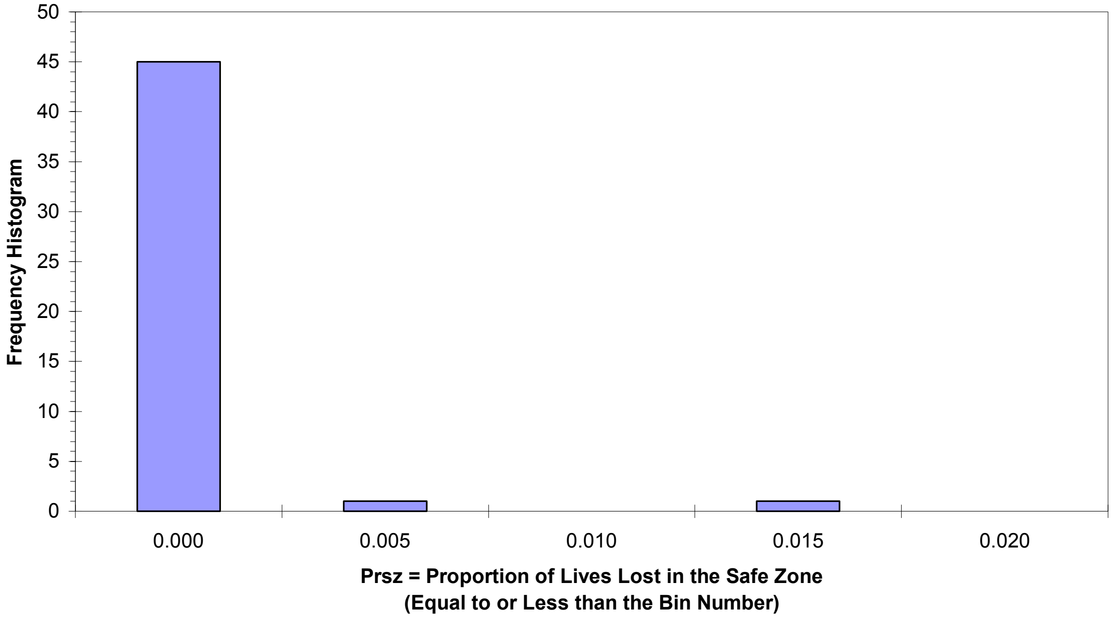

Figure 7.29. Histogram of proportion of lives lost in safe zones.

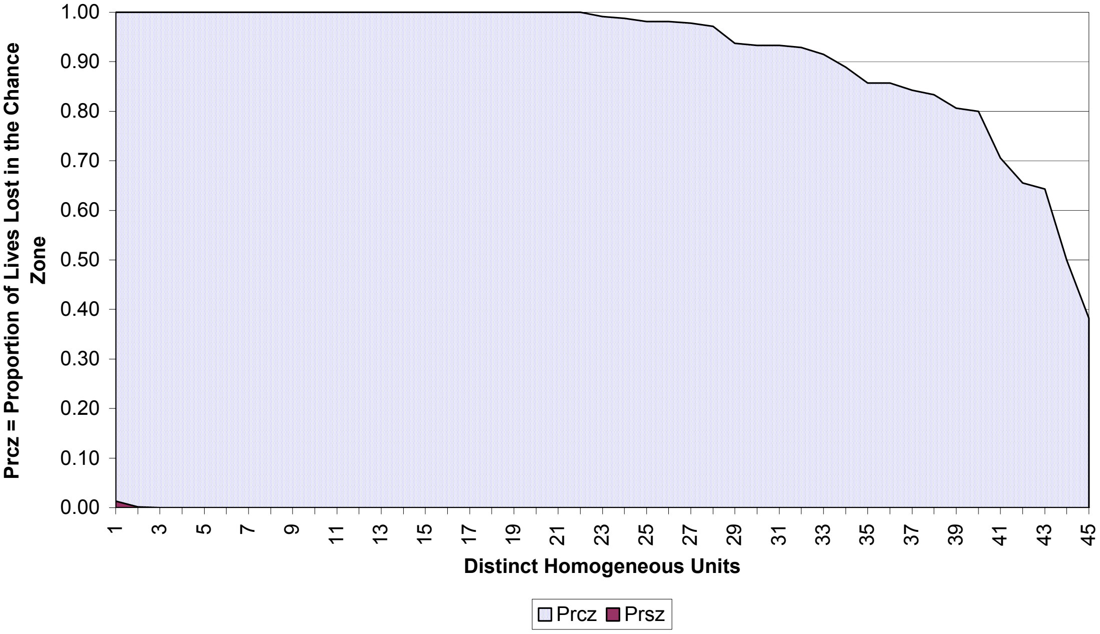

Figure 7.30. Graphical display of the percentage of lives lost in chance zones and safe zones. The size of the shaded regions compared to the entire graph represents the average values of $Prcz_{avg} = 0.918$ and $Prsz_{avg} = 0.0003$.

As such, the previous summary comments regarding predictive variables hold true when they refer to Ls = H100%.

1. Peak depth (D) in isolation:

    a) If $D > 100$ ft, the entire subPar is a chance zone and the proportion of lives lost in the chance zone (Prcz) is represented by that portion of Figure 7.27 for which Prcz ≥ 0.94 or possibly Prcz ≥ 0.9.
    b) When every building has $D_{ij} \geq 20$ ft, the entire subPar is a chance zone, unless some buildings are 3 stories tall and resistant to the prevailing velocities.
    c) Wwr offers no clear predictive advantage over peak depth (D).

2. V*D in isolation:

    a) When $D*V > 600$ ft^2/s accurately represents a residential area, the area is a chance zone and Prcz ≥ 0.8.
    b) When $D*V > 2{,}500$ ft^2/s accurately represents a residential area, the area is a chance zone and Prcz ≥ 0.94.

3. Dv_{min} in isolation:
    a) Above $Dv_{min} = 1{,}000$ ft^2/s, most or all of the area is a chance zone. Also, Prcz ≥ 0.95.

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CHAPTER VIII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Estimating Life Loss for Dam Safety Risk Assessment chronicles a journey that begins with the importance of credible and defensible life-loss estimates in dam safety risk assessment, moves to the need for an improved life-loss model, spends extensive time behind the scenes gleaning insights through the characterization of flood events using new variables and new approaches, and rests for a moment before presenting these insights in the form of a conceptual model. A model is under development and has yet to be tested, so the journey is far from over, but preliminary concepts are presented in a working document as a companion report entitled, *Working Paper Draft Report: A Proposed Life-Loss Model Under Development* (hereafter called *A Proposed Model).*

With respect to the text itself, Chapter I introduced the topic of dam safety risk assessment and the central role that life-loss estimation plays in that field. Chapter II discussed important preliminary considerations in model development. Chapter III provided a detailed review of previous life-loss models that pertained to floods, including a critique of each. Chapter IV explored the DeKay-McClelland model in detail and raised serious concerns regarding its future use. Chapter V defined nearly 100 variables and their respective categories for use in characterizing flood events. Chapter VI provided a detailed outline of historical insights that relate to flood events in one of 18 logical categories. Chapter VII explored relationships between potentially promising characterizing variables and life loss. This analysis is repeated and related to a proposed model in the companion report, *A Proposed Model*.

Conclusions

The following are the most important conclusions and contributions from the chapters.

Conclusions from Chapter I

It is critically important for the future of dam safety risk assessment that credible estimates of life loss be developed.

Conclusions from Chapter II

There are enough interdependent variables to make every catastrophic flood event extremely unique and large-scale statistical analysis problematic. Any successful model must confront this complexity and represent the most important life-loss variables to avoid having predictions dominated by unrecognized life-loss influences.

Selecting an unbiased data set on which to base regression or development of a parametric model is difficult, especially as it pertains to events with no life loss.

Conclusions from Chapter III

Historic attempts to model life loss have evolved over time, moving from purely conceptual models to pure regression equations and finally toward an incomplete attempt to mix the two. No historic models have been based on a look at life-loss dynamics and human behavior on the level of the individual in actual floods.

There are at least six components that every life-loss model should contain, each with guidelines on how these components can best be approached.

Important contributions from Chapter III

This chapter provided a detailed critique of the B.C. Hydro Model under development by Assaf, Hartford, and Cattanach (1998) and a thorough presentation and evaluation of every model that had been developed at the time of the writing.

Conclusions from Chapter IV

Chapter IV lists 32 shortcomings related to the DeKay-McClelland equation, the way in which it is used, the logit procedure on which it is based, the treatment of the underlying data set, the choice and definition of the variables on which it relies, and the inherent biases it contains. Without elaboration, the main shortcomings can be summarized as follows:

1. Life loss is nonlinear with respect to Par, causing inflated and highly variable estimates of L when the model is applied to subPar.
2. The model relies on heterogeneous Par, making application to homogeneous Par or unique Par unreliable.
3. The model does not distinguish between life-loss dynamics experienced by those who fail to evacuate and those who successfully evacuate.
4. The model uses the point estimate, Wt, rather than E, ignoring important issues regarding Ret, Wt_{avg}, Sc, the urgency and credibility of the warning, the time of day or night, the benefits of improved warning dissemination, and those most at risk.

5. Fd is too coarse for refined estimates, it implicitly assumes a Par has heterogeneous levels of damage rather than extreme and consistent damage, and it fails to recognize that the difference in life loss between buildings with major damage and total destruction is one of the most important predictors of life loss.

6. The data set itself is treated in ways that distort life-loss dynamics, such as combining multiple watersheds into a single event, quantifying Par without regard to the location or nature of the life loss (ignoring Pt), and characterizing variables in a manner that can now be viewed as historically inaccurate.

7. The DeKay-McClelland logit procedure, in combination with the data set under consideration, produces an equation that is biased toward ever greater underestimation of life loss as L grows and as P approaches 0.5.

8. The underlying data set makes application of the equation to extreme flood events inappropriate.

9. The confidence limits surrounding the life-loss estimates are very large, seriously undermining the equation's credibility, unless they are taken into account when using the method.

Important contributions from Chapter IV

This chapter provided a detailed examination and critique of the equation developed by DeKay and McClelland (1993b) and the methods with which it is commonly used in dam safety risk assessment. Chapter IV offered an in-depth examination of the implications of using a logit procedure in life-loss estimation and the inherent danger of using any equation that is nonlinear with respect to Par. The chapter provided quantitative demonstrations of the effects of nonlinearity and regression using the logit transformation, and a historically grounded critique of the variables dichotomous forcefulness (Fd) and warning time (Wt) on which the model relies.

Conclusions from Chapter V, Appendix A, and Appendix D

Life loss in flood events is influenced by an extremely large and complex set of interdependent variables that must be carefully defined and categorized if events are to be characterized in a comprehensive, meaningful, and consistent manner.

Important contributions from Chapter V, Appendix A, and Appendix D

While a wide range of variables has been discussed in the abstract by previous authors, this is the first time that most of them have been carefully defined, given a unique symbol, and given categories and descriptions by which they can be characterized. The chapter also proposes simple and consistent rules of nomenclature for symbol development. Dozens of new variables and concepts have been identified and carefully defined, including those most central to the conceptual model presented in *A Proposed Model*.

Conclusions from Chapter VI and Appendix B

Flood events are not easy to understand in the abstract. Event characterization is as much an art as a science. If an analyst wishes to avoid making historically unjustifiable errors, there is no substitute for immersing oneself in the literature that describes historic flood events and the stories of those who perished and of those who survived.

A complex tapestry of historic insights can be woven around 18 logical topics that describe the factors influencing life loss or life-loss models: 1) The type of failure, 2) detectability of the failure, 3) warning times and warning effectiveness, 4) evacuation rates, 5) excess evacuation time, 6) subPar types and evacuation modes, 7) homogeneity of subPar, 8) flood dynamics, 9) loss of shelter, 10) havens, 11) flood zones and the distribution of people among those zones, 12) the lethality rate outside safe havens or zones, 13) the lethality rate inside safe havens or zones, 14) the lethality rate on dry land, 15) life-saving interventions, 16) complications and aberrations, 17) post-flood trauma psychological trauma, and 18) the applicability of historic events to future events via an empirical life-loss model.

Important contributions from Chapter VI and Appendix B

This is the first time that any historic flood events have been examined on a subPar basis (Par_i), by loss of shelter (Ls), or by flood zones. This is the first time that any historic events have been characterized with the level of detail present in the unpublished working documents. Dozens of variables have never before been characterized, including such fundamental variables as average warning time (Wt_{avg}), representative evacuation time (Ret), and excess evacuation time (E). The characterizations have been carefully recorded and documented so that future researchers can refine past characterizations, attempt to be consistent when making future characterizations, and have access to previous research.

Conclusions from Chapter VII and Appendix C

Distributions describing the proportion of lives lost are empirically grounded and intuitively defensible. The nature of dam safety risk assessment is to deal in hypotheticals and sometimes-crude estimates, but within these constraints, the uncertainties should be made explicit so that the results can be appropriately interpreted.

Important contributions from
Chapter VII and Appendix C

See the companion report, *A Proposed Model,* where suggestions are made on how to estimate life loss using concepts and characterizing variables discussed throughout this report.

Recommendations

The companion report, *A Proposed Model*, makes six recommendations of how additional research could help advance the working model that is under development.

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APPENDICES

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Appendix A

Table of Flood Wave Events

Table A.1 is a comprehensive list of every life-loss event reviewed for characterization in Appendix B. It may be the most comprehensive list of fatal dam-failure events in existence today, although it could be greatly expanded by hundreds of additional flash flood events. Some of the events have been listed twice when more than one designation is found in the literature.

Columns 5-8 are explained in the footnotes to the table. In brief, column 5 gives a representative estimate of the life loss reported in the source documents. These values do not necessarily correspond to the values chosen in Appendix B and they may need to be revised if the events are characterized more fully.

Column 6 classifies each event according to its dominant characteristics, with the first symbol carrying the greater weight. Column 7 indicates the 28 events in the database explored by DeKay and McClelland (1993b), with the division of the Teton failure into two separate cases from a single event producing a total of 29 case studies. Of those 28 events, they rejected 3 events as statistical outliers and treated over half of the remaining events in a manner that this author considers potentially misleading because they either combined multiple watersheds into a single event (events 3, 23, 69, 111, 143), they selected historic values significantly different from those chosen for Appendix B [events 3 (Par), 13 (Wt), 15 (Wt), 19 (Par or Tpar), 21 (Wt), 23 (Par, Wt), 28 (L, Par), 69 (Wt), 72 (Par), 86 (Par), 128 (Par), 159 (Par); and probably 96 (Wt) and 103 (Wt); see Figure 26 in Chapter IV], or Par is quantified based on a different Par type (Pt) than the one experiencing fatalities (events 3, 13, 69 and possibly others).

Column 8 indicates the relative usefulness of the information contained in this author's files for characterizing Par and subPar, the number of lives lost, and various warning times for each event. B indicates that the event has already been characterized in Appendix B, while "B, L" indicates the characterization was lacking essential information and had to be excluded from the master table in Appendix C. L indicates that there is limited information available and that, in most cases, the needed information will be difficult or impossible to obtain. P indicates that an event could potentially yield a useful characterization, in some cases without the need for additional source material. The combination "L, P" indicates that additional source material would be needed. As such, P and "L, P" can help researchers target their efforts if they wish to expand Appendix B.

Table A.1. Comprehensive list of every flood-wave event collected in files and examined for characterization in Appendix B

	EVENT	DATE	COUNTRY	[a]L	[b]Flt	[c]D-M	[d]Value
1	Alla Sella Zerbino Dam (near Genoa)	8/13/35	Italy	>100	D		B, L
2	Allegheny and Ohio River floods (Penn. & Ohio)	1937	USA	<900	F		B, L
3	Allegheny County (Little Pine Creek, Penn.)	5/30/86	USA	9	Ff	U, M	B
4	Angels Dam (California)	4/10/1885	USA	1	D		B, L
5	Anzalduas Dam (Mission, Texas)	2/6/72	USA	4	D		B
6	Arás alluvial fan flood (Central Pyrenees)	8/7/96	Spain	87	Ff, D		B
7	Arno River flood	11/3f/66	Italy	127	F		B
8	Arno River flood (Florence)	1333	Italy	300	F		B, L
9	Ashburnham Reservoir Dam (Massachusettes)	5/6/1850	USA	2	D		L
10	Asherville Dam (North Carolina)	2/22/76	USA	4	D		B
11	Austin [Bayless Pulp & Paper Company] Dam (Penn.)	9/30/11	USA	>88	D		B
12	Austin Dam (Colorado River, Texas)	4/7/00	USA	8	D		B
13	Austin flash floods (Texas)	5/24f/81	USA	13	Ff	U, M	B
14	Babii Yar Dam (Ukraine)	3/25/61	USSR	145	D		B, L
15	Baldwin Hills Dam (California)	12/14/63	USA	5	D	U, M	B
16	Bangladesh storm surge (coast)	11/12/70	Bangladesh	500000	S		B, L
17	Banqiao & Shimantan Dams (China)	8/8/75	China	85000	D, F		B
18	Bass Haven Lake Dam (Texas)	8/17/84	USA	1	D		B
19	Bear Wallow Dam (North Carolina)	2/22/76	USA	4	D	U, M	B
20	Bergeron Pond [Meadow Pond or Alton] Dam (N. H.)	3/13/96	USA	1	D		B
21	Big Thompson flood (Colorado)	7/31/76	USA	139	Ff	U, M	B, L
22	Bila Desna Dam (near Jablonec nad Nisou)	9/16	Czech.	65	D		L
23	Black Hills & Canyon Lake Dam (S. D.)	6/9f/72	USA	245	Ff, D	U, M	B
24	Bolan Dam (26 villages, northeastern Pakistan)	9/76	Pakistan	low	D		L
25	Boston molasses flood (Massachusettes)	1/15/19	USA	21	D, O		L
26	Bouzey Dam (Moselle River near Epinal)	4/27/1895	France	>100	D		L
27	Brazil floods (widespread)	3f/74	Brazil	>1500	F		L
28	Buffalo Creek coal waste dam (West Virginia)	9/26/72	USA	125	D	U, M	B
29	Burgess Falls Power Dam (Tennessee)	6/29/28	USA	0	D		L
30	Bushy Hill Pond Dam [+7 dams downstream] (Conn.)	6/6/82	USA	0	D	U	P
31	Cabin Creek flood (West Virginia)	8/9/16	USA	44-50	Ff		L
32	Castlewood Dam (Colorado)	1933	USA	2	D		L
33	Chimney Rock & Bat Cave flood (N.C.)	7/16/16	USA	34	Ff		B
34	Connecticut flash floods (Conn.)	6/4ff/82	USA	12	Ff		L
35	D.M.A.D. (Utah)	6/23/83	USA	1	D	R	P
36	Dale Dykes [Bradfield] Dam (Sheffield, England)	3/11/64	England	263	D		B
37	Dam #2 (Pennsylvania)	6/17/92	USA	1	D		L
38	Del Rio flash floods (Texas)	8/24/98	USA	12-42	Ff, F		P
39	Denver flood (Southe Platte River, Colorado)	6/14ff/65	USA	1	F	U	P
40	Dozier Lake Dam (Georgia)	1994	USA	3?	D		L, P
41	Dry Creek flash flood, train wreck (Colorado)	8/7/04	USA	96+	F		B
42	East Lee (Mud Pond) Dam (Massachusettes)	3/68	USA	2	D		L
43	Eastover Mining Co. sludge pond (Kentucky)	12/18/81	USA	1	D		B
44	Eastwick RR Fill (Washington)	2/32	USA	7	D		L
45	El Cajoncito dike (La Paz, Baja Cal. Sur)	10/4/76	Mexico	600+	Dy		B
46	El Habra Dam (3 failures; 3/10/1872, 11/26/27)	12/1881	Algeria	209	D		L
47	Eldorado Canyon flood (Nevada)	9/14/74	USA	>9	Ff		B
48	Enid flash flood (Oklahoma)	10/10/73	USA	9	Ff		L

Table A.1. Continued

	EVENT	DATE	COUNTRY	[a]L	[b]Flt	[c]D-M	[d]Value
49	Evans & Lockwood Dams (North Carolina)	1989	USA	2	D		B
50	Fort Pitt Dam (Pennsylvania)	7/5/03	USA	2	D		L
51	Frias Dam (probably the same as Pardo Dam)	1970	Argentina	42-102	D		L
52	Fushan Dam	A.D. 516	China	10000	D		L
53	Gaokou Village Dam (Hubei province, China)	3/8/98	China	7	D		L
54	Gleno Dam (Alps of north-central Italy)	12/1/23	Italy	600	D		L
55	Grenoble Dam	1219	France	high	D		L
56	Harris County flash flood (Texas)	6/15/76	USA	8	Ff		L
57	Hill (Woodward) Dam (New Hampshire)	5/29/18	USA	1	D		B
58	Holland Dykes (Netherlands)	1/31f/53	Holland	1835+	Dy, S		L
59	Holland Dykes (Netherlands)	11/1421	Holland	10000	Dy, S		L
60	Holland Dykes (Netherlands)	12/1287	Holland	50000	Dy, S		L
61	Hwang-Ho River Dyke (act of war)	4/38	China	500000	Dy		L
62	Hwang-Ho River flood	1933	China	18000	Dy, F		L
63	Hwang-Ho River flood	10/1887	China	900000	Dy, F		L
64	Hyokiri Dam	7/12/61	S. Korea	127	D		L
65	Isahaya floods (west Japan)	1957	Japan	>600	F/Ff		L
66	Japan's Izu Peninsula	1/14/78	Japan	21+	D, F		L
67	Jarrolds Valley flood (West Virginia)	8/9f/16	USA	75	D		L
68	Johnstown flood (Pennsylvania)	3/17/36	USA	30	D		L
69	Kansas City floods (Kansas, Missouri)	9/12f/77	USA	25	F	U, M	B
70	Kansas River (Kansas City)	7/10ff/51	USA	11	F	R	P
71	Kantalai "tank" Dam (Sri Lanka)	4/21/86	India	>135	D		L
72	Kelly Barnes Dam (Toccoa Falls, Georgia)	11/6/77	USA	39	D	U, M	B
73	Kendall Lake Dam (South Carolina)	10/10/90	USA	4	D		P
74	Kenduskeag Village Dam (Maine)	11/13/1853	USA	1	D		L
75	Kerville-Medina area flash floods (Texas)	1978	USA	26	Ff		L
76	Knife Lake Dam (Minnesota)	7/72	USA	4	D		L
77	Kuala Lumpur Dam	1961	Malaya	600	D		L
78	Kuban-Kel Lake Dam (Uzbekistan & Kyrgyzstan)	7/8/98	Asia	43+	D		L
79	Lake Keowee Cofferdam (South Carolina)	10/78	USA	7	D		L, P
80	Lake Ludlow Club Dam (New York)	1935	USA	3	D		L
81	Lake O' the Hills Dam (Arkansas)	4/72	USA	1	D		L
82	Lakes Eigiau & Coedty Dams (Dolgarrog)	11/2/25	Wales	16	D		L
83	Lakeside Dam (South Carolina)	9/18/75	USA	1	D		B
84	Laurel Run Dam (Johnstown area, Penn.)	7/19f/77	USA	40	D	U	L, P
85	Lawn Lake and Cascade Lake Dams (Colorado)	7/15/82	USA	3	D	U	P
86	Lee Lake Dam (Massachusetts)	3/24/68	USA	2	D	U, M	B
87	Little Deer Creek Dam (Utah)	6/16/63	USA	1	D	U	P
88	Little Indian Creek (Tennessee)	6/29/28	USA	3	D		L
89	Little Pine Creek flash flood (see Allegheny County)	5/30/86	USA	9	Ff		B
90	Lower Otay Dam (San Diego, California)	1/27/16	USA	14 or 30	D		L
91	Lyman Dam (Arizona)	4/15/15	USA	8	D		L
92	Lynchburg & Scottsville (Virginia)	8/19/69	USA	107	F/Ff		L
93	Lynchburg Dam (Virginia)	6/95	USA	2	D		L
94	Lynmouth fast-rising flood	8/15/52	England	24	F		L
95	Machchu II Dam (Morvi, West India)	8/11/79	India	>1300	D		L
96	Malpasset Dam (France)	12/2/59	France	421	D	U, M	L

Table A.1. Continued

	EVENT	DATE	COUNTRY	[a]L	[b]Flt	[c]D-M	[d]Value
97	Mammoth Dam (Utah)	6/24f/17	USA	1	D		L, P
98	McMinnvill flash flood (Tennessee)	1902	USA	5	Ff		L
99	Melzingah Dams 1 & 2 (New York)	7/14/1897	USA	7	D		L
100	Merriespruit Tailings Dam (Republic of South Africa)	?	S. Africa	17	D		L
101	Mill River Dam (Massachusetts)	1874	USA	143	D		B
102	Mississippi flood (Lower Mississippi)	spring, '27	USA	313	F		L
103	Mohegan Park [Spaulding Pond] Dam (Connecticut)	3/6/63	USA	6	D	U, M	L, P
104	Mohne Dam	5/17/43	Germany	1200	D		L
105	Moldavia Region, Belciu Dam (Onesti)	8/15/91	Romania	107	D		L
106	Mountjoy Hill Reservoir (Maine)	8/6/1893	USA	4	D		L
107	Nanak Sagar Dam (32 villages, Northern India)	9/8/67	India	100	D		L
108	Nevado Del Ruiz volcano glacier burst (Columbia)	11/85	Columbia	20000	GB		L
109	Nix Lake Dam (Texas)	3/89	USA	1	D		L, P
110	Northeastern U.S. floods	1/96	USA	33	F		L
111	Northern New Jersey flood	4/5/84	USA	2	Ff	U, M	P
112	Oakford Park Dam (Jeannette, Penn.)	7/5/03	USA	23	D		L
113	Ohio floods (Ohio)	3/13	USA	<700	F/Ff		L
114	Orós Dam	3/25/60	Brazil	30-50	D		L
115	Palagnedra	1978	Switzerland	24	?		L
116	Panshet & Khadakwasla Dams (Poona, Maharastra)	7/12/61	India	heavy	D		L
117	Pardo or Frias Dam (Mendoza, 1970)	1970	Argentina	42-102	D		L
118	Prospect Dam & Lord Reservoir (Colorado)	2/10/80	USA	0	D	R	P
119	Puentes Dam	4/30/1802	Spain	608	D		L
120	Quebrada la Chapa	1963	Colombia	250	?		L
121	Randall's Pond Dam [Lower] (Road Island)	3/11/01	USA	1	D		L
122	River Ouse sea inundation	1/31f/53	England	307	Dy, S		L
123	San Ildefonso Dam	3/1626	Bolivia	<4000	D		L
124	Sandy Run Dam (Johnstown, Penn.)	7/19f/77	USA	5	D		L, P
125	Schoelldopf Station rock slide (New York)	6/7/56	USA	1?	O		L, P
126	Seminary Hill Reservoir (Centralia, Washington)	10/5/91	USA	0	D	U	P
127	Sempor Dam (central Java)	12/1/67	Java	200	D		L
128	Shadyside [Wegee and Pipe Creeks] (Ohio)	6/14/90	USA	24	Ff	U	B
129	Skagway Dam (Pueblo, Colorado)	1965	USA	2	D		L
130	South Fork Dam (Johnstown, Penn.)	5/31/1889	USA	2209	D		P
131	Spain flash flood	1973	Spain	150	Ff		L
132	Spaulding Pond Dam (Mohegan Park, Connecticut)	3/6/63	USA	6	D	U, M	L, P
133	Spring Creek flash flood (Colorado)	7/28/97	USA	5	Ff		L, P
134	Spring Lake Dam (Fiskeville, Rhode Island)	8/25/1889	USA	3	D		L
135	St. Francis Dam (California)	3/12/28	USA	450	D		B
136	Stava Dam (Italy)	7/9/85	Italy	232	D	U	B
137	Swift & Lower Two Medicine Dams (Montana)	6/8/64	USA	35	D	U	P
138	Swimming Pool Dam (New York)	1979	USA	4	D		L
139	Tarbela Dam	7/77	Pakistan	2	D		L, P
140	Tennessee flash floods	3/28/02	USA	23+	Ff	Ff	P
141	Teton Dam (Lower Reach, Idaho)	6/5/76	USA	4	D	U	P
142	Teton Dam (upper reach, Idaho)	6/5/76	USA	7	D	U	P
143	Texas Hill Country	8/1ff/78	USA	25	Ff	U, M	P
144	Thompson Mill Dam (Tennessee)	8/2/16	USA	24	D		B

Table A.1. Continued

	EVENT	DATE	COUNTRY	[a]L	[b]Flt	[c]D-M	[d]Value
145	Tigra Dam (Madhya Pradesh)	8/14/17	India	???	D		L
146	Timber Lake Dam (Virginia)	6/22/95	USA	1	D		B
147	Tsao-Lin Natural Reservoir Earth Dam	5/18/51	Taiwan	134	D		L, P
148	unnamed dam #1 (Colorado)	1923-29	USA	1	D		L
149	unnamed dam #2 (Colorado)	1923-29	USA	1	D		L
150	unnamed dam (Minas Gerais)	5/86	Brazil	7	D		L
151	unnamed dam (Newfound, Noth Carolina)	1976	USA	4	D		L
152	unnamed dam (Portland, Maine)	1893	USA	4	D		L
153	unnamed dam (South Carolina)	10/10/90	USA	4	D		L
154	unnamed dam (West Germany)	9/77	Germany	0	D		L
155	unnamed dam (Wisconsin)	6/79	USA	2	D		L
156	unnamed dam failure & flash flood (Puerto Rico)	8/79	USA	37	D		L
157	Vaiont Dam	10/9/63	Italy	2000	D		B
158	Valparaíso Dam	8/11/1888	Chile	>100	D		L
159	Vega de Tera Dam	1/9/59	Spain	150	D	U, M	B
160	Virden Creek Dam (Iowa)	7/17/68	USA	1	D		L
161	Wagner [Loop Loop] Dam (Washington)	4/19/38	USA	1	D		L
162	Walnut Grove Dam (Arizona)	2/22/1890	USA	150	D		P
163	Wegee Creek flash flood (near Shadyside, Ohio)	7/19/19	USA	9	Ff		B
164	West Virginia flash floods	11/4f/85	USA	56	Ff		L
165	White River Incident (Washington)	7/76	USA	2	D		L
166	Willow Creek flash flood (Oregon)	1903	USA	200	Ff		L
167	Winston Reservoir (North Carolina)	11/2/04	USA	11	D		P
168	Wise River Dam (Montana)	6/14/27	USA	4	D		L
169	Womack Dam No. 1 (Colorado)	6/27	USA	1	D		L
170	Woodward (Hill) Dam (New Hampshire)	5/29/18	USA	1	D		B
171	Yangtze Kiang River flood	1911	China	100000	Dy, F		L
172	Yangtze Kiang River flood	1931	China	200000	Dy, F		L
173	Yangtze Kiang River flood	1954	China	30000	Dy, F		L
174	Yangtze Kiang River flood	7/81	China	>3000	Dy, F		L
175	Yangtze Kiang River flood	8/98	China	3656	Dy, F		L
176	Zgorigrad Dam (northwestern Bulgaria)	5/1/66	Bulgaria	121	D		L, P

[a] L = loss of life. Values are only preliminary estimates.

[b] Flt = flood type: D = dam failure; Dy = dyke failure; Ff = flash flood; F = flood; Ts = tsunami; S = sea surge; H = hurricane flooding; GB = glacier burst; O = other flooding.

[c] D-M = data set explored by DeKay and McClelland. U = used in their regression; R = rejected as an outlier; M = their treatment is potentially misleading because they combined multiple watersheds, their value for Par, L, or Wt was significantly different from the best historical estimate, and/or L had very little relationship to Par (i.e., Par = residential and L = motorists outside the neighborhoods).

[d] Value: B = characterized in Appendix B; L = lacking key information on Par_i, L_i, or Wt_i; P = looks promising.

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Appendix B

Characterized Flood Events

The complete characterization of every flood event that was studied in detail as part of this investigation was recorded in over 900 pages of single-spaced working documents. These documents followed a specific format developed for this research, but to date they have not been formally published. To summarize and illustrate aspects of these documents, and to supply future researchers with the tools found helpful in producing these documents, four types of information have been published here in Appendix B: 1) an alphabetical list of the events that have been characterized, numbered to provide a key for references in the text, 2) an example of a complete event characterization using the Kelly Barnes Dam failure in Toccoa Falls, Georgia, 3) striking characteristics and valuable quotations (Schvq) from various subPar, and 4) event-specific bibliographies. Due to the nature of these working documents, excerpts found herein will generally not conform to the format found throughout the rest of the report.

Alphabetical list and numeric key

Table B.1 lists every event and every subPar that has been characterized to date. The list is ordered alphabetically by event and in numerical sequence by subPar. Events that were lacking critical information have not been numbered (left column), but every event included in the master table of Appendix C has been numbered consistently here and there. Thus, this list serves as a master index for citations and for cross-referencing. As an example of how the index works, subPar 17.1 refers to the community of Saunders along Buffalo Creek in West Virginia.

Table B.1. Master list and key for every event characterized in the unpublished version of Appendix B

Event	SubPar Name	SubPar #
1	Alla Sella Zerbino Dam Allegheny County Flash Flood: motorists, Saxonburg Blvd. Allegheny and Ohio River Floods Angels Dam	1
2	Anzalduas Dam	1
3	Arás alluvial fan flood (Spain)	1
4	Arno River flood (Italy) Arno River flood (1333)	1
5	Asherville Dam	1
6	Austin, Penn. (Bayless Pulp & Paper Co.) Dam: Austin City	1
6	Austin, Penn. (Bayless Pulp & Paper Co.) Dam: to paper mill Austin, Penn. (Bayless Pulp & Paper Co.) Dam: Costello	2
7	Austin (Colorado River) Dam (Texas)	1
8	Austin, Texas, flash floods: residential	1
8	Austin, Texas, flash floods: Shoal Creek crossings	2
8	Austin, Texas, flash floods: Bee Creek crossing	3
8	Austin, Texas, flash floods: Bull Creek crossing	4
8	Austin, Texas, flash floods: Walnut Creek tributary crossing	5
8	Austin, Texas, flash floods: Hwy 35 and U.S. 183 crossing	6
8	Austin, Texas, flash floods: Dry Creek South crossing Babii Yar Dam	7
9	Baldwin Hills Dam: to Village Green	1
9	Baldwin Hills Dam: other residential	2
9	Baldwin Hills Dam: commercial districts	3
10	Banqiao & Shimantan Dams (China): global event	1
10	Banqiao & Shimantan Dams (China): Shahedian Town	2
10	Banqiao & Shimantan Dams (China): Wencheng commune	3
10	Banqiao & Shimantan Dams (China): Weiwan Brigade	4
11	Bass Haven Lake Dam	1
12	Bat Cave and Chimney Rock Flash Flood	1
13	Bear Wallow	1
14	Bergeron Pond (also Meadow Pond or Alton) Dam	1
15	Big Thompson flood	1
16	Black Hills flash flood: Rapid City below Canyon Lake Dam	1
16	Black Hills flash flood: Rapid Creek & rural Pennington County	2
16	Black Hills flash flood: Keystone on Battle Creek	3
16	Black Hills flash flood: Box Elder on Box Elder Creek	4
16	Black Hills flash flood: Highway 79 where crosses Spring Creek	5

Table B.1. Continued

Event	SubPar Name	SubPar #
16	Black Hills flash flood: Sturgis on Bear Butte Creek	6
16	Black Hills flash flood: 16 widely scattered cities in 3 counties	7
17	Buffalo Creek Dams: Saunders	1
17	Buffalo Creek Dams: backwater up North Fork	2
17	Buffalo Creek Dams: 3 houses 0.4 mi below Saunders	3
17	Buffalo Creek Dams: farm between Saunders/Pardee	4
17	Buffalo Creek Dams: vehicles between Saunders/Pardee	5
17	Buffalo Creek Dams: Lorado and Pardee	6
17	Buffalo Creek Dams: Lundale and Craneco	7
17	Buffalo Creek Dams: Stowe	8
17	Buffalo Creek Dams: Crites	9
17	Buffalo Creek Dams: Latrobe	10
17	Buffalo Creek Dams: Robinette	11
17	Buffalo Creek Dams: Amherstdale and Becco	12
17	Buffalo Creek Dams: Braeholm and Fanco	13
17	Buffalo Creek Dams: Accoville	14
17	Buffalo Creek Dams: Kistler and Crown	15
17	Buffalo Creek Dams: Upper and Lower Man	16
18	Dale Dyke Dam: Bradfield	1
18	Dale Dyke Dam: Bradfield, destroyed	1a
18	Dale Dyke Dam: Bradfield, major damage	1b
18	Dale Dyke Dam: Roebuck House	2
18	Dale Dyke Dam: Damflask	3a
18	Dale Dyke Dam: Damflask, destroyed	3a1
18	Dale Dyke Dam: Damflask, major damage	3a2
18	Dale Dyke Dam: Storrs Bridge	3b
18	Dale Dyke Dam: Loxley and Rowell Bridge	4
18	Dale Dyke Dam: Little Matlock	5
18	Dale Dyke Dam: 1.5 miles of steep, narrow gorge	6
18	Dale Dyke Dam: Harrison’s Tilt & Forge	6a
18	Dale Dyke Dam: Harrison’s house	6b
18	Dale Dyke Dam: Malin Bridge (high force)	7
18	Dale Dyke Dam: Malin Bridge (Ls = H100%)	7a
18	Dale Dyke Dam: Malin Bridge (Ls = M100%)	7b
18	Dale Dyke Dam: Malin Bridge (low force)	8
18	Dale Dyke Dam: Limerick Wheel and houses	9
18	Dale Dyke Dam: Limerick Wheel	9a
18	Dale Dyke Dam: houses above Limerick Wheel	9b

Table B.1. Continued

Event	SubPar Name	SubPar #
18	Dale Dyke Dam: Hillsbro'	10
18	Dale Dyke Dam: Hillsbro', destroyed	10a
18	Dale Dyke Dam: Hillsbro', major damage	10b
18	Dale Dyke Dam: Hillsbro', minor damage	10c
18	Dale Dyke Dam: Hill Bridge	11
18	Dale Dyke Dam: Owlerton	12
18	Dale Dyke Dam: Owlerton, destroyed	12a
18	Dale Dyke Dam: Owlerton, major damage	12b
18	Dale Dyke Dam: Owlerton, minor damage	12c
18	Dale Dyke Dam: across from Owlerton	13
18	Dale Dyke Dam: across from Owlerton, destroyed	13a
18	Dale Dyke Dam: across from Owlerton, minor damage	13b
18	Dale Dyke Dam: works below Par13	14
18	Dale Dyke Dam: Farfield Gardens	15
18	Dale Dyke Dam: Hillfoot	16
18	Dale Dyke Dam: Neepsend Lane	17
18	Dale Dyke Dam: Neepsend downstream of Neepsend Lane	18
18	Dale Dyke Dam: Rutland Road	19
18	Dale Dyke Dam: Harvest and Orchard Lanes	20
18	Dale Dyke Dam: Bacon Island	21
18	Dale Dyke Dam: Bacon Island, destroyed	21a
18	Dale Dyke Dam: Bacon Island, major damage	21b
18	Dale Dyke Dam: Philadelphia District	22
18	Dale Dyke Dam: Green Lane Dist. and area	23
18	Dale Dyke Dam: Long Croft (Ls = H)	24a
18	Dale Dyke Dam: Long Croft (Ls = L)	24b
18	Dale Dyke Dam: Kelham Island	25
18	Dale Dyke Dam: Kelham Island houses	25a
18	Dale Dyke Dam: Kelham Island mill	25b
18	Dale Dyke Dam: adjacent and downstream of Kelham Island	26
18	Dale Dyke Dam: Nursery Lane District	27
18	Dale Dyke Dam: Nursery Lane District, major damage	27a
18	Dale Dyke Dam: Nursery Lane District, minor damage	27b
18	Dale Dyke Dam: Lady's Bridge to Midland Railway Station	28
18	Dale Dyke Dam: Brightside and environs	29
18	Dale Dyke Dam: other/inland Sheffield neighborhoods	30
19	Dry Creek Flash Flood (Train Wreck)	1
20	Eastover Mining Company Sludge Pond Dam	1
21	El Cajoncito Dike (La Paz, BCS, Mexico)	1

Table B.1. Continued

Event	SubPar Name	SubPar #
22	Eldorado Canyon Flash Flood: restaurant	1
22	Eldorado Canyon Flash Flood: trailers swept away	2
22	Eldorado Canyon Flash Flood: trailers with mild damage	3
22	Eldorado Canyon Flash Flood: icehouse	4
22	Eldorado Canyon Flash Flood: half of boat dock nearest shore	5
22	Eldorado Canyon Flash Flood: half of boat dock farthest from shore	6
22	Eldorado Canyon Flash Flood: on Lake Mohave	7
23	Evans and Lockwood Pond Dam: van on highway	1
23	Evans and Lockwood Pond Dam: downtown	2
24	Hyokiri Dam (S. Korea)	1
25	Kansas City Floods: private/public bldgs.	1
25	Kansas City Floods: motorists + pedestrians	2
26	Kelly Barnes Dam: Forrest Hall Dormitory	1
26	Kelly Barnes Dam: Residence Row	2
26	Kelly Barnes Dam: Trailerville	3
26	Kelly Barnes Dam: automotive	4
26	Kelly Barnes Dam: below Hwy. 17 bridge	5
27	Lakeside Dam: Lakeside Road across dam	1
27	Lakeside Dam: houses in Greenville County	2
28	Lee Lake Dam: dwellings destroyed	1
28	Lee Lake Dam: dwellings w/major damage	2
28	Lee Lake Dam: dwellings w/minor damage	3
28	Lee Lake Dam: Clark-Aiken plant (Ls = M100%)	4
29	Mill River Dam: Williamsburg residences (Ls = H)	1
29	Mill River Dam: Williamsburg commercial (Ls = H)	2
29	Mill River Dam: Williamsburg residences (Ls = M)	3
29	Mill River Dam: Williamsburg commercial (Ls = M)	4
29	Mill River Dam: Williamsburg residences (Ls = L)	5
29	Mill River Dam: Skinnerville residences (Ls = H)	6
29	Mill River Dam: Skinnerville commercial (Ls = H)	7
29	Mill River Dam: Skinnerville residences (Ls = M)	8
29	Mill River Dam: Haydenville residences & tobacco co. (Ls = H)	9
29	Mill River Dam: Haydenville commercial (Ls = H)	10
29	Mill River Dam: Haydenville residences (Ls = M)	11
29	Mill River Dam: Haydenville residences & commercial (Ls = L)	12
29	Mill River Dam: Leeds silk factory & boarding house (Ls = H)	13
29	Mill River Dam: Tpar by river/bridge = campers (Ls = H)	13b
29	Mill River Dam: Tpar by river/bridge = waders (Ls = H)	13c
29	Mill River Dam: Leeds button factory (Ls = H)	14

Table B.1. Continued

Event	SubPar Name	SubPar #
29	Mill River Dam: Leeds residences (Ls = H)	15
29	Mill River Dam: Leeds, water closet & Quigley (Ls = M)	16
29	Mill River Dam: Florence (Ls = L)	17
29	Mill River Dam: Northampton (Ls = L)	18
30	Shadyside Flash Floods: Wegee Creek	1
30	Shadyside Flash Floods: Pipe Creek	2
31	St. Francis Dam: Powerhouse No. 2	1
31	St. Francis Dam: ranches	2
31	St. Francis Dam: Castaic Junction	3
31	St. Francis Dam: S. Pac. Section camp near Castaic (tents)	4a
31	St. Francis Dam: S. Pac. Section camp near Castaic (bldgs)	4b
31	St. Francis Dam: Edison tent camp at Kemp	5
31	St. Francis Dam: motorists on Hwy. 126	6
32	Stava Dams (Italy): all destroyed structues in Stava	1
32	Stava Dams (Italy): undamaged Dolomiti Hotel	2
33	Thompson Mill Dam: houses detroyed	1
33	Thompson Mill Dam: houses with major damage	2
33	Thompson Mill Dam: houses with minor damage	3
34	Timber Lake Dam: U.S. 460 Bridge	1
34	Timber Lake Dam: U.S. 460 Bridge (boaters)	1a
34	Timber Lake Dam: Turkey Foot Road Bridge	2
35	Vaiont Dam (Italy): town of Longarone	1
35	Vaiont Dam (Italy): high corner of Longarone	2
35	Vaiont Dam (Italy): Longarone Commune (6 villages)	3
35	Vaiont Dam (Italy): abutments of dam	4
35	Vaiont Dam (Italy): lakeside communities	5
35	Vaiont Dam (Italy): Belluno, 10 mi downstream	6
36	Vega de Tera Dam (Spain)	1
37	Wegee Creek Flash Flood of 1919	1
37	Wegee Creek Flash Flood of 1919: destroyed	1a
38	Woodward (Hill) Dam	1
TOTALS: 38 events included in Appendix A, 179 subPar, and 163 non-duplicate subPar.		

Selected Example: Kelly Barnes Dam failure

What follows is the complete characterization of the Kelly Barnes dam failure that occurred on November 6, 1977 at Toccoa Falls, Georgia. Since it is included here only to illustrate the template style and nature of the characterizations used throughout the unpublished working documents, this case study is presented exactly as it appears in the otherwise unpublished working documents rather than in the traditional thesis format. The illustration ends on page 389, so intermediate headings are part of the example and do not follow the pattern found throughout this thesis. In this example, there are five subPar.

KELLY BARNES DAM FAILURE (TOCCOA FALLS)

DELINEATION OF PAR, LIFE LOSS, AND VARIABLES MORE EASILY PRESENTED THROUGH A GLOBAL ANALYSIS

Par: Toccoa Falls College and Toccoa Creek, Georgia, 1977
Par = 140; L = 39; P = 0.28

There were several dam failures or flash floods in the early 20th and late 19th centuries that impacted relatively small populations located in the 100-year floodplain along narrow river valleys with little or no warning. This event is similar in many ways, providing an excellent opportunity to compare these early failures with a modern failure. Since the fatality rates were comparable, it suggests these early failures should be included in historical studies meant to predict future life loss, so long as housing damages and warning times are adequately defined.

To allow for global commentary and the efficient presentation of variables, many aspects of the flood have been described in this preliminary global overview to avoid cluttering the individual subPar. When one of those subPar uses an *asterisk* (*) it refers to the information contained in this report.

Global Introductory Summary

Kelly Barnes Lake was located about half a mile above the 186-ft high Toccoa Falls near Toccoa City, Georgia. A short distance downstream from the waterfall was the small community of Toccoa Falls. The area impacted by the flood consisted of one-third of Toccoa Falls Institute or Bible College and its faculty, staff, and students. At about 1:20 AM, the dam failed in such a way that it released 2 flood waves over a short interval, the first 5-ft high and the second 30-ft deep. These waves plummeted over the falls, then shot with tremendous speed across the 200-500 ft floodplain to destroy nearly every residence they touched. Individual spouts of water carried debris 65 ft above the normal creek surface as the waves slammed into objects, and as high as 100 ft when a second, 30-ft wave collided with the initial 5-ft wave as it backed upstream behind the bridge on Georgian Highway 17. Since it was night and most people were asleep, the upstream residents had little if any warning. There were, however, a few people who were quick to respond and who ran downstream with urgent cries that reduced the life loss with distance (6).

Source 6 is one of the most detailed texts available on the human drama encountered during a catastrophic flood. Foster begins his narrative with a foreword that includes the following credentials: “I knew most of the people who died and all of those who survived” (6, p. 9). Combined, sources 1 and 6 give a house-by-house account of the flood and the resulting life loss, providing an excellent opportunity to quantify subPar and L_i with high accuracy. Foster also provides an inspiring account of the way faith shaped the attitudes of students and faculty just before they died or after they lost family members.

The subPar were:

1. Those living on the ground level of Forrest Hall, the single men’s dormitory.

2. Those living in Residence Row, a series of houses near the creek.
3. Those living in or adjacent to Trailerville, a cluster of mobile homes occupied by married students and their families.
4. Those occupying vehicles when they were hit by the flood.
5. Those living downstream from Georgia Highway 17 which was 1.5 miles below the falls.

Global Event

Par (Population at Risk) DeKay and McClelland followed the U.S.B.R. in quantifying Par at 250. This value probably came from source 4, which stated, “some 250 persons lived in dormitories, houses and mobile homes at the foot of the falls.” Fortunately, this early ball-park estimate was followed by extremely detailed accounts that allow us to quantify both Par and subPar with more accuracy. The subPar are defined above in the Introductory Summary. Par_1 and Par_4 will be quantified first, followed by Par_2, Par_3, and Par_5 with the help of a table.

The flood hit 7 buildings on the main campus (8). In sequence, they were Gate Cottage, a restaurant; the Bandy residence owned by a former college president; Forrest Hall, a college dormitory; the music building; Morrison Hall, a college dormitory; Ralls Hall, a dormitory for the closed high school (it floated down the creek, p. 112); and a guard house. Fortunately, only Forrest Hall and the Bandy Residence were occupied (6).

Although the flood surrounded the Bandy residence, the main current bypassed this structure (6). Where the Bandy residence would appear on a map, source 8 shows a structure on an oval of high ground that escaped flooding altogether. Apparently, the flooding was quite mild and it might have touched only one side of the building. Only 24-year-old Greg was home, in an upper room 30 ft above the creek. Since this person never had to move and never got wet, and since the flooding did not threaten the integrity of the building, and since this situation was unlike the flooding in any other subPar (6), this single individual will be ignored as one who was never truly threatened.

Par_1, ground-level of Forrest Hall: Forrest Hall was a multi-story men’s dormitory with capacity for 147 students (6; source 2 indicates 140). Based on the flood maps in sources 6 and 8, the building was L-shaped, with only the lower part of the L in the path of the flood (9, also). The flooded portion had 4-stories (6, text and photograph), but since the lowest level was called the “basement” in source 2 and the stem of the L was not flooded, it is likely the stem had only 3 stories. This is significant in quantifying Par_1, since it means that the ground floor was roughly 0.5 – 0.7 times as large as each of the three stories above it, depending on the dimensions of the L.

The ground-floor windows were all broken, but the structural integrity of the building was not compromised and the upper floors were not damaged. Since flood depths reached only 8 ft (9), the first floor could not have had more than a few inches of water, if it got wet at all (9). A post-flood photograph (6, p. 83) confirms this general description. The building was surrounded without warning at night, so no one in the upper floors had time to enter the ground floor and endanger themselves. Moreover, the natural route of escape would have been to exit onto the hillside from the first floor (2, 6, 9). Since there was no damage, essentially no flooding, and no danger above the ground floor, only those on the ground floor should be included in Par_1.

Although the dormitory's capacity was 147, there were 124 students in residence when all were present, with far fewer on the weekends. Foster makes the observation that 75 men could have died had the walls collapsed, so this appears to be his estimate of the weekend occupancy when the wave hit (6). Dividing these 75 occupants proportionally over the 3.5 – 3.7 floors places a preliminary estimate of 11 – 14 students on the smaller ground floor.

There are at least three reasons to assume this range is still too high, however. First, only 124 of the 147 beds were filled, leaving 23 beds unfilled. A disproportionate number of empty beds were probably on the ground floor, since college students generally prefer upper stories with better views.

Second, source 6 mentions the names of only 7 students who were on the ground floor. These were Kenny Carroll, who had been asleep less than an hour after ending a date with Marcy Rees; Bobby Carter and Jon Kerr who caught Carroll running the wrong way and turned him toward the stairwell (all 3 squeezed through the door together); Chuck Dowell, who climbed the stairs to ground level on the uphill side of the building; and Gerry Brittin, Rick Swires, and Cary Hanna who drowned when they were unable to open their room doors against the water. While it is not certain that this accounting was comprehensive, the author did give a comprehensive accounting of every individual in every other structure in which people died. As such, it is highly likely that these were the only 7 students present on the ground floor.

Third, a review of the narratives in sources 6 and 2 (source 2 mentions 4 of these 7 students) reveals that all 7 were alone in their rooms. While the number of rooms is not reported, most dormitories include a mix of double and single-occupancy rooms. Based on the fact that these 7 students were alone in their rooms and the fact that the privilege of a single room was likely balanced by the less-desirable location of the ground floor, it is likely that many of the ground-floor rooms had only one bed.

Overall, then, the range of 11 – 14 is a high estimate, reduced by a disproportionate number of single-occupancy rooms, empty rooms, and a highly credible accounting of those actually present: $Par_1 = 7$, $Tpar_1 = 7$, and $L_1 = 3$.

Par_4, those occupying vehicles: This level of detail is only found in source 6. There were 4 people that encountered the flood while in vehicles.

Before the first flood wave arrived, the creek was high and rising. After having cookies and coffee at Ron Ginther's, firemen David Fledderjohann, Bill Ehrensberger, and Eldon Elsberry decided to move the Sproulls and the Woerners, the two families at the lowest elevation in the residential areas. Elsberry turned to see the first 4- or 5-ft wall of water approaching and shouted a warning. Fledderjahann sent him and Ehrensberger to sound the alarm across the creek. The two men splashed through water to reach the truck, but the truck was pushed sideways before they could reach the bridge. They agreed to abandon the truck, but Ehrensberger hesitated. When he stepped out, his hip boots filled with water and pulled him under to his death. Elsberry grabbed a tree, but it gave way and he was pulled under, too. After getting his boots off, he was pinned to a rock underwater and fought other obstacles, but he eventually made it to shore.

Dee Pinney was a volunteer fireman who worked for Fledderjohann. He stayed behind when the others left the Ginthers', then left at about 1:20 AM. When the power went out, he drove along the creek road toward the approaching flood, looking for an electrician and a fire truck. The water began to trickle 6 inches across the road, but it quickly rose to the floorboards. He tried to back up, but hit a tree and stepped into knee-deep, then waste-deep water. He managed to scramble up the hill on campus.

His sister, Eloise, lived in Trailerville. It is not known with certainty what transpired, but she first called the operator at 1:30, thinking the explosion she heard was the print shop on fire. When she became aware of the flood, she attempted to drive to Upper Trailerville, but the car stalled or was washed away and she drowned: $Par_4 = 4$, $Tpar_4 = 4$, and $L_4 = 2$.

Par_2 and Par_3 can be quantified with the help of a table which summarizes the detailed descriptions in sources 1 and 6. Although details concerning warnings, actions, and words are recorded for virtually every person in the flood, these are largely omitted here for the sake of space. All the deaths can be considered general drowning deaths.

Par_2, Resident Row: There were five houses in residence row (6, p. 113). Beside these, away from the river, was a mobile home with a frame addition (owned by the Ginthers). Based on a photo of where Residence Row once stood (6, p. 84) and commentary in the text, every structure in Residence Row was obliterated, including the Ginthers' residence. As shown in Table B.2, lives were lost in every one of these residences: $Par_2 = 29$, $Tpar_2 = 29$, and $L_2 = 19$.

Par_3, Trailerville and nearby trailers: There is some question as to the number of structures that were flooded. Source 6 shares the estimate from one report that indicated "twenty-seven trailers were swept away" (p. 123). According to source 8, "Approximately nine houses, 18 house trailers, two college buildings, and many motor vehicles were completely demolished. Four houses and five college buildings were damaged by water. Only two houses downstream from Georgia Highway 17 were damaged" (sheet 2). Source 2 indicates that there were "11 houses, 25 trailer homes and various other buildings" at Toccoa Falls Bible College (p. 34), but this says little about the number damaged.

The discrepancies appear to be primarily ones of classification. Sources 6 and 8 each contain a flood map marked with buildings. With respect to the flood zone, they are essentially the same, except that source 8 appears to include some small outbuildings and source 8 adds 2 trailers to an inner row in Trailerville. Ignoring apparent outbuildings, the structures within the flood imprint were as follows:

1. 7 buildings that were either clearly on the main campus or large enough to be college buildings rather than individual residences;
2. 2 large buildings that were only partially flooded and another at the mouth of Trailerville (the latter was probably a wood frame garage and one of the former was probably a maintenance building, both of which were partially destroyed; source 9);
3. 5 houses in a row along Residence Row and 1 residence next to these closer to the bank (sum of Par_2);
4. 4 buildings (source 6 calls them trailers in the text) immediately beyond Residence Row and across the river where the river made a sharp turn to the right; and
5. 22 (6) or 24 (8) residences close by in Trailerville, of which 2 escaped flooding. Trailerville as a whole was "demolished" when the trailers were either smashed or floated away (9, p. 15).

The 27 dwellings classified as trailers by source 6 can be accounted for by the 20 flooded in Trailerville, the 4 just across the river, the trailer/frame-addition associated with Residence Row, and 2 more below Highway 17, not shown on the map. The 27 trailers and 5 frame houses in residence row make a total of 32 single-family dwellings.

Table B.2. Record of Par$_{ij}$, L$_{ij}$, damages, and warning by family/home

<table>
<tr><th colspan="5">PAR$_2$: RESIDENCE ROW and GINTHERS NEXT DOOR</th></tr>
<tr><th>Family Name</th><th>Number Present</th><th>No. of Deaths</th><th>Degree of Damage</th><th>Warning?</th></tr>
<tr><td>David Fledderjohann</td><td>1</td><td>1</td><td>Fireman, no house</td><td>10 – 30 seconds from Elsberry's warning to deadly water.</td></tr>
<tr><td>Pepsney and 3 Sproull girls</td><td>7</td><td>7</td><td>Destroyed</td><td>Center of flood, 1st residence in Residence Row, no evident Wt.</td></tr>
<tr><td>Williams</td><td>2</td><td>2</td><td>Destroyed</td><td>None</td></tr>
<tr><td>Dr. Jerry Sproull</td><td>2</td><td>1</td><td>Destroyed</td><td>Moved 3 girls to Pepsneys' and returned. Then heard Elsberry's warning (above).</td></tr>
<tr><td>Woerners</td><td>5</td><td>2</td><td>Destroyed</td><td>Denise heard thunder of fuses going out, waking up at 1:26. She sensed the dam had broken and ran outside a minute later, then ran through Trailerville shouting and pounding on trailers. Brother, David, initially followed, then ran back for family. They all ran along path of flood, not thinking to run up the mountain.</td></tr>
<tr><td>Veer</td><td>6</td><td>1</td><td>Destroyed</td><td>Saw approaching Ww, but rose to chest by time got family up ladder to attic.</td></tr>
<tr><td>Ginther</td><td>6</td><td>5</td><td>Destroyed</td><td>Ginther a fireman. Ran home, thinking dam had broken. Water to knees after rousing children.</td></tr>
<tr><td>TOTALS:</td><td>29</td><td>19</td><td>100% destroyed</td><td></td></tr>
<tr><th colspan="5">PAR$_3$: TRAILERVILLE</th></tr>
<tr><td>Kemp (1st trailer to go)</td><td>5</td><td>1</td><td></td><td>Mother shouted warning when water already 2 ft deep.</td></tr>
<tr><td>Metzger</td><td>4</td><td>2</td><td></td><td>Awakened by people screaming warnings, but after putting on pants, trailer began to move before could look outside.</td></tr>
<tr><td>Harner</td><td>3</td><td>2</td><td></td><td></td></tr>
<tr><td>Ehrensberger (Bill in Par$_4$)</td><td>5</td><td>4</td><td>destroyed</td><td></td></tr>
<tr><td>Moore</td><td>4</td><td>2</td><td></td><td>None.</td></tr>
<tr><td>Rupp</td><td>2</td><td>1</td><td></td><td>Maybe 20 seconds, based on Sc.</td></tr>
<tr><td>Anderson</td><td>7</td><td>3</td><td>destroyed</td><td>Heard warning from Denise Woerner. Trailer moved after dressed and children roused.</td></tr>
<tr><td>Nicholson</td><td>4</td><td>0</td><td>Destroyed</td><td>Didn't look outside until the flood hit the trailer.</td></tr>
<tr><td>Smith</td><td>3+</td><td>0</td><td></td><td>They were running across the floodplain toward Upper Trailerville when the flood hit them.</td></tr>
<tr><td>Eloise Pinney, Dee Pinney's twin (in Par$_4$)</td><td>1</td><td>Par$_4$</td><td></td><td>She had enough warning to get in her car and attempt to flee before getting caught.</td></tr>
<tr><td>TOTALS:</td><td>---</td><td>15</td><td></td><td></td></tr>
</table>

Based on one interpretation of source 8 (see the quote above), there was an "approximate" total of 13 houses near the college, 2 houses downstream from Highway 17, 18 house trailers, and 7 college buildings, for a total of 33 single-family dwellings. If the 2 houses that were damaged below Highway 17 were included in the 4 (total) houses that were damaged, there were a total of 31 single-family dwellings that were damaged or destroyed.

Source 1 distinguished between "trailers" and "permanent trailers." With respect to "permanent trailers," it appears that source 6 calls them trailers and source 8 calls them houses, accounting for the different subtotals in each source. Source 8 attempts a more detailed accounting of damages, so these will be given precedence, but since the totals from source 8 were admittedly "approximate," and could fall on either side of 32, the total of 32 structures from source 6 will be accepted.

Since the 2 houses below Georgia Highway 17 were spatially removed from Par_3 and they experienced the flood after it was weakened, they are treated as Par_5. Since Eloise Pinney has been included in Par_4, her vacant trailer should be excluded from Par_3. Hence, Par_3 will be based on 32 dwellings, minus the 6 in Par_2, minus the 2 in Par_5, minus Mrs. Pinney's trailer since she was in Par_4 and the trailer was vacant, yielding 23 trailers in Par_3. Of these, 19 trailers were completely destroyed and 4 were damaged.

The trailers held a distinct demographic population, consisting primarily of married students and their children, but also faculty and other college employees (6, 9). While Eloise Pinney has been excluded from Par_3, she nevertheless informs the average occupancy rate in Trailerville. Based on known occupancies, there was an average of 3.88 persons per trailer, including guests and excluding those who were away from home. Applying the average occupancy to the remaining trailers that were flooded yields a total of $34 + (23 - 8)*3.88 = 92$ and $L_3 = 15$ (excluding Par_4).

Par_5, 2 houses below Georgia Highway 17: The 2 damaged houses below Highway 17 form the basis for quantifying Par_5. A debris dam formed behind the bridge, causing the flood to pond until it eroded around each abutment and continued with reduced velocities. In this area, "there was flooding of farm land, local erosion, and bridge damage, but apparently no major damage" (9, p. 13). Flood depths reached 5 – 7 ft on the floodplain. Using the same average as for Par_3, $Par_5 = 8$ and $L_5 = 0$. As indicated under $Tpar_5$, it is highly likely that $Tpar_5 = 8$.

In summary, $Par_1 = Tpar_1 = 7$, $L_1 = 3$; $Par_2 = Tpar_2 = 29$, $L_2 = 19$; $Par_3 = 92$, $Tpar_3 = 64$ (see Tpar), $L_3 = 15$; $Par_4 = Tpar_4 = 4$, $L_4 = 2$; $Par_5 = Tpar_5 = 8$, $L_5 = 0$; and $Par = 7 + 29 + 92 + 4 + 8 = 140$, $Tpar = 7 + 29 + 64 + 4 + 8 = 112$, and $L = 39$.

L ***(Life Loss)*** Some sources report $L = 37$ (3) or $L = 38$ (2, 9), but this is because the reports were immediately after the event (3) or based on the number of recovered bodies. One person, Paul Williams, was swept away with his wife, but his body was never found (1). See Par: $L = 39$ (1, 6, 7, 8).

Tpar (Threatened Population) In addition to 39 fatalities, 60 people were injured (7), meaning over 71% of Par came in contact with dangerous flooding. This helps provide an estimate of Tpar$_3$. Four students escaped from Par$_1$ without injury. Of the 10 survivors from Par$_2$, all were washed out of their homes and all were likely injured. Of the 2 that escaped from Par$_4$, 1 almost died and was probably injured and the other waded to safety without injury before the flooding peaked (6). Based on the calmer currents, lack of damage, and moderate depths in Par$_5$, there would have been few injuries there and probably none.

This leaves 77 survivors in Par$_3$, of which approximately 49 were injured. We know that the warning issued by Denise Woerner allowed a number of people to escape before the flood reached them (see Wt). If 7 out of the 23 families evacuated, it would account for the 77 – 41 = 28 = 7*4 people that escaped injury. This is a reasonable estimate on its face, but we also know that the flood was filled with debris and universally destructive, so those who did not evacuate were highly likely to be swept downstream and killed or injured. Combined, then, 92 – 28 who evacuated = 49 injured + 15 who died = 64 people who were in Tpar$_3$. While an approximation, it is an informed approximation that fits well with the known facts and which should closely approximate the true value for Tpar$_3$: Tpar$_3$ = 64.

Combining this value with those for Tpar$_{1,2,4,5}$ (see Par): Tpar = 7 + 29 + 64 + 4 + 8 = 112.

SubPar

Par$_1$ (Current SubPar) See Par: Par$_1$ = 7, Par$_2$ = 29, Par$_3$ = 104, Par$_4$ = 4, Par$_5$ = 8.
L$_1$ (L Among SubPar) See Par: L$_1$ = 3, L$_2$ = 19, L$_3$ = 15, L$_4$ = 2, L$_5$ = 0.
Tpar$_1$ (Tpar Among subPar) See Par and Tpar: Tpar$_1$ = 7, Tpar$_2$ = 29, Tpar$_3$ = ---, Tpar$_4$ = 4, Tpar$_5$ = 8.

Incremental Losses and Data on Fatalities

Ln, Ldr, Lnf (Natural Channel-, Dam Removal-, No Failure Life Loss) There was high water from the storm, but the flood had begun to go down again prior to failure, so every fatality was a direct result of the dam break: Ln = Lnf = 0 and Ldr = unknown.
Ft (Fatality Type) Ft$_{1\text{-}3}$ = D= 100%; Ft$_4$ = Af = 100%; Ft$_5$ = N
Identification/Location of Fatalities: See Par.
Flood Characteristics

Flt (Flood Type) D

V (Peak Velocity) There is no direct estimate of V, but "Hydrologists on the scene would say only that the water could have been going between 50 and 150 miles per hour [73 – 220 fps]" (6, p. 26). Although these velocities are extremely high, they were a product of the water cascading 186 ft over the falls. The floodplain at the base of the falls was 1/3 to 1/6 as wide as the floodplain downstream, so the water was forced out of the narrow canyon by the water thundering down from above. Even so, by the time the water reached each subPar, it would have slowed to the point that even the lowest end of this range seems improbable. The Metzgers in Trailerville gave a subjective estimate of at least 35 mph (51 fps) as they watched a car wash by (6, p. 76). As a reasonable approximation, $V_{1\text{-}4}$ = 50 fps and V_5 = unknown but much less.

***D* (*Maximum Depth*)** The in-channel depth of the wave was as great as 30 ft (3). The flood rose 8 ft at Forrest Hall, essentially filling the ground floor to the ceiling (9): D_1 = 8 ft. D_3 = 10 ft (9). Downstream of Georgia Highway 17, depths above the floodplain were 5 – 7 ft (9), but they were probably less at the residences. Without more information, the lower estimate will be chosen: D_5 = 5 ft. D_2 and D_4 shared the same area and would have had depths comparable to those in D_3, since they were close together and both were near the channel: D_2 = D_4 = 10 ft.

***Qp* (*Peak Flow Rate*)** Based on statistics and station marks in source 8 and a curve fitting the 4 computed velocities below the falls (y = -10,031*ln(distance in feet) + 107,710), values for Qp$_i$ are shown in Table B.3 below:

Table B.3. Values of Qp by Par$_i$

Drainage Area	Distance Below the Dam	Peak Discharge			Par$_i$	Approx. Dist. of Par$_i$ Below the Dam	Qp$_i$
(mi^2)	(ft)	(mi)	(cfs)		(#)	(ft)	(cfs)
4.6	1,100	0.21	23,000 above falls		1	3,900	24,750
6.2	4,270	0.81	24,000		2	5,300	21,700
8.6	10,860	2.06	14,300		3	6,100	20,300
12.8	23,870	4.52	6,380		4	5,300	21,700
25.5	32,870	6.23	3,660		5	>10,000	---

***Qb* (*Bankfull Flow Rate*)** The peak outflow from Kelly Barnes Dam prior to failure was 400 cfs (8). This threatened the lowest houses in Par$_2$ with flooding and produced minor flooding in Trailerville: Qb = 300 cfs.

***W* (*Maximum Width*)** Based on the flood map in source 8, Wmax/Wmin were as follows: W_1 = 325/325, W_2 = 400/250, W_3 = 600/300, W_4 = 600/250 (because part near Par$_2$ and part near Par$_3$), and W_5 = ---.

***Dv* (*Destructive Velocity*)** Dvmin/Dvmax is as follows: Dv$_1$ = 75/75, Dv$_2$ =53/85 , Dv$_3$ = 33/66, Dv$_4$ = 36/85, and Dv$_5$ = ---.

***R* (*Maximum Rise Rate*)** There were two waves, the first about 5 ft high, followed soon after by another 30 ft above the creek bottom. When the first wave hit the bridge at Georgia Highway 17, it sent a backwash upstream that collided with the second wave.

Observers at $\text{Par}_{2\text{-}4}$ say this collision sent debris 100 ft above the normal level of the creek (6).

The initial surge shot over the falls, fell 186 ft, stalled a second or two until the box canyon at the base filled, and then shot out of the canyon mouth with great velocity and force like a "fire hose" (6, p. 27). The flow had sufficient momentum that outside the main current, the water was actually calm in places. The Brandy residence was spared at the head of the reach and the Metzgers found themselves in stagnant water as they stepped outside in Trailerville. A car raced by them in the flood, traveling at least 35 mph (6, p. 76).

At Residence Row, Eldon Elsberry was standing outside. He "wheeled to see a wave of water four or five feet high rolling along soundlessly like rapids." He shouted, "Look out! There's a wall of water" (6, p. 37). Looking at the sensory clues summarized in the table under Par and expanded upon in source 6, others also saw the wave approaching, but the initial wave did not crash over people's heads or trailers in an instant. Rather, it rose so quickly that they were unable to rouse their families and evacuate before they were trapped. Seconds later, and up to a minute or two, homes disintegrated and the occupants were washed downstream (6). "Most of the damage, at any given place, occurred in about 20 seconds" (6, p. 22).

Overall, then, both waves came initially as walls, but the first wall collapsed enough to resemble fast-rising rapids, rising to full force in less than a minute. Once trapped, there was no escape, and many experienced the full force of the second wall of water: R = Ww, except R_5 = V (see Ww).

Ww (Height of Wall of Water) The largest wall of water was described as 30 ft tall (2, 4), but this was deep in the channel and would have included the depths from previous flooding and the first wave. Since D was substantially less than 30 ft at each subPar, it is more appropriate to equate Ww with D. Since flooding below Georgia Highway 17 was mitigated by the debris dam at the bridge, the wall of water was likely transformed to a very rapidly rising flood in Par_5 (Ww_5 = 0 ft).

Dd (Damage and Destruction) See Par.

Dd_1: The water rushed rapidly and violently through the windows, pinning doors closed before some students could escape. Since the building was brick and near the edge of the flood, the structural integrity of the building was in no way compromised, but in terms of flood dynamics and the impact on the interior, this flood was characteristic of floods causing major damage.

Dd_2: All 6 dwellings were destroyed.

Dd_3: 19 dwellings were destroyed and 4 had major damage.

Dd_4: There were no dwellings, since this subPar was associated with vehicles, but the vehicles were among Par_2 and Par_3, where virtually every structure was swept away and destroyed. Forcefulness should be assigned assuming complete destruction.

Dd_5: Since there was "no major damage" around this subPar (9, p. 13), these 2 dwellings had minor damage.

Fp* *(Proportional Forcefulness) $Fp_1 = 1.0$, $Fp_2 = 1.0$, $Fp_3 = 1.0$, $Fp_4 = 1.0$, $Fp_5 = 0.0$.

Fd* *(Dichotomous Forcefulness) $Fd_1 = 1$, $Fd_2 = 1$, $Fd_3 = 1$, $Fd_4 = 1$, $Fd_5 = 0$.

F_5* *(Incremental Forcefulness) $F5_1 = E$, $F5_2 = E$, $F5_3 = E$, $F5_4 = E$, $F5_5 = L$.

Fpar* *(Forcefulness per SubPar) $Fpar_1 = 0.14$, $Fpar_2 = 0.21$, $Fpar_3 = 0.21$, $Fpar_4 = 0.0$, $Fpar_5 = 0.0$.

H* *(Height of the Dam) Source 3 placed the height at 26 ft. The basis for this is unclear. The Federal Inventory listed the dam height as 20 ft, but measurements after failure indicated that the dam was about 40 ft (9). Source 5 reports that the dam was 42 ft after scouring, 38 ft of which was fill material: H = 38 ft.

Hp* *(Height of Reservoir Pool) Source 9 indicates that there was 1.5 – 2 ft of freeboard below the dam crest, with 3.8 ft of water in the spillway, when the dam failed (9). Source 8 offers a more recent and more detailed estimate, with the maximum water surface before failure at elevation 1,141.6 ft, compared to a low-point crest elevation of about 1,147 ft. The water was dropping at failure, so Hp = H – 6 = 32 ft.

B* *(Breadth of Dam) Source 3 placed the width at 100 – 200 ft. Source 5 puts B at 400 ft, but the section taller than 20 ft was only 200 ft long: B = 200 ft.

Vol* *(Volume of Release) Based on the highest pool elevation prior to failure (some of which was released before the catastrophic failure): Vol = 630 acre-ft (5, 8).

Rf* *(Rate of Failure) There were no witnesses, but, "Apparently failure was sudden. According to residents below the dam, a roar was heard accompanied by popping sounds probably from breaking of trees and the impact of the old crib logs [buried in the center of the dam] on the walls of the gorge" (9, p. 15). Since Fm assumes some erosion and not an instantaneous blowout, Rf > 0.5 min: Rf = 2 min.

A* *(Area of Final Breach) ---

Spatial and Temporal Relationships Between Par_i and the Flood

T* *(Time Summary) The dam failed about 1:20 or 1:30 AM, Sunday, Nov. 6, 1977 (5, 6, 8, 9) and reached the residences shortly afterward. The river rose and then dropped again before that, around 9:00 PM, at the same time the peak reservoir level subsided. This suggests that there may have been a partial, temporary failure prior to the catastrophic break (5).

Td (Time of Day) N
Tw (Time of Week) Wend
Ty (Time of Year) 11
Ts (Time of Season) W

Wt (Warning Time) Denise Woerner somehow sensed the danger when she awoke at 1:26 AM. A minute later she was outside and "As she ran through Trailerville she kept screaming and, according to one report, thumping trailers hard with her open palm. A number of people who were thus awakened were saved" (6, p. 61). Based on the subtleties listed under Sc (in minutes): $Wt_1 = 0$, $Wt_2 = 0.33$, $Wt_3 = 1.5$, $Wt_4 = 0.33$, $Wt_5 = 0$.

Wt_{avg} (Avg. Individual Wt) Based on the subtleties under Sc (in minutes): $Wtavg_1 = 0$, $Wtavg_2 = 0.4$, $Wtavg_3 = 1$, $Wtavg_4 = 0.33$, $Wtavg_5 = 0.25$.

Bt (Building Types, %) See Par_3 under Par. The houses were frame and brick construction (6, p. 50). Treating the trailer with a frame addition as a house and treating "permanent trailers" as trailers, Bt_1 = H = 100%, Bt_2 = R = 100%, Bt_3 = M = 100%, Bt_4 = N, Bt_5 = R or M.

Dev (Development/Urbanization) The flood maps reveal that the majority of dwellings in Toccoa Falls were not flooding (8), making the community a small town, but below Highway 17 there were almost no dwellings: $Dev_{1\text{-}4}$ = L and Dev_5 = N.

Gf (Goodness of Fit) $Gf_{1\text{-}5}$ = H

O (Outdoors) It was night and only Par_4 were outdoors.

Sc (Sensory Clues) Some residents heard the roar of the flood and the popping sound of trees and logs hitting the canyon wall. This enabled some to scramble to safety (6, 9). Nearer the campus, power lines and a transformer fell exploding with sparks (2, 6). Immediately after this, the dark waters turned red from freshly suspended Georgia clay (6).

On the ground floor of Forrest Hall, the first clues were the sights and sounds of the flood itself as it leaked into the dorm rooms or burst the windows (6). For example, Bobby Carter had just finished his nightly Bible reading and was falling asleep when his windowsill fan washed across the room (2): $Sc_1 = 0$.

At Residence Row, firemen Eldon Elsberry, Bill Ehrensberger, and David Fledderjohann were attempting to move the reluctant Sproulls to higher ground since their yard was flooded. The Sproulls moved their daughters to another house and the couple was back home with the firemen on their doorstep when Elsberry saw the first wave coming and shouted a warning. Two of the rescuers attempted to drive across the river to the head of Par_3 to warn others, but as soon as they reached their truck, the wave hit.

This account and the others in the table under Par_2 suggest Sc was about 20 seconds for those who noticed sensory clues, reducing to zero for the children that had to be awakened. The exception was the Woerners, who were alerted by Denise. It is unclear what alerted her, but somehow she knew the dam had failed about 4 minutes before the others. It appears she lived in the second-to-last house in the row and that, apart from her family, she did not warn Par_2 but did warn people in Par_3. Tracing the warnings listed in the table under Par for Par_2 and assigning 0 Wt_i to children that were awakened as the flood hit the houses: Fledderjohann, Mr. and Mrs. Sproull, and Mr. Veer had Sc = 0.33 min; Mr. Ginther had Sc = 1 min; Denise Woerner had Sc = 4 min; David Woerner had Wt_i = 3 min and Sc = 0.33 min.; 3 other Woerners had Wt_i = 1 min and Sc = 0.33 min; and 19 people had Sc = Wt_i = 0 min. Hence, taking a weighted average, Sc_2 rounds to 0.25 min and $Wtavg_2$ = rounds to 0.4 min.

By the time Denise Woerner reached Trailerville, she had only 1 or 2 minutes to pound on trailers and shout warnings. Since people were asleep, it took them a moment to respond. It is unclear how many trailers she reached. She may have reached the Metzgers, Andersons, Smiths, and Pinney (see table under Par), but she did not apparently reach the other families which experienced fatalities. Combined with Denise's warnings and the warnings that propagated through Trailerville, perhaps 2/3 of these residents had some level of verbal warning, and roughly half appear to have escaped without being washed downstream, although this is largely an argument from silence. In terms of Sc alone, it would have been comparable to that for Par_2, but in terms of Wt_{avg}, it would have been on the order of 1 min: $Sc_3 = Sc_2$ = 0.25 min and $Wtavg_3$ = 1 min.

$Sc_4 = Sc_2$ = 0.25 min and Sc_5 = unknown, but phone lines were down so it is reasonable to assign it the same value.

Pr ***(Preparedness)*** Since the flood rose and then fell around 9:00 PM, "Some cars were moved and there was idle talk, but no apprehension" (6, p. 75). The firemen were concerned about flooding because the water covered the only bridge to Trailerville with a foot of water before it began to subside and the creek had flooded before. About 10:30 PM, Ron Ginther mentioned the dam with mild concern, so Ginther and Fledderjohann rode up to take a look. The water appeared far down and the dam appeared safe, so they radioed back that the dam posed no threat. Upon his return, Fledderjohann commented, "It's as normal as ever. I've seen it much higher many times." The water continued to drop until the bridge to Trailerville was no longer submerged (6, p. 36). Despite suggestions to the contrary in some sources, Fledderjohann was warning people of ordinary flooding when the failure occurred, not a potential dam failure: Pr = N.

We ***(Warning Effectiveness)*** Recognizing that although there was often some kind of warning, it was generally not timely in light of Sc and Tpar, We in minutes was: We_1 = N, We_2 = N, We_3 = L, We_4 = N, We_5 = N.

Epar (Evacuation SubPar)* and *Ret (Representative Evacuation Time):

(Epar$_1$) Par$_i$ *(Ret$_1$)* The floodplain was not more than about 500 ft and the distance to high ground was less than half of this for nearly every location, often much less. Hence, Ret$_1$ generally entailed waking up, ascertaining the danger, getting minimally dressed, rousing children, and running a short distance across easily-traversed terrain to safety: Ret1$_{2, 3, 5}$ = 2 min.

Par$_4$, being already outside and aware of the approaching flood, had only to make a quick lateral dash: Ret1$_4$ = 0.33 min.

Evacuation of Forrest Hall did not begin until water crashed through the windows. Evacuation entailed running down the hall and up the stairs to the dry first floor. Those who escaped estimated this flight, through water, as 7 – 10 seconds (6, p. 31). However, the three students who drowned could not open their doors against the water pressure, so their rate of evacuation may have been slower: Ret1$_1$ = 15 seconds = 0.25 min.

E* *(Ease of Evacuation) In minutes: E$_1$ = -0.25, E$_2$ = -1.66, E$_3$ = -1, E$_4$ = 0, E$_5$ = -1.75.

Natural Circumstances that Attend the Flood

Fm* *(Failure Mode) A 12 ft by 30 ft sharp irregularity with sloping trees suggested that the dam face had slumped years or decades prior to 1977 (8, 9). Almost continual seepage had also been evident for some time (8). The dam was also permeated by an extensive root system since it was heavily vegetated and some trees were more than 1 ft in diameter (5). While piping may have contributed, the 1977 failure was most likely dominated by a second flood-induced slump, followed by rapid erosion (5, 9): Fm = Fe.

Ac* *(Attendant Circumstances) N

M* *(Magnitude of Loading) Moderate rains had persisted for 5 days prior to the failure, dropping 5.6 inches on nearby Toccoa. This amount was not unusual (9). The precipitation above the headwaters of Toccoa Creek was greater and was estimated at 7.2 inches. The heaviest rainfall fell between 6:30 and 7:30 PM and return periods for various lengths of time all fell within a range of 2 – 5 years (5, 8): M = L.

Ml* *(Mag. of Loading, Locally) The rainfall was intense at the college in the hours before the failure and there was some flooding (9), the college was built on the floodplain (8): Ml = L.

Human Circumstances that Attend the Flood

Dt* *(Dam Type) The dam was built in 2 to 4 stages over decades, with incomplete historical records. The best summary is found in source 5. The initial stage was a rock-filled log crib (9), but the bulk of the finished dam was earthen (2): Dt = E.

Rr (Rescue Resources) The local fire department and civil defense from nearby Toccoa began rescue efforts before the flood subsided. This was significant in getting the wounded to the County Hospital a quarter mile north (9). National Guard units and helicopters were available later on Sunday. Overall, however, the rescue resources available during the most critical stages of the flood were limited: Rr = L.

Det (Detectability) Local firemen inspected the dam an hour before the failure, but they saw nothing to cause alarm. They were not, however, trained in dam safety (9). Based on the historical slide and the continual seepage (see Fm), there was cause for concern: Det = L.

Schvq (Striking Characteristics and Valuable Quotations): H in every case.

See the opening paragraph at the head of this global overview. The rates of life loss in this event help validate the use of comparable events that occurred prior to the advent of modern transportation, communication, etc., so long as housing damages and warning times are carefully defined.

Despite newspaper articles to the contrary, the dam had not been officially inspected for safety (3, 9).

There was strong attenuation of Qp with distance, as was assumed for the Dale Dyke Dame failure, and as is typical of catastrophic floods. Computed values are listed under Qp.

See Tpar. Among the 4 hardest-hit subPar, 60 out of 93 survivors were injured. This is one of the highest injury rates for any flood, indicating that the warning was generally shorter than the necessary evacuation time and that Tpar ≈ Par.

The fact that the entire community impacted by this event was characterized by an exceptionally strong Christian faith and a resulting strong sense of solidarity seems to have dramatically reduced or eliminated the kinds of psychological debilitation seen in other events with a high rate of community mortality (i.e., see Buffalo Creek). The underlying burden of source 6 was to illustrate this perception by presenting every family that experienced life loss and to present the impressions of those who came in contact with them. First Lady Rosalynn Carter wrote the following introduction:

> This is a story about faith. . . . a personal testimony that there is inherent courage within us to face the challenges of life and death.
>
> I visited Toccoa Falls College on the day after the disaster that you will read about in this book. I went because I hoped that I could comfort those who had survived. Instead I was enveloped by hope and courage and love.
>
> The miracle of Toccoa Falls confirms what I believe. God loves us and will help us always. He gives us unlimited strength when we trust in Him. (6, p. 13)

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KELLY BARNES DAM FAILURE (TOCCOA FALLS)

Par: Par: Toccoa Falls College and Toccoa Creek, Georgia, 1977 = 140

Par$_1$: ground floor of Forrest Hall Dormitory

$L_1 = 3$, $P_1 = 0.43$

Global Event				Subpopulations			
L Life Loss (p)	**P** Proportion of Lives Lost (u)	**Par** Population at Risk (p)	**Tpar** Threatened Population (p)	**L$_i$** Life Loss at Current SubPar (p)	**P$_i$** Proportion at Current SubPar (u)	**Par$_i$** Current SubPar (p)	**Tpar$_i$** Tpar at Current SubPar (p)
39	0.28	140	112	3	0.43	7	7

Incremental Life Loss					Flood Characteristics		
Ln Natural Channel Life L. (p)	**Lnf** Dam Removal Life Loss (p)	**Li$_n$** Incremental L Using Ln (p)	**Li$_{nf}$** Incremental L Using Lnf (p)	**Ft** Fatality Types (N,C,W,E,Af, Aa,D,Sf,O,U)	**Flt** Flood Type (D,Dy,Ff,F,Ts, S,H,Gb,O)	**V** Peak Velocity (ft/s)	**D** Maximum Depth (ft)
0	0	3	3	D$_{100}$	D	50	8

Flood Characteristics (Continued)							
Qp Peak Flow Rate (cfs)	**Qb** Bankful Flow Rate (cfs)	**W** Maximum Width (ft)	**Dv** Destructive Velocity (ft^2/s)	**R** Max. Rise Rate (M,H,V,Ww) (cfs/min)	**Ww** Wall of Water (Height) (ft; 0 --> R)	**Fp** Proportional Forcefulness (0.0 - 1.0)	**Fd** Dichotomous Forcefulness (0 or 1)
24750	300	325/325	75/75	Ww	8	1.0	1

Flood Characteristics (Continued)							
F$_5$ Incremental Forcefulness (L,M,H,V,E)	**Fpar** Forcefulness per SubPar (bldg/p)	**H** Height of Dam (ft)	**Hp** Height of Reservoir (ft)	**B** Breadth of Dam (Crest Length) (ft)	**Vol** Volume of Release (acre-ft)	**Rf** Rate of 80% Failure (min)	**A** Area of Final Breach (ft^2)
E	0.14	38	32	200	630	2	---

Spatial and Temporal Relationships							
Td Time of Day (Night, Home, Separation)	**Tw** Time of Week (Wend or Wday)	**Ty** Time of Year (1 - 12)	**Ts** Time of Season (Summer or Winter)	**Wt** Warning Time (min)	**Wt$_{avg}$** Avg. Individual Warning Time (min)	**Bt** Bldg Types (%) (N,T,Sh,M,R, C,H,Lm)	**Dev** Development (Urbanization) (N,L,M,H)
N	Wend	11	W	0	0	H$_{100}$	L

Spatial and Temporal Relationships (Continued)					
Gf Goodness of Fit (L,M,H,V)	**O** Outdoors (Indoors or Outdoors)	**Sc** Sensory Clues (min)	**Pr** Preparedness (N,L,M,H)	**We** Warning Effectiveness (N,L,M,H)	**E** Ease of Evacuation (min)
H	I	0	N	N	-0.25

Attendant Circumstances							
Fm Failure Mode (Ip,Ie;F,Ff,Ff/D,Fo, Fe;Sp,Se;G,L)	**Ac** Attendant Circumstances (N,L,M,H)	**M** Magnitude of Loading (N,L,M,H,V,E)	**Ml** Magnitude of Local Loading (N,L,M,H,V,E)	**Dt** Dam Type (N,E,R,M,C,A)	**Rr** Rescue Resources (N,L,M,H)	**Det** Detectability (N,L,M,H,V)	**Schvq** Striking . . . (Predictor Fit) (L,H)
Fe	N	L	L	E	L	L	H

Introductory Summary

See the Global Introductory Summary under * (before the individual subPar).

Global Event

Par (Population at Risk) * 140
L (Life Loss) * 39
Tpar (Threatened Population) 112

SubPar

Par_1 (Current SubPar) * 7
L_1 (L Among SubPar) * 3
$Tpar_1$ (Tpar Among subPar) * 7

Incremental Losses and Data on Fatalities

Ln, Ldr, Lnf (Natural Channel-, Dam Removal-, No Failure Life Loss) * Ln = Lnf = 0 and Ldr = unknown.
Ft (Fatality Type) * D = 100%
Identification/Location of Fatalities: See Par *.

Flood Characteristics

Flt (Flood Type) * D
V (Peak Velocity) * 50 ft/s
D (Maximum Depth) * 8 ft
Qp (Peak Flow Rate) * 24,750 cfs
Qb (Bankfull Flow Rate) * 300 cfs
W (Maximum Width) * Wmax/Wmin = 325/325 ft.
Dv (Destructive Velocity) * Dvmin/Dvmax = 75/75 ft^2/s.
R (Maximum Rise Rate) * Ww
Ww (Height of Wall of Water) * 30 ft, but based on D in this case: Ww = 8 ft.
Dd (Damage and Destruction) * Despite the lack of external structural damage, the internal damages were probably sufficient to classify this as major damage. Every window was broken violently and students were washed downstream.
Fp (Proportional Forcefulness) * 1.0
Fd (Dichotomous Forcefulness) * 1
F_5 (Incremental Forcefulness) * E
Fpar (Forcefulness per SubPar) * 0.14
H (Height of the Dam) * 38 ft
Hp (Height of Reservoir Pool) * 32 ft
B (Breadth of Dam) * 200 ft

Vol	***(Volume of Release)***	* 630 ft
Rf	***(Rate of Failure)***	* 2 min
A	***(Area of Final Breach)***	---

Spatial and Temporal Relationships Between Par$_i$ and the Flood

T	***(Time Summary)***	The dam failed about 1:20 or 1:30 AM, Sunday, Nov. 6, 1977 (5, 6, 8, 9) and reached the residences shortly afterward. The river rose and then dropped again before that, around 9:00 PM, at the same time the peak reservoir level subsided. This suggests that there may have been a partial, temporary failure prior to the catastrophic break (5).
Td	***(Time of Day)***	N
Tw	***(Time of Week)***	Wend
Ty	***(Time of Year)***	11
Ts	***(Time of Season)***	W
Wt	***(Warning Time)***	* 0 min
Wt_{avg}	***(Avg. Individual Wt)***	* 0 min
Bt	***(Building Types, %)***	* H = 100%
Dev	***(Development/Urbanization)***	* L
Gf	***(Goodness of Fit)***	* H
O	***(Outdoors)***	* I
Sc	***(Sensory Clues)***	* 0 min
Pr	***(Preparedness)***	* N
We	***(Warning Effectiveness)***	* N
Epar	***(Evacuation SubPar)*** **and** ***Ret***	***(Representative Evacuation Time):***
	(Epar$_1$) Par$_i$	*(Ret$_1$)* * 0.25 min
E	***(Ease of Evacuation)***	* -0.25 min

Natural Circumstances that Attend the Flood

Fm	***(Failure Mode)***	* Fe
Ac	***(Attendant Circumstances)***	* N
M	***(Magnitude of Loading)***	* L
Ml	***(Mag. of Loading, Locally)***	* L

Human Circumstances that Attend the Flood

Dt	***(Dam Type)***	* E
Rr	***(Rescue Resources)***	* L
Det	***(Detectability)***	* L
Schvq	***(Striking Characteristics and Valuable Quotations):***	* H

Case Bibliography

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KELLY BARNES DAM FAILURE (TOCCOA FALLS)

Par: Par: Toccoa Falls College and Toccoa Creek, Georgia, 1977 = 140

Par$_2$: those in or adjacent to Residence Row, apart from Par$_4$

$L_2 = 19$, $P_2 = 0.66$

Global Event				Subpopulations			
L Life Loss (p)	**P** Proportion of Lives Lost (u)	**Par** Population at Risk (p)	**Tpar** Threatened Population (p)	**L_i** Life Loss at Current SubPar (p)	**P_i** Proportion at Current SubPar (u)	**Par_i** Current SubPar (p)	**$Tpar_i$** Tpar at Current SubPar (p)
39	0.28	140	112	19	0.66	29	29

Incremental Life Loss					Flood Characteristics		
Ln Natural Channel Life L. (p)	**Lnf** Dam Removal Life Loss (p)	**Li_n** Incremental L Using Ln (p)	**Li_{nf}** Incremental L Using Lnf (p)	**Ft** Fatality Types (N,C,W,E,Af, Aa,D,Sf,O,U)	**Flt** Flood Type (D,Dy,Ff,F,Ts, S,H,Gb,O)	**V** Peak Velocity (ft/s)	**D** Maximum Depth (ft)
0	0	19	19	D_{100}	D	50	10

Flood Characteristics (Continued)							
Qp Peak Flow Rate (cfs)	**Qb** Bankful Flow Rate (cfs)	**W** Maximum Width (ft)	**Dv** Destructive Velocity (ft^2/s)	**R** Max. Rise Rate (M,H,V,Ww) (cfs/min)	**Ww** Wall of Water (Height) (ft; 0 --> R)	**Fp** Proportional Forcefulness (0.0 - 1.0)	**Fd** Dichotomous Forcefulness (0 or 1)
21700	300	400/260	58/85	Ww	10	1.0	1

Flood Characteristics (Continued)							
F_5 Incremental Forcefulness (L,M,H,V,E)	**Fpar** Forcefulness per SubPar (bldg/p)	**H** Height of Dam (ft)	**Hp** Height of Reservoir (ft)	**B** Breadth of Dam (Crest Length) (ft)	**Vol** Volume of Release (acre-ft)	**Rf** Rate of 80% Failure (min)	**A** Area of Final Breach (ft^2)
E	0.21	38	32	200	630	2	---

Spatial and Temporal Relationships							
Td Time of Day (Night, Home, Separation)	**Tw** Time of Week (Wend or Wday)	**Ty** Time of Year (1 - 12)	**Ts** Time of Season (Summer or Winter)	**Wt** Warning Time (min)	**Wt_{avg}** Avg. Individual Warning Time (min)	**Bt** Bldg Types (%) (N,T,Sh,M,R, C,H,Lm)	**Dev** Development (Urbanization) (N,L,M,H)
N	Wend	11	W	0.33	0.4	R_{100}	L

Spatial and Temporal Relationships (Continued)					
Gf Goodness of Fit (L,M,H,V)	**O** Outdoors (Indoors or Outdoors)	**Sc** Sensory Clues (min)	**Pr** Preparedness (N,L,M,H)	**We** Warning Effectiveness (N,L,M,H)	**E** Ease of Evacuation (min)
H	I	0.25	N	N	-1.66

Attendant Circumstances							
Fm Failure Mode (Ip,Ie;F,Ff,Ff/D,Fo, Fe;Sp,Se;G,L)	**Ac** Attendant Circumstances (N,L,M,H)	**M** Magnitude of Loading (N,L,M,H,V,E)	**Ml** Magnitude of Local Loading (N,L,M,H,V,E)	**Dt** Dam Type (N,E,R,M,C,A)	**Rr** Rescue Resources (N,L,M,H)	**Det** Detectability (N,L,M,H,V)	**Schvq** Striking . . . (Predictor Fit) (L,H)
Fe	N	L	L	E	L	L	H

Introductory Summary

See the Global Introductory Summary under * (before the individual subPar).

Global Event

Par (Population at Risk)	* 140
L (Life Loss)	* 39
Tpar (Threatened Population)	* 112

SubPar

Par$_2$ ***(Current SubPar)***	* 29
L$_2$ ***(L Among SubPar)***	* 19
Tpar$_2$ ***(Tpar Among subPar)***	* 29

Incremental Losses and Data on Fatalities

Ln, Ldr, Lnf (Natural Channel-, Dam Removal-, No Failure Life Loss) * Ln = Lnf = 0 and Ldr = unknown.

Ft (Fatality Type) * D = 100%

Identification/Location of Fatalities: See Par *.

Flood Characteristics

Flt (Flood Type)	* D
V (Peak Velocity)	* 50 ft/s
D (Maximum Depth)	* 10 ft
Qp (Peak Flow Rate)	* 21,700 cfs
Qb (Bankfull Flow Rate)	* 300 cfs
W (Maximum Width)	* Wmax/Wmin = 400/260 ft.
Dv (Destructive Velocity)	* Dvmin/Dvmax = 58/85 ft^2/s.
R (Maximum Rise Rate)	* Ww
Ww (Height of Wall of Water)	* 30 ft, but adjusted to match D: Ww = 10 ft.
Dd (Damage and Destruction)	* All 6 residences were destroyed.
Fp (Proportional Forcefulness)	* 1.0
Fd (Dichotomous Forcefulness)	* 1
F$_5$ ***(Incremental Forcefulness)***	* E
Fpar (Forcefulness per SubPar)	* 0.21
H (Height of the Dam)	* 38 ft
Hp (Height of Reservoir Pool)	* 32 ft
B (Breadth of Dam)	* 200 ft
Vol (Volume of Release)	* 630 ft
Rf (Rate of Failure)	* 2 min
A (Area of Final Breach)	---

Spatial and Temporal Relationships Between Par_i and the Flood

T (Time Summary) The dam failed about 1:20 or 1:30 AM, Sunday, Nov. 6, 1977 (5, 6, 8, 9) and reached the residences shortly afterward. The river rose and then dropped again before that, around 9:00 PM, at the same time the peak reservoir level subsided. This suggests that there may have been a partial, temporary failure prior to the catastrophic break (5).

Td (Time of Day) N
Tw (Time of Week) Wend
Ty (Time of Year) 11
Ts (Time of Season) W
Wt (Warning Time) * 0.33 min
Wt_{avg} (Avg. Individual Wt) * 0.4 min
Bt (Building Types, %) * R = 100%
Dev (Development/Urbanization) * L
Gf (Goodness of Fit) * H
O (Outdoors) * I
Sc (Sensory Clues) * 0.25 min
Pr (Preparedness) * N
We (Warning Effectiveness) * N
Epar (Evacuation SubPar)* and *Ret (Representative Evacuation Time):
($Epar_1$) Par_i *(Ret_1)* * 2 min
E (Ease of Evacuation) * -1.66 min

Natural Circumstances that Attend the Flood

Fm (Failure Mode) * Fe
Ac (Attendant Circumstances) * N
M (Magnitude of Loading) * L
Ml (Mag. of Loading, Locally) * L

Human Circumstances that Attend the Flood

Dt (Dam Type) * E
Rr (Rescue Resources) * L
Det (Detectability) * L
Schvq (Striking Characteristics and Valuable Quotations): * H

Daniel Woerner, a young soccer player, reached shore as the flood rose around him by jumping from one car roof to the next before the vehicles became mobile (6).

People do not always take the safest or shortest route to safety in a flood. As an example, the Woerners ran downstream along the road that paralleled the river, never once thinking to run laterally up the mountain to high ground (6, p. 61). This was, however, unusual.

Ten-year-old Kirk Veer survived by opening the door to a truck that passed by him underwater and climbing in to breath the bubble of air inside. Later, he reemerged to rise to the surface (6, p. 67).

Case Bibliography

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KELLY BARNES DAM FAILURE (TOCCOA FALLS)
Par: Par: Toccoa Falls College and Toccoa Creek, Georgia, 1977 = 140
Par_3: Trailerville and closely-associated trailers across the river
L_3 = 15, P_3 = 0.16

Global Event				Subpopulations			
L Life Loss (p)	**P** Proportion of Lives Lost (u)	**Par** Population at Risk (p)	**Tpar** Threatened Population (p)	**L_i** Life Loss at Current SubPar (p)	**P_i** Proportion at Current SubPar (u)	**Par_i** Current SubPar (p)	**$Tpar_i$** Tpar at Current SubPar (p)
39	0.28	140	112	15	0.16	92	64

Incremental Life Loss					Flood Characteristics		
Ln Natural Channel Life L. (p)	**Lnf** Dam Removal Life Loss (p)	**Li_n** Incremental L Using Ln (p)	**Li_{nf}** Incremental L Using Lnf (p)	**Ft** Fatality Types (N,C,W,E,Af, Aa,D,Sf,O,U)	**Flt** Flood Type (D,Dy,Ff,F,Ts, S,H,Gb,O)	**V** Peak Velocity (ft/s)	**D** Maximum Depth (ft)
0	0	15	15	D_{100}	D	50	10

Flood Characteristics (Continued)							
Qp Peak Flow Rate (cfs)	**Qb** Bankful Flow Rate (cfs)	**W** Maximum Width (ft)	**Dv** Destructive Velocity (ft^2/s)	**R** Max. Rise Rate (M,H,V,Ww) (cfs/min)	**Ww** Wall of Water (Height) (ft; 0 --> R)	**Fp** Proportional Forcefulness (0.0 - 1.0)	**Fd** Dichotomous Forcefulness (0 or 1)
20300	300	600/300	33/66	Ww	10	1.0	1

Flood Characteristics (Continued)							
F_5 Incremental Forcefulness (L,M,H,V,E)	**Fpar** Forcefulness per SubPar (bldg/p)	**H** Height of Dam (ft)	**Hp** Height of Reservoir (ft)	**B** Breadth of Dam (Crest Length) (ft)	**Vol** Volume of Release (acre-ft)	**Rf** Rate of 80% Failure (min)	**A** Area of Final Breach (ft^2)
E	0.21	38	32	200	630	2	---

Spatial and Temporal Relationships							
Td Time of Day (Night, Home, Separation)	**Tw** Time of Week (Wend or Wday)	**Ty** Time of Year (1 - 12)	**Ts** Time of Season (Summer or Winter)	**Wt** Warning Time (min)	**Wt_{avg}** Avg. Individual Warning Time (min)	**Bt** Bldg Types (%) (N,T,Sh,M,R, C,H,Lm)	**Dev** Development (Urbanization) (N,L,M,H)
N	Wend	11	W	1.5	1	M_{100}	L

Spatial and Temporal Relationships (Continued)					
Gf Goodness of Fit (L,M,H,V)	**O** Outdoors (Indoors or Outdoors)	**Sc** Sensory Clues (min)	**Pr** Preparedness (N,L,M,H)	**We** Warning Effectiveness (N,L,M,H)	**E** Ease of Evacuation (min)
H	I	0.25	N	L	-1

Attendant Circumstances							
Fm Failure Mode (Ip,Ie;F,Ff,Ff/D,Fo, Fe;Sp,Se;G,L)	**Ac** Attendant Circumstances (N,L,M,H)	**M** Magnitude of Loading (N,L,M,H,V,E)	**Ml** Magnitude of Local Loading (N,L,M,H,V,E)	**Dt** Dam Type (N,E,R,M,C,A)	**Rr** Rescue Resources (N,L,M,H)	**Det** Detectability (N,L,M,H,V)	**Schvq** Striking . . . (Predictor Fit) (L,H)
Fe	N	L	L	E	L	L	H

Introductory Summary

See the Global Introductory Summary under * (before the individual subPar).

Global Event

Par	***(Population at Risk)***	* 140
L	***(Life Loss)***	* 39
Tpar	***(Threatened Population)***	* 112

SubPar

Par_3	***(Current SubPar)***	* 92
L_3	***(L Among SubPar)***	* 15
$Tpar_3$	***(Tpar Among subPar)***	* 64

Incremental Losses and Data on Fatalities

Ln, Ldr, Lnf (Natural Channel-, Dam Removal-, No Failure Life Loss) * Ln = Lnf = 0 and Ldr = unknown.

Ft (Fatality Type) * D = 100%

Identification/Location of Fatalities: See Par *.

Flood Characteristics

Flt	***(Flood Type)***	* D
V	***(Peak Velocity)***	* 50 ft/s
D	***(Maximum Depth)***	* 10 ft
Qp	***(Peak Flow Rate)***	* 20,300 cfs
Qb	***(Bankfull Flow Rate)***	* 300 cfs
W	***(Maximum Width)***	* Wmax/Wmin = 600/300 ft.
Dv	***(Destructive Velocity)***	* Dvmin/Dvmax = 33/66 ft^2/s.
R	***(Maximum Rise Rate)***	* Ww
Ww	***(Height of Wall of Water)***	* 10 ft
Dd	***(Damage and Destruction)***	* 19 mobile homes were destroyed and 4 had major damage.
Fp	***(Proportional Forcefulness)***	* 1.0
Fd	***(Dichotomous Forcefulness)***	* 1
F_5	***(Incremental Forcefulness)***	* E
Fpar	***(Forcefulness per SubPar)***	* 0.21
H	***(Height of the Dam)***	* 38 ft
Hp	***(Height of Reservoir Pool)***	* 32 ft
B	***(Breadth of Dam)***	* 200 ft
Vol	***(Volume of Release)***	* 630 ft

Rf	***(Rate of Failure)***	* 2 min
A	***(Area of Final Breach)***	---

Spatial and Temporal Relationships Between Par$_i$ and the Flood

T	***(Time Summary)***	The dam failed about 1:20 or 1:30 AM, Sunday, Nov. 6, 1977 (5, 6, 8, 9) and reached the residences shortly afterward. The river rose and then dropped again before that, around 9:00 PM, at the same time the peak reservoir level subsided. This suggests that there may have been a partial, temporary failure prior to the catastrophic break (5).
Td	***(Time of Day)***	N
Tw	***(Time of Week)***	Wend
Ty	***(Time of Year)***	11
Ts	***(Time of Season)***	W
Wt	***(Warning Time)***	* 1.5 min
Wt$_{avg}$	***(Avg. Individual Wt)***	* 1 min
Bt	***(Building Types, %)***	* M = 100%
Dev	***(Development/Urbanization)***	* L
Gf	***(Goodness of Fit)***	* H
O	***(Outdoors)***	* I
Sc	***(Sensory Clues)***	* 0.25 min
Pr	***(Preparedness)***	* N
We	***(Warning Effectiveness)***	* L
Epar	***(Evacuation SubPar)*** **and** ***Ret*** ***(Representative Evacuation Time):***	
	(Epar$_1$) Par$_i$	*(Ret$_1$)* * 2 min
E	***(Ease of Evacuation)***	* -1 min

Natural Circumstances that Attend the Flood

Fm	***(Failure Mode)***	* Fe
Ac	***(Attendant Circumstances)***	* N
M	***(Magnitude of Loading)***	* L
Ml	***(Mag. of Loading, Locally)***	* L

Human Circumstances that Attend the Flood

Dt	***(Dam Type)***	* E
Rr	***(Rescue Resources)***	* L
Det	***(Detectability)***	* L
Schvq	***(Striking Characteristics and Valuable Quotations):***	* H

Where the main channel curved, water-surface elevations on the left bank exceeded those on the right bank by as much as 10 ft due to superelevation. Even in these high velocity areas, however, there were calm waters in the backwaters of creek mouths (8).

Mobile homes generally stayed intact as they floated away, unless they hit another mobile home or other obstacle in the water. In that case, they disintegrated (6).

Case Bibliography

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KELLY BARNES DAM FAILURE (TOCCOA FALLS)

Par: Par: Toccoa Falls College and Toccoa Creek, Georgia, 1977 = 140

Par$_4$: those known to be in automobiles when the flood hit

$L_4 = 2$, $P_4 = 0.5$

Global Event				Subpopulations			
L Life Loss (p)	**P** Proportion of Lives Lost (u)	**Par** Population at Risk (p)	**Tpar** Threatened Population (p)	**L_i** Life Loss at Current SubPar (p)	**P_i** Proportion at Current SubPar (u)	**Par_i** Current SubPar (p)	**$Tpar_i$** Tpar at Current SubPar (p)
39	0.28	140	112	2	0.5	4	4

Incremental Life Loss					Flood Characteristics		
Ln Natural Channel Life L. (p)	**Lnf** Dam Removal Life Loss (p)	**Li_n** Incremental L Using Ln (p)	**Li_{nf}** Incremental L Using Lnf (p)	**Ft** Fatality Types (N,C,W,E,Af, Aa,D,Sf,O,U)	**Flt** Flood Type (D,Dy,Ff,F,Ts, S,H,Gb,O)	**V** Peak Velocity (ft/s)	**D** Maximum Depth (ft)
0	0	2	2	Af$_{100}$	D	50	10

Flood Characteristics (Continued)							
Qp Peak Flow Rate (cfs)	**Qb** Bankful Flow Rate (cfs)	**W** Maximum Width (ft)	**Dv** Destructive Velocity (ft^2/s)	**R** Max. Rise Rate (M,H,V,Ww) (cfs/min)	**Ww** Wall of Water (Height) (ft; 0 --> R)	**Fp** Proportional Forcefulness (0.0 - 1.0)	**Fd** Dichotomous Forcefulness (0 or 1)
21700	300	600/250	36/85	Ww	10	1.0	1

Flood Characteristics (Continued)							
F_5 Incremental Forcefulness (L,M,H,V,E)	**Fpar** Forcefulness per SubPar (bldg/p)	**H** Height of Dam (ft)	**Hp** Height of Reservoir (ft)	**B** Breadth of Dam (Crest Length) (ft)	**Vol** Volume of Release (acre-ft)	**Rf** Rate of 80% Failure (min)	**A** Area of Final Breach (ft^2)
E	0.0	38	32	200	630	2	---

Spatial and Temporal Relationships							
Td Time of Day (Night, Home, Separation)	**Tw** Time of Week (Wend or Wday)	**Ty** Time of Year (1 - 12)	**Ts** Time of Season (Summer or Winter)	**Wt** Warning Time (min)	**Wt_{avg}** Avg. Individual Warning Time (min)	**Bt** Bldg Types (%) (N,T,Sh,M,R, C,H,Lm)	**Dev** Development (Urbanization) (N,L,M,H)
N	Wend	11	W	0.33	0.33	N	L

Spatial and Temporal Relationships (Continued)					
Gf Goodness of Fit (L,M,H,V)	**O** Outdoors (Indoors or Outdoors)	**Sc** Sensory Clues (min)	**Pr** Preparedness (N,L,M,H)	**We** Warning Effectiveness (N,L,M,H)	**E** Ease of Evacuation (min)
H	O	0.25	N	N	0

Attendant Circumstances							
Fm Failure Mode (Ip,Ie;F,Ff,Ff/D,Fo, Fe;Sp,Se;G,L)	**Ac** Attendant Circumstances (N,L,M,H)	**M** Magnitude of Loading (N,L,M,H,V,E)	**Ml** Magnitude of Local Loading (N,L,M,H,V,E)	**Dt** Dam Type (N,E,R,M,C,A)	**Rr** Rescue Resources (N,L,M,H)	**Det** Detectability (N,L,M,H,V)	**Schvq** Striking . . . (Predictor Fit) (L,H)
Fe	N	L	L	E	L	L	H

Introductory Summary

See the Global Introductory Summary under * (before the individual subPar).

Global Event

Par	***(Population at Risk)***	* 140
L	***(Life Loss)***	* 39
Tpar	***(Threatened Population)***	* 112

SubPar

Par$_4$	***(Current SubPar)***	* 4
L$_4$	***(L Among SubPar)***	* 2
Tpar$_4$	***(Tpar Among subPar)***	* 4

Incremental Losses and Data on Fatalities

Ln, Ldr, Lnf (Natural Channel-, Dam Removal-, No Failure Life Loss) * Ln = Lnf = 0 and Ldr = unknown.

Ft (Fatality Type) * Af = 100%

Identification/Location of Fatalities: See Par *.

Flood Characteristics

Flt	***(Flood Type)***	* D
V	***(Peak Velocity)***	* 50 ft/s
D	***(Maximum Depth)***	* 10 ft
Qp	***(Peak Flow Rate)***	* 21,700 cfs
Qb	***(Bankfull Flow Rate)***	* 300 cfs
W	***(Maximum Width)***	* Wmax/Wmin = 600/250 ft.
Dv	***(Destructive Velocity)***	* Dvmin/Dvmax = 36/85 ft^2/s.
R	***(Maximum Rise Rate)***	* Ww
Ww	***(Height of Wall of Water)***	* 30 ft, but adjusted for D: Ww = 10 ft.
Dd	***(Damage and Destruction)***	* This subPar was automotive, but the cars were very near to buildings in Par$_2$ and Par$_3$ where virtually every structure was destroyed.
Fp	***(Proportional Forcefulness)***	* 1.0
Fd	***(Dichotomous Forcefulness)***	* 1
F$_5$	***(Incremental Forcefulness)***	* E
Fpar	***(Forcefulness per SubPar)***	* No buildings: Fpar = 0.0.
H	***(Height of the Dam)***	* 38 ft
Hp	***(Height of Reservoir Pool)***	* 32 ft
B	***(Breadth of Dam)***	* 200 ft
Vol	***(Volume of Release)***	* 630 ft
Rf	***(Rate of Failure)***	* 2 min
A	***(Area of Final Breach)***	---

Spatial and Temporal Relationships Between Par$_i$ and the Flood

T	***(Time Summary)***	The dam failed about 1:20 or 1:30 AM, Sunday, Nov. 6, 1977 (5, 6, 8, 9) and reached the residences shortly afterward. The river rose and then dropped again before that, around 9:00 PM, at the same time the peak reservoir level subsided. This suggests that there may have been a partial, temporary failure prior to the catastrophic break (5).
Td	***(Time of Day)***	N
Tw	***(Time of Week)***	Wend
Ty	***(Time of Year)***	11
Ts	***(Time of Season)***	W
Wt	***(Warning Time)***	* 0.33 min
Wt_{avg}	***(Avg. Individual Wt)***	* 0.33 min
Bt	***(Building Types, %)***	* N
Dev	***(Development/Urbanization)***	* L
Gf	***(Goodness of Fit)***	* H
O	***(Outdoors)***	* O
Sc	***(Sensory Clues)***	* 0.25 min
Pr	***(Preparedness)***	* N
We	***(Warning Effectiveness)***	* N
Epar	***(Evacuation SubPar)*** **and** ***Ret***	***(Representative Evacuation Time):***
	(Epar$_1$) Par$_i$	*(Ret$_1$)* * 0.25 min
E	***(Ease of Evacuation)***	* 0 min

Natural Circumstances that Attend the Flood

Fm	***(Failure Mode)***	* Fe
Ac	***(Attendant Circumstances)***	* N
M	***(Magnitude of Loading)***	* L
Ml	***(Mag. of Loading, Locally)***	* L

Human Circumstances that Attend the Flood

Dt	***(Dam Type)***	* E
Rr	***(Rescue Resources)***	* L
Det	***(Detectability)***	* L
Schvq	***(Striking Characteristics and Valuable Quotations):***	* H

In the case of the firemen, their hip boots helped to pull them under (6). A similar danger could apply to fishermen wearing waders.

Case Bibliography

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KELLY BARNES DAM FAILURE (TOCCOA FALLS)
Par: Par: Toccoa Falls College and Toccoa Creek, Georgia, 1977 = 140
Par$_5$: 2 houses below Georgia Highway 17
$L_5 = 0, P_5 = 0.0$

Global Event				Subpopulations			
L	**P**	**Par**	**Tpar**	**L_i**	**P_i**	**Par_i**	**$Tpar_i$**
Life Loss (p)	Proportion of Lives Lost (u)	Population at Risk (p)	Threatened Population (p)	Life Loss at Current SubPar (p)	Proportion at Current SubPar (u)	Current SubPar (p)	Tpar at Current SubPar (p)
39	0.28	140	112	0	0.0	8	8

Incremental Life Loss					Flood Characteristics		
Ln	**Lnf**	**Li_n**	**Li_{nf}**	**Ft**	**Flt**	**V**	**D**
Natural Channel Life L. (p)	Dam Removal Life Loss (p)	Incremental L Using Ln (p)	Incremental L Using Lnf (p)	Fatality Types (N,C,W,E,Af, Aa,D,Sf,O,U)	Flood Type (D,Dy,Ff,F,Ts, S,H,Gb,O)	Peak Velocity (ft/s)	Maximum Depth (ft)
0	0	0	0	N	D	---	5

Flood Characteristics (Continued)							
Qp	**Qb**	**W**	**Dv**	**R**	**Ww**	**Fp**	**Fd**
Peak Flow Rate (cfs)	Bankful Flow Rate (cfs)	Maximum Width (ft)	Destructive Velocity (ft^2/s)	Max. Rise Rate (M,H,V,Ww) (cfs/min)	Wall of Water (Height) (ft; 0 --> R)	Proportional Forcefulness (0.0 - 1.0)	Dichotomous Forcefulness (0 or 1)
---	300	---	---	V	0	1.0	1

Flood Characteristics (Continued)							
F_5	**Fpar**	**H**	**Hp**	**B**	**Vol**	**Rf**	**A**
Incremental Forcefulness (L,M,H,V,E)	Forcefulness per SubPar (bldg/p)	Height of Dam (ft)	Height of Reservoir (ft)	Breadth of Dam (Crest Length) (ft)	Volume of Release (acre-ft)	Rate of 80% Failure (min)	Area of Final Breach (ft^2)
E	0.14	38	32	200	630	2	---

Spatial and Temporal Relationships							
Td	**Tw**	**Ty**	**Ts**	**Wt**	**Wt_{avg}**	**Bt**	**Dev**
Time of Day (Night, Home, Separation)	Time of Week (Wend or Wday)	Time of Year (1 - 12)	Time of Season (Summer or Winter)	Warning Time (min)	Avg. Individual Warning Time (min)	Bldg Types (%) (N,T,Sh,M,R, C,H,Lm)	Development (Urbanization) (N,L,M,H)
N	Wend	11	W	0	0.25	R or M	L

Spatial and Temporal Relationships (Continued)					
Gf	**O**	**Sc**	**Pr**	**We**	**E**
Goodness of Fit (L,M,H,V)	Outdoors (Indoors or Outdoors)	Sensory Clues (min)	Preparedness (N,L,M,H)	Warning Effectiveness (N,L,M,H)	Ease of Evacuation (min)
H	I	0.25	N	N	-1.75

Attendant Circumstances							
Fm	**Ac**	**M**	**Ml**	**Dt**	**Rr**	**Det**	**Schvq**
Failure Mode (Ip,Ie;F,Ff,Ff/D,Fo, Fe;Sp,Se;G,L)	Attendant Circumstances (N,L,M,H)	Magnitude of Loading (N,L,M,H,V,E)	Magnitude of Local Loading (N,L,M,H,V,E)	Dam Type (N,E,R,M,C,A)	Rescue Resources (N,L,M,H)	Detectability (N,L,M,H,V)	Striking . . . (Predictor Fit) (L,H)
Fe	N	L	L	E	L	L	H

Introductory Summary

See the Global Introductory Summary under * (before the individual subPar).

Global Event

Par (Population at Risk) * 140
L (Life Loss) * 39
Tpar (Threatened Population) * 112

SubPar

Par_5 (Current SubPar) * 8
L_5 (L Among SubPar) * 0
$Tpar_5$ (Tpar Among subPar) See Par_5 under Par *. There is no direct historical account of these two families. Nevertheless, since Sc was on the order of 0.25 minutes or less, riverside phones were knocked out by the flood, nobody lived nearby to issue a verbal warning, and the families would have been asleep, it is highly unlikely that these families evacuated before being flooded: $Tpar_5 = 8$.

Incremental Losses and Data on Fatalities

Ln, Ldr, Lnf (Natural Channel-, Dam Removal-, No Failure Life Loss) * Ln = Lnf = 0 and Ldr = unknown.
Ft (Fatality Type) N
Identification/Location of Fatalities: None

Flood Characteristics

Flt (Flood Type) * D
V (Peak Velocity) ---
D (Maximum Depth) * 5 ft
Qp (Peak Flow Rate) ---
Qb (Bankfull Flow Rate) * 300 cfs
W (Maximum Width) ---
Dv (Destructive Velocity) ---
R (Maximum Rise Rate) * V
Ww (Height of Wall of Water) * 0 ft
Dd (Damage and Destruction) * 2 dwellings had minor damage.
Fp (Proportional Forcefulness) * 0.0
Fd (Dichotomous Forcefulness) * 0
F_5 (Incremental Forcefulness) * L
Fpar (Forcefulness per SubPar) * 0.0
H (Height of the Dam) * 38 ft
Hp (Height of Reservoir Pool) * 32 ft

B	***(Breadth of Dam)***	* 200 ft
Vol	***(Volume of Release)***	* 630 ft
Rf	***(Rate of Failure)***	* 2 min
A	***(Area of Final Breach)***	---

Spatial and Temporal Relationships Between Par$_i$ and the Flood

T	***(Time Summary)***	The dam failed about 1:20 or 1:30 AM, Sunday, Nov. 6, 1977 (5, 6, 8, 9) and reached the residences shortly afterward. The river rose and then dropped again before that, around 9:00 PM, at the same time the peak reservoir level subsided. This suggests that there may have been a partial, temporary failure prior to the catastrophic break (5).
Td	***(Time of Day)***	N
Tw	***(Time of Week)***	Wend
Ty	***(Time of Year)***	11
Ts	***(Time of Season)***	W
Wt	***(Warning Time)***	* 0 min
Wt_{avg}	***(Avg. Individual Wt)***	* 0.25 min
Bt	***(Building Types, %)***	* R or M
Dev	***(Development/Urbanization)***	* N
Gf	***(Goodness of Fit)***	* H
O	***(Outdoors)***	* I
Sc	***(Sensory Clues)***	* 0.25 min
Pr	***(Preparedness)***	* N
We	***(Warning Effectiveness)***	* N

Epar ***(Evacuation SubPar)*** **and** ***Ret*** ***(Representative Evacuation Time):***

(Epar$_1$) Par$_i$ *(Ret$_1$)* * 2 min

E	***(Ease of Evacuation)***	* -1.75 min

Natural Circumstances that Attend the Flood

Fm	***(Failure Mode)***	* Fe
Ac	***(Attendant Circumstances)***	* N
M	***(Magnitude of Loading)***	* L
Ml	***(Mag. of Loading, Locally)***	* L

Human Circumstances that Attend the Flood

Dt	***(Dam Type)***	* E
Rr	***(Rescue Resources)***	* L
Det	***(Detectability)***	* L

Schvq (Striking Characteristics and Valuable Quotations): * H

Case Bibliography

*

Striking characteristics and
valuable quotations

The following section is excerpted and in some cases modified or expanded from the larger, unpublished version of Appendix B. The formatting and style are generally preserved from the original appendix. Reference numbers refer to the event-specific bibliographies in the next section.

ALLEGHENY COUNTY (FLASH) FLOOD, PENNSYLVANIA

Par: several watersheds in Allegheny County, Pennsylvania, 1986 = 1,700
Par_1: motorists on Saxonburg Boulevard below its intersection with Harts Run Road on Little Pine Creek north of Pittsburg; $L_1 = 9$, $P_1 = 0.33$

To understand this event, it is important to distinguish between the flood's peak, characterized by a wall of water up to 4 or 5 ft high, and the slow rise that preceded it. During the fastest rise leading up to the peak, the flood rose 3.5 ft over 45 minutes at the intersection of Harts Run Road and Saxonburg Boulevard, upstream from most of the damage and all of the life loss. Since the homes were primarily located between the river and the road, an even slower rise rate first flooded the homes. Under these conditions, the sensory clues of flooding would have given homeowners time to climb the hillside a few seconds away long before the flooding reached lethal proportions. In the same way, rather than being overwhelmed, most or all motorists were swept away only because they did not abandon their vehicles during the long period when the rise rate primarily posed a threat to property and not to life.

The consistent message from this event and from other life-loss events involving flash floods is that modern tools used to predict flash flooding are prone to error and failure. See Wt for reasons warnings are often delayed in flash floods. Also, in transitioning to a computer-aided model, the NWS predicted that 5.5 inches of rainfall would be required to cause flash flooding when 3.8 inches would have been more realistic.

> ***Wt (Warning Time)*** A NWS flash flood warning was issued at 5:53 PM, about 1 hr after extreme flooding began. It was not issued earlier because the true intensity of the storms was not expected. Although radar estimates did indicate high rainfall estimates, forecasters attributed these to anomalous propagation patterns that had frequently occurred in the past. Electrical outages in the flooded area hampered verbal confirmations, and reports of flooding on Saxonburg Boulevard were confused with the town of Saxonburg, where rainfall was light.
>
> Once the flash flood warning was finally disseminated over the Emergency Broadcast System, no one from the local TV or radio stations could remember broadcasting it, nor could they remember receiving the warning over the UPI or AP wire services: Wt = 0 min.

Sometimes, victims of flooding will climb onto the roofs of their vehicles rather than wading to high ground, not realizing that a vehicle can be floated and washed away by moderate flooding. In this way, they bypass their window of opportunity for escape and drown when the flood rises high enough to mobilize the vehicle or when an unexpected surge or wall of water suddenly sweeps them away. At least 3 victims died in this way in this event.

ANGELS DAM

Par: down San Domingo Creek, Calaveras County, California, 1895 = unknown
Par_1: same as Par
$L_1 = 1$, P_1 = unknown

Workmen apparently left portions of cottonwood roots under the masonry section, leaving the foundation vulnerable to piping.

ARÁS ALLUVIAL FAN FLASH FLOOD AND DAM FAILURES

Par: Central Pyrenees, Spain, 1996 = unknown
Par_1: Las Nieves Campground
$L_1 = 87$, $P_1 = 0.58$

"In terms of human lives lost, this flood has been the largest natural disaster in Spain in the last 23 years" (1, p.268). In 1973, 150 people died in a flash flood.

The Arás barranco was the main feeder channel to the Arás alluvial fan. It contained more than 30 check dams which had long since filled with sediment (some had pine trees around 40 years old), giving it a terraced appearance. During the flash flood, most of these dams were destroyed and much of the sediment was deposited via sheet flow across the alluvial fan.

"The people that survived the disaster are mainly those who were able to take shelter in one of the buildings or those who climbed the poplars planted on the camping area. Most of those who died were drowned, trapped or buried in the sediment and hit by moving debris." (1, p.277-8)

"The roadways of the camp site were scoured and acted as preferential flow paths . . . . The highly turbulent flow generated scours up to 1.5 m deep on bare surfaces and next to obstructions like the road whose asphalt cover was torn off." (1, p. 279)

Of those killed, about 50% were women and 25% children, so strength may have been a factor. (1, p. 278)

AUSTIN DAM (BAYLESS PULP & PAPER COMPANY DAM)

Par: Freeman Run River Valley, Pennsylvania, 1911 = unknown
Par_1: Austin City below the Bayless paper mill
$L_1 = 88$, $P_1 = 0.045$

The concrete structure was built about 800 ft (less reliably reported as 500 yards) below an original earthen dam that was in good shape and that held nicely when the reservoir behind the concrete structure was drained in 1910. This earthen structure was 29 ft high, 380 ft wide, and had 1 ft of freeboard. It was designed to impound 25,000,000 gallons of water (76.7 acre-ft; 12, p. 8). When the concrete structure failed, it created a vacuum that sucked the earthen dam with it, leaving virtually no trace of its existence.

Mary Blailse was interviewed in the hospital by a reporter shortly after the disaster. She was doing accounting work at the Bayless mill when suddenly one of the big pulp grinding stones crashed through her wall. The ceiling caved in and the flood washed over her, but she must have been very near the edge of the flood because rescuers later found her alive (and several others), with her leg pinned beneath the stone. The stone was too big to move, so she pleaded with them to get an ax and chop off her leg. "No man would volunteer. 'Cut if off,' I pleaded. 'You can stand it if I can.'" After her friends said they couldn't do it, she asked a large stranger. "By the lantern light I saw the descending blade glisten. I think he chopped it four or five times before they could pry me loose." Blailse apparently survived. Others were also rescued alive from wrecked buildings, even three days after the event, sometimes located near dead bodies. (1).

When Grace Baldwin Collins heard of the danger, she called her mother (blind) and father (old and lame) who were living with her and began slowly toward the nearest mountain, supporting each one on an arm. She saw the flood approaching closer and closer, and all who watched from safety urged her to leave her parents and save herself. Instead, she held her head higher and was engulfed with her parents.

Three people were saved by riding above the logs on their beds when their homes were destroyed.

Saturday was bath day, so many people were taking baths when the dam broke.

Turner street bordered the mountains, so people naturally ran that direction. Most escaped, but "they discovered that high fences of all types bordered the lots back of the houses . . . and many people lost their lives trying to get over the fences. There were several instances where older people frightened to exhaustion looked at the barriers and the approaching flood so threw children over the fence just minutes before they were swept away." (11, p. 11)

AUSTIN DAM (COLORADO RIVER DAM)

Par: Colorado River, Austin, Texas, 1900 = unknown

Par_1: Power plant beside and just downstream of the dam

$L_1 = 8, P_1 = 0.8$

Twenty-eight feet of silt behind the dam was comparable to a liquid with unit weight of 85 lb/ft3. This was probably a significant contribution to the failure forces that shoved the dam downstream.

AUSTIN, TEXAS, FLASH FLOODS

Par: creeks that flowed into Lake Austin/Town Lake, Austin, Texas, 1981 = 1,196
Par_1: residential areas, primarily on Shoal, Walnut, and Little Walnut Creeks
$L_1 = 2$, $P_1 = 0.0017$

Based on R = 260 cfs/min = M, the global flood was truly threatening only for those who waited too long to evacuate and for those who underestimated the ability of shallow but very swift water to sweep away an automobile (subPar 2 – 7). "In general, the common factor in nearly all the drownings was that they probably could have been avoided if the victims had better understood the potential risks from extreme flood conditions" (2, p. 12).

The moderately fast-rising flood itself would have provided sufficient notice for many residents to contemplate evacuation before the flood became lethal. The flood rose slowly enough to drive or walk away from it without great hurry. The only residential fatalities involved a couple who refused to evacuate after being warned.

AUSTIN, TEXAS, FLASH FLOODS

Par: creeks that flowed into Lake Austin/Town Lake, Austin, Texas, 1981 = 1,196
Par_2: 3 vehicles at 3 crossings along Shoal Creek
$L_2 = 4$, $P_2 = 0.8$

Despite the high rate of fatalities at low-water crossings or hydraulically deficient bridges, and despite the large quantities of debris in the flows, "it is indeed surprising that no bridges were destroyed" (2, p. 11).

The rise rate was only moderately fast, so none of the cars were broadsided by an unexpected wave of water. Rather, each driver chose to enter a flooded crossing, believing it to be passable. Although the darkness and rain probably contributed to the deception, such choices are commonly observed in other events during the day, as well. Even baricades and warnings do not necessarily prevent motorists from attempting crossings when the waters appear shallow and slow enough to cross. Drivers can not be trusted to accurately judge the ability of flowing water to float or move a vehicle into deeper and more lethal water.

Variables like Dv and Qp have limited application to vehicle fatalities at crossings since the vehicles initially encounter only the water flowing over the road surface and not the water flowing under the bridge or through a culvert.

Variables like E really misrepresent this type of Par, because this is really a form of convergence after the warning has been issued and the area is cleared.

AUSTIN, TEXAS, FLASH FLOODS

Par: creeks that flowed into Lake Austin/Town Lake, Austin, Texas, 1981 = 1,196

Par_3: West Lake Drive where it crossed Bee Creek

$L_3 = 2$, $P_3 = 0.67$

The fact that two cars could be swept away when crossing the same intersection more than an hour apart demonstrates how deceptively safe an intersection may appear when covered by relatively shallow but swift water.

Wt is not an important predictor for convergence fatalities at river crossings.

AUSTIN, TEXAS, FLASH FLOODS

Par: creeks that flowed into Lake Austin/Town Lake, Austin, Texas, 1981 = 1,196

Par_4: Bull Creek crossing

$L_4 = 2$, $P_4 = 1.0$

As in other subPar during this event, the fact that the motorists were from out of town may have decreased their awareness of the danger posed by any particular flooded crossing.

AUSTIN, TEXAS, FLASH FLOODS

Par: creeks that flowed into Lake Austin/Town Lake, Austin, Texas, 1981 = 1,196

Par_5: crossing at a tributary to Walnut Creek

$L_5 = 1$, $P_5 = 0.5$

Significantly, this fatality occurred during the very earliest stages of flooding on a tributary to the main channel. Flooding need not be extreme to pose a significant hazard to motorists at river crossings.

BALDWIN HILLS DAM

Par: Baldwin Hills, western Los Angeles, California, 1963 = 16,500

Par_1: Residential regions from the dam to Village Green

$L_1 = 4$, $P_1 = 0.0028$

"Automobiles were transported by comparatively moderate velocities across pavements lubricated by a layer of sediment when the water was deep enough to give the car some bouyancy. . . . In several cases, people were rescued from cars being transported by floodwaters by men wading alongside" (17, p. 121f). At Coliseum and Rodeo, human chains braved the swirling waters to try to rescue motorists being transported by the flood waters (9).

The age of the 5 victims may not have been a factor in their drowning (the flood was strong enough to sweep people from their apartments), but it may have been a factor affecting why they did not evacuate. Hundreds of others did not evacuate either, however.

"Several telephone poles, their wires still flowing with electricity, flamed at the tops like giant candles." (9, p. B10)

> While the Hermans worked frantically to get their little guests back to their own homes [at the interruption to the birthday party] ("Did you ever ask a six-year-old her phone number? some of them don't even know how to spell their last names!"), doorbells rang insistently all over Baldwin Hills. . . . There wasn't time to think or ask questions or pack anything or even think much about the danger. Parents just seized their children, piled into their cars in silence, and stepped on the accelerators. Nobody looked back. . . . "One minute we were driving, the next we were floating," Mrs. Herman remembered. "We got out. The water was up to my waist. It was freezing cold, filthy, and full of debris. We got out of the way of a tree just in time. My husband had our youngest child and the dog. I had the two girls who weren't mine under my armpits. My other two girls were holding onto them." (14, p. 91)

BALDWIN HILLS DAM

Par: Baldwin Hills, western Los Angeles, California, 1963 = 16,500
Par_3: Commercial districts and their surrounding roads; primarily shopping centers
$L_3 = 1$, $P_3 = 0.000069$

The 12-ft deep, 30 x 20 ft. excavation for an 81-inch sewer pipe into which Mrs. Schwartz car sank was totally obscured by the flood waters, rendering it invisible (2).

BANGLADESH STORM SURGE AND CYCLONE

Par: Bangladesh, 1970 = unknown
Par_1: same as Par
$L_1 = 225{,}000$, P_1 = unknown

Being a storm surge, this flood was quite dissimilar to a flash flood or dam failure in that it did not diminish with width. Nevertheless, it did reveal the tremendous loss of life that is possible when immense quantities of water are released on an unprepared population. In this case, 225,000 people died. Despite an officially warning time of about 3 days, the dissemination of the warning was limited.

Wt (Warning Time) The cyclone was tracked for three days, through the Bay of Bengal, until it struck on Nov. 12, 1970, at night. Warnings reached Dacca early, but not the low lying islands to the south at greatest risk.

BANQIAU AND SHIMANTAN DAM FAILURES

Par: Huai River Basin, Henan, China, (tributaries to the Yangtze), 1975 = 3 million
Par_1: The global event, minus the 3 remaining, identifiable subPar
$L_1 = 65773$, $P_1 = 0.022$

The flood was simply too large and in too foreign a setting to understand it fully.

The fact that E was an extremely large, negative number (E = -1380 min), suggests that this failure may point toward an upper envelope on the potential lethality of a flood with relatively minor F-values and a Dv value less than 3.

As Par_i grows, parameters like V and Ww become less representative, being localized maximums and not representative values. On the flip side, parameters like E also become less representative, being averages rather than localized extremes that could be more damaging. Parameters like Dv may still apply, on average, since localized, peak flows tend to increase the value while localized peak widths tend to decrease the value. On the whole, a representative value may still result.

BASS HAVEN LAKE DAM

Par: Tributary of Coon Creek, near Athens, Texas, 1984 = 8
Par_1: same as Par
$L_1 = 1$, $P_1 = 0.15$

This failure is unique in that no members of Par were downstream when the dam failed, none were threatened by flooding, and all danger was from the material of the embankment itself. The failure was initiated intentionally but progressed at an unexpected rate, leading to a rapid draw-down slope failure.

BEAR WALLOW DAM

Par: two homes along river, near Asheville, N.C. = 7
Par_1: same as Par
$L_1 = 4$, $P_1 = 0.57$

Apart from the small Par and the small Volume, this flood approaches a worst-case scenario: a flood that destroys all homes, without warning, at night, in the winter. For this reason, it is critical to determine whether the second home had occupants that should be included in the Par.

BERGERON POND DAM
(also known as ALTON DAM or MEADOW POND DAM (11))

Par: Alton, New Hampshire, 1996 = 25; Par_1: same as Par
$L_1 = 1$, $P_1 = 0.040$

The dam was constructed in 1992 and last inspected in July of 1994. The emergency action plan was approved two months later. It was followed, resulting in the notification and evacuation of some 50 people (11).

The Thoroughgoods tried to escape in their car when the saw the flood coming, but the flood caught them in the garage, filling up to their windows. They retreated with their dog upstairs as the water rose 5 ft in their first floor, collapsed several first floor rooms, and filled their basement. This again shows the relative safety of roofs and levels above the flood stage (8).

BIG THOMPSON FLASH FLOOD (AND DIVERSION DAM)

Par: Big Thompson River/Canyon, 1976 = 2500
Par_1: same as Par
$L_1 = 145$, $P_1 = 0.058$

There was a general impression from people analyzing the event that the evacuation warnings were disbelieved because at the lowest end of the canyon the local weather was often fair or produced only light rain during the day, and because previous floods had not exceeded 10 ft compared to the 20 that occurred this time (4, 8). In other words, mild conditions and prior experience with milder floods can create a kind of detrimental, upbeat attendant circumstance (Ac) that deters evacuation.

Rather than panic, people typically disregarded warnings that were not repeated or otherwise made more believable. For example, one waitress reported that no one in her restaurant moved after being warned of landslides and flooding, but they left after receiving a second, false report that a dam upstream in Estes Park had broken (4, 5).

There was not a wall of water but a steady, rapid rise. In Drake, Sensory clues were the only warning most people received (4). These included heavy rainfall, a visually rising river, and the change in the sound of the river as the flows increased. Those who attempted to evacuate by automobile or who did nothing seriously imperiled themselves, while those who immediately sought high ground were the safest.

"Trees with trunks over 2 feet thick were gouged from the canyon's walls, and boulders 10 feet in diameter were rolled down the riverbed . . . . Dotted about the canyon were many concrete slabs, all that remained of the buildings the flood had swept away" (6, p. 125).

There was tremendous scour and deposition. "In a few hours [the flood] turned Tom Hart's tomato patch into a ten-feet-deep ravine strewn with three-ton boulders" (Cynthia Russ Ramsay, in 6, p. 125). Elsewhere, cars were buried 6 feet beneath the bed of the Big Thompson River.

Although some trees withstood the waters, “The ground became so sodden that the roots could barely support the trunk and branches: 30-foot-tall pine trees could be felled by a vigorous push" (6, p. 125).

The last cry heard over the CB of one victim buried in her car was "My God! It's the end of the world!" (6, p125)

A family which survived the Rapid City flood (1972), one which was familiar with severe flooding in Texas, and one familiar with tornadoes all responded to warnings immediately by heading toward higher ground. While not a scientific sample, these examples represented what investigators considered a benefit from experience with severe disasters. By contrast, those familiar with local flooding that routinely failed to threaten lives were often reluctant to respond to warning, explaining later that they had survived it before; why should this time be any more dangerous (4)?

The likelihood of people to respond to evacuation warnings increased with the number of warnings they received (4).

BLACK HILLS FLASH FLOOD AND CANYON LAKE DAM FAILURE

Par: Rapid, Box Elder, Battle, Spring, & Bear Butte Creeks, South Dakota = 12,375
Par_1: Rapid City, S. D., below Canyon Lake Dam along Rapid Creek
$L_1 = 171$, $P_1 = 0.040$

Pactola Reservoir was 25 stream miles above Canyon Lake Dam (3). It contributed virtually nothing to the flood (4), so runnoff was limited to the 66 mi2 drainage between the reservoirs (4).

There was no real-time reporting system for river flow and rainfall (5).
"We learned that people had been hesitant to leave their homes as they couldn't relate to the danger because of previous smaller floods in other years." (7, p 11)

Between 8:00 and 9:25, Mayor Barnett asked Lt. Hennies to again call the radio stations, this time to ask people to stay away from the west end of town, nearest the dam. Expecting curiosity seekers and resulting traffic problems, the Lieutenant asked him to cancel the request and the call was never made.

"The water was chest high and the front of the truck was floating from time to time. From the rear of the fire truck we could see with the aid of large spotlights . . . ; people were clinging to anything that would float. Roofs and walls from damaged homes all had people clinging to them, floating refrigerators, cars and propane tanks. People were hanging in trees, the roar of the water was terrible and the sounds of screams [for] help were even loader than that. People floated by just out of reach and we couldn't get to them. . . . The screams died down as people fell from the trees and rooftops and were swept away." (7.2, p. 30)

"There was [this] boat [that] came down the creek with three or four people in it, moving at a tremendous speed, totally out of control and about the time it got to where the water fountain was, the boat shot 30 or 40 feet straight in the air. This was the last time we saw the boat or the people" (7.15, p. 371).

""Across the street a house caught fire and burned. An electric substation exploded and lighted the sky. . . . Near W. Blvd and Main the stench of gas was heavy and it was apparent that gas was rising out of the filling station gas tanks and the danger of fire was great." (7.2, p. 30)

St. John's Hospital lost power along with 93% of the city. The emergency generator was also unavailable because the natural gas line which fueled it had been shut down to reduce the danger from dozens of broken gas lines. Service was not restored until 2:42 AM, 2 hr and 45 min after power was lost (7.5, p. 64f). The hospital was also surrounded by flood waters, so not a single doctor could reach the building. The sole medical authority was the night nursing supervisor (7.14, p. 347).

Chuck Hewitt, a worker at the hospital, recounts fighting a waterfall of water to climb the hospital stairs to reach entrance, of being knocked down 2 or 3 times while trying to clear dangerous debris from around the building, and of wading through shoulder-high water to get food from the Safeway store for patients (7.15, p. 366ff).

Some invalids died, while others required special effort to save. One 71-year-old lady saved her daughter by holding her on a mattress, standing herself in water up to her chest because she couldn't get her on the roof. The water was slimy, it was hard to stand, and if it had risen higher, they both would have perished (8, p. 43).

Most of the bodies were mangled and beyond recognition (7.7, p. 130).

Though Pennington County had an emergency plan, few were familiar with it and "no one could relate it to their current situation" (7.8, p. 204).

"The NWS had an unlisted number but it was not available to State Radio. State Radio also tried to call on a hotline, part of the National Air Raid warning service. . . . Unfortunately, the loud speaker at NWS was probably turned off" as it frequently was and the call was not answered (7.12, p. 304).

Two reasons dominated people's reluctance to evacuate when receiving warnings: 1) there was no experiential precedent for a flood of this magnitude; the most recent large flood 10 years earlier had only flooded lawns and basements, and 2) the stream rose at night, when people couldn't see what was happening (7.20, p. 617). Due to this darkness, there are no pictures of the flood.

"All bridge approaches were overtopped except in the outer fringes of the flood zone. Water surface profiles were highly irregular; natural formations, debris piles, and urban improvements partially diverted flows, causing the water to flow at different elevations in a cross section across many of the streams. The differences in cross-sectional water surface elevations were most obvious in the mountain areas upstream from Rapid city, in Keystone, and in Sturgis, where flood depths were relatively shallow. Superelevation of flows on the outside of curves caused stages to rise and flood land that was elevated well above the average flood stages." (9, p. 38)

The post-flood emotional disturbances were many (see source 7.18 for excellent and sobering examples).

We (Warning Effectiveness) "Although these [early media] warnings were timely and useful . . . they did not carry with them a sense of urgency" because the magnitude of precipitation was unknown. "One person remarked that, 'It (the first warning for Rapid

Creek) was the kind of warning that suggested that I should bring in the lawn furniture' " (5, p. 15).

Later, REACT, 4-wheelers, the Rapid City Police, the Fire Departments, and the National Guard all made door-to-door warnings in the Canyon Lake Area (7, p. 137). In some cases, they also used sirens and bullhorns (7.20, p. 614). Still, over 10% of Par was trapped by flood waters and later rescued (over 1,000 persons) or perished (7.8, p. 203; 7.13, p. 316; 7.20, p. 618), most of these in Rapid City (about 25% of Par_1). Many refused to believe the reports, even when contacted by friends, relatives, or emergency personnel, and some were so angered by the media reports that they called the radio station to chastise them for scaring people (7.8, p. 203).

The door-to-door efforts were sincere and urgent, but a lot of people did not attempt to leave "until they heard it [the flood] next door" (7.20, p. 615) or the extent of the flood was obvious (9).

While the city had civil defense sirens, it did not occur to anyone to sound them (7.20, p. 617).

A large number of people who heard the media reports drove to watch the flood, many losing their lives (7.20, p. 618; other sources).

Since somewhere between 50% and 90% evacuated, We = M.

Ac* *(Attendant Circumstances) At least 9,500 telephones lost service and long-distance service to towns such as Keystone was lost (7.3, p. 52). "By 11:30 p.m., the flood had disrupted communications to nine Northwestern Bell exchanges, two Independent company exchanges, [and] five Minuteman Missile sites . . . " (7.4, p. 58).

About 11:47, 93% of the electrical load was out of service in Rapid City due to houses floating down the creek and destroying the main transmission feeder lines. Lines were shut down to avoid electrocuting people in the flood (7.5, p. 64f). Prior to this, lights went out in the flooding area, making rescue operations difficult, especially with downed wires everywhere and large debris moving up to 40 mph (7.13, p. 316).

In particular, the darkness hindered both warnings and rescues: Ac = H.

BLACK HILLS FLASH FLOOD AND CANYON LAKE DAM FAILURE

Par: Rapid, Box Elder, Battle, Spring, & Bear Butte Creeks, South Dakota = 12,375

Par_2: The flooded, rural/unincorporated portions of Pennington County, including Rapid Creek above Canyon Lake Dam; $L_2 = 36$, $P_2 = 0.0068$

Schvq (Striking Characteristics and Valuable Quotations): Would be H if only Rapid Creek, but due to the large number of locations and creeks, Schvq = L.

"Many of the victims, campers in the Black Hills area near the streams," were overcome while they slept or before they could reach high ground. In one cabin, 3 out of 7 campers perished

> A little before 11 p.m., Tom heard water coming in the cabin. He woke us all up. We couldn't open the cabin door to get out because of water outside. I kicked out a window and right then a car smashed into it. We all grabbed a mattress in the one room in the cabin and floated in the water—it was four or five feet deep—and the cabin started floating downstream. It went at least a mile and then one wall of the cabin broke away from the rest of it. (8, p. 43).

Although Wt was 120 min, and Wtavg around 55 min, personal Wt_i was 0 for many people in the most danger (camping) and the effectiveness of the warnings was likely very low.

BLACK HILLS FLASH FLOOD AND CANYON LAKE DAM FAILURE

Par: Rapid, Box Elder, Battle, Spring, & Bear Butte Creeks, South Dakota = 12,375

Par_3: Battle Creek in and near Keystone

$L_3 = 12$, $P_3 = 0.075$

"The Black Hills attracts many campers and visitors, and it was difficult to warn those people in the more remote canyons and valleys. This is a [growing] national problem . . ." (5, p. v)

BLACK HILLS FLASH FLOOD AND CANYON LAKE DAM FAILURE

Par: Rapid, Box Elder, Battle, Spring, & Bear Butte Creeks, South Dakota = 12,375

Par_4: Box Elder Creek near the town of Box Elder and Black Hawk

$L_4 = 15$, $P_4 = 0.038$

What is striking is that Box Elder experienced an attenuated flood (only 17,000 cfs compared to 51,000 cfs near Doty School on Nemo Road or 30,100 near Nemo) because it was located on the plains (8, 9). This means the flood should also have been shallower, albeit more widespread. Yet, compared to no deaths along its length in the canyons, where the waters were deeper and swifter, there were 15 deaths in Box Elder. This suggests several observations: 1) death rates are highly variable and not easy to predict based on flood characteristics alone; 2) the fact that the flood peaked at 5:00 AM in Box Elder, when everyone was asleep, compared to 9:00 PM the night before near Nemo, when people were still awake (Nemo was evacuated by 7:45; see Wt7), appears to have been a key factor; 3) Even though Box Elder could have had 5 to 8 hr of warning time from officials experiencing great loss of life in streams with comparable canyon flow (notably in Rapid City), either the warning was not passed on or the evacuation was not effective; 4) the absence of record-breaking thunderstorms locally probably made few residents of Box Elder expect great flooding; and 5) once a flood reaches lethal proportions, the flood magnitude is probably far less important than temporal/spatial considerations.

BLACK HILLS FLASH FLOOD AND CANYON LAKE DAM FAILURE

Par: Rapid, Box Elder, Battle, Spring, & Bear Butte Creeks, South Dakota = 12,375
Par_6: City of Sturgis on Bear Butte Creek
$L_6 = 0$, $P_6 = 0.0$

This case demonstrates how variables like Dv can misrepresent a case. Dv is measured for the main flow, but in this case, the main flow impacted very few structures. Instead, a large number of structures were inundated by quiescent backwaters. A variable like Schvq can help flag this.

BUFFALO CREEK MINE-WASTE EMBANKMENT FAILURES

DELINEATION OF PAR, LIFE LOSS, AND VARIABLES DEPENDENT ON SHARED ANALYSES

Par: 17 mining towns along the 15-mile Buffalo Creek valley, 1972
Par = 3,170; L = 139; P = 0.044

Pearl Woodrum wrote the Governor of West Virginia 4 years before the failure on Feb. 5, 1968: "Every time it rains it scares everyone to death. We are all afraid we will be washed away and drowned . . . please for God's sake have the dump and water destroyed. Our lives are in danger." She urged others to write, but they were afraid of losing their jobs with the mines (24).

Considering the death of Michael, who died 3-4 months after conception when his mother died, "I still wonder everyday about what my other baby would have been. Michael would have been 24 now" (7, Larry Owens, p. 168).

A poisonous snake bit a little girl, even though it was winter. "The flood water brought them out. One of the most dangerous things to contend with after a flood is snakes" (7, James Singleton, p. 179). Hundreds of snakes were swimming in the lake following the Eldorada Canyon flood, as well.

Some reported as many as 1,000 people injured (25), but Jason Riggins, the hospital administrator, indicated they treated 511 in the emergency room, with 20 being admitted to the hospital. Another 645 were directed to Red Cross shelters (7, p. 172).

In this event, as with most similar events, there was widespread looting of stores that survived the flood, evacuated homes, and debris piles (3, etc.). It did not stop until the National Guard arrived (7, Harold Hale, p. 97).

As in other violent floods (i.e., see Eldorado Canyon), most recovered bodies had no clothes, the clothes having been torn off the bodies by the currents. Many who survived also lost their clothes to the flood (7, 14).

Like the flood in Eldorado Canyon and other floods preceded by debris dams and a wall of water, the wave road the valley a bit like a bobsled. "Clusters of homes on one side of the tracks were swept away altogether while clusters on the other side, lying at precisely the same elevation, were barely splashed." According to an anonymous eyewitness, "This water, when it came down through here, it acted real funny. It would go this way on this side of the hill and take a house out, take one house out of all the rows, and then go back the other way. It would just go from one hillside to the other" (10, p. 30).

The emotional problems following this flood were extreme and ubiquitous. Wilbur and Deborah are good examples. Their account of the flood is presented under Schvq for Par_6 in Lorado. Afterward, they moved to a new house far up the hillside above any conceivable flood, above Man where flooding was the mildest (10). Two years after the flood, Wilbur described his state:

> Every time it rains I get that old dirty feeling that it is just a natural thing for it to become another flood. . . . If there's a storm warning out, why I don't go to bed that night. I set up. I tell my wife, "Don't undress our little girls. . . ."
>
> My nerves is my problem. Every time it rains, every time it storms, I just can't take it. I walk the floor. I get so nervous I break out in a rash. I'm taking shots for it now. . . .
>
> Every time it rains or goes to come up a storm, I get my flashlight—if it's 2:00 in the morning or if it's three. Now it's approximately 500 feet from my house to the creek, but I make me a round about every thirty minutes, looking at that creek. . . . to see if the creek has raised any.
>
> What I went through on Buffalo Creek is the cause. . . . The whole thing just happens over and over again in my dreams.
>
> I don't want to get out, see no people. I despise even going to town, going to the supermarket. I just want to be by myself . . . don't want to see nobody. . . . Why? I don't know. I'm just a different person. . . . I didn't event go to the cemetery when my father died [about a year after the flood].

Deborah also described her state:

> I'm neglecting my children. I've just completely quit cooking. I don't do no housework. I just won't do nothing. Can't sleep. Can't eat. I just want to take me a lot of pills and just go to bed and go to sleep and not wake up. . . . I loved to cook. I loved to sew. I loved to keep house. . . . But now I've just got to the point where it don't mean a thing in the world to me. I haven't cooked a hot meal and put it on the table for my children in almost three weeks. . . .
>
> I just didn't want to live. . . . I just cried all the time.

At one point, she planned a suicide, but her family stopped her, drug her back into the house, and gave her some nerve medicine (10, p. 143-145).

Many had worked very hard all their lives and were just starting to feel like they were getting ahead, having purchased and remodeled their homes, when their life's work was stripped away in a few minutes. Some time after the flood, testimonies like these were common: "I've just about given up all hope. . . . It seems like it's useless to even want to go on and try again," and "There were months and months and months where I felt I was just sitting around waiting to die. And I believe a lot of these people was the same way" (10, p. 158).

Others were devastated by the manner in which they lost loved ones. “One of our very close friends stayed drunk for almost five months because he could still hear his brother and sister screaming . . . when the water hit them” (10, p. 171). Carol Hoosier, who ran from her parents porch while her mom ran inside and died with Hoosier’s father, “was under constant care of doctors” for two years following the flood for “physical as well as emotional problems” (7, Carol Hoosier, p. 106).

Most of those who survived the flood were subjected to the horror of seeing bodies wash by, seeing bodies wash into their homes or into nearby debris piles, seeing bodies dug out of the mud by bulldozers or rescue workers, or scanning rows of black, mutilated, corpses in the temporary morgues in an effort to identify family or friends. It often took multiple passes before people could identify close relatives, the flood so distorted their appearances (7). “The bodies were mangled. I saw arms twisted just like you’d wring out a dish rag. . . . Some had the back of their heads missing. It was horrible (7, Ruth Morris, p. 142f).

Numerous witnesses along the length of the valley recall being traumatized by a false report that another dam had broken or was ready to break, sending people in a panic back up the mountainsides (7).

Structural anchors can actually make a house more dangerous, causing it to be destroyed rather than floating on the flood as a temporary raft: “We noticed the houses that had chimneys busted up and washed off, but the ones without chimneys just floated over and piles up” (7, Leroy Mays, p. 127).

Whether winter or summer, one of the lasting dangers of a large flood is that it can sweep poisonous snakes out into the open or near residential areas: “We had a little girl to be bitten by a snake, and though that seems unusual for that time of the year, what people don’t realize is that the flood water brought them out. One of the most dangerous things to contend with after a flood is snakes” (7, James Singleton, p. 179). In a similar way, hundreds of rattlesnakes were washed out of Eldorado Canyon and into the lake downstream during that flash flood.

The discrepancies between Wt and Wt_{avg} point to several shortcomings of Wt. First, warnings prior to failure do not carry the urgency or credibility of warnings after failure. Second, an official warning can be issues such that the early warning effectiveness is extremely low. This can result in high life loss with a long warning time, or it can be masked by a highly effective evacuation in the final few minutes based on post-failure warnings or sensory clues. Third, the official Wt may be 0 while the sensory clues provide adequate warning for most people to escape. In all three cases, Wt has very little predictive power, distorting reality as it pertains to most members of the subPar.

BUFFALO CREEK MINE-WASTE EMBANKMENT FAILURES

Par: 17 mining towns along the 15-mile Buffalo Creek valley, 1972 = 3,171

Par_1: Saunders

$L_1 = 8$, $P_1 = 0.40$

In reviewing the list of fatalities in source 7 and those in other events such as the Dale Dyke Dam failure, it is clear that entire families often perish in floods. The lethality of a flooding situation can broadly be broken down into three types of functions: 1) Above a certain threshold and at a certain distance from safety, the function is horizontal--the flood is lethal to virtually everyone it touches. Those who escape do so by outrunning the flood altogether or by experiencing a fluke of the current that washes them to safety. 2) At the other end, the function is also flat—the flood may be extremely inconvenient and cause non-structural damages, but fatalities are the exception. Such floods may rise deeply or run swiftly, but not at the same time. There is adequate safety on a nearby hillside or on a higher story within a building, and fatalities occur due to flukes not experienced by the majority of the population. 3) In between, the fatality rate follows a rising or falling curve that depends on many factors, where "flukes" that cost lives are common and "flukes" that save lives are also plentiful.

Roger Lambert indicated that "houses would float a small distance in the water, but then bigger waves would crush them to pieces while they were in the air" (16).

Lambert had one leg and an artificial one. Since the limb was in the trunk of the car, he had to use crutches to begin climbing the hillside. He lost one crutch rushing to get out of the car, lost the other a few more feet up the hill, and had to crawl the rest of the way to reach safety (16). This gives a good idea of the urgency the evacuees felt as they struggled to beat the flood in the few seconds that were available.

BUFFALO CREEK MINE-WASTE EMBANKMENT FAILURES

Par: 17 mining towns along the 15-mile Buffalo Creek valley, 1972 = 3,171

Par_3: 3 houses clustered 0.4 mi downstream from Saunders

$L_3 = 4$, $P_3 = 0.12$

Danny Peters noticed 3 waves of water at their hillside house (7, Danny Peters, p. 169).

BUFFALO CREEK MINE-WASTE EMBANKMENT FAILURES

Par: 17 mining towns along the 15-mile Buffalo Creek valley, 1972 = 3,171

Par_6: Lorado and Pardee

$L_6 = 32$, $P_6 = 0.11$

"The wall of water roaring down Buffalo Creek swept a good deal of seepage before it like an enormous broom. That is why a yard could be overrun with water and small debris before the wave itself arrived" (10, p. 138). One man named Wilbur reported his family's experience in Lorado, confirmed by his wife: "For some reason, I opened the inside door and looked up the road—and there it came. Just a big black cloud. . . . like . . . seeing barges coming down four or five abreast. . . . It was coming slow, but my wife was still asleep [downstairs] . . . and the other kids were still upstairs asleep." He screamed to his wife, she leaped up and looked outside, and there was already shallow water and small debris washing into their yard, well ahead of the wall of water. She roused the kids and they piled into the car. The only escape route was upstream, so they drove toward the approaching mass of houses, decided to abandon the car, and scrambled under a gondola (railroad car) on the way toward the hillside. While under the gondola, it was struck by their neighbors house, wrecking it, but also turning the bulk of the flood toward the center of the valley and giving them time to scramble out and up the hill. Wilbur saw about 14 people in the 5 houses above his washed away in their homes. Many others were scrambling up the bank near them. Shortly after this, Wilbur passed out (10, p. 138ff).

The erratic selectivity of the flood could be seen at one site where a house was completely washed away, but the fence and gate were still standing and the *Logan Banner* paper box was still attached (7, anonymous female, p. 29).

BUFFALO CREEK MINE-WASTE EMBANKMENT FAILURES

Par: 17 mining towns along the 15-mile Buffalo Creek valley, 1972 = 3,171

Par_7: Lundale and Craneco

$L_7 = 66, P_7 = 0.15$

Bill Owens survived, without any physical harm, after being washed up into a tree. His sister and sister-in-law died (7, anonymous female, p. 28).

The train on the track at Craneco diverted a lot of water, sparing the houses behind it on higher ground (7, Barbara Brunty, p. 50, and others).

BUFFALO CREEK MINE-WASTE EMBANKMENT FAILURES

Par: 17 mining towns along the 15-mile Buffalo Creek valley, 1972 = 3,171

Par_{10}: Latrobe

$L_{10} = 6, P_{10} = 0.10$

Josephene Adkins was caught by the edge of the flood because she turned back during the evacuation to get her pocket book. She almost pulled her husband under with her, but he managed to hold onto the railroad tracks and he pulled her out after his mother came over to help (7, Adkins, p. 12f).

"When it hit, the debris just piled up against the coal cars on the tracks, and it formed a sort of barricade that protected us from the water. I will always believe that was the hand of God protecting us. The water was diverted away from us" (7, Barbara Burton, p. 57). Other houses in Lundale were similarly protected by the coal cars (7, Evelyn Mays, p. 125).

BUFFALO CREEK MINE-WASTE EMBANKMENT FAILURES

Par: 17 mining towns along the 15-mile Buffalo Creek valley, 1972 = 3,171

Par_{11}: Robinette

$L_{11} = 3$, $P_{11} = 0.011$

> Jeana, my youngest, looked up at me and asked, “Mommy, is this the end of time?” I said, “No, honey, the end of time will come with fire, not water.” Just as I said that, a transformer hit the train trestle, and fire was shooting out everywhere, and then the railroad trestle came down in the water. That just about scared Jeana to death. (7, Barbara Spears, p. 184).

BUFFALO CREEK MINE-WASTE EMBANKMENT FAILURES

Par: 17 mining towns along the 15-mile Buffalo Creek valley, 1972 = 3,171

Par_{12}: Amherstdale and Becco

$L_{12} = 2$, $P_{12} = 0.0039$

> I seen the first house hit the bridge, then the second, then the third and fourth. And then a mobile home hit those houses where they had done jammed up against the bridge, and I guess the pressure and the impact was rolling under and that mobile home just vanished underneath. I never did see no more of it. There were three women in it. They were standing in a big picture window and their mouths were moving. I gathered they were hollering. (10, p. 33 under “the view from Braeholm” but with respect to Amherst Camp upstream)

When the sensory clue is rising water and debris, it does not necessarily prompt an urgent response, even when it is known a dam is in danger of failing, unless the true magnitude of the event is understood. For example, Barbara Brunty in Amherstdale had discussed the possibility of the dam failing many times, but she felt such an event would only put 2 or 3 ft of water in the yard. Her sister Opal called that morning to warn her that miners feared the dam would soon fail. She looked out the window every few minutes to keep tabs, but she let her husband sleep until she saw the creek rising fast. Soon after that, the creek began to bulge in the middle (see Sc). Her husband told her to evacuate. She started to leave, but then went rummaging for a change of clothes for her daughter, looking for something old that could get dirty. Once outside, she returned for her pocket book. Once outside a second time, she returned to call her neighbor, but the phone was out. Before she ran next door, she went to get an umbrella and grab a blanket. There was not enough time to warn her neighbor as the water rose, flooding the roads, then the car, then her house (7, Barbara Brunty, p. 48ff).

In Amherstdale, as at other towns, when the drifting houses jammed together behind bridges, forming temporary or permanent debris dams, it provided an opportunity for many to escape their houses and walk across the mass of debris to safety on the hillside (7, several witnesses, including Barbara Brunty, p. 48ff).

BUFFALO CREEK MINE-WASTE EMBANKMENT FAILURES

Par: 17 mining towns along the 15-mile Buffalo Creek valley, 1972 = 3,171

Par_{14}: Accoville

$L_{14} = 2$, $P_{14} = 0.048$

The tendency of people to seek to evacuate by automobile is not only based on a false sense of efficiency but on the fact that it is a very valuable commodity that people want to save from a flood. There was evidence of this in many eyewitness reports (7). As an example, instead of running up the nearby hillside, Mikey Wilson insisted on running over to his neighbors volkswagen so he could drive it up the hillside. Those on foot reached the hill long before he did, and the water washed over the back of the vehicle, coming within seconds of causing Wilson's death (7, Barbara Spears, p. 183).

DALE DYKE DAM (also called BRADFIELD DAM)

DELINEATION OF PAR, SUBPAR, LIFE LOSS, AND PARAMETERS COMMON TO ALL 30 SUBPAR

Par: Dale Dyke, Loxley and Don Rivers near Sheffield, Yorkshire, England, 1864

Par = 20,800, L = 263, P = 0.013

Schvq (Striking Characteristics and Valuable Quotations): It would be extremely rare to have subPar defined in a more homogeneous manner, or to have them described more thoroughly. Without exception (except perhaps Par_{30}), Schvq = H.

Many bodies were never identified because in many cases every member of the family died and nobody was left to recognize key features.

DALE DYKE DAM (also called BRADFIELD DAM)

Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800

Par_{3a}: Damflask, 2.5 miles below Dale Dyke Dam

$L_{3a} = 5$, $P_{3a} = 0.20$

A strange phenomona was seen in Mr. Hobson's garden after the flood. There was a hole 12 ft deep and many yards in diameter, apparently caused by a flood vortex. Such holes occurred many places along the length of the flood.

All five deaths occurred to people who did not heed the timely warnings. One refused to believe the report and delayed in bed. The other four were at work at the mill, one of the few places were it was normal to work all night. Since the earliest warnings occurred before the dam actually failed, they likely felt pressured to keep their normal work shifts, despite the danger.

Although a small minority of the total number of casualties in the entire event, there were many deaths like those of the 4 mill workers. Since these water-powered facilities were very near or even on the river, they were exposed to the full force of the flood. A very high percentage of those who were working late in such facilities died. If the flood had occurred in the early evening, after dark, instead of at midnight when very few workers were present, there might have been many times as many deaths

DALE DYKE DAM (also called BRADFIELD DAM)

Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800
Par_{3b}: Storrs Bridge, between Damflask and Loxley
$L_{3b} = 0$, $P_{3b} = 0.0$

Schvq (Striking Characteristics and Valuable Quotations): The fit is good, except that the houses were near the edge of the flood so Dv is not representative.

DALE DYKE DAM (also called BRADFIELD DAM)

Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800
Par_5: Little Matlock, below Rowell Bridge and about 3.6 miles below the dam
$L_5 = 9$, $P_5 = 0.56$

Here, like most places, the deaths were concentrated in the home, where the flooding was the most severe. In this case, the front houses provided a buffer, protecting those behind. In a row of 5 apartment-style houses, the first (empty) unit was removed in its entirety, the second was severely damaged and 7 of 7 people died. In the next house back, sheltered still further, only 1 of 7 died—not because the wall was removed but because he washed out a second-story window.

DALE DYKE DAM (also called BRADFIELD DAM)

Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800
Par_6: 1.5 miles of steep, narrow gorge from Little Matlock to Malin Bridge
$L_6 = 2$, $P_6 = 0.33$

Based on the 100% mortality rate at the streamside commercial structures—here, at Par_{3a}, and elsewhere—the late hour was a key factor in reducing this type of fatality by perhaps 30 or 40 fold. When people were at work, the shift was a small fraction of the day crew, but the majority of riverside mills, wheels, forges, and the like were completely unoccupied. The local work-patterns are a key ingredient in quantifying subPar in commercial districts.

DALE DYKE DAM (also called BRADFIELD DAM)

Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800
Par_7: the contiguous half of Malin Bridge with exceptionally violent flooding
$L_7 = 102$, $P_7 = 0.93$

“A large number of the bodies were never identified, the reason being that in many cases entire families were drowned, no one surviving who could recognise the features of corpses which were recovered” (1, p. 37). Moreover, none of the closest neighbors survived.

Corpses from this area often had very few clothes on—maybe a single stocking or a coat—suggesting to researchers at the time that the sleeping occupants had no time to dress before their houses collapsed and were washed away. In light of other events, floods often strip the clothing off people who are fully dressed, but the weight of other evidence supports the notion that there was little time for people to get dressed during the Dale Dyke Dam failure.

Stone or brick houses do not readily float, so that if they fail, they are more likely to collapse on the occupants than to provide a raft.

Life loss here was so complete, it is educational to examine the lives that were *not* lost:

1. The two who survived from the Spooner household floated out the second-story windows on their beds and were washed to adjacent fields, where they were rescued. In both this event and many other events, lives have often been saved by mattresses, either by floating on them inside a room, or by riding them downstream until they bump into a place of refuge. Also, in other instances, people have been drowned when swept out their window on a mattress.
2. The watchman was standing outside Ann Mount's house, speaking with her at her door. On seeing the flood coming (Sc), he ran for high ground and escaped; she ran inside and drowned.
3. William Watson's house was destroyed and he was swept downstream with 4 other family members. He was holding onto a "balk of timber" (1, p. 40) for support. The family stayed together at first, but then the current carried him apart and deposited him on top of a pile of debris that had washed against the Widdowson's house. This is the only house in this subPar that was not destroyed. He called out for help and they pulled him through a window.
4. The 4 Widdowsons just mentioned were the only other survivors.

This indicates the life loss expected when an entire neighborhood is swept away in an instant by a flood less than 2-stories deep: 1 survived by evacuating ahead of the flood, 3 by riding rafts to a refuge and then being rescued, and 4 by experiencing less-severe flooding; 102 died. Although the houses were 2-stories, they provided no refuge when they were erased.

DALE DYKE DAM (also called BRADFIELD DAM)

Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800

Par$_8$: the contiguous half of Malin Bridge called Holme Row

$L_8 = 0, P_8 = 0.0$

Harrison attributes the lower lethality of the flood in this area to the sheltering effect of adjacent buildings and to more substantial construction in Holme Row. These adjacent buildings were not described. Perhaps they were well-situated end houses that received the greatest damage, perhaps Par7 was close enough to temporarily deflect or absorb the strongest currents before being removed by the flood, or perhaps there were non-residential structures such as barns or shops on the periphery. In any case, reports indicate that the flood rose and fell in about 15 minutes, so even structures that were completely washed away could conceivably have deflected the peak flows—first as a wall and then as a temporary pile of stone rubble.

It is most likely that Holme Row benefited from being the second line of defense, as it were. The depth here was half as deep (or less) as in Par7, and since Par7 occupied a strip of land adjacent to the river, Holme Row was probably some distance inland. Par7 would have helped direct the major currents downstream, buffering the land behind it: Par8 = 24*4 = 96 and L8 = 0.

Although the first floors were flooded to 5 or 6 ft, every home had a second story, where most people slept. Without this refuge, under $Wt_{avg} = 0$, there would likely have been life loss. With this refuge, they were able to get up, get dressed, and watch the flood. There were at least 3 close calls for people who encountered the flood while downstairs. Two managed to climb the stairs to the second story, while the third broke a hole into a neighbors house and was rescued.

DALE DYKE DAM (also called BRADFIELD DAM)

Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800

Par_9: Limerick Wheel and houses across from Malin Bridge

$L_9 = 3$, $P_9 = 0.33$

Even when flooding is nearly 2-stories deep, people may survive by holding near the ceiling for air. This assumes that currents are sufficiently mild to avoid destroying the structure or washing the occupants out through windows or damaged walls, that people have time to reach the second story, and that the victims can stand on furniture or tread water throughout the duration of the flood.

Corresponding to the observation above, notice that because the structure was sturdy stone, the flooding was able to rise to a great depth while causing no more than minor structural damage. If the structure had been a frame house, it would have floated away and perhaps been destroyed when colliding with other houses or obstacles.

DALE DYKE DAM (also called BRADFIELD DAM)

Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800

Par_{10}: Hillsbro', 6 miles from the dam and below Malin Bridge

$L_{10} = 39$, $P_{10} = 0.45$

Par_7, Par_{10}, and $Par_{11,}$ all experienced severe flooding, but in ways that distinguish the life loss in each. Par_7 had flooding that, in combination with the buildings present, was powerful enough to strip away even the foundations. Almost everyone died. Par_{10} had flooding which washed away some homes, flooded others above the rooftops, and damaged others, but left just enough space in about half of the homes to breathe. Consequently, life loss was close to 50%. If Brick Row had not been 3 stories tall, life loss would probably have been comparable to that for Par_7. Par_{11} had flooding very similar to Par_7, but a debris dam deflected enough of the current that the buildings remained standing, despite their major damage. Life loss here was reduced to 10%. This study suggests some hypotheses worth exploring:

- When Par are present, life loss is very near to 100% when homes are completely destroyed or entirely submerged.

- When a community is marked by severe damages, including complete destruction of many homes, life loss may approach 50%, with life loss concentrated primarily where damages are greatest or houses are submerged.
- Even when suffering extreme damage, if a home is not destroyed and maintains a refuge, life loss can be dropped to between 10 and 50%. Here, life loss occurs where major damage exposes occupants to currents that can sweep them out a door or window or through a broken wall; where occupants are overcome quickly before they can get to the refuge; or where occupants can't swim, they fall into swirling waters, and others are not able to rescue them.
- There may be value in exploring life loss separately for houses which are completely submerged or completely destroyed, and for those which are damaged severely but without eliminating places of refuge. If separate functions could be developed, these could then be applied to the expected damage statistics in predicting life loss. Of course, these examples are limited to cases where $Wt_{avg} = 0$, so there was no prior evacuation.

DALE DYKE DAM (also called BRADFIELD DAM)
SubPar # 10: Hillsbro', 6 miles from the dam and below Malin Bridge
Par_{10b}: houses that were partially destroyed (major damage)
$L_{10b} = 32$, $P_{10b} = 0.44$

Dd ***(Damage and Destruction)*** 15 houses and 2 inns had major damage. In some cases, the flood completely submerged the structures, but many structures were on higher ground or had 3 stories. The inns were only flooded to the first floor, the 9 three-story houses in Brick Row were partially flooded in the highest floor, and a few people like George Cooper and his wife escaped by climbing to the top of their two-story house (1).

As suggested under Dd, above, it appears that everyone or virtually everyone who survived was able to reach a high point in a structure where they could keep their head above water. Everyone appears to have died in structures that were completely submerged (largely single story). Had Brick Row not been three stories high, life loss would probably have been much greater. This suggests that for Tpar, the main difference in life loss between cases where structures are destroyed and those where buildings remain standing with major damage is the availability of a comparatively safe refuge on an upper floor or the roof. If this refuge is removed through complete submergence, life loss is comparable in buildings with complete destruction and with only major damage.

DALE DYKE DAM (also called BRADFIELD DAM)
Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800
Par_{11}: Hill Bridge, over 5 miles from the dam
$L_{11} = 10$, $P_{11} = 0.096$

D ***(Maximum Depth)*** "The waterline was nearly on a level with the top of the second storys" (1, p. 44). This is consistent with Mallin Bridge upstream: D = 14 ft.

Dv (Destructive Velocity) 99,500/W = 378 ft
Dd (Damage and Destruction) See the description under Par_i above. Crooke's home had minor damage, but the rest appear to have suffered some level of structural destruction.
Fp (Proportional Forcefulness) 0.96
Fd (Dichotomous Forcefulness) 1
F_5 (Incremental Forcefulness) E

This subPar, Par_8, and Par_7 make an interesting set that demonstrates the relationship between flood lethality and life loss. Par_7 was utterly washed away and only the exceptions survived. Although Par_{11} had almost identical values for D, Dv, Fp, Fd, and F_5, the true structural damage was much less—only 4 structures were destroyed and there was no indication that any structures were washed away. The remaining damage was quite serious, including in many cases the loss of entire walls and most of the second-story floors, but the remnants of most houses allowed over 90% of the subPar to survive. Par_8 had flooding that filled most of the first story, but structural damage was almost nonexistent and the vast majority of this subPar never got wet. Life loss there was 0.

As a side note to the discussion above, Hill Bridge could have resembled Par_7 with respect to both structural removal and life loss, but "a barricade formed of the accumulation of trees, chairs, sofas, and other articles brought down by the flood," providing protection to this housing development. This is one small example of how uncertain flood routing can be under the dynamic action of a catastrophic flood.

DALE DYKE DAM (also called BRADFIELD DAM)

Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800
Par_{12}: Owlerton, the first large community on the plains, over 6 miles from the dam
$L_{12} = 5$, $P_{12} = 0.0063$

Over and again, the sensory clues indicating the flood was coming were missed until the houses were surrounded or filled with water. There were 3 possible reasons for this: 1) the flood rose exceptionally quickly, but it did not usually come as a wall, instantaneously breaking trees and houses, 2) there was an exceptionally strong wind, so people sometimes confused the flood with the gale, and 3) most people were asleep. However, even when people were awake, unless they actually saw the flood coming, sounds alone were insufficient to trigger a timely response. Here are two examples of reactions from those who were awake:

> Mrs. Proctor herself did not go to bed, but sat up reading. Soon after half-past twelve she heard a tremendous roar like the sound of many waters, and she immediately went to the door, to see what was the cause of the commotion. Just as she was about to open the door the water began to come in. She ran into the room where her daughter and the others were sleeping, and had only just time to get them upstairs when the door and windows gave way, and the water filled the lower rooms up to the ceiling. Had the inmates been three minutes later they would assuredly have been drowned. (1, p. 51)

> Sergeant Foulds and his wife went to bed about eleven o'clock. Mrs. Foulds was awoke in about an hour by a great noise in the room. She exclaimed to her husband, "The wind is breaking the windows of the room." He jumped out of bed, and was astonished to find himself up to his hips in water. (1, p. 52)

There are two important footnotes to the Foulds' story (above). First, the pressure from the water made it difficult or impossible to open doors. This dilemma was observed by Harrison with respect to many houses and some failed rescue attempts. In this case, Sergeant Foulds was unable to open the door to the bedroom of his two young children and both of them drowned. Second, the Foulds were sleeping on the ground floor. In areas with flooding less than 10 ft deep, most of the deaths occurred to people so located.

DALE DYKE DAM (also called BRADFIELD DAM)
SubPar # 12: Owlerton—first large community on the plains, > 6 mi from the dam
Par$_{12b}$: houses/barracks with major damage
L$_{12b}$ = 2, P$_{12b}$ = 0.013

Defining F (Fp, Fd, F_5) in such a way that major damages and totally-destroyed structures are lumped together as a single category produces identical F values for Par_{12a} and Par_{12b}, even though $P_{12a} = 1.0$ and $P_{12b} = 0.013$.

DALE DYKE DAM (also called BRADFIELD DAM)
Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800
Par$_{13}$: an enclave across the river from Owlerton
L$_{13}$ = 0, P$_{13}$ = 0.0

Deep floods are not necessarily lethal, even with short warning time. Here, safety was very near because the hills were very steep and the houses were close enough to cross directly from the second story of the homes. This was a common means of escape in similar reaches upstream when the houses were surrounded by the flood. If the flood had come with higher velocity, however, the houses may have been washed away before escape was possible. In terms of priority, floods with high velocity appear to be more lethal than floods which are relatively deep.

DALE DYKE DAM (also called BRADFIELD DAM)
SubPar # 13: an enclave across the river from Owlerton
Par$_{13b}$: 5 houses with minor damage
L$_{13b}$ = 0, P$_{13b}$ = 0.0

V_{13} (Peak Velocity) * Since the flooding was deep, but the structural damage was light (see D and Dd), this subPar did not experience the flood's peak velocity of 26.5 fps. Most likely the mill dam and steep hills worked together to shield this enclave, producing a deep backwater. For consistency, the 13.5 fps assumed in the next reach below will be used here also (see V_{15}): V = 13.5 fps.

V_{13b}* *(Peak Velocity) As indicated under V_{13}, the water was deep, but the structural damage was minimal, indicating a deep backwater. V is difficult to estimate, but it was slow, probably on the order of 1 – 3 fps: V = 2 fps.

Dv* *(Destructive Velocity) 99,500/W = 185

This is a good example of how Dv can completely misrepresent an isolated location, in this case a deep backwater with very mild currents.

Although $Tpar_{13b} = 6$, all 6 escaped to the hillside from the second story without getting wet *after* the flood arrived.

DALE DYKE DAM (also called BRADFIELD DAM)
Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800
Par_{15}: Farfield Gardens, above Neepsend, about 7.5 miles below the dam
$L_{15} = 24$, $P_{15} = 0.44$

When houses are single story, life loss can be very great even when the number of houses destroyed is small. Although almost two thirds of these structures had only minor structural damage, the flood reached the ceiling or higher in many cases and the resultant life loss was nearly 50%.

Among those who survived, most or all appear to have climbed on their roofs. This was not always safe, however, since at least one person was swept off the roof and drowned.

DALE DYKE DAM (also called BRADFIELD DAM)
Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800
Par_{18}: all of Neepsend downstream of Neepsend Lane
$L_{18} = 15$, $P_{18} = 0.021$

Three deaths were caused because John Mayor's wife was an invalid and so the family chose to sleep downstairs. It is likely that many persons today with limited mobility choose to live or sleep on the ground floor, where escape from flood waters that come without warning is much more difficult.

The following story illustrates why simple velocity*depth curves derived through laboratory studies fall short of the practical realities some people face in a flood.

> Mrs. Needham managed to get into Austin's house, but the water was so deep that she was lifted off her feet. All this time she had a young child in her arms, which added to the difficulties of her desperate struggle for preservation. She tried to get up stairs into the bedroom, but the door was shut, and the pressure of the water was so great that the Austins could not push the door open. Mrs. Needham exerted herself to the utmost to hold the child out of the water, notwithstanding which it was drowned in her arms, and

> she was obliged to let it go, in order to save herself from being swept away by clinging to the nearest object she could lay hold of. This happened to be a table, and it floated up nearly to the ceiling with Mrs. Needham clinging to it. Her other child was also swept away and drowned. (1, p. 60)

DALE DYKE DAM (also called BRADFIELD DAM)

Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800
Par$_{20}$: Harvest and Orchard Lanes, the first flooded district in Sheffield
$L_{20} = 8$, $P_{20} = 0.0034$

All 8 deaths occurred to people who slept downstairs on the first floor. Such sleeping quarters were unusual in this area, since most houses were 2-stories with upstairs bedrooms.

DALE DYKE DAM (also called BRADFIELD DAM)

Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800
Par$_{21}$: Bacon Island, in the center of the channel in upper Sheffield
$L_{21} = 3$, $P_{21} = 0.032$

There is inherent difficulty in defining such things as “evacuation time” since the time it takes to evacuate the flood zone is often much greater than the time it takes to reach a place of moderate safety. In the case of two-story buildings, safety might be a few seconds away on the second floor. Even when one’s house provides no refuge, and the peripheries of the flood are out of reach, safety may not be far away.

Consider the story of the Sharmans. Bacon Island was entirely flooded, and with such depths and velocities that 100% of the homes were partially or completely destroyed. The Sharman’s house quickly filled part way up the second story. Fortunately, there was an adjacent hill that rose so steeply that police-constable John Thorpe was able to stand waste-deep on it, in the flood, and catch all 9 occupants as they jumped without a ladder. This was within inches of the torrent which moments after the rescue swept the house away so that only its foundation remained. Behind him, there was ground of sufficient height that Thorpe was able to first catch their baby and deposit it in safety before helping the rest of the family.

Although John Thorpe was not able to warn anyone before the water entered their houses, his warning was early enough to allow many to evacuate, often with his help, before they were killed. Here, again, Wt, Wt_{avg}, and E do not fully capture the time dynamics.

DALE DYKE DAM (also called BRADFIELD DAM)

Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800
Par$_{23}$: the Green Lane District and contiguous neighborhoods, upper Sheffield
$L_{23} = 1$, $P_{23} = 0.00065$

D ***(Maximum Depth)*** One of the works was flooded 4 ft deep. On Dun Street, in Green Lane, Dennis M'Laughlin drowned when his ground-floor room was flooded to the ceiling. All of Ball Street was flooded part way up the second-floor bedrooms, and street lamps were extinguished by the flood: D = 10 ft.

Despite considerable depth in places, since the structures were 2-stories tall and only one had any structural damage, only one person died. Again, this person lived downstairs.

DALE DYKE DAM (also called BRADFIELD DAM)

Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800
Par_{24}: Long Croft, between Green Lane and the river
$L_{24} = 6$, $P_{24} = 0.026$

V ***(Peak Velocity)*** * 10 fps
D ***(Maximum Depth)*** * Some houses were flooded above the first-floor ceiling. This being between Par_{23} and the river, depths here were comparable to or greater than D_{23}: D = 10 ft.

The flood conditions here were almost identical to those for Par_{23}, although currents may have been swifter since this subPar was closer to the identical reach. Together, they give an idea of the life-loss potential when 2-story buildings are flooded up to 10 ft deep, currents are swift enough to carry people far down stream, but the combined forces of the water are insufficient to tear away walls or dislodge houses.

When trying to wade through a flood, the size, age, and stamina of the wader are critical, as are the vagaries of the flood itself. Consider the following story:

> When the watchman alarmed Mrs. Ryder, she ran down stairs, followed by her two children. She managed to open the door; but had no sooner done so than a torrent of water rushed into the house. Mrs. Ryder seized hold of her daughter, and, breasting the waves, though quite undressed, carried the girl to the top of the street. The boy followed, clinging to his mother's night-dress. Mrs. Ryder was almost exhausted, and, in order to rest for a moment, clung to a lamp-post which had not yet been washed down. Just at this moment, a sudden rush of water carried the boy off his feet. "Oh, mother!" he screamed out. "Oh, Bob! Shrieked his little sister in reply. The next moment the torrent bore him away on its surface, and his cries soon died away amid the roar of the flood. Mrs. Ryder, though up to her neck in the water, still struggled for her own life and for that of her daughter. The water swept them in the direction of the King William Inn, the inmates of which house pulled Mrs. Ryder in, and she and her daughter were saved . . ." (1, p. 75)

DALE DYKE DAM (also called BRADFIELD DAM)

Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800

Par$_{25}$: Kelham Island, in the center of the river about the middle of Sheffield

$L_{25} = 2$, $P_{25} = 0.083$

Identification/Location of Fatalities: Mr. Eaton died when he left his second-story bedroom to try to save his pig, and Mrs. Eaton died trying to help her husband.

Evacuations are rarely as quick as they could be and people can not be counted on to choose the safest behavior when faced with a visible flood. There were several examples during this event of people rushing back to their houses or yards to get something they forgot, to rescue a pet, or to free valuable livestock. These often resulted in very close calls, or, in this case, the only two fatalities.

Fires are remarkably common during floods, having occurred in several different historical events (i.e. Johnstown and others). In this one, the men at the Kelham Rolling Mills managed somehow to set the building on fire while climbing into the rafters for safety. Fortunately, the flood rose quickly enough that the flames were soon extinguished.

DALE DYKE DAM (also called BRADFIELD DAM)

Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800

Par$_{26}$: the communities adjacent to and downstream of Kelham Island

$L_{26} = 2$, $P_{26} = 0.0028$

In this case, a woman evacuated her first-floor apartment when the flood waters burst in. A second family lived upstairs, and seeing her, they quickly extended a sheet to pull her up. While clinging to the sheet, a second wave knocked the woman loose and she drowned. This was just one of several stories in which an individual was lost while being rescued or had a child swept away or knocked out of their arms by a sudden wave. This second wave may have been the result of the dam failing in what some recalled as two distinct stages. In any case, there is no doubt that sudden wave surges or localized pockets of unexpectedly high velocity can prove to be especially lethal.

DALE DYKE DAM (also called BRADFIELD DAM)

Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800

Par$_{28}$: Lady's Bridge to the Midland Railway Station, the final reach in Sheffield

$L_{28} = 2$, $P_{28} = 0.0027$

It was winter and the wind was very strong, so there was a real risk of freezing to death. Undoubtedly, some who were swept away were soon overcome by cold. Here, some watched a man clinging to a lamp post who "perished, as much from the benumbing influence of the cold as from the effects of the water" (1, p. 83).

DALE DYKE DAM (also called BRADFIELD DAM)
Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800
Par_{29}: Brightside & environs, downstream suburb of Sheffield below Wicker Station
$L_{29} = 2$, $P_{29} = 0.0016$

Sc (Sensory Clues) * The occupants of the Shuttle House in Brightside at the head of Sanderson's Dam slept through the flood as it surrounded their house. They were not aware it had come until the next morning, long after it had departed again: Sc = 0

See Sc. This is strong evidence supporting significant attenuation of the flood by this point, as assumed in quantifying Qp, V, and R throughout Sheffield and its suburbs (see *).

DALE DYKE DAM (also called BRADFIELD DAM)
Par: Dale Dyke, Loxley and Don Rivers near Sheffield, England, 1864 = 20,800
Par_{30}: Sheffield neighborhoods primarily inland of Par_{15} through Par_{29}
$L_{30} = 0$, $P_{30} = 0.0$

There is always the potential for life loss around water. People might be electrocuted, stumble and knock themselves unconscious and drown, have limited mobility and fall into the water while alone, or panic and suffer lethal medical side-effects. However, when flooding is shallow and slow, such deaths have been quite rare, historically.

Par_{30} is limited to areas with almost uniformly minor flooding—more so than any of the previous subPar. As such, it is not an inherently biased conglomerate of areas which by chance had zero life loss. Instead it pools many areas, some contiguous and some not, that shared a uniform set of descriptive variables. Some of the previous subPar also had zero fatalities, but they were distinguished by the nature of flooding at those locations. It follows that this subPar was expansive enough, the flood damages consistent enough, and the life loss predictable enough that Par_{30} suggests flooding conditions at or below which life loss is not expected except under unusual circumstances.

DRY CREEK FLASH FLOOD
Par: Dry Creek train crossing near Eden, Colorado, 1904 = 138
Par_1: train called the Missouri Pacific Exposition Flyer
$L_1 = 96$, $P_1 = 0.70$

Floods which compromise the integrity of train crossings, or flooded regions occupied by a train, can cause high numbers of fatalities either by drowning trapped occupants or through fatal injuries resulting from a crash.

Significantly, the track itself was not flooded, but the bridge failed under extreme flooding conditions when crossed by the train.

This type of fatality, along with fatalities caused by roads being overtopped or undermined by floods, should probably be treated separately from general drowning deaths in residential areas.

EASTOVER MINING COMPANY SLUDGE POND DAM

Par: Ages, Harlan County, Kentucky, 1981 = 100
Par_1: same as Par
$L_1 = 1, P_1 = 0.01$

"Residents heard two explosions before the break, raising the possibility of sabotage. The dam was inspected by the Mine Safety and Health Administration Dec. 14 [4 days before the failure]" (1, p. 5).

EL CAJONCITO DYKE FAILURE

Par: El Cajoncity River through La Paz, Baja California Sur, 1976 = 2,000
Par_1: same as Par
$L_1 = 800, P_1 = 0.40$

Identification/Location of Fatalities: These were poor shack-dwellers living in and along a dry riverbed, made dry by diverting the flow with a dike.

Bt (Building Types, %) Sh = 100%.

It is unclear what kind of forcefulness would have been experienced had the building been more substantial. On the one hand, a 6 ft wave, after attenuating, may have done little damage farther downstream or toward the edges of the flood. On the other hand, the peak discharge was maintained for 7.5 hours, so damages may have been higher than one might expect. In any case, the presence of flimsy shacks removed places of refuge that would have likely reduced life loss had the flood occurred in a region with better building standards.

ELDORADO CANYON FLASH FLOOD

DELINEATION OF PAR, LIFE LOSS, AND PARAMETERS COMMON TO SEVERAL SUBPAR

Par: Eldorado Canyon Resort and Lake Mohave, Nevada, 1974
Par = 50, L = 10, P = 0.2

A flash flood sent a huge wall of water through the normally dry mouth of Eldorado Canyon, Nevada.

This event was fairly unique in that all of the victims were immediately swept into Lake Mohave on the Colorado River, rather than down a stream corridor, a dynamic which dramatically changed the hydraulic characteristics of the flood (see $Schvq_7$).

Damages were almost exclusively limited to the Eldorado Canyon Resort. Just 2 miles upstream in a tributary called Eagles Wash, there was no wall of water but a series of rapid pulses that increased until the flood reached 4 to 6 ft deep through a section 400 to 600 ft wide. Dr. J. H. Sessums was forced to abandon his car at this location and watch it bob downstream like a cork. It traveled only a mile before the flood subsided enough to set it down again (1; 2I, statement). Ninety to 95% of the 2,000 acre-ft of sediment-laden water that flowed into Lake Mohave passed the resort within 30 minutes (1, hydrograph). Flows from Eagles Wash, Techatticup Wash, and Eldorado Canyon converged slightly more than a mile above the lake, half a mile above the upstream portions of Nelson's Landing. Intense rainfall moving down-basin, fairly uniform slopes close to 400 ft/mi along each channel, and a noted lack of vegetation caused very rapid and closely coordinated runoff. A constriction just above the restaurant then helped push the instantaneous flow into an even greater wall of mud, debris, and water. This canyon had a history of flooding, but this particular flood was by far the worst on record (1).

"Peak flow apparently followed, rather than coincided with, the initial surge of the flood. Therefore, peak flow estimates probably do not bear directly on damage and casualties" (1, p. 8).

The flood destroyed all power and telephone lines into the area, so survivors had to travel by boat before anyone outside the event knew about the disaster.

As the commentary under Ac indicates, the intense hail and rain on site probably reduced life loss in many cases by causing people to leave the flood zone, or it may have endangered some by masking auditory sensory clues.

The local downpour caused many to seek shelter, especially at the icehouse. John Gallifent barely escaped from his trailer after observing abnormally large runoff in many small gullies and rills through his window. Mrs. Kirby Koop described the runoff along the normally dry canyon floor as knee- to thigh-deep before the first major wave arrived (1). In an area prone to flash floods, such visual clues were significant.

"Rattlesnakes—hundreds of them—were swimming in the water" (2I, statement by Patsy Johnson).

ELDORADO CANYON FLASH FLOOD

Par: Eldorado Canyon Resort and Lake Mohave, Nevada, 1974 = 50

Par$_2$: those among trailers that were swept away and destroyed at the trailer park

$L_2 = 4$, $P_2 = 0.57$

When there is no warning time and a building is completely destroyed, the fatality rate may depend on whether or not that building is near the edge of the flood. When far from safety, fatality rates approach 100% for these conditions (as in the restaurant, Par$_1$). When near the edge, a flood may come in surges or rise slowly enough that occupants can flee out a back door or window, or quickly wade to safety and flee up the adjacent hillside before the structure is swept away (as in the present case). Whether a building is destroyed or not is less critical when it is destroyed slowly, in stages, or following sensory clues and it is near safety.

When the flood moved down the canyon, it sloshed from side to side, ricocheting off the walls, and yielding dramatically uneven high water marks on either side. For example, the greatest depth on the wall immediately behind the trailer court along the left bank was 4 ft. Across the nearly-level canyon on the right bank, one piece of debris was left 16 ft above the canyon floor (1). Ricocheting across the canyon, the main flow reversed within a few hundred feet. Seven-hundred feet beyond the trailer area, the left bank around the restaurant was submerged 20 to 25 ft. Directly across on the right bank, the concessioner's home came within 3 ft of being flooded, but the water only rose 5 ft high (1, p. 19, fig. 14). Such uneven water-surface profiles, though dramatic, are not uncommon with catastrophic floods involving huge walls of water. Not only do curves in the channel, protruding ridges, high volumes, and high velocities increase the effects of superelevation and turbulent sloshing, but debris dams routinely form from boulders, trees, mudslides and man-made obstacles like bridges, trailers, houses, and automobiles. These can accumulate on one side of the channel, forcing the water to pile up; they can constrict a channel, backing up water generally; or they can redirect the flow in an unexpected direction not suggested by the original channel geometry. Such dynamics reveal the limitations of using modern modeling programs that assume a level water service or that neglect the effects of debris dams during dam-failures or flash-flood events.

ELDORADO CANYON FLASH FLOOD

Par: Eldorado Canyon Resort and Lake Mohave, Nevada, 1974 = 50

Par_5: the half of the boat dock closest to shore, ground up and sucked underwater

$L_5 = 2$, $P_5 = 0.5$

At the canyon mouth was a marina with a ramp to the shore off to one side. This created a gap across the water of about 200 ft when measured from shore in line with the canyon. The canyon entered the long and narrow reservoir at a right angle. The dock was about 450 ft long and extended away from the canyon and at a slight angle. Since the reservoir was formed in the Colorado River, the bed slope beneath the dock was roughly the same as that throughout Nelson's Landing—about 280 ft/mi or a little over 5 ft/100 ft (1, see $Schvq_7$).

There were three occupied boats at the dock when the flood hit, two in the first half of the dock and one in the second half. When the flood hit, the dock broke in half—possibly as a result of being hit by a vehicle. The flood affected these two halves quite differently based on their respective distances from shore, so they have been divided into separate subPar.

$Schvq_7$ describes the flood's general hydraulic behavior once it reached the lake. A summary follows, with additional details derived from statements from Manuel Cortez and Craig Grugel who watched the event from an elevated parking area beside the boats, and statements from Maryanna and Helen Grugel who were in one of the boats when the flood arrived (2I, statements).

Those in the boats expected a flood, but not a wall of water. Without warning, a wall of water and debris 25-30 ft high skated across the lake and broke, crashing down about 200 ft from shore, taking out the first part of the dock and gas pumps, and causing the lake surface immediately beyond to temporarily mound up (Craig told his mother it looked like 50 ft). Subsequent waves closely followed, causing the many moored boats to smash together. The extremely dense flow did not continue across the surface, but rushed to the bottom, carrying objects like trucks, trailers, telephone poles, and boats with it. These objects did not resurface. This strong undertow, continually fed by the flood and new surges, created a turbulent boundary like a paddle-wheel or someone mixing eggs that pulled nearby surface objects toward shore and the violence. Eventually, this action would grind up the entire first half of the dock.

The nearest occupied boat contained Frank Olsen, whose boat quickly went down. He drowned. The other boat held Herbert Grugel, his wife Helen, and Craig Grugel's wife Maryanna. After the first wave struck, Mr. Grugel told the two women to put on life-preservers and Mrs. Grugel told Maryanna to sit down and pray. Mr. Grugel went to the bow to try to find another life-preserver. As he was putting it on, the boat was hit broadside by the fourth or fifth wave and sank. Apart from God's hand, it is likely that the two life jackets saved the only two who survived—Helen and Maryanna. Even so, their clothes were partially ripped off. Each were under so long they expected to die, but they surfaced far from the flood in calm water and managed to swim to shore: $Par_5 = 4$ and $L_5 = 2$.

This flood pulverized debris and ripped the clothes off its victims—both those who died and those who survived (1, 2). Stripping of clothes is a common feature found in many other violent floods as well, and does not indicate that the victims were undressed when the flood arrived.

See $Schvq_7$.

ELDORADO CANYON FLASH FLOOD

Par: Eldorado Canyon Resort and Lake Mohave, Nevada, 1974 = 50

Par_7: those on or in Lake Mohave close to the canyon mouth or adjacent shoreline

$L_7 = 2$, $P_7 = 0.5$

John K. Daily was in one boat and Rod and Barbara Hallin were in another—a green and white tri-hull. Both boats capsized and Daily drowned. It is not reported exactly where these boats were located, but since the flood affected the surface flow only close to shore, they must have been near the shoreline and not far from the canyon mouth. However, since they were not seen at the dock, they were floating freely at some lateral distance.

The morning after the flood, at 11:00 AM on Sept 15, a 19-year-old boy named Tsutomu Robert Kinugasa drowned when he waded 15 ft from shore while his companions chatted on the bank. He was caught by an unexpected undertow, surfaced once, and went down. He could not swim.

This death has been included in this subPar, despite its late timing, because the undertow was generated or greatly exacerbated by the flood. The flood sent about 2,000 acre-ft of dense, sediment-laden water, at 40 fps and in about 30 minutes, in such a way that it developed a localized, violent, spiral flow very close to shore (1, 2). The canyon was about 35 miles upstream from Davis Dam on the 50-mile long reservoir in the Colorado River (1, p. 10 and map on p. 3). Since the lake would have had a residence time greatly in excess of one day and since the flood event was characterized by a large volume, great violence, and a dramatically different density than the rest of the river, spiral currents would have continued to hug the shoreline for some time after the event. Whatever the natural currents would have been at the site where Kinugasa drowned, their potential lethality was greatly increased at the time of his death: $\text{Par}_7 = 4$ and $L_7 = 2$.

Eyewitness accounts from Kirby Koop, Lemuel Washington, and Manuel Cortez (1; 2I, statements) indicate that the 20-ft wall of water did not propagate across the lake. Rather, it skated a short distance across the surface due to momentum, then sought the lowest reaches in the lake as the large amounts of sediment and debris had made the flood much denser than the cleaner lake water. There was very little pushing action at the surface and very little disturbance of the lake beyond the point of entry. Watermarks gave no evidence of a wave through the lake higher than 1.75 ft (1). Beyond the first few hundred feet, the dock and boats were displaced safely away from shore. Nearer to shore, the flood generated a swift and violent undertow, described as being free from pushing or whirlpool action and instead resembling someone beating eggs or a paddlewheel back-paddling. This action drew the near-shore surface waters toward the flood—even against active boat motors—and sucked large objects like trucks, boats, a dock, and trailers beneath the surface, grinding the dock and trailers to pieces and ripping off the clothes of those who were sucked under. As the death of Kinugasa (Par_7) indicates, abnormally strong undertows continued to circulate around the shoreline of the lake the next day, miles away.

This particular flood was noteworthy for the density of its leading edge. Located in a dry desert, there was virtually no vegetation to resist erosion. Both Lemuel Washington and Kirby

Koop described the initial flood surge—which would have determined the flow path to follow—as having a viscosity equal to or slightly less than that of freshly mixed concrete. The mixture sprayed out gravel and was stacked with trucks, trailers, and other debris (1; 2I, statements by Kirby Koop and the Washington brothers with Lucas; 2K, Supplemental Report).

Even so, such descriptions are not unique to this event. Not only is this a common characteristic of flash floods in Nevada-like deserts (1), but it appears to be a common characteristics of nearly all floods with a leading wall: the wall is partially sustained by muck—initially mud, rocks, sticks, and trees, followed by houses, bridges, fences, automobiles, and other obstacles (see, for example, the Buffalo Creek dam failure). Since nearly all catastrophic floods are densely sediment-laden, the action of this flood would likely be imitated by most walls of water that plunged suddenly into a large, deep reservoir.

Lake Mohave was narrow and the flood entered it at close to a 90 degree angle, so the "length" of the lake was about 1 mile and the "width" was about 50 miles. Due to sediments deposited in the lake, the shoreline was extended about 350 feet and gained 1.1 acres of land surface. The average estimated thickness of deposits between the pre-flood and post-flood shorelines was 9 ft (1, p. 14, Table 4), suggesting the lake (Colorado River) reached a depth of around 18 ft within 300 to 400 ft of the shore. This fits the general slope at Nelson's Landing of 280 ft/mi (1, p. 10 and fig. 12), which would drop 18 ft over a distance of 339 ft.

Conditions under which a flood might be expected to significantly impact a lake's surface for more than a few hundred feet would include a shallow lake or if a flood wave was superimposed on a substantial existing flow that had previously conditioned the lake to have a dense current in the direction the wave was traveling.

EVANS AND LOCKWOOD POND (also called SUMMERTIME LAKE) DAMS

Par: Hybarts Branch, Fayetteville, Cumberland County, N. Carolina, 1989 = 471

Par_1: vehicle occupants on the flooded portion of the 5-lane Morganton Road

$L_1 = 2$, $P_1 = 0.33$

Wt (Warning Time) The occupants of the van were warned not to cross the flooded Morganton Road (1). Reasonable estimates of Wt are possible based on circumstantial evidence. Evans dam was known to have overtopped for 1 hour, followed by Lockwood Pond Dam being overtopped for 30 minutes. Clearly, both dams were being watched. All four lakes in this series were visible from houses dotting their shores; and being well within the city, they were surrounded by heavily populated areas and busy, multilane highways. By 1989, there would have been regular traffic reports for the area, and news crews in helicopters could have quickly captured a dam failure in this area on film. The failure of Evans Dam could not have gone unnoticed, resulting in intense monitoring of the subsequent dams in the series and rapid news flashes.

Since Lockwood Pond Dam overtopped by about 1 ft for 30 minutes prior to failure, it is safe to assume that people were actively warned to avoid the flooded

Morganton Road crossing for a minimum of 0.5 hr (the period of steady-state flow) and perhaps as long as 1.5 hr. Being conservative, Wt_1 = 30 min.

Wt_{avg} (Avg. Individual Wt) Apparently all cars were being warned to avoid this stretch of Morganton Road. Although traffic reports probably issued warnings, warnings appear to have been given to drivers as they arrived at the flood edge, also, so Wt_{avg} = 0.5*Wt = 15 min.

Par_1 indicates a common problem: How does one predict the number of people who will ignore a clear warning when there is ample time to evacuate or avoid entering a potential flood zone? In this case, the threatened population entered the hazardous region moments before the wave arrived, despite warnings not to cross.

KANSAS CITY FLOODS

Par: greater metropolitan area, Kansas and Missouri, 1977 = 3000

Par_1: residents and shoppers not associated with their vehicles

L_1 = 4, P_1 = 0.0015

The greater Kansas City metropolitan area experienced 2 record-breaking storms within a 24-hr period. The first storm began about 1:00 AM on September 12, 1977, causing the small creeks and rivers that lace the area to crest around 6:00 AM with minor flooding. The second storm began about 8:00 PM that evening.

Since the ground was saturated, 90% of this storm immediately ran off. Nuisance flooding began by 8:22, when basements and some streets got wet (5), and severe flooding began by 9:00 PM. There was widespread flooding across 10 counties, causing damages in nearly every basin within a 1000 mi^2 area, 60% of which was metropolitan.

The area was relatively level with gently rolling hills. Even in the hardest-hit areas, the flood does not appear to have exceeded much above 7 ft. There are no reports of a wall of water or a sudden surge, so the event was atypical of a sudden dam failure. However, over the span of an hour or two, flood waters gained sufficient breadth, depth, and strength to cause about $80 million in damages in the two hardest-hit basins and 25 people lost their lives (2).

Although atypical of catastrophic dam failures or floods through narrow canyons, this event might be similar to the progressive, slow release of a large reservoir behind a short dam above a large, metropolitan community that extends a long distance downstream with a very modest slope. It does not necessarily correspond to a wide flood across a plain, however, since the size of this Par was a function of the number of streams involved, not the distance from the channels.

The striking thing about this event was that none of the deaths were due to drowning associated with a residential or commercial structure: 17 fatalities were drivers or passengers of vehicles, 4 were pedestrians, and 4 were heart attacks, electrocutions, or unknown causes (3). Two of the fatalities had been watching the flood waters (5).

Tpar (Threatened Population) If flooding begins 40 minutes before it becomes threatening, what fraction of Par evacuates during that time? How many people remain out of curiosity or to try to salvage a vehicle or belongings? How many refuse to abandon a vehicle while it is still safe to wade, not knowing how high the water will rise or the threat posed once the vehicle is mobilized? How bad does flooding have to get before people are willing to go out in a downpour? A reasonable guess at Tpar might be 5% or 10% of Par, after flooding became dangerous but before it reached its peak, but there is no basis for estimating the true value.

R (Maximum Rise Rate) Based on the hydrograph for Brush Creek at Main (see Qp), the creek rose in linear fashion from a flow close to zero (the morning peak had already dissipated) to a flow of 17,600 cfs in about 2.5 hours.

T (Time Summary) The second storm began about 8:00 at night, flooding low streets and basements by 8:22 PM and reaching levels of incipient lethality by 9:00 PM.

We (Warning Effectiveness) The flood does not appear to have been viewed as life-threatening, and for most it was probably not. Source 5 recounts a story revealing people's attitudes and the fact that the flood rose slowly enough to retreat before it:

> Most people took action only when water reached them. At a restaurant near Brush Creek, the managers and customers watched the water rise, and some "toasted the flood." When water reached the door of the restaurant, the door was closed. When water broke windows, the building occupants evacuated via the back door to a higher level. ...
>
> There is evidence that a portion of the public heard the flash flood watches and warnings, but paid no attention to them because they had heard so many watches and warnings of all types before without personally experiencing any disastrous consequences. (5, p. III-73f)

The two critical factors that limited life loss in this event were: 1) the flood rose slowly, giving adequate sensory warnings for evacuation, and 2) the topography was not steep and the flooding spread away from the stream channels, so although it was deep enough in places to require swimming, the currents were not uniformly lethal.

KELLY BARNES DAM FAILURE (TOCCOA FALLS)

DELINEATION OF PAR, LIFE LOSS, AND VARIABLES MORE EASILY PRESENTED THROUGH A GLOBAL ANALYSIS

Par: Toccoa Falls College and Toccoa Creek, Georgia, 1977

Par = 140; L = 39; P = 0.28

There were several dam failures or flash floods in the early 20th and late 19th centuries that impacted relatively small populations located in the 100-year floodplain along narrow river valleys with little or no warning. This event is similar in many ways, providing an excellent opportunity to compare those early failures with this modern failure. Since the fatality rates across the centuries were comparable, the rates of life loss in this event help validate the use of events that occurred prior to the advent of modern transportation, communication, etc., so long as housing damages and warning times are careful defined.

Despite newspaper articles to the contrary, the dam had not been officially inspected for safety (3, 9).

There was strong attenuation of Qp with distance, as was assumed for the Dale Dyke Dame failure, and as is typical of catastrophic floods. Computed values are listed under Qp.

See Tpar. Among the 4 hardest-hit subPar, 60 out of 93 survivors were injured. This is one of the highest injury rates for any flood, indicating that the warning was generally shorter than the necessary evacuation time and that Tpar ≈ Par.

The fact that the entire community impacted by this event was characterized by an exceptionally strong Christian faith and a resulting strong sense of solidarity seems to have dramatically reduced or eliminated the kinds of psychological debilitation seen in other events with a high rate of community mortality (i.e., see Buffalo Creek). The underlying burden of source 6 was to illustrate this perception by presenting every family that experienced life loss and to present the impressions of those who came in contact with them. First Lady Rosalynn Carter wrote the following introduction:

> This is a story about faith. . . . a personal testimony that there is inherent courage within us to face the challenges of life and death.
>
> I visited Toccoa Falls College on the day after the disaster that you will read about in this book. I went because I hoped that I could comfort those who had survived. Instead I was enveloped by hope and courage and love.
>
> The miracle of Toccoa Falls confirms what I believe. God loves us and will help us always. He gives us unlimited strength when we trust in him. (6, p. 13)

KELLY BARNES DAM FAILURE (TOCCOA FALLS)

Par: Par: Toccoa Falls College and Toccoa Creek, Georgia, 1977 = 140

Par_2: those in or adjacent to Residence Row, apart from Par_4

$L_2 = 19$, $P_2 = 0.66$

Daniel Woerner, a young soccer player, reached shore as the flood rose around him by jumping from one car roof to the next before the vehicles became mobile (6).

People do not always take the safest or shortest route to safety in a flood. As an example, the Woerners ran downstream along the road that paralleled the river, never once thinking to run laterally up the mountain to high ground (6, p. 61). This was, however, unusual.

Ten-year-old Kirk Veer survived by opening the door to a truck that passed by him underwater and climbing in to breath the bubble of air inside. Later, he reemerged to rise to the surface (6, p. 67).

KELLY BARNES DAM FAILURE (TOCCOA FALLS)

Par: Par: Toccoa Falls College and Toccoa Creek, Georgia, 1977 = 140
Par_3: Trailerville and closely-associated trailers across the river
$L_3 = 15, P_3 = 0.16$

Where the main channel curved, water-surface elevations on the left bank exceeded those on the right bank by as much as 10 ft due to superelevation. Even in these high velocity areas, however, there were calm waters in the backwaters of creek mouths (8).

Mobile homes generally stayed intact as they floated away, unless they hit another mobile home or other obstacle in the water. In that case, they disintegrated (6).

KELLY BARNES DAM FAILURE (TOCCOA FALLS)

Par: Par: Toccoa Falls College and Toccoa Creek, Georgia, 1977 = 140
Par_4: those known to be in automobiles when the flood hit
$L_4 = 2, P_4 = 0.5$

In the case of the firemen, their hip boots helped to pull them under (6). A similar danger could apply to fishermen wearing waders.

LAKESIDE DAM

Par: Greenville County, South Carolina, 1975 = 60
Par_1: Lakeside Road near Piedmont where it crossed Lakeside Dam
$L_1 = 1, P_1 = 0.33$

Par (Population at Risk) At 6:30 AM, Avanell Myers, age 25, drove her 1964 Dodge through a misty rain to drop off her 3-year-old daughter, Melody Ann, at her sisters on the way to work. At 6:40, she hit her brakes, but the car plunged off Lakeside Road into a 50-ft deep and 100-ft wide hole where Lakeside Dam used to be. She received internal injuries and injuries to her back, but she managed to climb out of her car. She was, however, unable to free her daughter sitting beside her, who drowned as floodwaters carried the car a short distance downstream. It is unclear whether Melody Ann was washed free of the car or whether the car eventually disappeared into the flood, but she did fight to get free and it took rescuers 4 hours to find her body (1, 2).

Myers' next-door neighbor, Ernest Bryant, age 42, left for work moments after the accident. He said, "When I came around the curve, it looked misty, dusky, not right. I hit my brakes and slid" (2). The front wheels of his truck stopped part way over the edge of the broken pavement. When he got out, he saw headlights glowing in the water below. He ran back home, told his wife to get help, and drove his other car around the lake to barricade the street on the other side. Leroy Bryant, age 16, went with his mother to help Avanell Myers who was standing ankle-deep in water (1, 2).

The primary danger to Par_1 was the 50-ft plunge. After such a fall, even water with little force had a high potential to cause drowning, especially to a young child.

LAKESIDE DAM

Par: Greenville County, South Carolina, 1975 = 60
Par_2: damaged houses in Greenville County
$L_2 = 0, P_2 = 0.0$

This case demonstrates the importance of defining Forcefulness more precisely. Even though Fp = 0.47, Fd = 1, and $Wt_{avg} = 0$, no houses were destroyed, no lives were lost, major damages were primarily non-structural damages from mud, and the maximum depth was about 4 ft, sufficiently shallow in which to stand.

LEE LAKE DAM FAILURE

Par: houses along East Lee Brook, Massachusettes, 1968 = 123
Par_1: dwellings that were destroyed
$L_1 = 2, P_1 = 0.4$

A 20-ft wide dam in the same location failed in 1886, killing 7 people (7).

If it had been any other time than Sunday, day or night, there would likely have been significant life loss at the Clark-Eiken plant (7).

MILL RIVER DAM FAILURE

DELINEATION OF PAR, LIFE LOSS, AND VARIABLES MORE EASILY PRESENTED THROUGH A GLOBAL ANALYSIS
Par: 6 towns along 10 miles of the Mill River above its mouth, Massachusettes, 1874
Par = 1,700; L = 151; P = 0.089

The flood dynamics were comparable in the first 4 villages, killing virtually everyone who was unable to reach high ground before their corresponding structures were destroyed. However, since only a few minutes of warning were available to each community as local Paul Reveres road ahead of the flood, this event provides an excellent opportunity to estimate the evacuation rate over a small range of Wt and Wt_{avg}. Due to the detailed, house-by-house narrative that was common after 19th century floods, this event also provides an excellent opportunity to compare life loss under varying degrees of structural damage (Ls = H, M, or L).

Poor choices due to panic are uncommon during floods, but when panic occurs, life loss can be increased dramatically. As an example, 12 people died while evacuating the Nonotuck silk mill in Leeds, despite the fact that the flood barely grazed the building. Thirteen people became confused about where to go, panicked, ran to cross the bridge on the river in hopes of reaching high ground on the other side, and were swept away.

People were similarly stupefied while evacuating the button factory in Leeds. Here, the buildings were utterly destroyed, but during the evacuation, rather than running for high ground, many ran into the city streets, either trying to reach their homes and their families or simply trying to outrun the flood. According to the papers at the time, there was general panic among this set of workers. As examples of behavior, Carrie Bonney, Sarah Ryan, and her 4-year-old son Charles “had ample time to save themselves but were completely stupefied with terror, and, with a fixed stare, stood motionless” until swept to their deaths. About half of those who died in Leeds were employees of the button factory (3).

It is significant that, due to panic among two sets of factory workers, roughly 75% of the deaths in Leeds occurred among those least threatened by the flood. The workers in the button factory were the first to be warned in this village and those in the silk mill would scarcely have gotten wet had they not run downhill.

As an example of panic during the Dale Dyke Dam failure, a man ignored the protests of his family and jumped from an upper story window, causing himself fatal injuries, even though flooding was extremely minor at his residence, posing no direct threat to life.

Although Wt_1 was twice as long as $Wt_{6\text{-}8}$ in Skinnerville, $Wtavg_1$ was approximately half as long as $Wtavg_{6\text{-}8}$. The difference lay in the rate of warning propagation and dissemination, which Wtavg considered but Wt neglects. Here, the relative magnitudes of Wtavg are in line with $Tpar_i/Par_i$, but the trend is counterintuitive with respect to Wt.

Note that the evacuation time was increased substantially due to families being separated during work hours. This was very, very significant in this event, contributing up to 50% of the fatalities in Leeds.

A young boy described the flood as follows: *A great mass of brush, trees, and trash was rolling rapidly toward me. I have tried many times to describe how this appeared; perhaps the best simile is that of hay rolling over and over as a hayrake moves along the field, only this roll seemed twenty feet high, and the spears of grass in the hayrake enlarged to limbs and trunks of trees mixed with boards and timbers; at this time I saw no water.* (3, p. 97).

For two weeks, huge crowds came everyday to the area by road and train to see the damage (3).

SHADYSIDE (WEGEE AND PIPE CREEKS) FLASH FLOODS

Par: Wegee and Pipe Creeks near Shadyside, Ohio, 1990 = 547

Par_1: Wegee Creek (see also Wegee Creek Flash Flood of 1919 for a similar event)

$L_1 = 11$, $P_1 = 0.40$

In a long, narrow river valley, when a wall of water progresses slower than people can evacuate by car, there will typically be motorists or residents who detect the flood through sensory clues and who flee downstream in an automobile. If they can gain distance, these motorists may stop along the way to warn residents or to pick up family or neighbors. At the least, they will typically turn on their lights, honk their horns, and possibly shout quick warnings out their windows. Such warnings do not always communicate the approaching danger effectively, but they generally prompt a curiosity that alerts other residents to sensory clues or alternate forms of warning. This allows many to run up a nearby hillside or to evacuate by automobile. Such actions generate a chain reaction, as more vehicles evacuate, people warn their neighbors, or people notice the swarm of unusual activity outside their windows. This contagious process can mobilize the better part of a community, saving countless lives, even in the absence of warnings by public officials. However, it is by nature much more random than a formal evacuation plan implemented by trained public officials. As such, when many houses are rapidly destroyed, the chances that at least some people will remain ignorant of the approaching danger and fall victim to the flood remains high. The Buffalo Creek Dam Failure provides an excellent example of this process as it worked itself out over 15 miles (see Wt,Wt_{avg}, and Sc under the Buffalo Creek Dam Failure). Since there were flood alerts but no formal flood warnings, this type of informal warning propagation undoubtedly unfolded in both Wegee and Pipe Creeks, as well.

Post-flood profile surveys did not indicate that debris dams necessarily formed, but a photograph of a huge pile of boards behind a bridge indicates that such dams formed at least partially (2). Such dams tend to counteract the natural attenuation of a wall of water, renewing its height.

SAINT FRANCIS DAM FAILURE

Par: along San Francisquito Creek and Santa Clara River, California, 1928 = 2,250

Par_1: work camp at Powerhouse No. 2

$L_1 = 81$, $P_1 = 0.99$

Less than 2 years after completion, Saint Francis Dam in San Francisquito Canyon, failed catastrophically and without warning just before midnight. The failure released a wall of water ranging from 50 – 120 ft high on numerous sleeping families in small encampments along 9 miles of San Francisquito Creek. The flood then followed the Santa Clara River 43.5 miles to the ocean, killing people in several small communities along the way.

The flood is unique in U.S. history in terms of the depth of the flood and in terms of the distance over which the flood remained highly lethal. Summaries from Source 1 indicate that 2 days after the event, 53 were listed as dead in Santa Paula, 19 in Moorpark, 48 in Fillmore, 13 in Castaic, 53 in Newhall, 14 in Ventura, 89 in Edison Camp, and 20 in the South Pacific section camp near Castaic. While these values would have been revised over time, this demonstrates that the flood caused significant life loss all the way to the ocean (Santa Paula, then Ventura), nearly 53 miles below the dam.

Also, in light of Par_6, a significant percentage of these were motorists.

Life loss is a function of distance from the dam only as it is affected by warning times, depths, velocities, widths, loss of shelter, or other variables that are themselves indirect functions of distance from the dam. As the original wave increases in depth and magnitude when $Wt_{avg} = 0$, life loss can be extended indefinitely until the wave itself loses lethal potential.

STAVA DAM FAILURES

Par: Stava, Italy, 1985 = 300
Par_1: all structures destroyed in Stava
$L_1 = 270$, $P_1 = 0.94$

This was one of the deepest, most violent, and most lethal floods on record. There were two mine-waste tailing dams high on the mountain. Photographs (2) reveal that they were built one immediately behind the other, terrace-style on a 30 – 45 degree slope. Such compact construction meant that the volume of the embankments was probably equal to or greater than the volume of the water they impounded, resulting in a flood dense with mud.

On July 19, 1985, the upper pond collapsed, immediately removing the lower pond and releasing a 100-ft wall of water and mud that erased the village of Stava half a mile below in 20 seconds, burying residents in mud and debris up to 18 ft deep. There was no official warning, the sites of the previous buildings could not be identified from the air or the ground, and life loss was virtually 100%. As Franco Ruggero described the expanse of mud, wreckage and uprooted greenery that was once Stava, "This is Stava, where you see nothing" (8). With the help of helicopters and dogs trained to sniff out buried victims, 18 survivors out of nearly 300 victims were dug from the mud (4, 6, 8, 9, 10, etc.).

The lethality of a sudden wave of water can be enhanced by a large sediment load that makes swimming difficult and which can literally bury victims alive, hiding them from rescuers and preventing escape under their own power. In some respects, such floods resemble mudslides. Nineteen victims were recovered alive from the mud at Stava, but far more were unearthed after they had died.

Flash floods in dry regions (see Eldorado Canyon) and flood waves from earthen embankment failures—especially embankments made from mine tailings (see Buffalo Creek)—are often characterized by a dense concentration of suspended solids and even preceded by a wall of mud. In the case of the Stava failure, the sediment concentrations were extreme. Photographs of the reservoirs reveal that the volume of the two embankments was probably comparable to the volume of the deep, 150 ft by 300 ft ponds (2), yet "the dam itself was flattened" (9) and "the dam was washed away completely" (6). Source 3 indicates that the wave carried equivalent amounts of water and mud. It is likely that much of this mud settled near its origin, but at Stava, a wave up to 130 ft (4, 5, 6) deep deposited sediment up to 18 ft deep (3) as it quickly passed, then continued to deposit mud for another 3 miles (5).

Rescue workers reported that some of the bodies had been dismembered (9). Among the first 150 bodies recovered, 15 were so disfigured that it was impossible to tell the victim's sex (10).

"Civil Protection Minister Guiseppe Zamberlette recounted, 'The sites of the hotels and houses had to be pointed out to me. It's as if they never existed' (3, p. 11).

Huge walls of water tend to create sufficient spray and dust and to be sufficiently unexpected that they are not always easy to identify as they approach. In case after case, walls of water are described as resembling fog, smoke or fire. In this case, one survivor described the 100-ft wall of water as follows: "I saw the end of the world. I saw a white wall coming toward me. I couldn't tell if it was fire or what" (9).

Here, like in many catastrophic floods, more than one distinct wave was observed. A man called Pietro told reporters his brother had climbed a tree to escape the first wave, but a second wave carried him away.

THOMPSON MILL DAM FAILURE

Par: Barren Creek below the Thompson Mill dam, Tennessee, 1916 = 78
Par_1: every house that was destroyed
$L_1 = 24$, $P_1 = 0.59$

On Aug. 3, 1916, Thompson's mill pond collapsed suddenly while most people slept. The wall of water traveled 5 miles to the next creek, causing major damage or destruction to most homes it touched. Life loss was limited to homes that were completely destroyed, being swept away before members could evacuate.

Although this event occurred in 1916, there is no reason to think L would be less today if no warning were given, structures were within the floodplain, and the structures sustained the same degree of damages. In other words, based on housing damages alone and a very short Wt_{avg}, modern failures would be no less lethal. However, current abilities to monitor dams, alert communities, restrict floodplain development, and enforce stricter building codes for multi-story residences might reduce L in a modern setting.

TIMBER LAKE DAM

Par: road crossings and a few trailers on Buffalo Creek, 1995 = 7
Par_1: bridge across Buffalo Creek on Highway U.S. 460
$L_1 = 1$, $P_1 = 0.17$

Par (Population at Risk) Par for this event is obscured by the fact that dozens or perhaps hundreds of watersheds were flooded throughout the state. Based on the statistics in the Introductory Summary, the most expansive view of Par would be roughly (1,622 houses statewide that were destroyed or seriously damage + ???? houses with minor damage)*(3 persons per house) > 5,000 and perhaps as great as 30,000. This expansive view of Par would be consistent with the approach taken by Dekay and McClelland in Allegheny County, Kansas City, or the Black Hills floods. Since we are looking only at flooding caused by the dam failure on Buffalo Creek, Par was considerably smaller.

The main threat to life loss was posed to motorists, since there were 7 river crossings in the first 6 or 7 miles downstream.

Pr (Preparedness) Although the Timberlake Homeowner's Association had an emergency action plan for their dam (9), the members of Par were completely unprepared for a dam failure: Pr = N.

See Fm for the role of human failure in dam failures.

Fm (Failure Mode) Although the spillway was repaired one year previously, the dam failed when the only person with a key to the spillway first waited too long to begin his trip to the dam and then got stranded on the way due to flooding (6). Water flowed over the top of the dam, and then it burst quite suddenly under the excessive pressure (12): Fm = Fe.

See Pr and Fm: an emergency action plan did not help save lives or prevent the failure of the dam.

Ac (Attendant Circumstances) Flooding prior to failure blocked traffic from crossing the bridge on U.S. 460, the location likely to have more traffic than all the other bridges combined. In place of vehicle traffic, rescuers were present. Even so, the rescuers had a better chance of floating to safety than would have motorists trapped in their cars. In the case of Par_1, Ac_1 = N.

Although the dam was declared inadequate in 1981 due to an undersized spillway, it was "grandfathered in" after the spillway was improved (6). The dam was certified in 1991, and an engineer's review in September of 1994 rated the dam as in "good condition/maintenance is better." The homeowners were praised for repairing the spillway after winter storms (5).

Jonathon Wright was one of those stabilizing Martin's rope (the rescue worker looking for occupants in the cars stranded on the bridge). While ducking under the rope, prior to the dam failure, he fell and rescuers grabbed him before he was swept away. He reflected, "I have a new respect for water. It was an incredible force. Words can't describe it . . . Your foot leaves the ground and you're gone" (14).

VAIONT DAM (ALSO SPELLED VAJONT)

DELINEATION OF PAR, LIFE LOSS, AND VARIABLES MORE EASILY PRESENTED THROUGH A GLOBAL ANALYSIS

Par: communities along 12 miles of the Piave River and the shoreline behind Vaiont Dam on the Vaiont River in Italy, 1963

Par = 3,000; L = 2,056; P = 0.69

Due to the unprecedented magnitude of the flood waves generated in this event, the Vaiont disaster provides a unique opportunity to explore the impact of huge waves on several different communities. While rather unique in terms of its cause, floods with similar characteristics might be generated if a high concrete arch dam or a high concrete gravity dam were to fail instantaneously, either through internal weaknesses or as a result of an earthquake or explosion. Earthen or rock fill dams perched high on steep slopes or which fail very rapidly have similar potential for destruction (i.e, see Stava Dam for a much smaller reservoir that caused nearly comparable fatality rates).

Vaiont Dam is a double-curved, thin-arch, concrete dam that was the tallest dam of its kind and the second-tallest dam in the world, rising 871 ft. Following years of slow movement, a massive portion of Mt. Toc plummeted into the reservoir, displacing a huge quantity of water that washed over lakeside communities and plunged over the dam, obliterating the towns below. As a testimony to the design of the dam, the dam itself did not fail, even though the forces it experience far exceeded those for which it was designed. The following summary is a composite drawn from sources 1, 2, 3, 4, 5, and 6.

Mt. Toc had a reputation for unstable slopes, causing some to question whether the dam should be built. Nevertheless, construction on the dam began in 1956 and it was completed in 1960, when the reservoir began filling. On Nov. 4, 1960, a crack on Mt. Toc opened 1 ft wide and 8,000 ft long. Engineers placed markers on the slope to help monitor its movements. Based on scale models of the dam and the entire basin, engineers decided that the worst landslide they could envision would be safe to human life if the lake were kept 75 ft below the dam's crest. It was believed that a wave no more than 5 ft deep could pass over the crest and the primary concerns applied to the communities around the reservoir.

Due to demand for power, however, the reservoir was raised to within 41 ft of the crest, beginning in April of 1963. As a result, another long crack appeared on the mountain. From July to September there were small earth tremors and the lake water "boiled up." Over the three years leading up to the failure, the average rate was 3/8 of an inch per week. This rate increased dramatically during the three weeks leading up to the failure. From Sept. 18 – 24, the rate was 3/8 of an inch per day, from Sept. 25 – Oct. 1 it was 4 – 8 inches per day, from Oct. 2 – 7, it was 8 – 16 inches per day, Oct. 8 saw 16 inches and the slope moved 2.64 ft on Oct. 9 prior to the complete failure. Animals which customarily grazed on the slope must have sensed the movement since they left the area around October 1.

On September 26, Nino Biadene, the deputy director-general for technical matters, ordered the valves to be opened so the water level could be reduced. Based on previous calculations, this rate was limited so as not to unbalance the hydraulic pressures in the slope. As the water drained, the rate of slippage increased, causing the many scientists now monitoring the slope to install floodlights to help read the slope markers at night.

By the end of September, engineers and geologists considered it highly probable that there would be a landslide by the end of November. By October 8, engineering-geologists realized that the markers were moving in unison and that they involved a slide area 5 times greater than previously thought. The morning of the 8th, the day before the failure, Biadene and the mayor of Erto sent warning messages throughout the lakeside communities. In the letters, the mayor urged residents to evacuate on government trucks at 4:00 PM. The power company supplied trucks to help remove families and livestock, some people were removed by police helicopter, and the evacuation was enforced through stationed police guards.

The evening of October 9, 1963, was rainy and dark. Just before 9:00 PM, additional warnings were sent to select areas downstream and efforts were made to block the roads, but there was not a strong sense of danger since very little water was expected to fall over the dam. At 10:40:41 PM, illuminated by the floodlights, 312 million (4) or 314 million (6) yd^3 of mostly rock fell off Mt. Toc, completely filling the reservoir for 1.1 miles immediately behind the dam to heights of 490 ft (6) or 574 ft (4) above the reservoir service. Seismic records demonstrate that the entire slide quit moving in less than 30 seconds, with most of it over within 14 seconds, after travelling up to 100 fps (68 mph). Seismographs detected this event across Europe at Rome, Trieste, Vienna, Basel, Stuttgard, and Brussels; the readings indicated that an earthquake did not precede the slide.

According to observers at Erto, the entire reservoir for 1.2 miles formed one, vast, curving wave that hung in the air for 10 seconds. Measurements would indicate that the highest wave rose 460 ft above the reservoir, but the strong updraft created by the nearly instantaneous displacement carried water and rocks still higher to at least 885 ft. This blast of air blew out windows around the lake and a similar blast ahead of the wall of water downstream would blow out windows in Longarone. The wind violently shook a house 850 ft above the reservoir at Casso before lifting up the roof and hurtling in rocks, spray, and rain for what seemed like 30 seconds to the owner. The man jumped from bed and left the room just before the roof crushed his bed.

Part of the water backed up in the reservoir, engulfing the lowest portions of the various lakeside villages. Two huge waves came together and crested at least 325 ft above the top of the 871-ft dam, forcing the bulk of the displaced reservoir downstream. The wave crest fell nearly a quarter of a vertical mile into the Vaiont River below. The flood wave was 230 ft high when it left the mouth of the Vaiont canyon 0.5 miles away and crossed the Piave River at an orthogonal angle. The wall of water rushed across the mile-wide Piave River valley and up the opposite slope. Along this trajectory, on the far side of the valley, was the town of Longarone. The water smoothed the physical surface of the valley and completely removed every structure in this town except for a few fortunate buildings poised high on the mountain. Part of the flood backed far up the Piave River, but most of it washed downstream, carving a swath a mile wide and utterly destroying everything it touched for 4 or 5 miles. Due to the width of the valley, the flood had attenuated significantly after the first few miles until it rose only 15 ft at Belluno 10 miles away. There, 150 houses were damaged that were not sufficiently protected by dikes.

Based on the flood hydraulics, this wave probably carried more lethal force than any other flood wave associated with a reservoir in recorded history. As such, it tended to utterly destroy everything it touched in an all-or-nothing rampage. The number of dead outnumbered those who were injured by 40 to 1. "Almost all persons who survived, including those around the major impact areas, did not lose any of their material possessions" (5, p. 211).

Cultural, religious, organizational and political considerations hindered an accurate accounting of the dead in this disaster. The following points were observed during the investigation presented in source 5:

- As of October 15, 6 days after the event, the official count of recovered bodies was only 1,100—roughly half of those who actually died and a little over 40% of the semi-official estimates.
- Fire officials did not begin to systematically move down the valley to look for bodies below the impact point until the 5th day.
- When the Italian Army concluded there were no more injured to rescue, they decided not to uncover the dead with heavy equipment. Instead, they used only shovels (5)—tools that could not possibly clear the debris over such a broad region (2 miles wide with bodies found 60 miles downstream).
- There was a great reluctance on the part of residents to help officials carry dead bodies in any form. The task was eventually assigned exclusively to the fire department.
- The press consistently reported life-loss figures about 50% higher than the official estimates.
- The nature of the human-impact was poorly understood. Compared to more than 2,000 fatalities, there were only 86 injured survivors. The reason was simply that the wave had such lethal potential that it killed nearly everyone that it touched. Those who were only injured were located farther from the dam or in the mountain communities around the reservoir. In contrast to the small number of injuries, several thousand hospital beds were prepared by relief organizations. In contrast to the areas where assistance was most needed, early efforts were concentrated at the heart of the disaster where few remained who needed assistance. It took 36 hr to get a communication line to the lakeside communities.
- In many cases, whole families died, along with their neighbors, so none remained who could identify the bodies or name those who were still missing.
- The area attracted large numbers of tourists, making it more difficult to identify bodies or to compile a comprehensive list of the missing.
- Officials were not highly motivated to recover bodies: "Many of the authorities felt that the search for bodies should have been stopped much earlier since any new corpse found would very likely be in a highly deteriorated condition." Officials were complaining about corpses that leaked or lost limbs when touched by the third day after the failure. One high ranking official complained: "It's absurd to dig down 10 ft of rocks and stones and find a body so we can re-bury it in only 5 ft of dirt" (p. 209).

Beyond these observations should be added the fact that no source provided an official estimate of missing persons. Unofficially, officials estimated that there were another 200 to 300 persons missing, but such a vast range indicates any list was far from accurate or complete, if it existed at all. Official lists of fatalities were strictly limited to the number of recovered bodies (3). This practice suggests why the press routinely made estimates 50% higher than officials, especially in the first days after the disaster.

The differences in the reported height of the dam (see H) reveal the difficulty in obtaining even the most verifiable statistics. This kind of divergence is common for many variables in a great many of failure events. What is especially frustrating is that sources almost never report the basis for these statistics nor the fact that other sources have reported different values.

Here are a few close calls at the extreme edge of the flood (3):

1. Twenty-two-year-old Maria Teresa Galli was closing her balcony shutters when the house dissolved and she was swept away in a combination of wind and water. She thought, “I’m flying . . . walking . . . swimming!” She survived after washing into the ground floor of a 2-story home that survived.
2. A paralyzed man asked his wife what was going on. She stepped out on the balcony to look and was snatched away by a passing edge of the wave before he even knew it was a flood.
3. In one family, a cousin opened the door to see what the roar was about, then slammed it shut again crying, “We’re all dead!” Water washed over them—presumably from run-up—then retreated a moment later, leaving some with broken bones but only one dead.

Apparently referring to a larger area than Longarone village—perhaps with reference to Longarone commune—source 3 indicated: “Out of every six children in Longarone proper, five died. . . . One boy said wonderingly, “When I walk past grownups, they all look at me as if they want me” (3, p. 66).

The impact on the living can be far greater when many people die. In this event, 1 woman survived from a family group of 55. In another family group of 36, only the Giacinta Vignago and her grandson survived. The psychological impact was severe:

> An unharmed woman with an unharmed baby in her arms, the only survivors of a large family, wandered from soldier to reporter to priest, to anybody, begging in a gentle voice, “Kill me. Please kill me.” (3, p. 66)

Sc ***(Sensory Clues)*** Animals behaved strangely as the time for the failure approached. The evening of the event, cattle and dogs demonstrated unease. A caged canary fluttered violently until it strangled itself to death in the bars of its cage. The owner turned to his wife and said, “Something’s going to happen! The dam . . . ?” (3, p. 60).

VAIONT DAM (ALSO SPELLED VAJONT)

Par: the Piave River and behind the dam on the Vaiont River, Italy, 1963 = 3,000

Par_5: the lowest reaches of Casso, Pineda and San Martino

$L_5 = 158$; $P_5 = 1.0$

The high fatality rate around the lake demonstrates the danger of defining Wt so that it can begin before an actual failure. The sense of urgency before a failure is sometimes missing, causing people to ignore or circumvent even coordinated and officially enforced evacuation efforts.

The communities around the lake were evacuated the day before the disaster. Casso was considered to be in danger of sliding into the reservoir. The mayor of Erto sent warning notices throughout the region, urging residents to leave on ENEL-SADE trucks that would come at 4:00 PM on Oct. 8, the day before the failure. (ENEL-SADE was the government-controlled power company that governed the dam following its nationalization.) The carabinieri (national police) ordered evacuations of Casso, Erto, and San Martino. Inhabitants were removed not only by truck but by helicopter, over their protests. Some returned at night and had to be evacuated a second time on October 9th. Patrols of 10 carabinieri stayed behind to guard each village. Those who died (at least 158) ignored the evacuation warnings and eluded the police (3, 5).

VEGA DE TERA DAM

Par: Vega on the Tera River in the Zamora District of northwest Spain, 1959 = 415
Par_1: same as Par
$L_1 = 153, P_1 = 0.37$

Two of the few differences between this event and the Vaiont Dam failures were the size of the wall of water and the brief warning time.

The flood wave dispersed in the lake below Rivadelago, so the heavily populated region down the next river valley along the Río Duero was not damaged (1). It is possible that over half of the population at Rivadelago survived because of the mitigating influence of this lake. Compared to the 20-ft wall of water that washed through town, the lake rose only 2 m (6 or 7 ft) where the flood entered. As at Eldorado Canyon, the lake was probably fairly calm once people were washed beyond the immediate shoreline.

WOODWARD DAM (also called HILL DAM) FAILURE

Par: Flander's Brook, from dam to Hill Village, New Hampshire, 1918 = 165
Par_1: same as Par
$L_1 = 1, P_1 = 0.0061$

The value of this case is that in the face of a flood wave that completely washed away or destroyed almost every inhabitable structure it touched, a warning of about 20 minutes was sufficient to reduce the life loss to one person.

Bibliographies specific to each event

The majority of reports available to me for various failure events were photocopied from files collected by Wayne Graham for the United States Bureau of Reclamation or by other researchers. In many cases these source files contained photocopies, fragments of sources, or typewritten copies that had incomplete reference information. In other cases, the documents consisted of surveys, notes of conversations with local officials, eyewitness testimonies, or staff summaries that were not formally published. It was not uncommon for source documents to be rare, existing today only in local libraries or private collections.

In light of the huge quantity of material collected and the number man hours required to accumulate the original files, it would have been prohibitive to search for the original documents or to obtain the missing reference information on each. Therefore, the following bibliographies contain only the information that was available to me.

These bibliographies are not comprehensive regarding the source material that was available, but they are comprehensive with respect to the source material that was found useful. In order to support fully the characterization of each event, it was necessary to make thousands of references to these sources. To facilitate this, bibliographic sets were numbered. This numbering has been preserved (and in some cases added) here.

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   A. Summary

   B. More summary

   C. Fact sheet on fatalities, damages, debris deposits, recovery costs, and agencies involved in the post-disaster operations.

   D. NPS Supplementary Case/Incident Report—an operational record of the search, cleanup, damage identification, and body recovery operations.

   E. National Weather Service information (map and handwritten notes).

F. Photographs

G. NPS meetings and decisions

H. Briefing sheets and summary of newspaper articles, 9/14/74 – 10/4/74.

I. Statements of witnesses regarding their observation of victims (combination of typed and handwritten reports from eyewitnesses)

J. Statements of witnesses about the event in general

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Wegee Creek Flash Flood of 1919
(See Shadyside for Same Creek)

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Appendix C

Summary Table of Assigned Variable Values

Appendix C consists of a master table of the coded characterizations of every subPar in the unpublished version of Appendix B. The greatly abbreviated, published version of Appendix B, above, describes and illustrates the nature of the data underlying the table. The meaning of the codes is defined at length in Chapter V and summarized in appendix D. The table itself, Table C.1, is located in a pocket at the back of this report.

Appendix C Table.xls

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Appendix D

Tools for Researchers

Alphabetical list of variables

Table D.1. An alphabetical list of variables

Variables		
A	La	Qb
Ac	Lcoz	Qp
Ah	Lcz	R
B	Ldr	Ret
Bpar	Le	Rf
Bt	Lh	Rr
Ch	Lidr	Sc
Coh	Lin	Schvq
Coz	Linf	Sh
Cozd	Ln	Sz
Cz	Lnf	Szd
Czd	Location-Deaths	T
D	Lpcz	Td
Dd	Ls	Tpar
De	Lsw	Ts
Det	Lsz	Tw
Dt	M	Ty
Dv	Ml	V
E	O	Vol
Ef	P	W
Eparj	Par	We
F5	Par_i	Wt
Fd	Pcz	Wtavg
Flt	Pczd	Wte
Fm	Pr	Wti
Fp	Prcoz	Wtpf
Fpar	Prcz	Wtpof
Ft	Prpcz	Ww
Gf	Prsz	Wwr
H	Psh	Zd
Hp	Pt	
L	Ptpar	

Summary reference table

Table D.2 lists each variable alphabetically, followed by its name, categorical breakdown, tips for accurate coding, and appropriate units in both the SI and English systems. The letter *p* represents the unit *persons*, living or dead; *bldg* represents buildings, and *u* indicates that a variable is unitless. Under coding, wrt is shorthand for *with respect to*. Ordinal variables are coded according to a subset of the following sequence: **N** = None, **L** = Low, **M** = Medium or Moderate, **H** = High, **V** = Very High, and **E** = Exceptionally High.

Explanation of variables

During event characterization, it was invaluable to have a concise, single-spaced summary of the definitions found in Chapter V, with tips on how to code the variables consistently. For the benefit of future reserachers, this working document has been reproduced here in its original form. Phrases have been left as incomplete sentences and it has not been reformated to fit the style in the body of the thesis because these changes would misrepresent its historic form, reduce its value as a concise working reference, and reduce its usefulness as a research aidthe only reasons for its inclusion in this appendix.

Populations at risk

Population at Risk (Par)

Historic: "The number of people that were evacuated or the number of people that would have been evacuated had there been any warning." (Dekay and McClelland, 1993, p.196). Or those likely to have encountered flooding that could have posed some reasonable threat.

1. Cutoff at extreme edge of flooding: canyon or little flow dispersal. V > 3 fps at 1 ft; lateral slope > 0.01.
2. Cutoff at 1.5 ft of flooding: leisurely flood/backwater. V < 0.5 fps at 2 ft.

Table D.2. Alphabetical reference table of variables (see Chapter V for detailed descriptions)

Symbol	Name	Coding	SI units	Eng. units
A	Area of Final Breach	Measures orthogonal to final flow	m^2	ft^2
Ac	Attendant Circumstances	Wrt the IMPACT Ac had on Wt, E, R, L, or other variables: **N, L, M, H**	u	u
Ah	Aerated Haven	Pocket of protection when building nearly destroyed.	u	u
B	Breadth of the Dam	Top width	m	ft
Bpar	Basis of Par	Is Par based on **Pre**-evacuation or **Post**-evacuation, regarding a preliminary wave prior to failure?	u	u

Table D.2. Continued

Symbol	Name	Coding	SI units	Eng. units
Bt	Building Types (by %)	**N** = None; **T** = tents; **Sh** = shacks or flimsy buildings; **M** = mobile homes or RVs; **R** = residential homes; **C** = commercial; **H** = commercial over 1 story; **Lm** = hospitals, nursing homes, elem. schools, or other buildings with less mobile populations.	bldg	bldg
Ch	Chance Haven	Tenuous refuges reached by chance.	u	u
Coh	Compromised Haven	Psh and Sh.	u	u
Coz	Compromised Zone	Roughly central 80% of Coh in terms of severity of flooding.	u	u
Cozd	Compromised Zone Density	Number from $Tpar_i$ likely to be in a compromised zone.	u	u
Cz	Chance Zone	All Ch, the open flood, and underwater.	u	u
Czd	Chance Zone Density	Number from $Tpar_i$ likely to be in a chance zone.	u	u
D	Depth	Deepest location potentially encountered by a member of Par_i.	m	ft
Dd	Damage and Destruction	List # of buildings destroyed, severely damaged, and slightly damaged by category.	bldg	bldg
Dev	Development (Degree of Urbanization)	**N** = none, **L** = small town, **M** = suburban, **H** = highly urbanized.	u	u
Det	Detectability	**N** = no signs of trouble; **L** = monitor wouldn't anticipate failure; **M** = alter operation, but don't expect failure this year; **H** = failure not unlikely if no action; **V** = failure imminent and not readily avoided.	u	u
Dt	Dam Type	Description: **N** = none, **E** = earthen, **R** = rock fill, **M** = masonry, **C** = concrete gravity, **A** = concrete gravity arch.	u	u
Dv	Destructive Velocity	(Qp - Qb)/W. Dv can be Dv_{min}, Dv_{max}, or Dv_{avg} depending on the choice of W.	m^2/s	ft^2/s
E	Ease of Evacuation = avg. surplus evacuation time	See equation under the definition.	min	min
Ef	Evacuation Nonsuccess Factor	Ef = $Tpar_i/Par_i$.	u	u
$Epar_i$	Evacuation subPar		p	p
F_5	Forcefulness coded using five even increments	**L** = (0 - 0.2), **M** = (0.2 - 0.4), **H** = (0.4 - 0.6), **V** = (0.6 - 0.8), **E** = (0.8 - 1.0)	u	u

Table D.2. Continued

Symbol	Name	Coding	SI units	Eng. units
Fd	Forcefulness coded dichotomously	Based on a qualitative guess at Fp, Fd is coded as 0 or 1 (1 for Fp ≥ 0.2)	u	u
Flt	Flood Type	**D** = dam failure, **Dy** = dyke failure, **Ff** = flash flood, **F** = flood, **Ts** = tsunami or tidal wave, **S** = sea surge, **H** = hurricane (deaths not limited to flood consequences), **Gb** = glacier burst, **O** = other (such as water tower or storage tank bursting)	u	u
Fm	Failure Mode	**I** = internal: **Ip** = piping, **Ie** = embankment failure: sliding, overturning, foundation failure, or blowout with normal water levels; **F** = flooding: **F** = flooding apart from dam failure, **Ff** = flash flood, **Ff/D** = dam failure contributes little volume to a flash flood, **Fo** = overtopping or spillway washout; **Fe** = embankment failure: slumping, sliding, overturning, foundation failure, or blowout during overtopping or higher-than-design reservoir elevations; **S** = seismic failure: **Sp** = piping or other gradual development following an earthquake, **Se** = a rapid embankment failure during or shortly after an earthquake;	u	u
		G = gate failure not leading to dam breach; **L** = landslide not leading to dam breach.		
Fp	Forcefulness coded as a proportion	Fp = (residences seriously damaged or destroyed)/(all residences with any damage)	u	u
Fpar	Forcefulness defined in terms of all habitable structures and Par_i	Fpar = (habitable structures severely damaged or destroyed)/(Par_i); habitable means residences, not businesses	bldg/p	bldg/p

Table D.2. Continued

Symbol	Name	Coding	SI units	Eng. units
Ft	Fatality Type	Quantify each, when possible: **N** = none; **C** = campers, riverside recreationists; **W** = waders and swimmers; B = boaters and rafters; **L** = boaters or swimmers on a lake; **E** = employees working at the dam; **Af** = auto-related; **Aa** = auto accident; **D** = general drowning in town; **Sf** = slope failure at dam; **O** = other non-drowning; **U** = Unknown mix.	u	u
Gf	Goodness of Fit	Variance in risk → spatial homogeneity wrt the river: **L, M, H, V**	u	u
H	Height of the Dam		m	ft
Hp	Height of Reservoir Pool at Failure	Measured in relation to the height of the dam, regardless of siltation.	m	ft
L	Life Loss (Loss of Life, LOL)		p	p
La	Adjusted Life Loss		p	p
Lcoz	Life Loss in the Compromised Zone		p	p
Lcz	Life Loss in the Chance Zone		p	p
Ldr	Life Loss Given Dam Removal		p	p
Le	Expected Life Loss		p	p
Lh	Historic Life Loss		p	p
Li_{dr}	Incremental Life Loss (using Ldr)		p	p
Li_{n}	Incremental Life Loss (using Ln)		p	p
Li_{nf}	Incremental Life Loss (using Ldf)		p	p
Ln	Natural Channel Life Loss *or* Never a Dam Life Loss		p	p
Lnf	No Failure Life Loss		p	p
Locations of Deaths	Locations of deaths		u	u
Lpcz	Life Loss in the Chance Zone		p	p
Ls	Loss of Shelter	Percent of buildings in each category: **L** = minor structural damage with flooding below 1 ft of first floor ceiling; **M** = major structural damage; **H** = complete submergence or destruction; **Mh** = uncertain whether M or H.	bldg	bldg
Lsw	Weighted Loss of Shelter	See Chapter V	u	u
Lsz	Life Loss in the Safe Zone		p	p

Table D.2. Continued

Symbol	Name	Coding	SI units	Eng. units
M	Magnitude of Loading	Description and code: **N** = none (sunny-day failure), **L** (expected every few years), **M** (once every 5-15 years), **H** (once every 15-50 years), **V** (once every 50-100 years), **E** (rarer than 1/100 years)	varies	varies
Ml	Magnitude of Local Loading	Same as M.	varies	varies
O	Outdoors	**I** = indoors (winter, work hours, night); **O** = outdoors (summer, recreationists, campgrounds)	u	u
P	Proportion of Life Loss	$P_i = L_i/Par_i$	u	u
Par	Population at Risk		p	p
Par_i	Subpopulation at Risk		p	p
Pcz	Pseudo-Chance Zones	Buildings for which it is uncertain whether will be destroyed, float away, or experience very major damage.	u	u
Pczd	Pseudo-Chance Zone Density	Number from $Tpar_i$ likely to be in a pseudo-chance zone.	u	u
Pr	Preparedness	**N** = unaware; **L** = aware, but don't think serious; **M** = alert for or experienced in evacuation; **H** = expecting to evacuate and steps	u	u
Prcoz	Proportion of Lives Lost in the Compromised Zone		u	u
Prcz	Proportion of Lives Lost in the Chance Zone		u	u
Prpcz	Proportion of Lives Lost in the pseudo-Chance Zone		u	u
Prsz	Proportion of Lives Lost in the Safe Zone		u	u
Psh	Pseudo-Safe Haven	A safe haven that drifts down stream less than 300 ft.	u	u
Pt	Par Type	The surroundings of a Pari, tagged with percents when mixed. **C** = campers, including recreationists near the river.	u	u

Table D.2. Continued

Symbol	Name	Coding	SI units	Eng. units
		W = wade fishermen, swimmers, etc. **B** = boaters and rafters. **L** = boaters and swimmers on a lake. **E** = employees working at the dam. Note, it may be desirable to reclassify this Pt as D, W, or another overlapping category. **Af** = motorists. **T** = those on trains. **D** = in or near buildings and general drowning deaths in town. **U** = unknown mix. Whenever possible, subPar should be broken down into pure Pt100%.		
Ptpar	Proportion of the Threatened Population	Proportion of the Threatened Population that dies	u	u
Qb	Bankfull Volumetric Flow Rate		cms	cfs
Qp	Peak Volumetric Flow Rate		cms	cfs
R	Maximum Rise Rate (of the flood wave)	Quantify numerically or: **M** = moderate (out walk), **H** = rapid (need rapid action), **V** = very rapid (hard or impossible to outpace), **Ww** = wall of water (quantify with Ww).	m/min	ft/min
Ret	Representative Evacuation Time	Code as 2, 15, 45, 120, 240 or more precisely if data permits (see chart above).	min	min
Rf	Rate of Failure	Not truly a rate: the minutes for the most rapid 80% of the breach.	min	min
Rr	Rescue Resources	**N** = none; **L** = limited (hand tools); **M** = modern (urban, post 1950); **H** = high (abundant extras)	u	u
Sc	Sensory Clues	Wt based on sensory detection of the flood.	min	min
Schvq	Striking Characteristics and Valuable Quotations	Insightful narrative, quotations, and a summary of distinctions. Wrt the overall fit of the variable set: **L** = low, **H** = high.	u	u
Sh	Safe Haven	A refuge where death is rare.	u	u
Sz	Safe Zone	Safe havens and mildly compromised havens	u	u
Szd	Safe Zone Density	Number from $Tpar_i$ likely to be in a safe zone.	u	u
T	Summary of mo/day/yr, hr, and day of week	List dates & times, narrative.	u	u
Td	Time of Day	**N** = night (most people are asleep; 11:30 PM - 6:00 AM);	u	u

Table D.2. Continued

Symbol	Name	Coding	SI units	Eng. units
		S = separation (most families are separated by school or work; 8:00 AM - 6:00 PM on weekdays); **H** = home (most families are together; 6:00 - 8:00 AM, 6:00 - 11:30 PM; weekends, holidays, or Par_i dominated by recreationists and day hours).		
Tpar	Threatened Population	Par present when flood arrives.	p	p
Ts	Time of Season	**S** = summer (May - October), **W** = winter (November - April)	u	u
Tw	Time of Week	**Wend** = weekend; **Wday** = weekday	u	u
Ty	Time of Year (month)	1 = Jan.; 12 = Dec.	u	u
V	Peak Velocity at Par_i	May be wave travel speed.	m/s	ft/s
Vol	Volume of Release		m^3	acre-ft
W	Maximum Flood Width at Par_i	W = W_{max}. Alternatively, one can use Wt_{min} or $Wt_{avg.}$	m	ft
We	Warning Effectiveness	**N** (no official warning), **L** (< 50% get and believe timely warning), **M** (up to 90% get and believe timely warning), **H** (nearly complete evacuation before flood wave arrives).	u	u
Wt	Warning Time		min	min
Wt_{avg}	Average Warning Time		min	min
Wt_e	Individual Escape Time *or* Warning Time for Escape	Not used directly.	min	min
Wt_i	Individual Warning Time	Not used directly.	min	min
Wtpf	Pre-failure Wt	Can begin prior to failure (= Wt)	min	min
Wtpof	Post-failue Wt	Does not begin until failure.	min	min
Ww	Wall of Water (Height of)	If "0", means no wall, so use R.	m	ft
Wwr	Wall of Water with D via R	See chapter V.	ft	ft
Zd	Zone Density(ies)	Number of people in a zone	p	p

3. Cutoff at a convenient contour between 6 and 12 inches: Between the extremes.

Life Loss (L)

Deaths of any kind and at any location that can be attributed directly or indirectly to flooding, without regard to whether or not the deaths would have occurred had the dam not failed under the same initiating hydrologic conditions. When victims remain on the list of missing in the most recent reports, they are included in L.

Threatened Population (Tpar)

All those present when the flood wave arrives.

SubPar (Par_i)

Subdivided whenever there is a clear change in a major variable.

Proportion of Life Loss (P)

$P = L/Par$ and $P_i = L_i/Par_i$.

Natural Channel [Never a Dam] Life Loss (Ln)

Expected L given that the dam had never been built. Assumes less flood plain development and different recreational patterns. Ln is counter-historical, except in the case of flash floods on undammed rivers.

Life Loss Given Dam Removal (Ldr)

Assumes the dam is removed, sediment issues are resolved, and the channel through the reservoir is restored, using the then-current development and geomorphology.

No Failure Life Loss (Lnf)

Had the dam not failed given the same initiating conditions.

Locations of Deaths

Where an individual was overcome, in contrast to where found. Associates death with a Par_i, or more detail when available.

Fatality Type (Ft)

Ideally, each symbol accompanied by an associated number of deaths.

N = none.
C = campers, including recreationists hiking/walking/standing near the river.
W = those in the river when the flood wave appears: wade fishermen, swimmers, rescue workers, etc.
B = those on the river when the flood wave appears: boaters and rafters.
L = those in or on a lake when the flood wave appears: boaters and swimmers.
E = employees of the dam who are at the dam for construction, repairs, monitoring, failure prevention, etc.
Af = automobile occupants killed by flood waters.
Aa = those killed in an automobile accident during evacuation.

D = general drowning deaths in town (trapped in a building or washed away) apart from the previous categories.
Sf = slope failure at or very near the dam itself.
O = other = non-drowning deaths other than auto-related or slope failure near the dam: mudslide associated with the flooding and not the dam failure itself, suicide, heart-attack, exposure, etc.
U = unknown mix.

Flood Characteristics

Flood Type (Flt)

D = dam failure.
Dy = failure of a dyke, thus being similar in some respects to a long dam.
Ff = a flash flood, meaning the flood wave is sudden and fast rising or a wall of water.
F = flood, meaning a widespread event that can't be described according to the other categories.
Ts = a tsunami or tidal wave.
S = a sea surge.
H = flooding caused by a hurricane and distinguished from F or Ff in that the deaths are not necessarily a result of the flooding.
Gb = a glacier burst.
O = other types of flooding difficult to categorize, such as when a storage tank or water tower bursts.

Peak velocity at Par_i (V)

Approaching flood wave or post-failure flood routing.

Maximum depth at Par_i (D)

Estimated using high water marks or the height of a wall of water (variable Ww). The datum should be the lowest point at which Par_i might have originally occupied.

Peak Volumetric Flow Rate (Qp)

Bankfull Volumetric Flow Rate (Qb)

Maximum Width of Floodwaters at Par_i (W)

$W = W_{max}$. Alternatively, one can use Wt_{min} or $Wt_{avg.}$

Destructive Velocity (Dv)

Dv = (Discharge above bankfull)/(width of flooded region) = $(Q_{peak} - Q_{bankfull})$/width.

- Not (maximum depth)*(velocity).
- Should use maximum values, even if at different times.
- Dv can be Dv_{min}, Dv_{max}, or Dv_{avg} depending on the choice of W.

Maximum Rise Rate (R)

Steepest portion of the rising edge of the outflow hydrograph (cfs/min):
M = moderate (can walk away from the flood waters if no lingering).

H = high = rapid (requires immediate, rapid action to avoid being trapped).
V = very rapid (difficult or impossible to outpace waters, even with immediate evacuation on foot or by automobile).
Ww = wall of water (indicates the rise rate is instantaneous and can only be quantified by measuring the height of the wall of water--variable Ww).

"Wall of Water" [height of] (Ww)

Most credible estimates should be averaged. Ww = 0 when not a wall.

Damage and Destruction (Dd)

The number of structures each destroyed, seriously damaged and damaged to any extent, by category of structure and degree of damage.

Forcefulness (Fp, Fd, F_5, Fpar):

(Fp) = (# residences destroyed or seriously damaged)/(all residences experiencing any damage).
(Fd) = 1 whenever Fp ≥ 0.2. subjective; includes the destruction that would have been likely if residences were physically present.
(F_5) L = low (0 - 0.2).
M = medium (0.2 - 0.4).
H = high (0.4 - 0.6).
V = very high (0.6 - 0.8).
E = exceptionally high, meaning there was nearly complete destruction (0.8 - 1.0).
(Fpar) = (# habitable structures [not businesses] of any type, damaged severely or destroyed)/(Par_i).

Height of the Reservoir Pool at Failure (Hp)

Given overtopping, the depth of overtopping is added to the height of the dam. In the absence of overtopping, the distance to the reservoir pool below the dam crest is subtracted from the height of the dam.

Height of the dam (H)

Ideally, this is measured from the streambed.

Breadth of the Dam (B)

This is the crest length, not the thickness. H and B describe the dam prior to failure.

Volume of Release (Vol)

Does not include additional inflows into the reservoir after failure.

Rate of Failure (Rf)

The "most rapid" 80% of the failure (in minutes).

To help standardize eye-witness accounts:

- nearly instantaneous (i.e., "as an explosion", "quicker than you can write these words", etc.) = 0.5 minutes.
- very rapid erosion or slope failure short of near-instantaneous = 5 min.

- more or less rapidly as evidence supports.

Area of Final Breach (A)

Spatial and Temporal Relationships
Between Par_i and the Flood

Summary of month/day/year, hour, and day of the week (T)

A complete record. T is broken out below.

Time of Day (Td)

N = night (most people are asleep; 11:30 PM - 6:00 AM).
S = separation (most families are separated by school or work; 8:00 AM - 6:00 PM on weekdays).
H = home (most families are together; 6:00 - 8:00 AM, 6:00 - 11:30 PM; weekends, holidays, or Pari dominated by recreationists during non-night hours).

Time of the Week (Tw)

Wend = weekend.
Wday = weekday.

Time of the Year (Ty)

Month, coded as 1-12.

Time of the Season (Ts)

S = summer (May - October).
W = winter (November - April).

Warning Time (Wt)

From when the first official warning to when the leading edge of potentially lethal flood waters first arrive at the leading edge of Par_i. Official warning is any warning that reaches a member of Par_i, is intended to be received by others, and encourages evacuation.

Average Warning Time (Wt_{avg})

Ballpark estimate of the average individual Wt_i, independent of the "official" Wt. It includes Sc, but excludes warnings that the population as a whole tends to discount, such as reports that a dam might fail following a history of false alarms.

Building Types by Percent (Bt)

Categories might need to be lumped together:

N = none.
T = tents.
Sh = shacks or flimsy buildings.
M = mobile homes or RVs.
R = residential homes.
C = commercial.
H = commercial over 2 stories.

Lm = structures with less mobile populations (hospitals, nursing homes, schools).

Development (Dev)

Degree of urbanization:

N = none (rural, communities under 100)
L = low = small town
M = medium = suburban
H = highly urbanized; large city, densely populated, high rises

Goodness of fit (Gf)

Spatial variable that describes the variance in risk--that is, their spatial homogeneity or heterogeneity with respect to the river:

L = low = poor (a large, urban area; multiple communities over a long reach of river; wide flood plain; mix of canyon and open plain; variable values would suggest excessive danger more often than not if applied on the individual level).
M = moderate = satisfactory (a typical small town or mountain community with some residences near the river and some on higher ground or in the hills; a series of small communities with similar warning time; a wide flood plain with urban/suburban development among which the flood rises slowly).
H = high = good (all of Pari reside within a narrow flood path; small canyon community clustered along the river; campgrounds; very small Par in a similar location, such as a few cars at a flooded road).
V = very high = very good (a huge wave which submerges an entire community without warning; a wave which annihilates virtually every structure within the area of Pari; no basis for saying some members of Pari are safer than others and no time to escape before the flood arrives).

Outdoors (O)

Tents are considered outdoors.

I = indoors (winter, work hours, night).
O = outdoors (summer, recreationists, campgrounds).

Sensory Clues (Sc)

Using testimony, estimate this warning (min.). Sc = 0 when none.

Preparedness (Pr)

Preparedness to evacuate at least half an hour before Wt begins. Considers news reports, false alarms, evacuation rehearsals, alerts, experience with flooding, etc.

N = none (not aware of the potential for danger 0.5 hr before Wt begins).
L = low (aware the safety of the dam is in question, but not considered serious).
M = moderate (alert to the potential for evacuation or experienced in evacuation).
H = high (expecting to evacuate and concrete steps toward that eventuality).

Warning Effectiveness (We)

How effectively a warning campaign mobilizes a community. It can be gauged historically by evacuation effectiveness: % of Par_i receiving a warning, rate warning propagates, and effectiveness in mobilization (believability and urgency).

N = no official warning.
L = low (fewer than 50% receiving or believing a timely warning).
M = moderate (up to 90% receiving and believing a timely warning).
H = high (virtually complete evacuation before the flood wave arrives).

If no numbers, guess using testimony. Note even a haphazard warning may propagate effectively given enough time.

Evacuation subPar (Epar$_j$)

A subgroup of Par_i characterized by the same Ret. Epar_j need not have equal numbers, and the number of groups can be one or more depending on the degree of heterogeneity within Par_i.

Representative Evacuation Time (Ret)

The number of minutes it will take to evacuate Epar_i, for use in calculating E. The following table can provide guidance, but case-specific information should govern.

Ease of Evacuation [Avg. Excess Evacuation Time] (E)

$$E_i = \frac{\sum_{j=1}^{n} Epar_j * (Wt_{avg} - \mathrm{Re}t_j)}{Par_i}$$

When E is negative, the average evacuation time needed was greater than the time available.

Table D.3. Reference guide to aid in estimating E and Ret

Width of the Flood (ft)	Outdoor Distance to Safety (ft)	Dev (N, L, M, H)	Sense of Urgency	Mobility (L, H)*	Range of Evacuation Times for a Family (min)		Ret$_i$ (min)	
					Day	Night	Day	Night
1,000	300	N-M	High	H	0.5-3	1-6	1	2
1,000	300	N-M	High	L	2-10	4-15	4	6
2,500	1,000	N-L	High	H	3-6	4-10	4	7
2,500	1,000	M-H	High	H	3-10	4-15	6	8
2,500	1,000	N-H	High	L	3-10	5-15	6	8
5,500	2,500	M	High	H	5-20	5-30	10	15
5,500	2,500	N-M	High	L	10-30	10-30	15	20
5,500	2,500	M-H	High	L-group home	20-180	30-180	45	60

*L implies one person with limited mobility living with one or more others with normal (H) mobility. The final row is an exception, where a nursing home or similar facility is in view.

Natural Circumstances that Attend the Flood

Failure Mode (Fm)

- I = internal
    - Ip = piping
    - Ie = embankment failure: sliding, overturning, foundation failure, or blowout with normal water levels
- F = flooding
    - F = flooding (dam failure not present or not relevant)
    - Ff = flash flood (no dam failure)
    - Ff/D = dam failure contributes little volume to a dominant flash flood
    - Fo = failure due to overtopping or spillway washout
    - Fe = embankment failure: slumping, sliding, overturning, foundation failure, or blowout during overtopping or reservoir elevations significantly higher than those for which the dam was designed to ordinarily operate.
- S = seismic failure
    - Sp = piping or other gradual development following an earthquake.
    - Se = a rapid embankment failure during or shortly after an earthquake.
- G = gate failure not leading to dam breach.
- L = landslide not leading to dam breach.

Attendant Circumstances (Ac)

Ac refers to conditions that attend a flood, the presence of which can increase the fatality rate of the event. Examples include an earthquake, extreme weather conditions such as snow or ice, hurricane-force winds, extreme prior flooding, or a downed radio tower.

It should be noted that power failures, darkness when Td = N, and rain are common features of many floods, and the latter two are already noted in the variables Td and Ml. As such, they should only be included under Ac if their impact was exceptional.

Attendant circumstances should first be described, then corporately assigned a subjective rank based on the impact the circumstances had on variables like Wt, E, and R.

N = none.
L = low impact.
M = moderate impact.
H = heavy impact.

Magnitude of Loading (M)

Narrative description: peak rainfall, representative rainfall measurements, and durations would be typical.

N = none (i.e., and internal failure).
L = low = small (loading is common; could be expected every few years).
M = moderate (loading is infrequent; once every 5-15 years).
H = high = large (loading is uncommon; could be expected once every 15-50 years).
V = very large (loading is quite rare; could be expected once every 50-100 years).
E = exceptionally large (loading is difficult to imagine; more rare than 1/100 years).

Magnitude of Local Loading (Ml)

Narrative; coded the same way as M.

Human Circumstances that Attend the Flood

Dam Type (Dt)

N = none.
E = earthen.
R = rock fill.
M = masonry.
C = concrete gravity.
A = concrete gravity arch.

Rescue Resources (Rr)

Helicopters, National Guard, paid or volunteer firefighters, police, emergency management and evacuation personnel, reliable communication, earth-moving equipment, boats, etc.

N = none (rescuers are prevented from assisting until the next day; victims are overwhelmed so quickly that no rescue attempts are feasible).
L = low = limited (rescuers are able to help some people, but they are mostly limited to hand tools: ropes, rowboats, floating debris, human chains, etc.).
M = medium = modern (modern communication, transportation, and rescue resources are available locally, at least in moderate supply; generally reflects the state of development present in urban areas of the USA after 1950).
H = high = exceptional (large numbers of military or rescue workers stationed nearby, immediate access to many local helicopters, an abundance of boats in the

community; plenty of floating debris, trees, tall buildings, or hills to sustain victims until they can be rescued; modern wireless communication systems; state-of-the art early-warning and evacuation system).

Detectability (Det)

Signs of imminent failure <u>more than 3 hours before failure</u>.

N = no signs of trouble.

L = low (one or more minor changes at the dam, but would not lead the typical dam monitor to anticipate failure).

M = moderate (sufficient changes to consider altering the reservoir operation as a precaution, but would not lead a typical monitor to expect failure within the year).

H = high (evidence demanding immediate attention, as it suggests a dam failure is not unlikely if no action is taken).

V = very high (dam failure appears probable or imminent and can not be readily avoided).

Striking Characteristics and Valuable Quotations (Schvq)

Brief narrative summarizing those aspects that are unique or are not adequately described by the variables. Eyewitness descriptions of deaths can provide insight.

L = low = poor (existing variables do a poor job of fully capturing the unique attributes of this flood event).

H = high = good (existing variables do a good job of fully capturing the nature of this flood event).

Important Variables Brought to Light During Characterization of Events

Pre-Failure Warning Time (Wtpf) and
Post-Failure Warning Time (Wtpof)

Wtpf indicates the full length of Wt when it begins prior to failure. Wtpof does not start counting until failure begins. Hence, if Wt begins an hour before failure and the flood travels for 30 minutes, Wtpf = Wt = 90 min and Wtpof = 30 min.

Wall of Water Weighted by the Rise Rate (Wwr)

See definition in Chapter V.

Basis of Par (Bpar)

This variable identifies cases where pre-failure jitters causes some to leave and Par is then based on those who choose not to leave until a subsequent warning mobilizes the entire population.

Pre = pre-evacuation, meaning before any evacuations have begun.

Post = post-evacuation, meaning Par is based on those left behind after the first group leaves and Tpar is based on those who become trapped in the flood.

Par Type (Pt)

List each separately and tag with its percent of Par_i.

C = campers, including recreationists hiking/walking/standing near the river.
W = those in the river when the flood wave appears: wade fishermen, swimmers, rescue workers, etc.
B = those on the river when the flood wave appars: boaters and rafters.
L = those in or on a lake when the flood wave appears: boaters and swimmers.
E = employees who are at the dam for construction, repairs, monitoring, failure prevention, etc. Note, it may be desirable to reclassify this Pt as D, W, or another overlapping category for purposes of analysis.
Af = automobile drivers or passengers.
T = people occupying a train.
D = those who, prior to evacuation, are in or near buildings. This corresponds to general drowning deaths in town. These people might encounter the flood while indoors, while evacuating on foot, or while evacuating in a vehicle, but generally speaking, they were quantified based on structural damages and the mode or place of death may not be known.
U = unknown mix. Whenever possible, subPar should be broken down into pure Pt (C, W, B, L, Af, or D) to facilitate characterization and analysis.

Proportion of the Threatened Population (Ptpar)

This is similar to P, except that it is the ratio L/Tpar.

Evacuation Nonsuccess Factor (Ef)

Ef = Tpar/Par.

Tpar and "flood arrival" are defined in such a way as to ignore trivial flooding that does not greatly hinder free movement (generally 6-12 inches for waders close to the hillside and lesser depths for those evacuating by automobile).

Safe Havens (Sh), Chance Havens (Ch), and Pseudo-Safe Havens (Psh)

See *Global Insights from the Case Studies* in Chapter VI.

Safe Havens (Sh)

Safe havens may or may not be flooded, but they represent places of shelter in which deaths have historically been extremely rare. When deaths occur, they generally involve young children or persons of limited mobility who can't swim and are trapped in an area without another person of average ability to assist them. Safe havens include the following:

1. An upper story with sufficiently shallow flooding that occupants are not washed out a window and can float on a bed or stand freely: flow does not rise more than one foot above the windowsills in the highest story (about 3 ft).
2. Quiescent flooding that does not trap people without air. Such flooding can come within 1 ft of a flat ceiling or 2 ft of the peak of a sloped ceiling, whether or not the ceiling is elevated.
3. An attic that is accessible from within a house or trailer.
4. An accessible rooftop that does not depend on chance to reach.
5. A stout tree that is easy to climb, taller than the flood, and not toppled.

6. Any island or region that experiences shallow flooding during the flood's peak, such that depths are easy to resist while standing or clinging to convenient anchors such as telephone poles or lampposts (depths of 1-5 ft, depending on the velocity).
7. The hillside beyond the flood if a member of $Tpar_i$ can readily drive or wade to it while the flood is still shallow, or if they can reach it directly from the roof or an upper story.

Chance Havens (Ch)

Chance havens are refuges in the flood, including floating debris and other types of havens, that are reached primarily by chance or whose benefits are highly unreliable. They contribute significantly to the variance in fatality rates across similar events. Chance havens fall into at least five categories:

1. Rafts and floatation aids: severed rooftops, mattresses, propane tanks, logs, etc.
2. The roof of a floating buildings whenever it drifts more than 100 yards.
3. Any immobile structure or refuge that is reached while drifting, including rooftops, upper-story windows, aerated havens, treetops, overhanging branches, debris dams at bridges that allow victims to walk to dry land, and the shore itself. If people must rely heavily on chance to reach a largely inaccessible roof, this would also constitute a chance haven.
4. Aquatic havens: any location from which shore can be easily reached without fighting high velocities, such as a lake or a quiescent backwater.
5. Wading havens: These are rare, falling in the narrow range of depths and velocities that are too high to be considered safe havens and too low to consistently sweep people away. Due to debris, waves, and unpredictable turbulence, such chance havens might not last long.

Pseudo-Safe Havens (Psh)

Pseudo-safe havens are safe havens on or in buildings that become reclassified once the building begins to drift. They exist only among a subset of buildings with major damage. Note that rooftops are considered chance havens (Ch) rather than pseudo-safe havens when a building drifts more 300 ft.

Aerated Havens (Ah)

Aerated havens are typically found only when parts of stationary buildings are torn away (the upper end of Ls = M). They are those pockets of protection formed by the remaining walls, floor, counters, etc., that provide a place for survival if the occupants are fortunate enough to have been located in that portion of the building.

Compromised Havens (Coh)

This simply places pseudo-safe havens and aerated havens in a single category.

Loss of Shelter (Ls)

The goal is to define subPar such that Ls = H100%, M100%, or L100%.

L = Low loss of shelter = no structural damage or minor structural damage limited to flooding on the first floor.
M = Major loss of shelter = major structural damage.
H = high (complete) loss of shelter = total destruction.

Mh = highly uncertain whether Ls = M or Ls = H.

Ls is not equivalent to economic damages. Ls = L implies relatively safe havens on every floor, Ls = M implies complete loss of a safe haven on the first floor, and Ls = H implies complete loss of all safe havens (and aerated pockets of less-safe shelter) including any accessible rooftops. Since loss of a safe haven is generally accompanied by structural damage, traditional categories of minor and major damage generally agree with Ls = L and Ls = M when they are based on structural damages and not mere water damage. By contrast, Ls = H only if no accessible, aerated pockets of protection remain, regardless of whether a building floats off its foundation or is later condemned.

The following refinements, based on historical observations, should be kept in mind (see *Global Insights from the Case Studies* in Chapter VI):

Ls = L

- When there is minor structural damage and the flood does not encroach within a foot of the first-floor ceiling or within 2 ft of the peak of a sloped ceiling.

Ls = M

- If the flood does not crest an accessible roof.
- If walls are ripped off but portions of walls and floors or counters remain to shelter occupants; but if only trivial structural members remain such that all shelter is lost, the dwelling is destroyed.
- If a building floats off its foundation and maintains an accessible pseudo-safe haven for the duration of the flood.

Ls = H

- Any time it is torn apart and submerged in the flood.
- If a rooftop is inaccessible and the top floor or accessible attic is submerged.
- If a roof is accessible, the building is considered destroyed only if the flood or flood waves wash across the crest of the roof to an extent likely to wash people into the flood. Since the momentum of the flood riding the slant of the roof will cause waves to run up, this elevation is generally on the order of a foot or two below the roof's crest.

Ls = Mh

- Ls = Mh means that, based on uncertainty, analysts view Ls = M and Ls = H as having roughly equal probabilities.

Weighted Loss of Shelter (Lsw)

Ls is put on a scale from 0 to 1 (see Chapter V for details).

Safe Zones (Sz), Compromised Zones (Coz)
Chance Zones (Cz),and Pseudo-Chance Zones (Pcz)

- *Safe Zones (Sz):* all safe havens and havens that have been only mildly compromised.
- *Compromised Zones (Coz):* that central portion of compromised havens that have not been purposely classified as safe zones or pseudo-chance zones.
- *Chance Zones (Cz):* places where people are submerged or face the open flood, and all chance havens that might be reached while drifting.

- *Pseudo-Chance Zones (Pcz):* buildings in that range of depths*velocities for which it is unclear whether the building is likely to be destroyed, float far downstream, or experience very major damage.

Zone Density or Zone Densities (Zd),
Safe Zone Density (Szd),
Compromised Zone Density (Cozd)
Chance Zone Density (Czd), and
Pseudo-Chance Zone Density (Pczd)

Density represents the distribution of $Tpar_i$ among flood zones based on topographic, structural, and hydraulic considerations as they interface with flood routing and the rise rate of the flood. The word "density" refers to the number of people who have access to a category rather than to the physical dimensions of flood zones themselves. Access includes the physical ability to move to a location and sufficient time to get there before being cut off by the flood. Accessibility is cut off if the flood rises too quickly, but this is rarely a concern when Ls = M, the usual case for which densities are widely distributed.

Thus, *Szd, Cozd, Pczd,* and *Czd,* each represent the number of people expected to be in each of the corresponding flood zones. People can be expected to choose Sz, Coz, Pcz, and Cz in that order, as they are available. People should be assigned to the highest level that persists for the duration of the flood, with the understanding that they are only assigned to Cz if the haven they previously reached ceases to exist.

Life Loss in Zones (Lsz, Lcoz, Lpcz, Lcz)

These are analogous to L_i, except that they are specific to the zones sz, coz, pcz, and cz.

Proportion of Lives Lost in Zones (Prsz, Prcoz, Prpcz, and Prcz)

These are analogous to $Ptpar_i$, except that they are specific to the zones sz, coz, pcz, and cz. Note that "proportion" is designated with Pr instead of the traditional P in order to avoid confusion between the pseudo-chance zone (Pcz) and the proportion of lives lost in the cz (Prcz).

Template used to characterize events in Appendix B

To assist in characterizing every event in a consistent manner, the data for each characterization was recorded on a template. The template leads with a summary table that lists every variable's value for that event, along with a brief reminder of the variable's name or meaning, and the choices from which it can be coded. Next, each variable is given its own section following the pattern of presentation in Chapter V. During characterization, every variable assignment is fully supported with narrative and source citations so that researchers can judge the relative merits of the characterizations, make their own informed adjustments, or refine them as additional information comes to light. When a variable is followed by an asterisk (*) it means that the narrative supporting the designation is found under the same variable for Par_1 or the global introductory characterization of the event as a whole. Three dashes (---) means that there is not currently enough information to estimate the variable.

Because the variables under the sixth category, “Important Variables Brought to Light During Characterization of Events and Subsequent Analysis,” were not part of the original analyses, they were not included in the event template. Future researchers may wish to update the template to reflect these important additions. In particular, they should add the important variables *Pt, Ptpar, Ef, Ls, Szd, Czd, Pczd, and Cozd*.

NAME OF DAM/FLASH FLOOD/FLOOD

Par: location, year = size

Par_1: same as Par OR Par_1: description

L_1 = ##, P_1 = 0.#####

Global Event				**Subpopulations**			
L Life Loss (p)	**P** Proportion of Lives Lost (u)	**Par** Population at Risk (p)	**Tpar** Threatened Population (p)	**L_i** Life Loss at Current SubPar (p)	**P_i** Proportion at Current SubPar (u)	**Par_i** Current SubPar (p)	**$Tpar_i$** Tpar at Current SubPar (p)
---	---	---	---	---	---	---	---

Incremental Life Loss					**Flood Characteristics**		
Ln Natural Channel Life L. (p)	**Lnf** No Failure Life Loss (p)	**Li_n** Incremental L Using Ln (p)	**Li_{nf}** Incremental L Using Lnf (p)	**Ft** Fatality Types (N,C,W,E,Af, Aa,D,Sf,O,U)	**Flt** Flood Type (D,Dy,Ff,F,Ts, S,H,Gb,O)	**V** Peak Velocity (ft/s)	**D** Maximum Depth (ft)
---	---	---	---	---	---	---	---

Flood Characteristics (Continued)							
Qp Peak Flow Rate (cfs)	**Qb** Bankfull Flow Rate (cfs)	**W** Maximum Width (ft)	**Dv** Destructive Velocity (ft^2/s)	**R** Max. Rise Rate (M,H,V,Ww) (cfs/min)	**Ww** Wall of Water (Height) (ft; 0 --> R)	**Fp** Proportional Forcefulness (0.0 - 1.0)	**Fd** Dichotomous Forcefulness (0 or 1)
---	---	---	---	---	---	---	---

Flood Characteristics (Continued)							
F_5 Incremental Forcefulness (L,M,H,V,E)	**Fpar** Forcefulness per SubPar (bldg/p)	**H** Height of Dam (ft)	**Hp** Height of Reservoir (ft)	**B** Breadth of Dam (Crest Length) (ft)	**Vol** Volume of Release (acre-ft)	**Rf** Rate of 80% Failure (min)	**A** Area of Final Breach (ft^2)
---	---	---	---	---	---	---	---

Spatial and Temporal Relationships							
Td Time of Day (Night, Home, Separation)	**Tw** Time of Week (Wend or Wday)	**Ty** Time of Year (1 - 12)	**Ts** Time of Season (Summer or Winter)	**Wt** Warning Time (min)	**Wt_{avg}** Avg. Individual Warning Time (min)	**Bt** Bldg Types (%) (N,T,Sh,M,R, C,H,Lm)	**Dev** Development (Urbanization) (N,L,M,H)
---	---	---	---	---	---	---	---

Spatial and Temporal Relationships (Continued)					
Gf Goodness of Fit (L,M,H,V)	**O** Outdoors (Indoors or Outdoors)	**Sc** Sensory Clues (min)	**Pr** Preparedness (N,L,M,H)	**We** Warning Effectiveness (N,L,M,H)	**E** Ease of Evacuation (min)
---	---	---	---	---	---

Attendant Circumstances							
Fm Failure Mode (Ip,Ie;F,Ff,Ff/D,Fo, Fe;Sp,Se;G,L)	**Ac** Attendant Circumstances (N,L,M,H)	**M** Magnitude of Loading (N,L,M,H,V,E)	**Ml** Magnitude of Local Loading (N,L,M,H,V,E)	**Dt** Dam Type (N,E,R,M,C,A)	**Rr** Rescue Resources (N,L,M,H)	**Det** Detectability (N,L,M,H,V)	**Schvq** Striking . . . (Predictor Fit) (L,H)
---	---	---	---	---	---	---	---

Introductory Summary

Global Event

Par	***(Population at Risk)***	*
L	***(Life Loss)***	*
Tpar	***(Threatened Population)***	---

SubPar

Par_1	***(Current SubPar)***	*
L_1	***(L Among SubPar)***	*
$Tpar_1$	***(Tpar Among subPar)***	---

Incremental Losses and Data on Fatalities

Ln, Ldr, Lnf	***(Natural Channel-, Dam Removal-, No Failure Life Loss)***	---
Ft	***(Fatality Type)***	
Identification/Location of Fatalities		---

Flood Characteristics

Flt	***(Flood Type)***	*
V	***(Peak Velocity)***	---
D	***(Maximum Depth)***	---
Qp	***(Peak Flow Rate)***	---
Qb	***(Bankfull Flow Rate)***	---
W	***(Maximum Width)***	---
Dv	***(Destructive Velocity)***	*
R	***(Maximum Rise Rate)***	*
Ww	***(Height of Wall of Water)***	*
Dd	***(Damage and Destruction)***	*
Fp	***(Proportional Forcefulness)***	*
Fd	***(Dichotomous Forcefulness)***	*
F_5	***(Incremental Forcefulness)***	*
Fpar	***(Forcefulness per SubPar)***	*
H	***(Height of the Dam)***	*
Hp	***(Height of Reservoir Pool)***	*
B	***(Breadth of Dam)***	*
Vol	***(Volume of Release)***	*
Rf	***(Rate of Failure)***	*
A	***(Area of Final Breach)***	*

Spatial and Temporal Relationships Between Par$_j$ and the Flood

T (Time Summary) *
Td (Time of Day) *
Tw (Time of Week) *
Ty (Time of Year) *
Ts (Time of Season) *
Wt (Warning Time) *
Wt_{avg} ***(Avg. Individual Wt)*** *
Bt (Building Types, %) ---
Dev (Development/Urbanization) *
Gf (Goodness of Fit) *
O (Outdoors) *
Sc (Sensory Clues) *
Pr (Preparedness) *
We (Warning Effectiveness) *
Epar (Evacuation SubPar) **and** ***Ret (Representative Evacuation Time):***
$(Epar_1)$ (Ret_1)
$(Epar_2)$ (Ret_2)
$(Epar_3)$ (Ret_3)
$(Epar_4)$ (Ret_4)
$(Epar_5)$ (Ret_5)
E (Ease of Evacuation) *

Natural Circumstances that Attend the Flood

Fm (Failure Mode) *
Ac (Attendant Circumstances) *
M (Magnitude of Loading) *
Ml (Mag. of Loading, Locally) *

Human Circumstances that Attend the Flood

Dt (Dam Type) *
Rr (Rescue Resources) *
Det (Detectability) *
Schvq (Striking Characteristics and Valuable Quotations): *

Case Bibliography

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Appendix E

Existing Automated Tools

Early in the search for existing models, an emphasis was placed on identifying software that might be adapted for use in analyzing life loss from flood events. Major agencies involved in dams, hydrology, or emergency management were contacted and asked about case histories and their current resources for quantifying Par, modeling evacuations, predicting life loss in the event of a dam failure, estimating warning times, and modeling with a computer. Each contact was also asked for additional contacts inside and outside their agency.

Agencies contacted included each of the state departments of dam safety through the central office of the Association of State Dam Safety Officials; the Federal Emergency Management Agency (FEMA); the National Institute of Building Sciences, associated with FEMA; Pacific Northwest National Laboratory, operated by Battelle in Richland, Washington, for the U.S. Department of Energy; The Utah Division of Comprehensive Emergency Management and Planning; the Natural Hazards Research and Applications Information Center at the University of Colorado; the National Weather Service; the U.S. Federal Highway Administration; the United States Bureau of Reclamation (USBR); the Information Technology Lab and the Institute of Water Resources in the U.S. Army Corps of Engineers; the Center on the Performance of Dams in the National Performance of Dams Program (NPDP) at Stanford University; the U.S. Committee on Large Dams (USCOLD); the International Committee on Large Dams (ICOLD); and Innovative Emergency Management, a private company in Banton Rouge, Louisiana, that contracted to do work initiated in FEMA and later the U.S. Army.

It soon became apparent that existing tools were inadequate, so efforts were shifted elsewhere. As such, what follows is not comprehensive, but it provides an introduction to resources that might be adapted for use in a life-loss model for flood events.

There are software designed to model specific disasters other than dam failures. FEMA produced a program called SLOSH to simulate a coastal storm surge generated by hurricane-force wind speeds (Zizil) and a program called HURRIVAC to simulate evacuation when roads are closed due to wind and water from a hurricane (Drury). Battelle Pacific Northwest Laboratory supports CAMEO, ALOHA, EPI, CHARM, and MARPLOT to simulate chemical clouds. CAMEO was developed primarily for safety officials responding to a chemical spill or leak. It provides an emergency response plan and maps the release area, tracking a plume with the other programs. ALOHA includes a database of physical properties for about 900 common hazardous chemicals and can be used to predict the rate at which vapors escape from a leak and their patterns of dispersion in the atmosphere in a straight line downwind of an outdoor chemical spill. The concentration on either side of the line is based on a Guassian distribution. EPI appears to have been ALOHA's predecessor. CHARM simulates an isolated puff without an ongoing source. MARPLOT maps plume patterns (Probasco).

None of these programs can be applied to floods directly, but they may provide guidance to those wishing to model floods or evacuations. There are three programs, however, that offer greater promise.

One is proprietary, called Q-world, and was developed by Innovative Emergency Management. In theory, in half a second it can track the movement of a chemical cloud, keeping track of its concentration, loss functions, and evacuation dynamics, to yield a central value for life loss and corresponding confidence levels. The principal of the company, Madhu Beriwal, thought it would be simple to customize the program to track a flood wave instead of a chemical plume, but, unfortunately, supporting documentation was never sent after repeated phone calls (Beriwal 1998).

The Pacific Northwest National Laboratory, operated by Battelle, develops and promotes the Federal Emergency Management Information System (FEMIS)—an automated decision support system that allows the user to plan emergency responses in advance and then call them up during an emergency for execution. The program tracks resources, provides a task list, provides a contact list, stores event logs, displays a status board, and models hazards and evacuation. The first four components are most useful for an emergency action plan (EAP), while the final two components are relevant to life-loss estimation. Currently, the program can only model the spread of a toxic chemical plume to support the Chemical Stockpile Emergency Preparedness Program (CSEPP), but programmers intend to expand its capabilities to model floods, hurricanes, earthquakes, and wildfires. The FEMIS program integrates geographic information systems (GIS via ArcView), a relational database management system (RDBMS), an electronic plan management system, and other software, all of which must be purchased commercially. It includes a normal mode, a planning mode, and an exercise training mode. The program is built on efforts encapsulated in a program called IEMIS by FEMA, The U.S. Army, state and local governments, and other contractors (Pacific Northwest National Laboratory).

FEMA is developing a software package called HAZUS (Hazards US) that is intended to provide damage estimates for various natural disasters. To date, it can only simulate damages from earthquakes, but FEMA plans to include preview models for floods and hurricanes in 2002. "This initial release of the two additional models will enable users to assess the potential for direct damage to residential, industrial, and commercial buildings" (Federal Emergency Management Agency, 1999, p. 1). In its present form, the supporting documentation seems to indicate that one can model structural damages caused by a dam failure resulting from an earthquake, but since the flood module has not yet been fully developed, this functionality must be limited. The model also includes casualty estimates in buildings with slight structural damage, moderate structural damage, extensive structural damage, and after collapse, but these loss functions follow from earth tremors rather than flooding. Significantly, one can enter custom casualty rates "if improved information is available" (National Institute of Building Sciences, 1997, p. 9-43). One can also provide custom flood mapping or rely on the default Flood Insurance Rate Maps. The program's land-use classifications might provide a first cut at Par types. HAZUS uses TIGER files (Topologically Integrated Geographic Encoding and Referencing system) developed by the U.S. Census Bureau based on 1990 census data. The files contain data on roads, streets, railways, waterways, and census boundaries.

Of these three, FEMIS appears to offer the greatest promise for making EAPs and HAZUS offers the greatest potential for rapidly implementing an improved life loss model for flood events using software that is currently in development. Most encouraging, the focal point of HAZUS is the estimation of structural damages to buildings and infrastructure, critical in estimating Ls and ultimately flood zones.

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