# TOWARDS IMPROVED LIFE LOSS ESTIMATION METHODS: LESSONS FROM CASE HISTORIES

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## ABSTRACT

An understanding of life-loss dynamics associated with floods is valuable for emergency management planning, the development of effective emergency action plans, and the estimation of life loss in dam safety risk assessment. This paper summarizes both qualitative and quantitative insights into factors that affect evacuation effectiveness, loss of life, and survival based on an initial group of case histories. It includes a summary of our overall research approach, a conceptual overview of our work, tabulations of means by which people perish or survive; 16 sections describing key insights governing evacuation, exposure, and rates of life loss; and foundational concepts considered critical to an improved life-loss model. As such, the paper should be foundational to the presentation of an improved life-loss model in the year 2001 or shortly thereafter. It also presents new terminology that should be important to the advancement of this field.

## LIST OF SYMBOLS

| | |
|---|---|
| $_i$ | subscript i generally indicates that the variable pertains to $Par_i$ |
| Ah | aerated haven |
| Ch | chance haven |
| Coh | compromised haven |
| Coz | compromised zone |
| Cozd | compromised zone density |
| Cz | chance zone |
| Czd | chance zone density |
| Det | detectability |
| E | excess evacuation time (minutes) |
| Ef | evacuation nonsuccess factor |
| Fm | failure mode |
| Ft | fatality type |
| HBU | homogeneous base unit |
| L | life loss |
| Lcoz | life loss in the compromised zone |
| Lcz | life loss in the chance zone |
| Lpcz | life loss in the pseudo-chance zone |
| Ls | loss of shelter (L = low, M = major, H = high) |

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|---|---|
| Lzd | life loss in the safe zone |
| L(zone) | life loss in a designated zone |
| P | proportional life loss (proportion of Par that dies) |
| Par | population at risk |
| $Par_i$ | subpopulation at risk; same as subPar |
| Pcz | pseudo-chance zone |
| Pczd | pseudo-chance zone density |
| Pr(zone) | proportion of lives lost in a designated flood zone |
| Prcoz | proportion of lives lost in the compromised zone |
| Prcz | proportion of lives lost in the chance zone |
| Prpcz | proportion of lives lost in the pseudo-chance zone |
| Prsz | proportion of lives lost in the safe zone |
| Psh | pseudo-safe haven |
| Pt | Par (population at risk) type |
| Ptpar | proportion of the threatened population (Tpar) that dies |
| Ret | representative evacuation time (minutes) |
| Rr | rescue resources |
| Sc | sensory clues (length of warning in minutes) |
| Sh | safe haven |
| subPar | same as $Par_i$ |
| Sz | safe zone |
| Szd | safe zone density |
| Tpar | threatened population (at risk) |
| $Tpar_i$ | threatened subpopulation (at risk) |
| Wt | warning time (the first formal warning, in minutes) |
| $Wt_i$ | individual warning time (also, Wt specific to $Par_i$). |
| $Wt_{avg}$ | average warning time (from any source, in minutes) |
| Zd | zone density |

## BACKGROUND

In order to reduce risks of life loss associated with dams in the most effective and expeditious manner, life-loss estimates are needed in dam safety risk assessment for the following purposes:

- To evaluate the risks associated with existing dams against life safety risk criteria.
- To assess the life safety benefits (i.e. risk reductions) of structural and non-structural risk reduction measures.
- To estimate the cost effectiveness of life safety risk reduction to aid in prioritising or justifying risk reduction measures.

In addition, an improved understanding of life-loss dynamics associated with floods on both the macro-scale and the micro-scale is valuable for emergency management planning and the development of effective emergency action plans.

Research into life-loss estimation has been underway at Utah State University's Institute for Dam Safety Risk Management since early 1998 with funding from the U.S. Bureau of Reclamation (USBR), the U.S. Army Corps of Engineers (USACE), the Australian National Committee on Large Dams (ANCOLD), and Utah State University (USU). The overall goal of our work is to develop an improved practical life-loss estimation model for use in dam safety risk assessment. The foundation for the new model will be historic life-loss dynamics captured through detailed characterisation of historic flood waves, their surrounding events, and their interaction with homogeneous subpopulations at risk (subPar). To date, over 160 subPar from 38 flood events have been fully characterized using nearly 100 quantitative or categorical variables, detailed narrative, and full documentation. The proportion of lives lost within these subPar ranged from zero percent to 100 percent, with good representation throughout this range.

## FOUNDATIONAL HISTORICAL INSIGHTS, BUT NOT A LIFE-LOSS MODEL

This paper summarizes initial insights into the dynamics that have led to life loss and survival during historic dam failures and flash floods. It is important for the reader to understand that we are not describing a new model in this paper; rather, we are describing what we have learned from reviewing case histories. Characterizing variables that are most useful for descriptions are not necessarily those that are most practical or useful for prediction, so the variables described herein will only be incorporated into a predictive model if they prove to be both practical and useful. Prior to model simplifications, however, it is justified to characterize case histories with high levels of detail since we want any simplification in model structure to be based on sound empirical evidence and not presumption about the underlying processes that determine life loss. What follows is a summary of our overall approach and a conceptual overview of our work. The remainder of the paper is divided into sections on evacuation, exposure, and rates of life loss. We close with some brief thoughts on developing an improved life-loss model.

## APPROACH

Phase 1 of our work is focusing on the collection and detailed review of case histories and development of a model to predict life-loss. In Phase 2 we plan to incorporate the model into computer software that will link it to inundation modeling and GIS databases. These will provide critical spatial, temporal, and structural inputs.

To date, we have identified about 180 flood events that have caused loss of life. Most of these involved failure of a dam, but some were dike failures, flash floods, expansive floods, or other types of floods. The characterization of each event entails dividing the population at risk (see below) into subpopulations at risk (subPar), assigning values to nearly 100 quantitative or categorical variables for each subPar, and documenting insights into life-loss dynamics. So far, 38 events have been characterized, yielding 163 non-overlapping subPar, including many cases for which life loss was zero.

We have begun exploratory data analysis on the first group of case histories to identify those characterising variables that may be useful as prediction variables for estimating the fraction of people that evacuate and the proportion of lives lost in the fraction of people that fail to evacuate. Additional case histories are being collected and added to those that have not yet been characterized. This second group will be characterized with special focus on those areas that are identified as being important for model development. The model will be formulated and tested based on the results obtained from additional analyses, and guidance will be developed for the estimation of prediction variables.

## NOMENCLATURE

With nearly 100 variables being used to characterize flood events, it is beneficial to standardize their names, definitions, and symbols for use in future literature and research. We propose the convention followed in this paper that variables should be designated with a single capital letter, followed by lower case letters and subscripts as needed to make each symbol unique and mnemonic. Using a single capital letter should make the use of symbols in equations unambiguous. As an aid to the reader, and to promote the use of a standard nomenclature, symbols are often accompanied by their name or a relevant description in the sections below. Technical definitions of every variable can be found in McClelland (2000), along with means for coding the categorical variables.

## CONCEPTUAL OVERVIEW

### Pieces of the Life-loss Puzzle

Deaths have historically occurred in the overlapping contexts presented in Table 1. People have survived catastrophic floods through the means presented in Table 2. To develop a realistic model for calculating how many people are likely to perish or survive, it is helpful to understand the many pieces to the life-loss puzzle. Just as one might sort puzzle pieces by shape or color, the life-loss pieces can generally be placed within one of 16 categories. While there is not space here to put the entire puzzle together, the most prominent pieces within each category are summarized in this section.

### Homogeneity of SubPar ($Par_i$, $Tpar_i$, $L_i$, $P_i$, $Ptpar_i$, Pr(zone), HBU)[3]

Population at risk (Par) quantifies the number of people who, without evacuating, would remain within those regions of the flood's imprint that exceed some minimum criteria of depth and velocity. SubPar ($Par_i$) are any subsets of Par. The threatened population (Tpar) quantifies members of Par that remain in the flood zone when flooding exceeds the aforementioned minimum criteria of depth and velocity.

For descriptive or predictive purposes, it would be of questionable value to derive a statistical function or distribution from a small set of Par that are heterogeneous with respect to a very large number of interdependent variables. Homogeneous subPar provide

[3] Par, and many other variables, are singular or plural based on context.

the means by which this problem can be overcome. Not only do $Par_i$ greatly increase the number of data points that can be analyzed, but if they are thoroughly characterized, they can be grouped according to statistical populations.

If subPar are truly homogeneous in every respect, they are called homogeneous base units (HBUs). HBUs are an ideal construct, which can only be approximated, but which are useful for descriptive purposes. They are analogous to subatomic particles. Protons, neutrons, and electrons fall into three separate populations, but within a population, they are consistent across substances, no matter how different those substances appear on a macroscale. In the same way, HBUs have predictable life-loss distributions, with variance governed largely by chance, but a small number of HBUs can be aggregated in numerous ways to create any historic, future, or hypothetical flood event.

To explore how an analyst might approximate an HBU, it is helpful to present a few preliminary definitions. *Par type* (Pt) refers to the unique physical *environment* surrounding members of a subPar. For example, the environment surrounding waders is typically the river, the open floodplain, and trees while the environment surrounding residents is characterized by houses and streets. *Excess evacuation time* (E) is the difference between two averages: the *average warning time* ($Wt_{avg}$) minus the *representative evacuation time* (Ret). $Wt_{avg}$ is the average value of the *individual warning time* ($Wt_i$)—the time an individual has to evacuate after becoming aware of an approaching flood and before the flood arrives. Ret is the average time each person requires to clear the flood imprint associated with Par. Although one could refer to the flood imprint as the flood zone, the term *flood zone* carries a different technical meaning. Flood zones are spatially discontinuous regions in the flood that have similar exposure characteristics and hence similar proportional life-loss distributions. *Life loss* (L) refers to the number of fatalities that are directly or indirectly caused by the flood in question. Drowning would be a direct cause while a heart attack due to grief would be an indirect cause. The *proportional life loss* is the fraction of lives lost: (lives lost)/(population present). It can be defined as the *proportion of Par* (P = L/Par), the *proportion of Tpar* (Ptpar = L/Tpar), or the proportion of their subdivisions. With respect to flood zones, Pr(zone) is the proportion of lives lost within the specified zone.

Analysts can approximate HBUs by noting the following: 1) isolating $Par_i$ by location promotes homogeneity on all levels, 2) distinguishing $Par_i$ by Par type (Pt) minimizes differences in the physical environment, 3) distinguishing $Par_i$ by the magnitude of the excess evacuation time (E) and reducing $Par_i$ to the threatened subpopulation ($Tpar_i$) minimizes differences in temporal-spatial dynamics. At the level of $Tpar_i$, an analyst can approximate HBUs by identifying flood zones. It is important that these zones are three-dimensional, since, in terms of proportional life loss, the HBU on the second or third story of a building might be the same HBU as shallow flooding near shore.

Detailed historical research is critical to verify that a given flood zone truly does approximate an HBU. It also provides important insights into how to divide a Par into homogeneous $Par_i$, how to quantify E and use it to reduce $Par_i$ to $Tpar_i$, and how to approximate the life-loss distributions that characterize each flood zone. Relevant insights are presented in the sections that follow.

Table 1. Means by which people die in a catastrophic flood.

| | | Buildings/ Damages | | | Other Locations | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Mode of Death** | **Destroyed** | **Major** | **Minor** | **Floodplain** | **Vehicle** | **Boat** | **Dry Land** | *** Relative Frequency** |
| 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 |
| 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 2. Means by which people survive a catastrophic flood.

| | | Buildings/ Damages | | | Other Locations | | |
|---|---|---|---|---|---|---|---|
| | **Mode of Survival** | **Destroyed** | **Major** | **Minor** | **Floodplain** | **Vehicle** | **Dry Land** | *** Relative Frequency** |
| 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.

## EVACUATION

Failure Mode (Fm)

The following broad causes of dam failures have all lead to deaths: high water, internal weaknesses, gates that are quickly opened, slope failure following drawdown, displacement of the reservoir by an upstream landslide, and sabotage or war-time bombing. Although an earthquake-induced failure is often considered to be the greatest hazard, there are currently no well-documented examples of flood-related life loss following an earthquake.

The cause of a failure affects life loss only in-so-far as it affects the detection time and thus the warning time, the local conditions that govern evacuation dynamics, the size and nature of the population at risk (thunderstorms follow diurnal and season patterns), and the hydraulic characteristics of the flood. The exception is slope failures, which can kill without water.

Detectability (Det)

When a safety concern has been detected, there has often been a reluctance to issue a warning until failure is imminent or has been confirmed. For example, during the Allegheny County flash flood[4], weather radar operators dismissed radar readings as false anomalies. Prior to the Buffalo Creek dam failure and the failure of Canyon Lake Dam in the Black Hills, company or civic officials actively tried to prevent public warnings. Following the Mill River dam failure, the owner delayed warning dissemination by arguing with an eyewitness over which part of the dam had failed.

Warning Times and Effectiveness ($Wt$, $Wt_{avg}$, $Sc$)

The initial warning time (Wt), whether restricted to official sources or defined to include any human source, captures nothing about the percentage of people warned, the urgency or effectiveness of the warning, the rate of warning propagation, the variety of times 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 about evacuation. As an extreme example, Wt for the Bangladesh storm surge of 1970 was three days, but dissemination of the warning was poor and 225,000 people died. The conclusion is that Wt is not a normalized variable and has limited use when comparing separate events.

A more useful measure of warning dynamics is the average warning time over a subPar. $Wt_{avg}$ is the average individual warning time ($Wt_i$) and includes all sources of information, human and environmental, formal and informal. Sources include sensory clues, telephone calls, honking motorists who shout warnings, shouts from fleeing neighbors, family or friends who stop by, the radio, the TV, CB radios, officials who use bullhorns or knock on doors, and self-appointed Paul Reveres.

It should be recognized that wired telephone service and power are quickly lost in virtually every catastrophic flood, so widespread warnings using mass media or telephone lines are usually possible only when they precede a failure or when a community is not near the dam. Since wireless communication is one of the fastest growing segments of the economy, cell phones and internet-enabled devices may provide new, rapid means of last-minute warning dissemination.

The average warning time provided by sensory clues (Sc, in minutes) has often made it possible for the majority of people to evacuate when a flood inundation area is narrow. Sources of visible clues have included a wall of water, piled high with debris and houses; a debris-filled, fast-rising flood that precedes a wall of water; power lines that swing violently from upstream disturbances; railroad tracks that snake violently; neighbors who

[4] See Appendix A for a list of flood events cited in the text. These are only a few of the approximately 180 events that we have reviewed.

move vehicles to high ground or congregate on the hillside; pets that become agitated; and power failures.

Auditory clues can carry several miles. They originate from tumbling waves that roar like thunder; trees and telephone poles that snap in two; logs, trees, and boulders that bounce off a canyon's walls; houses that collide and explode in a shower of splintered boards; a creek that rises with a crescendo; exploding power stations or transformers; severed power lines that buzz; motorists that honk their horns while racing by; and dead phone lines.

Heavy rain, hail, and strong winds can drive people indoors and mask sensory clues. Such was the case during the Eldorado Canyon flash flood and following the Mill River dam failure. Sensory clues can also be muted when a flood rises very quickly rather than crashing downstream as a wall. When this occurs at night, a flood can surround a house without advance detection. This was common during the Dale Dyke Dam failure and the Black Hills flash floods.

It is helpful to visualize how informal warnings propagate. 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 generate 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, and 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 fairly random, so if many houses are rapidly destroyed, chances are high that at least some people will remain ignorant of the approaching danger and fall victim to the flood. People recounting the Buffalo Creek dam failure provide excellent insights into this process as it worked itself out over 15 miles (Deitz and Mowery, 1992).

Although the average warning time ($Wt_{avg}$) captures many characteristics of a warning, it does not characterize those with the shortest individual warning times ($Wt_i$). The significance of this grows when subPar are heterogeneous. Those who are hardest to reach include motorists and people in isolated campsites, who may also be the most vulnerable. The inability of officials to warn campers contributed significantly to life loss during the Black Hills flash floods. Despite widespread warnings, motorists perished on six different creeks during the Austin, Texas, flash floods.

Another limitation to $Wt_{avg}$ is that it does not characterize a warning's urgency, credibility, or the extent to which those delivering the warning seek to ensure or enforce an evacuation. When warnings precede a failure, and thus reflect only the possibility of a flood, large segments of a population may postpone evacuation to “wait and see.” Rumors of an impending failure were rampant prior to the failure at Buffalo Creek, but many people reported that they ignored these warnings as the next link in a chain of false alarms. State police attempted to enforce an evacuation around Vaiont Lake, Italy, for 30 hours, but enough people slipped back through the patrols that 158 people died when the mountainside slipped and generated a huge wave. Sixty people died in buildings above the dam itself, many of whom were monitoring the slope movement and had provided the evidence on which the evacuation was based. Downstream, nearly 2,000 people died. A few areas received advance warnings, but the warnings did not indicate the magnitude of the ensuing event and they were not widely disseminated. These miscalculations indicate that warnings may be narrowly targeted and that the areas that should be evacuated may not be correctly assessed. When the worst flooding in memory has posed little threat to life, even a confirmed flood wave can be treated lightly. There was evidence of this as people awaited the Big Thompson flash flood, the Eldorado Canyon flash flood, the Rapid Creek flash flood, and the flood waves from failure of the Buffalo Creek and Mill River dams. Overall, 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. The least effective form of warning appear to have been National Weather Service announcements in the form of a “crawl” at the bottom of the TV screen.

Representative Evacuation Time (Ret)

When a flood is not more than 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 min for a family to evacuate during the day, and 1-6 min 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 they linger to get dressed, grab possessions, or warn neighbors. If the warning is slow to register, these ranges must be extended. The representative evacuation times (Ret) are on the order of 1-2 min during the day and 2-4 min at night. During the day, a wall of water can provide a $Wt_{avg}$ of 1-4 min based on sensory clues, explaining why some very destructive floods have killed a small percentage of Par when Wt = 0 min (i.e., the Shadyside and Eldorado Canyon flash floods).

When the excess evacuation time (E) is large, people may delay evacuation to put their households in order; but when E is short, people generally warn those immediately around them and take the quickest route to safety. There are, however, important exceptions. People often slow their evacuation to help others—a spouse, children, aged parents, a disabled relative, neighbors, and even strangers. This, combined with the fact that members of households generally receive a warning about the same time, often results in families evacuating together or perishing together. A small fraction of people will delay or turn back to grab a purse or wallet, pair of boots, coat, clean clothes for a child, or some other item of relatively minor importance. People also delay to grab a pet or to release livestock. Many working spouses died following the Mill River dam failure because, rather than evacuating the mills to safety, they tried to reach their families at home and were swept away.

There can be structural or topographic barriers to evacuation. Following the failure of the Austin Bayless Pulp & Paper Company Dam, elderly adults threw children over fences, but were themselves swept away. Following the Kelly Barnes Dam failure, one person nearly waded to safety, only to disappear when he stepped into a submerged creek.

While rare, evacuees can also panic. During the Buffalo Creek failure, one woman stood numbly in her tracks while others called to her. During the Dale Dyke failure, a man suffered fatal injuries after leaping from a second-story window into water so shallow it was nothing but mud. During the Kelly Barnes failure, one family ran parallel to the creek, never thinking to run laterally up the hillside. During the Mill River failure, groups of panicked workers ignored the safe hillside just behind them and chose to cross a bridge to try and reach the other side.

Evacuation by automobile deserves special consideration. People often choose to use vehicles when it would be safer, a shorter distance, and quicker to run up a hillside. There are several reasons for this. First, a vehicle may have great monetary value, so there is a desire to remove the vehicle from the flood zone. This desire is most apparent when people risk their lives to drive a car a few hundred feet to safety, or when they refuse to abandon a stalled vehicle while it is still safe to wade. Second, a vehicle is associated with speed, which is desirable during an evacuation. Third, a vehicle provides a means by which a family can reach food and shelter once their house is flooded. Fourth, many people are conditioned by habit to drive rather than to run. Fifth, a vehicle helps transport those with limited mobility.

Excess Evacuation Time (E, Ef)

In its simplest form, the excess evacuation time equals the average warning time minus the representative evacuation time ($E = Wt_{avg} – Ret$). The warning time from the first formal warning (Wt), the average warning time from any source ($Wt_{avg}$), and the average warning due to sensory clues (Sc) say something about the time available for evacuation, and Ret describes the time needed to evacuate, but only E relates the two. As such, E helps normalize the evacuation dynamics across events with different warning times and evacuation requirements.

Ef is the evacuation nonsuccess factor, equal to $Tpar_i/Par_i$. Values of E from 113 historic subPar for which $Tpar_i$ was known, or could be reasonably estimated, were plotted against Ef. The central portion of the graph is shown in Figure 1a and the entire plot is shown in Figure 1b.

The triangular symbols in Figure 1b were back-calculated from an additional 14 subPar using average values from distributions like those in Figure 2. In this case, since loss of shelter (Ls) was known, the distributions reflected the proportion of lives lost when Ls =

M and when Ls = H. Ls and its coding (L, M, and H) are defined in a subsequent section. Although merely suggestive, these extra data points add credence to the general trend evident among smaller values for E. Not shown in Figure 1b are points at graphed coordinates (E = -1,380, Ef = 1) and (E = 352.5, Ef = 0). The rectangular symbols in Figure 1b indicate that the first formal warning (Wt) was initiated prior to failure.

Figures 1a and 1b indicate that for negative values of E, Ef asymptotically approaches 1.0, and for positive values of E, Ef asymptotically approaches zero. Intuitively one would expect this, but the empirical data also provide a way to estimate the variability in Ef at different values of E. The skewness in this distribution shifts from positive to negative as E changes from negative to positive values. It is clear that any prediction of life loss that intends to capture real-world evacuation dynamics needs to incorporate this intrinsic variability.

E says a great deal about the likely size of the threatened subpopulation ($Tpar_i$), but it says nothing about the ability of people to reach a safe zone within the flood imprint or to evacuate after the flood arrives.

## EXPOSURE

### Par Type and Evacuation Modes (Pt)

The average warning time ($Wt_{avg}$), representative evacuation time (Ret), excess evacuation time (E), and evacuation nonsuccess factor (Ef) all vary depending on the environment in which people are located. This environment also has a profound impact on the flood dynamics to which members of the threatened subpopulation ($Tpar_i$) will be exposed. Distinct environments define the most common Par types (Pt): campers and recreationists near the river (C), waders and swimmers in the river (W), boaters on the river (B), recreationists on a lake (L), motorists (Af), train passengers (T), and those in or near buildings (D)[5].

Temporal considerations are especially relevant when quantifying each type of subPar. Whether people are at work, in school, commuting, at home, or asleep; and whether or not it is a tourist season; profoundly influences the quantification of each type of subPar. Weather conditions are also very important.

### Flood Dynamics

Catastrophic floods are violently turbulent, making swimming difficult or impossible. Most frequently, people die because they are tossed about or pinned underwater, struck by debris, driven into a stationary object, or buried in sediment (Table 1).

[5] Af and D are symbols derived from another category called fatality type (Ft). In that context, Af stands for automotive fatalities and D stands for general drowning deaths in town.

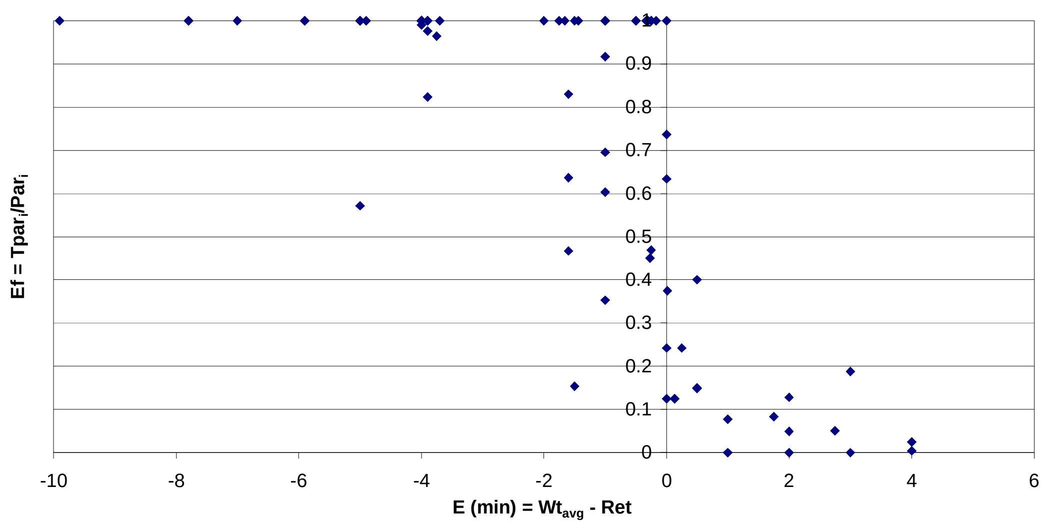


Figure 1a. Scatter plot of the excess evacuation time (E) vs. the evacuation nonsuccess factor (Ef) when absolute value of E is small.

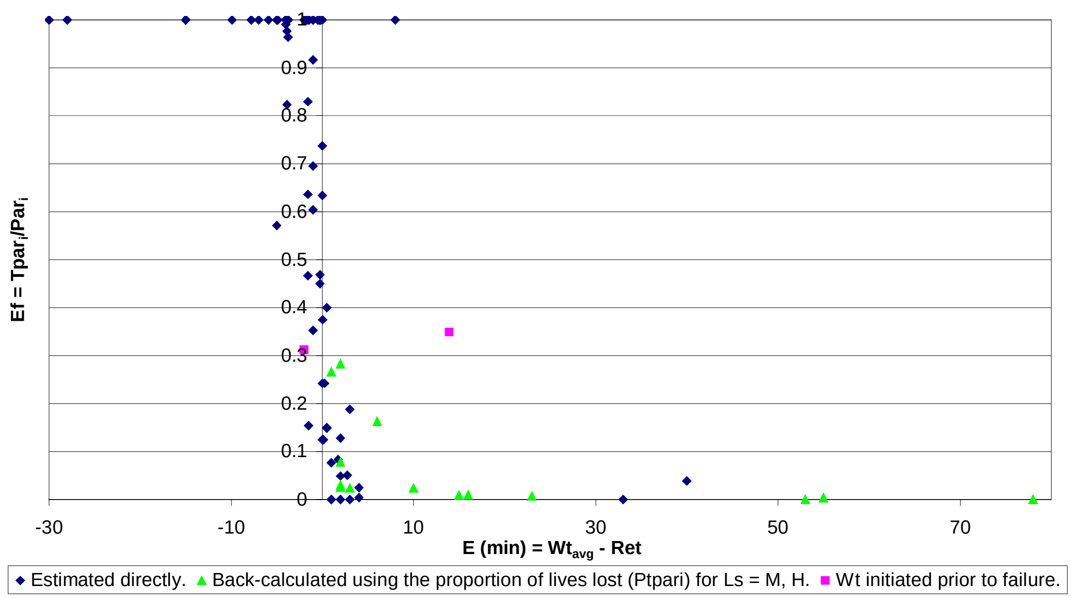


Figure 1b. Scatter plot of the excess evacuation time (E) vs. the evacuation nonsuccess factor (Ef). Where indicated, values were back-calculated using average values from a distribution like that in Figure 2, only based on loss of shelter (Ls) instead of flood zones.

If people know how to swim, velocity is the killer and depth is the accomplice. For example, 58% of the campers died when 3 ft of water raced across the Arás alluvial fan (Gutiérrez et al. 1998), but those who washed into the deep, calm waters of Lake Mohave below Eldorado Canyon remarked on how easy it was to swim to shore (National Park Service file; see note in References). Depth of the flood wave is principally important as it contributes to turning moment and traps people underwater by crashing down on them.

A large debris load characterizes catastrophic floods, consisting of earth, rocks, forest litter, felled trees, telephone poles, roofs and boards from shattered buildings, floating homes, vehicles, barbed wire, fences, propane tanks, railroad cars, railroad ties, furniture, and other objects. The leading edge of the Eldorado Canyon flash flood resembled freshly mixed concrete (Glancy and Harmsen 1975). The Mill River Dam failure was typical of a wall of water passing through forests and communities:

> *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, recording a quote from a young boy)*

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. This wall will tend to ride a winding canyon like a bobsled, sloshing up one side and then another. Superelevation differences of 10-20 ft have been observed, representing roughly 30% - 80% of the flood’s peak depth. Because a wave must generally be slowed to pile up into a wall of water and debris, such a wall may sweep a fast-rising, debris-filled flood before it as the mobile wall leaks and sections break away to travel more rapidly. This can provide an important sensory clue, giving residents precious seconds or minutes to wade to safety.

Related to this, floods often rise in progressive surges. This contributes to survival by prolonging the time over which people can struggle toward a haven, but it contributes to fatalities when unexpected waves topple waders and those on rooftops into the flood.

Debris dams tend to form behind bridges, reversing attenuation and causing a wave to rise in height. If the bridge or debris dam fails suddenly, 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, as was the case in the Buffalo Creek flood.

Debris can kill by piercing, crushing, or toppling people, but it can also save lives by providing a floatation aid. If they are not destroyed, homes can become mobilized rafts. Many people were seen walking to shore across the debris dams that formed at bridges along Buffalo Creek after their houses lodged in the mass. As for the sediment load, it increases the density of a flood, and generally its momentum. Combined, this makes people and buildings more buoyant and easier to topple than if they were located in clear water with the same depth and velocity.

Given identical volumes and no warning, an expansive flood is safer than a narrow flood because slopes diminish, velocities and depths drop, walls of water collapse, each successive row of houses buffers the next row, and structural damages reduce, leaving behind more havens.

<u>Loss of Shelter</u> (Ls = L, M, H)

Unless an occupant is trapped underwater or a structure is destroyed, a building offers shelter from a flood. The degree of shelter depends on the structural damage that occurs and the elevation of the top accessible level in relation to the peak flood level. *Loss of shelter* (Ls) seeks to describe the extent to which shelter is lost within a building and is distinct from economic damages and other traditional damage categories.

Ls depends, in part, on the concept of havens, presented below. When Ls is Low (L), it implies relatively safe havens on every floor. When Ls is major (M), it implies the loss of a safe haven on the first floor. When Ls is high (H), it implies complete loss of all reliable havens because the building has been submerged or destroyed. A building that drifts a few hundred feet and comes to rest without sinking or disintegrating has major loss of shelter since some level of shelter remains.

Historic accounts by survivors suggest more detailed distinctions, but there is space to present only one. Almost every room in a home 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 roof rafters. The Dale Dyke failure provides several examples of people who survived these conditions, but no examples of fatalities under such conditions have been found so far in our work. Thus, Ls = L when there is minor structural damage and the flood does not encroach within headroom—say within a foot of the ground floor ceiling. This form of shelter would obviously be compromised if the peak depths lasted more than 20-30 min or if the water was very cold, and survival would depend on the age and mobility of a room's occupants.

<u>Havens</u> (Sh, Ch, Psh, Ah, Coh)

When the excess evacuation time (E) is small or negative, members of the threatened subpopulation ($Tpar_i$) can still survive a flood if they reach some form of haven. Four categories of havens can be identified: safe havens (Sh), pseudo-safe havens (Psh), aerated havens (Ah), and chance havens (Ch). Compromised havens (Coh) are the combined total of Psh and Ah because the shelter has been compromised in both cases. Havens are informed by loss of shelter (Ls), but they transcend Ls and buildings.

Levels of flood exposure for which historic rates of life loss approach zero characterize a safe haven (Sh). Examples include the first floor when Ls = L, upper stories with quiescent flooding characteristic of Ls = L; flooding with higher velocities that have insufficient depths to sweep people out of windows, doors, or holes in the wall (i.e., flood depths less than about 3 ft above the floor); accessible rooftops and attics, calm or shallow waters in which people can wade, sturdy treetops that are easy to reach and sit in for hours, and hillsides after the flood arrives.

Pseudo-safe havens (Psh) begin as safe havens but become mobile. They only exist among a subset of buildings with major damage (Ls = M). When a house drifts more than a short distance, most occupants die because the house either sinks or breaks apart. As such, Psh are limited to buildings that float only a few feet off the bottom and come to rest again within 300 ft. This is most common with mobile homes.

An aerated haven (Ah) is another subset of Ls = M. When part of a stationary building is torn away and the flood does not rise more than a few feet above the remaining floor or highest counter, occupants can survive by clinging to what remains. Damage on this scale results when buildings collide, a tree crashes through a wall, a house at the edge of a flood is cut in half by a wall of water, a well-anchored house is broken apart by successive waves, or a central chimney or structural anchor supports a small platform. In the open, if a person must cling to an object like a lamppost, tree, or fence to remain stationary, that is also an aerated haven.

Chance havens (Ch) are reached primarily by chance through the whims of the current. Severed rooftops, mattresses, propane tanks, and logs are the most common floating Ch. People can also be washed to stationary rooftops, open windows, debris piles, overhanging branches, treetops, quiescent lakes or backwaters, and the shore itself. Pseudo-safe havens become chance havens once a building is swept far downstream in the open current. Significantly, because there is a velocity differential between the rate of travel of victims and of chance havens, Ch have the potential to kill as well as to save.

<u>Flood Zones and Zone Densities</u> (Sz, Cz, Pcz, Coz, Szd, Czd, Pczd, Cozd)

Flood zones are informed by loss of shelter (Ls) and havens, but they are not synonymous with either and they include the open flood. They are one step closer to homogeneous base units (HBUs) than are categories of Ls, they transcend buildings, and the historic proportion of lives lost within each zone varies primarily by chance. However, extreme depths, velocities, temperatures, or other conditions can limit the range of the distributions of proportional life loss that apply in a specific case.

Safe zones (Sz) include all safe havens (Sh) and mildly compromised havens. A compromised haven (Coh) is mildly compromised when exposure levels within the haven are comparable to those in a safe haven. As such, safe zones form a single statistical population with respect to their proportional life-loss distribution, comparable to that for Ls = L.

Chance zones (Cz) are places where people are submerged or face the open flood, including all chance havens (Ch) that might be reached while drifting. Common settings would be campgrounds, the open floodplain, and where Ls = H, which appears to have a nearly identical proportional life-loss distribution.

Pseudo-chance zones (Pcz) encompass that narrow range of flow conditions for which it is unclear whether a building is likely to be destroyed, float far downstream, or maintain a compromised haven (Coh). As such, the Pcz is defined because it may be useful for future life-loss prediction. To approximate the proportional life-loss distribution in this zone, one might combine the relevant tails from proportional life-loss distributions for Ls = H and Ls = M to capture the range of possible values and to make the uncertainty explicit.

Compromised zones (Coz) include that intermediate range of compromised havens (Coh) that intentionally have not been classified as safe zones (Sz) or pseudo-chance zones (Pcz). The proportional life-loss distribution should closely resemble that when the severity of structural damage for Ls = M is in the central 60% - 80%.

Zone densities (Zd = Szd, Czd, Pczd, and Cozd) represent the distribution of the threatened subpopulation ($Tpar_i$) among flood zones based on the accessibility of havens. The word "density" refers to the number of people who reach a particular zone category (Zd = people/zone), with the chance zone (Cz) populated only by those who cannot first reach another zone. Access to a zone includes the physical ability to move to the zone location and sufficient time to get there. When people are outdoors, this time is on the order of sensory clues (Sc). When they are indoors, this time is usually at least 30 seconds. History suggests that most members of $Tpar_i$ reach the safest haven to which they have access, but under a narrow set of circumstances they may forsake an upstairs refuge only to encounter the flood in the open while attempting to evacuate.

## RATES OF LIFE LOSS

<u>Lethality Rates in Flood Zones</u> (Lsz, Lcoz, Lpcz, Lcz; Prsz, Prcoz, Prpcz, Prcz)

The symbols L(zone) pertain to the number of lives lost in the designated zone. Pr(zone) indicates the proportion of lives lost in the designated zone. Historical values for Pr(zone) are presented in Figure 2 in the form of relative frequency diagrams. Theoretically, proportional life loss increases across zones in the order Pr(safe zone) = Prsz, Pr(compromised zone) = Prcoz, Pr (pseudo-chance zone) = Prpcz, and Pr(chance zone) = Prcz. Figure 2 indicates that this is indeed the case, although Prcz is not consistently higher than Prpcz. This can be explained by the fact that Prpcz applies more narrowly in historical contexts than in predictive contexts - if a haven survived, this is usually known. As such, only three data points fit the Prpcz category. In each case, local structural damages were so severe they resembled Ls = H, but without certainty. The conclusion is that Prpcz is more likely to resemble Ls = H and Prcz in historical contexts than in predictive contexts because the range of uncertainty in historical contexts is skewed toward greater damages. Ignoring Prpcz, the most dramatic jump in proportional life loss is between the compromised zone (Coz) and the chance zone (Cz), indicating a significant shortcoming in the definition of flood forcefulness used by DeKay and McClelland (1993): their definition treats Ls = M and Ls = H as identical.

As long as people can keep their heads above water by wading or treading water and they are sheltered from high velocities and violent impacts from debris, deaths are unusual. Hence, out of 47 historical safe zones that we have examined so far, people died in only two, and these deaths were in atypical circumstances.

In the chance zone, survival depends on being swept to a chance haven that lasts until the flood passes or one can reach shore. As such, it is common for everyone to perish and quite uncommon for more then 20% to survive. For a particular setting, some of the variability in this distribution depends on the water depths, velocities, and temperatures; the availability of chance havens; and the absence of lethal obstacles and debris. However, as the zone name implies, much of the variability evident in this distribution can be attributed to chance.

As would be expected, the proportion of lives lost in compromised zones (Coz) ranges between that in safe zones (Sz) and that at the extreme lower tail of the chance zone (Cz). This gives credence to the notion that these three zones can be treated as distinct populations that approximate homogeneous base units (HBUs) and can be used to reconstruct historic events, and to predict future or hypothetical life-loss events once zone densities are known. Furthermore, Figure 2 presents preliminary empirical distributions reflecting the anticipated variance in life loss within each zone based on chance or factors that may be beyond our ability to predict.

While exploring potential predictive variables that might give guidance as to cases for which only a portion of a given distribution might apply, the random patterns found in scatter diagrams suggest that chance is the dominant determinant of variability in the center of each distribution. However, when flood depths and velocities are unusually high or unusually low, proportional life loss has historically been limited to the corresponding tails of the distributions in the cases we have examined. With ongoing research, we hope to reduce uncertainty by identifying those ranges of key predictive variables that limit the proportional life loss to a particular band within a given distribution in Figure 2.

Figure 2 was developed exclusively using subPar with Par type equal to residential or commercial districts (Pt = D), but the zone environments to which people fled included regions inside and outside of buildings. This is consistent with the definition of zones.

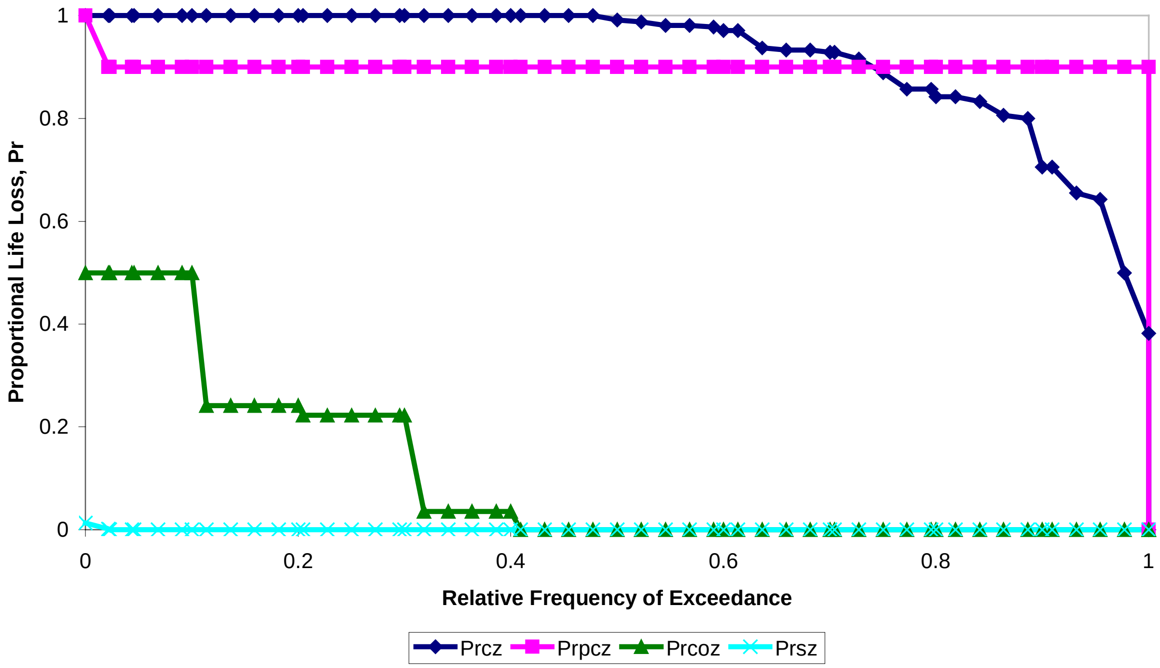


Figure 2. Relative frequencies of the proportion of lives lost in historic flood zones.

Although other Pt were not included in Figure 2, when zones could be identified within them, the proportion of life loss within those zones fell within the ranges shown in Figure 2. Nevertheless, it is helpful to highlight issues that affect life loss in other Pt.

People in any Pt can eventually find themselves attempting to wade to safety. 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. Walls of water, surges, waves, hidden obstacles, dense sediment, large debris, unpredictable turbulence, slick surfaces, the need to carry infants and children, and other factors all increase the chances that a wader will be swept away. As such, the ranges of depth and velocity that fall between the safe zone and the chance zone may be too narrow to accurately predict with existing flood routing models.

Motorists face a situation similar to those who become trapped in a room by external water pressure. If a flood sweeps a passenger vehicle into water more than 4 ft deep, those inside the vehicle are almost guaranteed to drown unless they are rescued while the vehicle is still floating. There were no examples, in the historical record that was examined, of people who escaped from submerged vehicles on their own.

Motorists could readily be subdivided based on the contexts in which they can die. Motorists have historically perished when: 1) a flood undermined a section of road, 2) they drove onto a flooded bridge before seeing the danger under conditions of poor visibility, 3) a dam bearing a road washed away leaving a gapping hole over which motorists could plunge, 4) they attempted to evacuate down a long canyon instead of climbing the hillside, 5) they were overtaken by a wall of water, 6) they refused to abandon their vehicles after stalling in a rising flood, 7) a sudden surge of water sideswiped the vehicle, 8) they attempted to cross a low-water crossing, 9) they were swept into a canal, gully, excavation, or drainage ditch, and 10) an expanse of city streets was inundated. Historic close calls included many who quickly moved a vehicle out of harms way and employees who were driving on a dam just before failure to examine it or to attempt repairs.

Water through which people can wade is often capable of washing a vehicle downstream. 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. For example, one woman drowned following the failure of Baldwin Hills Dam when her vehicle was swept down a street by slow currents about 3 ft deep. While rescue workers waded beside her car, it plunged into a deep pit. Excavations, ditches, canals, gullies, and other topographic depressions can turn an otherwise shallow flood into a death trap.

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 that a combination of relatively minor depths and velocities can carry away a vehicle. Eleven out of 13 deaths during the Austin, Texas, flash floods were of this nature. These types of fatalities are a form of convergence death that inherently limits $Par_i$ to $Tpar_i$. Motorists who see a lead motorist get into trouble will generally have time to stay clear themselves.

Trains are similar to automobiles if they are moving. When the railroad bridge collapsed during the Dry Creek flash flood, Many passengers died due to the impact of the train crash, apart from drowning. When stationary, however, as the trains were following the failure of the South Fork Dam in 1889, trains most closely resemble mobile homes with limited buoyancy.

Campgrounds offer few havens except trees, hills, and an occasional outbuilding, and the trees and buildings enter the chance zone if they topple. Moreover, campsites are often located near a river where valleys are steep and narrow so recreationists can readily be exposed to high velocities, great depths, and a wall of water.

Boaters have an advantage if wearing life jackets, but boaters also face increased risks since they are hard to warn and their evacuation time tends to be higher than for those on land. In the US, the popularity of guided fishing trips, river rafting, kayaking, and personal drift boats has increased dramatically over time. Many rivers now experience boats year-round. As such, this type of subPar is more relevant to future failures than to historic ones.

Lethality Rate Outside of Flood Zones

Deaths that have little or no relationship to flood zones fall into at least four categories: 1) those who die of a heart attack, stroke, or other medical condition brought on by fear for their personal safety, 2) those who die of a heart attack, stroke, or other medical condition shortly after learning that their loved ones have perished, 3) those who commit suicide during or after the flood, and 4) those who lose the will to live or develop self-destructive behavioral patterns. These deaths are typically omitted from the official lists of flood-related fatalities. In some cases, the individuals may have never come near the flood.

Since such deaths are not officially tallied, they are difficult to quantify, but overall they appear to be a tiny fraction of total deaths and they are most likely when life loss is large, making their relative contribution proportionately small.

Life-Saving Interventions (Rr)

Heroic rescues by family members, neighbors, and those giving warnings have helped to reduce life loss in the first seconds or minutes of a flood, but the floods with the greatest life loss have generally claimed their victims before professional rescuers were able to arrive. Once people are submerged or swept away, rescues are primarily a matter of chance. When people can reach treetops, stationary housetops, or islands, hundreds or thousands of people can be rescued by helicopter or boat over several hours, as was the case following the Baldwin Hills failure, but in such cases most of the individuals are not at high risk of drowning and could safely wait for the flood to pass. Overall, modern rescue resources (Rr) reduce life loss primarily by helping to shuttle people to hospitals, or by providing advanced medical care in the field to those who are injured.

Complications or Aberrations

Due to their striking uniqueness, every flood wave has the potential to cause life loss through rare or unexpected means. The nature and concentration of a debris load influences the likelihood that someone can drift to safety while avoiding being crushed or pierced. Fires were started by the Big Thompson, Black Hills, Dale Dyke, and South Fork floods. Some have been electrocuted before the power company shut off power to an inundated region. Lives can be lost in hospitals when flooding prevents essential medical professionals from reaching the building or interrupts a critical power supply. Persons with limited mobility are in greater danger and can endanger those who try to help them. Floods can sweep poisonous snakes out of riverside haunts, adding them to the hazards in the water and leaving them behind in inhabited areas. Prolonged floods or floods in winter can cause fatal hypothermia. Convergence deaths result when onlookers come to watch the flood or render assistance, and inadvertently become trapped and swept away.

Post-flood Psychological Trauma

When homes and life-investments are obliterated; people see naked, muddied, and mutilated corpses; families are relocated; and people's sense of security is cast asunder, it destroys social networks and a highly valued sense of community and belonging. Since large segments of families often perish together, survivors often face multiple losses. As an extreme example, one woman lost 55 members of her family during the Vaiont flood. Emotional and financial losses continue as there is almost always widespread looting following a destructive flood.

Combined, flood-induced trauma can cause extreme, debilitating, and even fatal psychological scaring. Symptoms observed following the Buffalo Creek disaster include an extreme 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 (Deitz and Mowery 1992; Erikson 1976). While not part of life-loss statistics, it is important to realize that traumatic flood events that destroy lives and property can continue to shorten lives long after the event.

The resiliency of the students at Toccoa Falls Bible College following the Kelly Barnes failure suggest that 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 (Foster and Mills 1978).

## TOWARDS AN IMPROVED PREDICTIVE MODEL

On a macroscale, flood events are sufficiently unique to make it difficult or impossible to produce credible life-loss estimates based on a lumped model using a single global Par unless one accepts a wide range of uncertainty. The variability in life-loss dynamics between different Par types alone makes a global comparison between events incongruent. To sustain credibility, a model should be grounded in, calibrated with, and validated using historically verifiable life-loss patterns. To improve the confidence of users, a model should explore these patterns on a level for which variation in proportional life loss varies largely by chance rather than dominant factors that are neglected through oversimplification of the model itself. However, to the extent that a practical model must exclude some factors that are too costly, or too poorly understood, to include, the resulting uncertainty in model predictions should account for both the variability in life loss that is inherent to real-world flood events and that which is introduced through model simplification.

As such, we believe that an improved practical approach must be founded on case histories at the level of subPar, flood zones, or other approximations to homogeneous base units (HBUs). We are therefore formulating an empirically grounded conceptual model with this in mind. The model needs to be refined, tested, and reviewed before it can be formally presented, but the model currently shows great promise.

## ACKNOWLEDGEMENTS

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## APPENDIX A. LIST OF FLOOD EVENTS CITED IN THE TEXT

- Allegheny County flash floods (especially Little Pine Creek), Pennsylvania, USA, May 30, 1986, L = 9.
- Arás alluvial fan flash flood, central Pyrenees, Spain, August 7, 1996, L = 87.

- Austin Bayless Pulp & Paper Company Dam failure, Austin, Pennsylvania, USA, Sept. 30, 1911, L = 88.
- Austin, Texas, flash floods, USA, May 24f, 1981, L = 13.
- Baldwin Hills Dam failure, California, USA, December 14, 1963, L = 5.
- Bangladesh storm surge, coast of Bangladesh, November 12, 1970, L = 225,000.
- Big Thompson flash flood, Colorado, USA, July 31, 1976, L = 145.
- Black Hills flash floods and failure of Canyon Lake Dam, South Dakota, USA, June 9f, 1972, L = 237.
- Buffalo Creek coal waste dam failures, West Virginia, USA, September 26, 1972, L = 139.
- Canyon Lake Dam failure in Rapid City, South Dakota, USA, June 9, 1972 (see Black Hills).
- Dale Dyke Dam failure, Sheffield, England, March 11, 1964, L = 263.
- Dry Creek flash flood resulting in a train wreck, Colorado, USA, August 7, 1904, L = 96.
- Eldorado Canyon flash flood, Nevada, USA, September 14, 1974, L = 10.
- Kelly Barnes Dam failure, Toccoa Falls, Georgia, USA, November 6, 1977, L = 39.
- Mill River dam failure near Williamsburg, Massachusetts, USA, 1874, L = 151.
- Rapid Creek flash flood (see Canyon Lake Dam failure and Black Hills flash flood), L = 207.
- Shadyside flash floods (Wegee and Pipe Creeks), near Shadyside, Ohio, USA, June 14, 1990, L = 24.
- South Fork Dam failure near Johnstown, Pennsylvania, USA, May 31, 1889, L = 2,209.
- Vaiont Dam overtopping generated by a massive landslide in the reservoir, Italy, October 9, 1963, L = 2,056 (or more).