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PREDICTING LOSS OF LIFE FROM FLOODS

Russell Lee
Patricia S. Hu**
David M. Neal**
Mark R. Ogles**
John H. Sorensen**
David A. Trumble**

Oak Ridge National Laboratory*

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** Co-authors listed alphabetically

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SUMMARY

Methods were developed to predict population at risk, threatened population, and loss of life from hypothetical flood events. The population at risk is the number of people who would be inundated by a flood if they took no action to evacuate. The threatened population is the number of people who are actually inundated by the flood.

Empirical analysis of past flood events revealed that the probability that an individual dies from a flood can be represented by a group logit formulation. The probability of loss of life was greater with little warning time, in less populated non-urban areas, with greater flood depths, and in areas which had experienced flooding in the last ten years. Many other explanatory variables were considered, including: quality of the warning, time of day, topography of the flood plain, existence of special institutions at risk in the inundation area, existence of a dam breach, and others. None of these was found to be statistically significant. This suggested that a limited number of dominant variables were able to discern systematic variations in loss of life on a country-wide basis, and that only these variables could be used in any general predictive model. This pointed out the importance of considering local factors in trying to predict loss of life in particular case studies, and the great uncertainty in such estimates.

Extensive discussion was provided on the application of the empirical loss of life function, that was calibrated from the data on past floods, to specific case studies. Analytical procedures were provided to estimate key data inputs: the population at risk, the warning

time, and the flood depth. Three methods were developed to estimate loss of life. All of the methods use a flood routing model to predict inundation depths. Secondary data sources are used to compile the population distribution.

The aggregate-empirical model treats each river reach as a single entity. The population at risk, a representative warning time, and average flood depth are estimated for each reach as a whole. The empirical function is used to estimate loss of life.

The empirical-flood-travel method also uses the empirical function. However, distinctions are made among the populations at risk based on their locations and elevations. This allows more precise estimates of warning times.

The flood-travel-evacuation method uses hydrograph data from the flood routing model. This provides estimates of flood elevations as a function of time at given locations. These estimates are compared with estimates of evacuation as a function of time, which are based on a traffic evacuation simulation model.

Software has been written to implement the aggregate-empirical method. Results from case studies suggest that the method provides a good qualitative comparison of loss of life from different inflow flood events, from both breach and non-breach scenarios, and for different dam remedial measures. Nevertheless, the method may under-estimate loss of life in failure floods in areas immediately downstream from the dam, and over-estimate loss of life in non-failure events.

1.0 INTRODUCTION

1.1 Purpose of Study

The purpose of this study was to develop methods to estimate the population at risk, the threatened population, and the loss of life due to dam-related flood events. The population at risk is the number of people who would be exposed to the flood if they did not take action to evacuate the inundation area. The threatened population is the number of people still in the inundation area when the flood arrives at their location (i.e., if they are outside, the flood water would touch them). A dam-related flood event is the spectrum of flooding that could result from operating a dam, including discharges from a dam failure, passing flood waters through a spillway, or backing up flood waters. The events that were considered were plausible, though extreme in magnitude and highly unlikely. The analysis was part of a larger U. S. Army Corps of Engineers program to implement hazard assessment and risk analysis methods for the evaluation of different alternatives for modifying existing dams (Institute for Water Resources, 1986b). The estimated population at risk (PAR), the threatened population (TP), and the loss of life (LOL) under various flood scenarios are among the criteria used by the Corps to evaluate the alternatives.

This report focuses on both empirical and conceptual models to estimate loss of life, and on procedures for applying these models to selected case studies. Empirical models are based on historical data. Conceptual models represent the behavior of individuals and the physical attributes of the flood. In each of the two approaches, the loss of life

estimate is based primarily on the population at risk, the flood travel time, and the warning time. For the flooding due to spillway discharge, the flood travel time is the interval between initial discharge from the spillway, and arrival of the flood. For the flooding due to dam failure the flood travel time is the interval between initial failure or formation of a breach, and arrival of the flood. The warning time is the interval between the first official evacuation notification to the public, and the arrival of the threatening flood wave. The population at risk, travel time, and warning time vary along different reaches of the river downstream (and upstream) from the dam.

Other factors that may affect the potential loss of life were also considered. These include: the depth of flooding; the recurrence interval of the flood (e.g. a 100 year flood); the peak discharge; the number of previous experiences that an area has had with floods; the year of the flood; existence and type of special institutions, such as hospitals, with people who would be more vulnerable to a flood; the time of day at which the flood occurred; the topography of the inundated area (i.e., either a canyon or a wide floodplain); the rural or urban character of the area; whether a dam breach occurred; the effectiveness of the evacuation warning; and traffic and the speed of evacuation.

The rest of this section summarizes background information on the study, and provides a list of definitions of important concepts. Section 2 is a review of previous, related studies. Section 3 presents the development of the empirical loss of life function which forms the basis of two of the three methods that were developed to estimate loss of life. The empirical function is derived from an identification of the factors

that have affected the number of lives lost in previous floods in the United States.

Section 4 discusses the procedure for estimating loss of life, which can be applied to specific case studies. Each of the steps that is necessary to compile the input data for the loss of life computational methods is discussed in detail: (1) establish the flood scenario, (2) estimate the population at risk, and (3) estimate the warning time for the population at risk. Section 5 provides a discussion of three methods that may be used to calculate loss of life, using the data discussed in Section 4. Section 6 gives a numerical example to illustrate the application of the aggregate-empirical model, discussed in Section 5.2, to the Beach City Dam, Ohio area.

1.2 Background[1]

The underlying motivation for this study was to develop a set of procedures for implementing U.S. Army Corps of Engineers' policy on "Evaluating Modifications of Existing Dams Related to Hydrologic Deficiencies" (IWR, 1986b). Many of the dams for which the Corps is responsible were designed and constructed under meteorological and hydrological assumptions that are now thought to underestimate the probable maximum flood (PMF). Rather than incur the high costs of modifying all dams to the PMF design standard, the Corps is developing

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[1] Information in this sub-section is taken directly from the U.S. Army Engineer Institute for Water Resources (1986b) report on Guidelines for Evaluating Modifications of Existing Dams Related to Hydrologic Deficiencies.

procedures to determine the appropriate extent of modifications on an individual dam basis.

A primary concept in these procedures is the base safety condition (BSC) which is the minimum flood event for which the proposed modification should be designed. The base safety condition flood event is that flood where there is no significant increase in adverse consequences with dam failure, compared to the adverse consequences without dam failure. With a BSC flood, there is no significant increase in loss of life and/or economic loss from dam failure compared to the spillway flood just prior to failure. If failure always results in a significant increase in losses, regardless of the inflow event, then the design flood event chosen for dam safety modification design purposes should be the probable maximum flood (PMF). In the event that the base safety condition is determined to be less than the PMF, then further analysis incorporating a probabilistic assessment of failure and non-failure losses may be initiated to evaluate modifications for events greater than the BSC. Thus, the potential for loss of life from dam failure is a primary motivation for considering safety improving investments.

1.3 Definitions of Important Concepts

Several terms used in this report are peculiar to or most often used in rather specialized technical disciplines. Others are used in special, restricted senses. Some such terms are defined when first used; others are not. For convenience, a number of those technical terms are defined in this section.

ANTECEDENT EVENT. The flood event which according to Corps guidelines precedes the event that is being considered. The antecedent event is assumed to be one-half the size of the considered event and is assumed to occur five days prior to that event.

AREAL UNIT. A spatial unit defined by political or census boundaries within a local or regional area, or grid cells formed by overlaying a grid on a map of the inundation area. An areal unit is the basic spatial unit for which economic and population data are collected. The areal unit may be as small as a city block within urbanized areas, or as large as Census tracts or enumeration districts in less urbanized or rural areas.

FLOOD DEPTH. The elevation of the surface of the flood water at peak stage minus the elevation of the inundated land.

FAILURE. An incident resulting in the uncontrolled release of water from a dam. May be from overtopping or a breach of the dam.

FLOOD ROUTING. The determination of the modifying or attenuating effect of passage of a flood through a valley, channel, or reservoir.

HYDROGRAPH. A graphical representation of discharge, stage, or other hydraulic property with respect to time for a particular point on a stream. At times the term is applied to the phenomenon the graphical representation describes; hence, a flood hydrograph is the passage of a flood discharge past the observation point.

INUNDATION AREA. An area adjoining a body of water or natural stream that has been or may be covered by flood water.

LOSS OF LIFE. In this report, loss of life includes all flood-related deaths.

POPULATION AT RISK. The number of people who would be inundated by a particular flood event if they took no action to evacuate the inundation area. 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.

PROBABLE MAXIMUM FLOOD (PMF). The flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in the region. The maximum possible inflow event is the PMF, and other flood events may be defined as a proportion of the PMF.

REACH. A part of the inundation area. It is defined arbitrarily, usually to encompass a major town or landmark. To facilitate analysis, a river reach should be defined and bounded by cross sections downstream from the dam. Reach definitions which separate one reach on one side of the river from another on the other side of the river should be avoided.

REFERENCE FLOOD. The combination of dam modification and probable maximum flood with breach which results in the maximum inundation of the flood plain. The Reference Flood is usually the PMF with breach with a modification of the existing dam by raising the crest (only) so as to pass the PMF.

SPILLWAY DESIGN FLOOD (SDF). The largest flood that a given project is designed to pass safely.

THRESHOLD FLOOD. The spillway design flood.

TIME (EVACUATION). A sequence of time intervals may be defined to represent major activities which comprise the evacuation warning process. These are listed in temporal order.

HAZARD DETECTION TIME. The time interval required to detect a possible threatening hazard.

HAZARD APPRAISAL TIME. The interval required for the Corps to fully appraise the situation.

NOTIFICATION TIME. The interval required for the Corps to notify the appropriate, responsible agencies, and for those agencies to in turn notify other agencies, as required in the official evacuation plans.

DECISION TIME. The interval required to make a decision on an appropriate announcement to the public.

DISSEMINATION TIME FOR FIRST WARNING. The time interval required to disseminate the public evacuation warning. At the end of this interval, the official public notification to evacuate has been issued to the public (though not all have necessarily received it), and this point in time marks the beginning of the warning time that the population at risk has to evacuate the hazard zone.

DISSEMINATION TIME. The time required to disseminate the evacuation warning to all of the population at risk.

TIME OF RECEIPT OF WARNING. The specific point in time at which the public evacuation notification is received by the population at risk. In the evacuation traffic simulation model, this point in time refers to the time at which the first members of the population at risk receive the official evacuation notification.

MOBILIZATION TIME. The interval required for individuals to decide to evacuate, to load important personal and household possessions into a vehicle, and to begin to drive out of the inundation area.

VEHICULAR TRAVEL TIME. The time required to drive out of the inundation area from the point of origin, assuming that the vehicle is already mobilized and begins its trip, and assuming no queuing delay time.

QUEUING DELAY TIME. The interval during which a vehicle is delayed and waiting in a queue in the transportation network because of transportation congestion.

CLEARANCE TIME OR EVACUATION TIME. The sum of mobilization time, vehicular travel time, and queuing delay time.

NETWORK CLEARANCE TIME. The clearance time required for all vehicles to evacuate the inundation area, if they take action to do so.

TIME (FLOOD). Other times refer to the flood itself.

TRAVEL TIME. The time interval that it takes for the flood water to arrive at a location from the beginning of flood discharge. For a non-failure or spillway flood, the beginning of the flood is at the time of initial spillway discharge. For travel time relating to a dam failure, the beginning of flooding is at the point at which there is initial discharge from the dam (the point of initial overtopping or the time at which a breach initially begins to form). The travel time extends to the time at which the population at risk is reached. Thus, for different individuals or populations at risk, each has a different travel time associated with him or her, depending on location and elevation. In computational analyses, a representative travel time may be defined for the reach as a whole.

WARNING TIME. The time interval between the time of the initial official notification to the public to evacuate the inundation area and the time of arrival of the flood. Depending on location and elevation, each

individual in the population at risk has a unique warning time associated with him or her.

ZONE. Refers to the part of a reach in the inundation area which is at the same elevation interval. A zone is typically defined by one-foot to five-foot interval categories.

2.0 PREVIOUS STUDIES

2.1 Overview of Previous Studies

This section provides a review of past literature on loss of life in floods. Session 2.1 provides a review of the circumstances in which loss of life has occurred in past flood events. The remaining subsections summarize major types of approaches for estimating loss of life. The first types are discussed in Sessions 2.3 and 2.4, in which estimates of loss of life are based on estimates of damages to buildings or of economic losses in general. A simple casualty ratio approach is presented in Session 2.5, in which loss of life is expressed as a proportion of the population at risk based on a subjective assessment of the flood conditions. The Bureau of Reclamation model is summarized in Session 2.6. This model represents the most detailed attempt to estimate the factors responsible for variations in loss of life in flood events across the country using historical data. Session 2.7 summarizes analyses done as part of this study in which the Bureau of Reclamation model was expanded somewhat using their data. Session 2.8 summarizes the Stanford/FEMA model which uses subjectively-determined coefficients to estimate the size of the threatened population as a proportion of the

population at risk, and simil rly which uses coefficients to represent flood lethality to estimate loss of life as a proportion of the threatened in population. Section 2.9 summarizes the Institute for Water Resources' extension of the Stanford/FEMA model, in which warning time plays a major role in affecting the size of the threatened population. Session 2.10 is a discussion of how the Bureau of Reclamation and the Stanford/FEMA/IWR models are related, and of some insights gained from a comparison of the two models -- one based on empirical evidence and the other based on conceptual underpinnings. Finally, Session 2.11 provides a summary of these previous approaches.

2.2 Why Fatalities Occur

Studies have addressed the question of why or how fatalities occurred. Some, but not extensive, data exist on the causes of fatalities. French et al. (1983) studied the causes of deaths from 16 floods and dam failures. They identified drowning as the chief cause of death (93%), followed by heart attack (3%), and trauma, electrocution and mud slide (1% each). They further differentiated drowning victims by cause of drowning. Most people died in floods when they were swept into the water while at home, at camp or crossing a bridge (a total of 43% of all deaths), or when they were in a car (also 43%). Three percent drowned while performing rescues, 2% while engaged in a water sport, and 2% while attempting to evacuate on foot.

In 1985, 166 persons died in floods (Natural Hazard Observer, 1986). Of these, 48% were vehicle-related. Thirty-seven percent occurred in residential structures, and 3% in mobile homes. Male casualties

outnumbered female 3 to 2. Three fatalities were attributed to rescue attempts. No mention of non-drowning fatalities was made.

Case studies and data on specific floods provide further documentation of why drownings occurred in specific cases. Examples of case studies were those by Gruntfest (1977) on what people did during the Big Thompson flood, Sorensen (1985) on the Cheyenne River flash flood, and Kircher (1985) on the circumstances of flood-related deaths in the Connecticut June 1982 flood. These studies suggest that drownings occur in a variety of circumstances:

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 waters 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.

Generally there are four basic reasons for drowning deaths. First, the flood stage is at a life threatening level. Second, people do not receive adequate warning and are caught in a threatening situation. Third, they do not take actions fast enough. Fourth, they do the wrong thing.

In practice it is extremely difficult to obtain quantitative information on, and especially to predict, the circumstances or actions of individuals. Instead, recent studies such as those by Stanford University (1984) and the Bureau of Reclamation (1985) have used the

population at risk, warning time, and flood depth as key explanatory variables in models to estimate loss of life.

2.3 Estimating Loss of Life From Data on Population and Damage to Buildings

In studies by Friedman (1975), the number of casualties due to flooding was estimated by the number of damaged residential structures. An estimate was obtained by multiplying the number of dwellings damaged by a factor of 1 casualty per 170 damaged dwellings. For flash floods, the casualty rate became 1 per 85 dwellings damaged. The rates were derived from annual flood tabulations of the American Red Cross. It was suggested that the number of damaged structures could be obtained by studying maps of the inundation areas. In the Friedman (1975) study, no attempt was made to use Census data to determine the population in the flood-prone areas. Instead, an estimate of the number of people at risk was obtained by multiplying the number of dwellings exposed in each hazard zone by a conversion factor of 3.0 persons per dwelling; this factor was derived from summary tabulations of the 1970 Housing Census.

The Allen and Hoshall (1985) approach to estimating casualties has been applied to earthquakes. It took into account the population, the employment, and the probable damage to buildings. These were described by the type of construction and by their location in each tract within the hazard zone. Casualties were estimated for two periods of the day--an "at work or school" period, and an "at home" period during the rest of the day.

For the night-time or early morning (i.e., "at home") casualties, it was assumed that most of these would occur in or near the residences.

Guided by this assumption, four basic elements of data were used for determining these casualties: population, the number of housing units, the number of single-family residential structures, and the number of multi-family residential structures in each area (Census tracts were used where possible). Estimates of the fragility of various types of dwellings were also used, since certain structures may have a higher likelihood of collapsing in an earthquake (or in the case of flooding, of being swept away). Some night-time casualties were also postulated to occur in non-residential buildings such as hospitals, hotels, and retail or industrial buildings with shoppers or night workers. The estimates of these casualties were expressed simply as a percentage of the expected daytime casualties in these structures.

For the "at work or school" time period, the Allen and Hoshall (1985) study assumed that the residential casualties could be estimated as some fraction of the residential casualties that would be expected under "at home" conditions; and that casualties in commercial, public, and industrial buildings could be based on employment estimates. In this case, the casualty rates were assumed to be some proportion of the number of affected buildings, with the rate varying depending on the nature of the structures.

2.4 Relationship Between Loss of Life and Economic Damage

The study by Petak and Atkisson (1982) estimated the number of lives lost in an extreme natural event as a function of the economic loss to buildings from that event. This relationship was estimated from data on past natural disasters. The method implicitly assumed that the recorded

dollar amounts of damage reflected only building damage, that the lives lost were directly caused by the event, that the vulnerability of the population was the same in all regions, and that the values of all types of structures in all events were the same. However, these assumptions are generally not met. For example, there are instances in which the dollar estimates of damage included loss of business or damage to other structures other than buildings, instances in which the cause of death was unrelated to the event, and differences in flood characteristics and in the vulnerability of the population. Any of these differences or variations will result in "statistical noise" in the empirical calibration.

In calibrating their model, Petak and Atkisson (1982) used data supplied by insurance companies. The researchers noted that building losses that are not paid often go unnoticed in this data source. Furthermore, other limitations of the approach were noted. The number of deaths may be partly related to the evacuation procedures and to the level of success of rescue operations, as well as to the physical condition or structural characteristics of the properties affected. Also, it was suggested that population density, amount of warning time, foreknowledge of the effects, psychological impressions of the population, availability of shelter, and time of day of the occurrence all influence the number of casualties. None of these factors was taken into account; and the authors in fact stated that in practice no estimate of mortality can take all of these factors into account.

A further complication in using a loss of life model, which relates fatalities to the economic loss of buildings, is the geographic

variability in the values of buildings and in population density across the country. Disasters in an area with a high value of building wealth per person will incur greater economic loss per capita in the given event than in areas exhibiting lower wealth per capita. To account for the regional variations, an adjustment based on relative income per capita or average selling price of residential structures may be required to eliminate spurious regional variations.

Also, several authors such as Dacy and Kunreuther (1969) and the U.S. Department of Commerce (1972) have observed a temporal variation in the relationship between the number of hazard-induced deaths and the economic value of hazard-induced damages to property. Time, as represented by the year of the event, provided a statistically significant correlation with the number of deaths per million dollars of damage, though there was still a considerable amount of unexplained variance.

2.5 Casualty Ratios

A straightforward approach used by Paté-Cornell and Tagaras (1985, 1986) used casualty ratios, in which loss of life was expressed as proportions of the population at risk. Census data were used in conjunction with inundation area maps to estimate the population at risk. The casualty ratio was defined as the proportion of inhabitants who might be killed if a dam fails, assuming a weighted average of night and day occupancy in the zones at risk. The casualty ratio was suggested to be as great as 90% on the path of the wave, and 10-15% in the rest of the inundation area. Assuming the absence of a warning and considering the

losses in sudden failures such as that of the Malpasset Dam in France, Paté-Cornell and Tagaras (1986) used 50% as the casualty ratio on the path of the wave. This figure was based on the assumption that depending on the time of the day, some regular inhabitants of that zone may be out of the area. Paté-Cornell and Tagaras (1985) also noted that the casualty ratios may be subjectively adjusted, depending on one's assessment of the effectiveness of the evacuation warning as well as on any other factors that may impact upon the casualty ratio.

2.6 Bureau of Reclamation Model

The Bureau of Reclamation (1985) flood loss of life model used warning time and population at risk as the two key variables. Population at risk was defined as the number of people who would be exposed to flooding if they took no action to evacuate. Warning time was defined as the time lapsed between initiation of the actual warning and the onset of flooding. These definitions are consistent with those used in this study.

The focus of their study was on threat to life from dam failures. Data were compiled from reports on historical flooding events that had occurred since 1950 in the United States or Europe. Only severe flooding events with high potential for loss of life were considered. The floods involved either a dam failure or a flash flood, whose consequences were similar enough to a dam failure to provide useful information about the likely consequences of dam failure. The population at risk was generally equated with the number of persons evacuated or the number made homeless. The Bureau of Reclamation (1985) study suggested that estimates of

population at risk probably had an error range of plus or minus 30%. Newspaper or agency accounts of the flood were used to estimate warning time. However, these accounts did not always define how warning time was measured.

The Bureau of Reclamation (1985) felt that the warning times for their historical events could not be estimated with enough precision to develop a reliable continuous relationship between warning time and loss of life. Therefore, the warning time variable was dichotomized into cases with either "good" or "insufficient" warning, and statistical relationships between the population at risk and loss of life were estimated separately for each of the two data sets. Based on inspection of the data, an arbitrary cutoff point of 1.5 hours was used.

With "good" warning time (greater than 1.5 hours), the estimated equation was:

$$L = \underset{(.0001)}{0.0002}\ P, \qquad (1)$$

where L = loss of life

P = population at risk

(.0001) = level of significance,

with an adjusted R^2 of 0.87 (sample size = 8).

For the "insufficient warning" situation, Vaiont and Stava in Italy were screened out as outliers and were used to define the upper boundary for loss of life. Likewise, Lawn Lake, Colorado and Teton, Idaho were dropped as outliers and used to define the lower boundary. A log-log relationship was used and the resulting equation was:

$$L = \underset{(.0001)}{P^{0.60}} \qquad (2)$$

The best fit exponent in the equation was actually 0.56, with an adjusted R^2 of 0.60. However, the Bureau adjusted this estimate subjectively to 0.60 so as to produce a more conservative (i.e., higher) estimate of the loss of life.

2.7 Extension of Bureau of Reclamation Model

The Bureau data were used to estimate an expanded equation for their "insufficient warning" case. The Vaiont and Stava Italy cases were not tabulated in the Bureau of Reclamation (1985; Appendix B) report and were not included in the analysis. However, the Lawn Lake and Upper Teton floods were included. In addition, data compiled by the Bureau on warning time were estimated to the closest 15 minute increment. In several cases this required some interpretation of their data. In general, the estimated warning time was set to be the average if a range of times was given, or to a value 15 minutes less than or greater than any upper or lower limit, respectively. For example, "less than 1.0 hour" was set to be 45 minutes, and "more than 1.5 hours" was set to be 75 minutes for all cases. Regression analysis of these data resulted in the equation:

$$\log(L) = \underset{(.0001)}{0.67} \log(P) - \underset{(.013)}{0.014} W, \qquad (3)$$

where

W = warning time (in minutes).

The adjusted R^2 was 0.89 which was significant at less than .0001.

This result suggests that for cases with poor warning time, in the 0 to 90 minute range, the specific amount of warning time is a statistically significant factor that affects the potential loss of life.

Although not as statistically significant as the population at risk, warning time still made a significant contribution to the overall fit of Equation (3). Warning time was also considered in the regression equation for the cases with good warning time, but was found to be insignificant; and the best equation was as given in Equation (1).

The Bureau of Reclamation (1985) study ranks as a very important study of an attempt to develop a model to estimate loss of life. Its significance is in its use of a number of historical events to estimate an empirical loss of life function through a statistical analysis of important past floods.

2.8 Stanford/FEMA Model

Another important model to estimate loss of life in floods was developed by McCann, Franzini, Kavazanjian and Shah (1984) of Stanford University under contract for the Federal Emergency Management Agency (FEMA). The importance of this model lies in its systematic incorporation of several key factors that affect the potential loss of life. Another important characteristic of the model is that it attempts to estimate loss of life in various reaches of an inundation area, rather than simply a total loss of life estimate for the whole area.

The Stanford/FEMA approach relies on subjective estimates of the proportion of the total population at risk which would be remaining in the various flood zones at the time of arrival of the flood wave; this remaining population is termed the "threatened population." The estimated threatened population in the Stanford/FEMA model was based on the assumption that the greater the distance of each population-at-risk

group from the dam, the smaller the proportion of the population at risk that will experience contact with the flood water. This assumption is consistent with both the Bureau of Reclamation's historical (1985) data, and the empirical function derived in Section 3. The quality of the evacuation warning and the distinction between urban residential versus rural flood zones were also considered to be important, and coefficient values in the model were assumed to vary depending on these factors. The empirical results in Section 3 tend to confirm this assumption as well.

A second set of subjective estimates was required in the Stanford/FEMA model to estimate the proportion of the threatened population that would die. It was assumed that this proportion varies by flood depth.

The equation for loss of life was defined as:

$$L = \sum_i \sum_j f(d_j)\, h(m_i)\, P_{ij} \tag{4}$$

where

L = the number of lives lost from a flooding event,

$f(d_j)$ = proportion of threatened population who die from the flood of depth d in flood zone j,

$h(m_i)$ = proportion of population at risk in reach i remaining in flooded zone j at time of arrival of flood wave; $h(\cdot)$ is also a function of the quality of evacuation warning, and of the distinction between urban and rural areas.

P_{ij} = population at risk in flood zone j, of reach i, m_i miles from dam,

d_j = depth of flooding in zone j, and

m_i = river miles from dam to reach i (a surrogate for flood travel time).

This equation can be regarded as a definition: the loss of life in a reach equals the percentage of people exposed to flooding who lose their lives (which depends on the flood depth), times the fraction of the people at risk who remain in the area at the time of inundation (which depends on the downstream distance, nature of the evacuation warning, and the distinction between rural and urban residential areas), times the population at risk (which is the number of people in the reach who would be exposed to flood water if they did not evacuate). The function $f(d_j)$ represents the lethality of the flood, and $h(m_i)\ P_{ij}$ is the size of the threatened population. The last term, the population at risk P_{ij}, may be estimated from Census data. Suggested values for the other terms were provided in the Stanford/FEMA (1984) study and are reproduced here as Tables 1 and 2. Table 1 gives a casualty ratio expressed as the number of deaths as a proportion of the threatened population. This idea is similar to the Paté-Cornell and Tagaras (1985, 1986) notion of casualty ratios, except that they expressed the potential loss of life as a ratio of the population at risk. Table 2 provides suggested values to estimate the threatened population as a proportion of the population at risk.

The drawback of the Stanford/FEMA (1984) model is that there is no specific empirical basis for the coefficient values. The model is like an accounting identity and is essentially true by definition. The crucial issue is in the specific numerical estimates of the coefficients listed in Tables 1 and 2.

The Stanford/FEMA (1984) study also provided an equation for estimating loss of life in commercial or industrial zones:

Table 1. Suggested Parameters of Stanford/FEMA Loss of Life Model. Loss of Life as Proportion of Threatened Population.

Depth of Inundation d_j	Proportion Loss of Life $f(d_j)$
2	0.00
4	0.05
6	0.20
8	0.40
10	0.60
12	0.80
>12	0.85

Table 2. Threatened Population as Proportion of Population at Risk [i.e., $h(m_i)$]

	Residential Area Warning System		Rural Area Warning System	
Distance (mi)	None	Good	None	Good
<10	0.80	0.50	1.00	0.70
20	0.50	0.20	0.80	0.40
30	0.10	0.00	0.20	0.10
50	0.00	0.00	0.10	0.00

$$L = \sum_i \sum_j f(d_j)\ h(m_i)\ b\ P_{ij}, \qquad (5)$$

where

P_{ij} = the population at risk in zone j of reach i during business hours, and

b = the percentage of time the business zone is occupied.

In essence, Equation (5) is a probable loss of life estimate, based on the time of day. For simplicity, it may be better to use Equation (4) for all zones and to provide different estimates of the population at risk in each zone, depending on the time of day of the flood event. For example, the Corps' Interim Procedures (IWR, 1986a), for evaluating modifications of existing dams related to hydrologic deficiencies, suggested estimating the population at risk for different times of the day (daytime between 0800 and 1600 hours, and night-time between 1600 and 0800 hours), as well as accounting for both seasonal and daily transient population.

2.9 Institute for Water Resources' Extension of Stanford/FEMA Model

Another method for estimating loss of life was developed by the Institute for Water Resources (1986a). This method was a modification of the Stanford/FEMA (1984) approach, and also relied on professional judgment. The difference between the Institute for Water Resources (IWR) approach and the Stanford/FEMA approach was that IWR estimated the threatened population by taking into account the warning time for each group of population at risk, instead of the river miles from the dam. The equation for estimating loss of life given by the Institute for Water Resources (1986a) was:

$$L = \sum_i \sum_j f(d_j)\, g(W_{ij})\, P_{ij} \tag{6}$$

where

$g(W_{ij})$ = proportion of population at risk in reach i remaining in flooded zone j at time of arrival of the flood wave, and

W_{ij} = the warning time for population in reach i in flood zone j.

The warning time was defined as the time between the commencement of the evacuation warning to the public, and the exposure of the zone to flood water. Table 3 shows some suggested values of the parameter $g(\cdot)$.

The approach used by the Institute for Water Resources (1986a) takes warning time explicitly into account, rather than indirectly through the number of miles from the dam to the reach, or through a surrogate measure such as the travel time of the threatening flood wave. Thus, to the extent that warning time can be estimated, the IWR approach appears to be preferable in that it directly takes the key concept of warning time into consideration. The number of miles from the dam to a reach is only a surrogate for warning time, which encompasses not only the geographical location of the reach but also the elevation of populated areas within the reach and the velocity of the flood wave.

Tables 4 and 5 provide an example of tabulations for the population at risk and the loss of life using the IWR method. Table 4 illustrates that for a given reach, the population at risk will generally vary depending on the time of day, season, and transient population. The population at risk also varies at different elevations within a reach. People situated in low-lying areas will be in a higher flood zone, as measured by depth of water over the ground at peak stage.

Table 3. Threatened Population as Proportion of Population at Risk, Expressed as Function of Warning Time

Warning Time, W_{ij} (hours)	Residential Area Warning System Poor	Residential Area Warning System Good	Rural Area
0.00	1.000	0.800	1.000
0.50	0.400	0.100	0.800
1.00	0.250	0.050	0.400
1.50	0.150	0.010	0.200
2.00	0.080	0.002	0.080
2.50	0.030	0.001	0.030
3.00	0.005	0.000	0.005
3.50	0.001	0.000	0.004

Table 4. Example of Table for Population at Risk in Specified Flood Zones in a Reach for Different Flood Event, by Season of the Year and Time of the Day.*

Flood Event	Flood Zone (interval) in feet)	Permanent Population		Seasonal Transient Population								Daily Transient Population	
				W		Sp		S		F			
		D	N	D	N	D	N	D	N	D	N	D	N
.10 PMF	0 - 4	50	75	2	0	2	0	40	10	2	0	0	0
	4 - 8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
(peak	8 -12	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
stage =	12 -16	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
4 ft)	Total	50	75	2	0	2	0	40	10	2	0	0	0
.25 PMF	0 - 4	50	75	2	0	2	0	40	10	2	0	0	0
	4 - 8	70	100	0	0	2	0	20	5	2	0	0	0
(peak	8 -12	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
stage =	12 -16	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
8 ft)	Total	120	175	2	0	4	0	60	15	4	0	0	0
.50 PMF	0 - 4	50	75	2	0	2	0	40	10	2	0	0	0
	4 - 8	70	100	0	0	2	0	20	5	2	0	0	0
(peak	8 -12	60	95	0	0	7	2	50	15	7	2	100	20
stage =	12 -16	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
12 ft)	Total	180	270	2	0	11	2	110	30	11	2	100	20
.75 PMF	0 - 4	50	75	2	0	2	0	40	10	2	0	0	0
	4 - 8	70	100	0	0	2	0	20	5	2	0	0	0
(peak	8 -12	60	95	0	0	7	2	50	15	7	2	100	20
stage =	12 -16	300	400	0	0	4	0	40	5	4	0	50	10
20 ft)	16 -20	500	800	0	0	5	1	350	65	10	4	40	10
	Total	980	1470	2	0	20	3	500	100	25	6	190	40

* 0 - 4 flood zone begins at bank-full stage
D = Daytime (between 0800 and 1600 hours)
N = Nighttime (between 1600 and 0800 hours)
W = Winter
Sp= Spring
S = Summer
F = Fall
ft = feet
n/a= not applicable
PMF= Probable Maximum Flood

Table 5. Example of Probable Loss of Life Tabulation*

Reach Number 1

Distance from Dam
to Downstream Boundary 10 miles

Elevation of Peak Flow in Reach 932 (ft. msl)

Bottom Zone 1 900 (ft. msl)

	Elevation (ft. msl.)	PAR in Zone	Warning Time in Zone (hr)	TP in Zone	LOL in Zone
Top of Zone 1	904	10	**	0	0
Top of Zone 2	908	20	**	0	0
Top of Zone 3	912	100	**	0	0
Top of Zone 4	916	50	1.0	13	11
Top of Zone 5	920	10	1.0	3	2
Top of Zone 6	924	20	1.0	5	3
Top of Zone 7	928	40	1.0	10	4
Top of Zone 8	932	5	1.1	1	0
	Totals	255		31	20

*ft. msl = feet, mean sea level
PAR = population at risk
TP = Threatened Population
LOL = Loss of Life

**PAR assumed to be evacuated prior to flooding

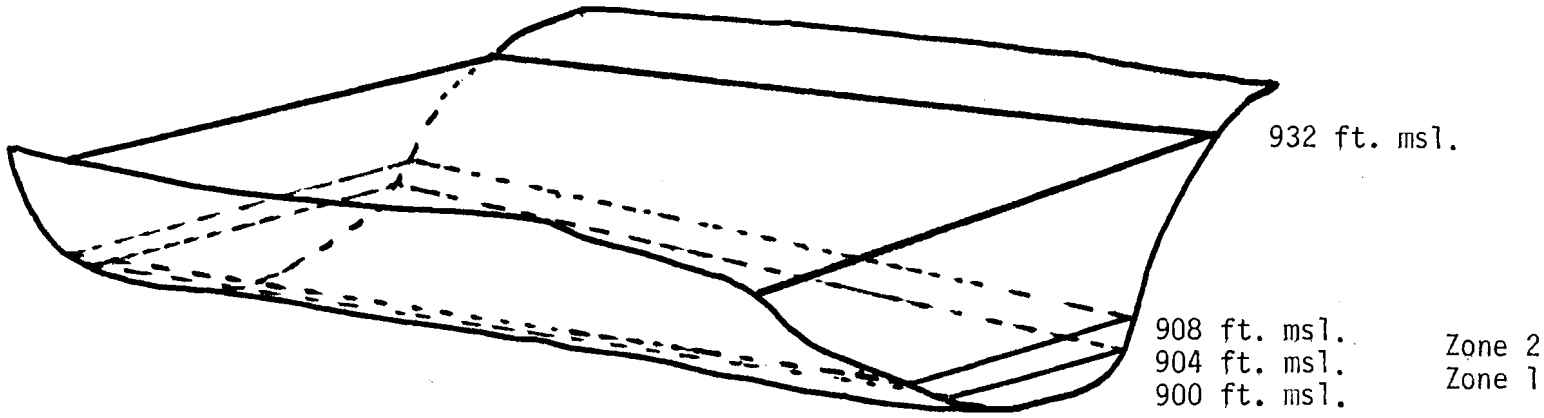
Table 5 illustrates the key factors used to calculate the loss of life. For a given reach, the populations at risk at different elevations are estimated. Warning times are estimated for each flood zone. Flood zones are defined on the basis of elevation, as illustrated in Figure 1. The threatened population is calculated as a proportion of the population at risk, depending on the warning time for the zone. The loss of life is computed as a proportion of the threatened population, the magnitude of the proportion depending on the depth of flooding.

2.10 Discussion of the Bureau of Reclamation and the Stanford/FEMA/IWR Models

Recall that in the Stanford/FEMA (1984) and IWR (1986a) models, the vector of factors affecting flood lethality, $\underline{x}$, consisted of one variable, depth of inundation in the flood zone. The function $f(\underline{x})$ may be described by the coefficient values tabulated in Table 1. The form of the function was approximately a logistic curve, with proportion loss of life as a function of depth of inundation. The logistic function had a slow rise in the proportion of loss of life between 0 to 4 feet, a steady linear increase between 4 to 12 feet, and then a leveling of the function at approximately .85 for values of $d_j > 12$ feet.

In the Stanford/FEMA study, the set of variables affecting the size of the threatened population was $\underline{y}$ = {distance from dam, being in a residential versus a rural area, effectiveness of warning system}. The function $g(\underline{y})$ was given by the parameter values listed in Table 2. In the IWR formulation, the distance from the dam was replaced by warning time.

Figure 1. Elevation zones within a river reach



If one adopts the formulation given by Equation (6) and applies it to the Bureau of Reclamation (1985) study, the function $f(\underline{x})$ appears to be equal to 1.0 in Equations (2) and (3). The reason for this may have been the lack of data but this was not discussed in the report. Another reason may have been that the Bureau of Reclamation (1985) study concentrated on deaths due to dam breaches or major flash floods. Floods of lesser importance were not included in the sample used to calibrate the loss of life equations. Consequently, the Bureau of Reclamation model was implicitly calibrated for inundation depths that were likely greater than 12 feet at peak stage. The Stanford/FEMA (1984) study postulated that the proportion of the threatened population which lose their lives is greater than 0.85 (i.e. approximately 1.0) if the depth exceeds 12 feet (refer to Table 1). If this subjective estimate of loss of life as a proportion of threatened population is reasonable, then the implied $f(\underline{x}) = 1$ term in the Bureau of Reclamation study may not be a severe problem. However, in reality the peak stage would be less than 12 feet in at least some of the zones in the inundation area. Thus, it is difficult to reconcile the Bureau of Reclamation's (1985) empirical result with the formulation in Equations (4) or (6), and the Bureau's equations may reflect some misspecification..

To consider the function $g(\underline{y})$, recall that different equations were used in the Bureau of Reclamation's formulations to predict loss of life for warning time situations with less than 90 minutes versus those with more than 90 minutes. Thus, the Bureau of Reclamation's empirical finding confirmed that warning time is one of the variables in $g(\underline{y})$ in Equations (4) or (6). For warning time greater than 90 minutes, $f(\underline{x})g(\underline{y})$

was a constant, as shown in Equation (1). For warning time less than 90 minutes, $\underline{y}$ implicitly included the population at risk, P. This means that, according to the Bureau of Reclamation's results, in floods with little warning, the effectiveness of the warning is greater in more populated areas. To explain this, recall Equation (6) and assume that for warning time less than 90 minutes,

$$g(\underline{y}) = g(W,P) = g_w(P) = \log(P^a). \tag{7}$$

The expression g(W,P) signifies that warning time, W, and population at risk, P, are the two important variables affecting the size of the threatened population relative to the population at risk. The notation $g_w(P)$ signifies: (a) that the form of the function $g(\cdot)$ depends on the assumption that we are dealing with a case in which warning time is less than 90 minutes, and (b) that the proportion is a function of P.

Substituting Equation (7) into (6), and taking the logarithm of both sides, one obtains:

$$\log(L) = \log(f(\underline{x})) + (1+a) \log(P). \tag{8}$$

With the definition of Equation (6), $\log(f(\underline{x}))$ exists and is greater than zero and less than or equal to one. Since $\log(f(\underline{x}))$ is "missing" from Equation (1), the estimated regression coefficient,

$$(1+a) = 0.0002, \tag{9}$$

is a biased estimate of the actual value unless $f(\underline{x}) = 1$. This statistical property of ordinary least squares estimators in regression models with misspecification was discussed in Draper and Smith (1981, pp.117-121). If one assumes no other misspecification in Equation (1), except for the omission of $\log(f(\underline{x}))$, then

$$a < 0, \tag{10}$$

since $\log(f) > 0$.

Equation (10) suggests that

$$\begin{aligned} \frac{\partial g(\underline{y})}{\partial P} &= \frac{\partial \log(P^a)}{\partial P} \\ &= 0.43\ a\ P^{-1} \\ &< 0 \end{aligned} \tag{11}$$

where

$$0.43 = \log_{10}(e).$$

Equation (11) reveals that the greater the population at risk, the smaller the threatened population as a proportion of the population at risk. This suggests that warning effectiveness was greater in more populated areas. In such areas, direct communication with or observation of neighboring people are more likely. A highly populated area is also more likely to have more emergency evacuation support services, and to be reached by such services.

Equation (11) and its interpretation are an empirical result of the Bureau of Reclamation (1985) study. By contrast, the threatened population proportions in the Stanford/FEMA/IWR approach were subjectively determined and were not explicitly based on empirical data. However, for given distances or warning times, the Stanford/FEMA/IWR estimates of the threatened population proportion were greater for rural reaches than for urban residential reaches. This was consistent with the Bureau's empirical finding. Thus, the Bureau of Reclamation (1985), Stanford/FEMA (1984), and IWR (1986a) models have structural similarities and may be specific versions of a general formulation to be advanced in Section 3.1.

2.11 Summary of Previous Approaches for Estimating Loss of Life

The studies which use economic damage, measured in either dollar amount or number of buildings, have a noteworthy shortcoming. The economic damage or number of structures is being used as a surrogate variable for the population at risk. It seems preferable to use population at risk directly rather than to use surrogate measures that may vary across geographical regions or over time.

The second general approach for estimating loss of life was that suggested by, for example, Paté-Cornell and Taragas (1986). It uses a casualty ratio. This approach may be acceptable in a small study with limited data resources, and may be an adequately accurate estimate of loss of life. Use of such a ratio, however, is limited by its simplicity and omission of important factors that affect the potential loss of life.

The more preferable methods appear be the Bureau of Reclamation (1985) model, and the Stanford/FEMA (1984) approach that was subsequently modified by the Institute for Water Resources (1986a). The advantage of the Bureau of Reclamation approach is that it used actual historical data to develop empirical relationships. The advantage of the Stanford/FEMA/IWR approach is its logical functional relationship between the population at risk, the threatened population, and loss of life. In addition, it takes important explanatory variables into account, such as warning time, quality of the evacuation warning, rural versus urban situations, and depth of flood water.

The Stanford/FEMA/IWR approach stated that loss of life should be calculated for different zones within each reach of the inundation area. Although the Bureau of Reclamation approach did not necessarily eschew

this kind of detail, the empirical data precluded the estimation of loss of life equations at the individual reach and/or zone level. Instead, loss of life was estimated for the whole inundation area, rather than for individual zones and/or reaches. Nevertheless, it may still be possible to apply the equations to individual reaches and/or zones for predictive purposes. This is discussed further in Section 4.0.

3.0 DEVELOPMENT OF EMPIRICAL FUNCTIONS TO ESTIMATE LOSS OF LIFE

3.1 General Equation

This section summarizes some results on developing empirical loss of life functions that may be used to estimate loss of life in the Cochiti Dam area (Volume II, Lee et al., 1986a), Beach City Dam area (Volume III, Lee et al., 1986b), and other inundation areas. The general approach in the development of the empirical functions was to combine aspects of both the Bureau of Reclamation (1985) model, and the Stanford/FEMA (1984) approach as adapted by the Institute for Water Resources (1986a).

The loss of life function was initially assumed to be given by Equation (12):

$$L_{ij} = f(\underline{x}_{ij})\ g(\underline{y}_{ij})\ P_{ij}\ , \qquad (12)$$

where

L = loss of life

i = reach

j = flood zone

$f(\underline{x})$ = the estimated proportion of the threatened population that will be killed by the flood

$\underline{x}$ = a vector of variables affecting the ratio of deaths to threatened population

$g(\underline{y})$ = the proportion of the population at risk that is estimated to remain in the flooded zone at the time of the arrival of the flood wave, i.e. the threatened population as a proportion of the population at risk

$\underline{y}$ = a vector of variables affecting the size of the threatened population relative to the population at risk

P = population at risk.

This formulation is simple and parsimonious. It is intuitively appealing, and its components distinguish between the two major elements affecting loss of life. One element relates to the effectiveness of warning and evacuation. The other element is a reflection of the physical severity of the flood. The two elements also have a natural temporal sequence. The effectiveness of warning and evacuation are of primary importance before the flood wave arrives. Once a zone is inundated, the physical severity of the flood tends to become more important in terms of affecting loss of life.

Equation (12) was modified somewhat to better reflect the interaction among the factors affecting the size of the threatened population, and the loss of life relative to the size of the threatened population:

$$L_{ij}/P_{ij} = p(\underline{x}_{ij},\underline{y}_{ij}) \ , \qquad (13)$$

where

p = the probability of loss of life of an individual in reach i at flood zone j.

In Equation (13), loss of life is expressed as a probability. An estimate of L_{ij} is simply $p(\underline{x}_{ij},\underline{y}_{ij})$ times P_{ij}. The function $p(\underline{x}_{ij},\underline{y}_{ij})$

is introduced to replace the functions $f(\underline{x}_{ij})$ and $g(\underline{y}_{ij})$ in Equation (12). The reason is that $f(\underline{x}_{ij})$ and $g(\underline{y}_{ij})$ are not truly separable. Some of the variables that affect the size of the threatened population (i.e., some of the variables in $\underline{y}_{ij}$) also affect the loss of life for a given size of threatened population (i.e., some of the variables in $\underline{x}_{ij}$). For example, an urban area may have a more efficient warning system that results in a smaller threatened population relative to the population at risk. Thus, an urban-area indicator may be one of the $\underline{y}_{ij}$. However, an urban area may also have better rescue operations, so that loss of life relative to the size of the threatened population is lower. Thus, the urban-area indicator may also be one of the $\underline{x}_{ij}$. There are several other variables which have this attribute. Because of this, it is not possible to separate statistically the contribution of a variable to $\underline{y}_{ij}$, and the contribution of that same variable to $\underline{x}_{ij}$. The function $f(\cdot)$ is more accurately represented as $f(\underline{x}_{ij}|g(\underline{y}_{ij}))$, and the function $g(\underline{y}_{ij})$ may have some x_{ij} in $\underline{y}_{ij}$.

3.2 Outline of Methodology for Developing Empirical Function

Past studies have suggested many different variables that may affect the potential loss of life (these are the elements in $\underline{x}$ and $\underline{y}$ in the function $p(\cdot)$ in Equation (13)). For example, although the Bureau of Reclamation's (1985) models only considered the population at risk and warning time, its report stressed that any loss of life predictions from its models should be regarded as "baseline" estimates that should be adjusted subjectively to take into account unique local factors. Among these, the Bureau of Reclamation (1985) report made note of:

(a) extreme lack of warning (less than 15 minutes)

(b) special characteristics of the population at risk, such as a large elderly population or an isolated community (for example, isolated in terms of a different language)

(c) special facilities such as retirement homes, nursing homes, hospitals, correction facilities, and others

(d) absence of previous public information, education or experience about the possibility of flooding

(e) ease of evacuation in terms of traffic congestion, speed of movement, and distance to a safe area

(f) convergence of population to dangerous river crossings

(g) depth and velocity of flood waters, especially those great enough to destroy buildings

(h) mud, debris, or extremely cold temperatures in the flood waters.

Petak and Atkisson (1982) had cautioned, however, that "no estimate of mortality can take all these factors into account." The basic problem is the lack of data for the area to be studied, and particularly for historical events that would be used to calibrate any empirical function. Nevertheless, the strategy in developing the loss of life models was to attempt to compile data on as many explanatory variables as possible to calibrate an empirical function. The goal was to use this function together with computed flood hydrographs, assessments of the quality of evacuation plans, and evacuation simulations to estimate the threatened population and loss of life. These methods are discussed in Sections 4 and 5.

The analysis in this section is limited to the empirical functions. To estimate this function, the approach was to:

(i) adopt the general formulation for loss of life given in Equation (13)

(ii) review the literature and compile a list of possible factors that may affect either the size of the threatened population (i.e. the $\underline{y}$ variables), or the lethality of the flood (i.e. the $\underline{x}$ variables)

(iii) identify recent past floods in the United States (there is an insufficient number of floods if limited to specific study areas), and compile data on loss of life, population at risk, and the $\underline{x}$ and $\underline{y}$ variables for these floods

(iv) do exploratory data analysis on the compiled data to identify general trends, outliers, or lack of data

(v) formulate alternative loss of life equations consistent with the form of Equation (13) and statistically calibrate the equations

(vi) study and assess the statistical results and select the best equation

(vii) compare the results with the Bureau of Reclamation and Stanford/FEMA/IWR models.

3.4 Selection of Variables

The selection of variables was based on a consideration of past research on factors affecting potential loss of life in floods, and on the likelihood of obtaining information on variables of interest from the

documents to be used as sources of the data. The following variables were postulated to affect the size of the threatened population relative to the population at risk:

(1) y -- factors affecting the size of the threatened population

(a) Warning Time (the interval between the time at which an official evacuation warning is initially given to the public and the time at which flood reaches the population at risk). In theory, each individual has a different warning time since each is situated at a unique location and elevation. In practice, only a single representative number is reported for warning time, for the whole inundation area, in the source documents for the past floods. Thus, the empirical function is estimated using very aggregate data, on a flood by flood basis, rather than using micro-data on zones and reaches within a given inundation area. Drawing on past research it was hypothesized that as warning time decreases, the population at risk has less opportunity to evacuate the inundation area. Consequently, the threatened population as a proportion of the population at risk would be relatively large. Conversely, longer warning time will allow more people to evacuate from areas at risk. The measurement and importance of warning time are discussed in greater detail in Section 4.3.

(b) Experience or Knowledge of Flooding in the Local Area within the Last 10 Years. It was hypothesized that if the population had previous experience with floods and evacuation, then they would evacuate more efficiently and readily, thus reducing the

proportion of threatened population relative to the population at risk. An opposing hypothesis was that population with prior experience with flooding may underestimate the impacts of a severe event, and may be more likely to remain in an area at risk.

(c) Existence of Hospital, Retirement Home, School, Recreation Area, or Other Unique Facility. Each of these was represented by a dummy variable (1 = existence of such a facility in the inundation area). It was hypothesized that such groups will be more likely to receive or to respond to a warning. The special status of these institutions and their ties with public agencies suggest that these institutions would have high priority to receive a warning. An alternative hypothesis was that language barriers, geographic or cultural isolation, or lack of social ties would make it less likely for these groups to receive or act upon a warning.

(d) Day or Night. This was a dummy variable (day = 1) to represent the postulate that if the flooding begins at night then the dissemination of the warning will be more difficult and less efficient, thus leading to a higher threatened population.

(e) Time of Day. These data provide more specific information on the day/night dichotomy above.

(f) Proportion of Elderly and Young Population. It was hypothesized that the elderly population may be less likely to receive a warning, less likely to respond, and less mobile. For the young population, it was postulated that some may lack

the maturity to respond properly. They may not take the appropriate action in an evacuation, or they may not realize the potentially high risk of a flood. For example, in the Connecticut flood in June 1982, at least eight of the eleven deaths involved people less than 21 years old or 62 years old or greater; and many of the circumstances surrounding the deaths of the younger victims involved tubing or rafting accidents. Demographic data for past flood events were unavailable, however, and this variable was not used in the empirical analysis.

(g) Effectiveness of the Evacuation Plan and System. The identification of a threat, decision to alert the public, interorganizational response, and efficiency of the warning process all contribute to the proportion of people who will be evacuated from the risk area. Recent study of the Cochiti Dam and Beach City Dam case studies identified general criteria for assessing the effectiveness of evacuation plans, developed a means of quantitatively rating the measures of effectiveness, and provided recommendations to improve the evacuation plan in the case study areas (Volumes I, II, and III, Sorensen and Neal, 1986a,b,c). The overall quality of the warning in the empirical analysis was represented by a three-category variable (needs improvement fair, and good).

(h) Evacuation Traffic. Simulation of a likely traffic pattern in an evacuation with the existing plan, as well as information on the optimal routing of traffic patterns, will provide

information on the expected and minimum times that it would take to evacuate a risk area. These estimates could be compared to estimates of the warning times, given some qualitative judgement of warning dissemination effectiveness and estimates of flood travel times. The efficiency of traffic evacuation would have an impact on the size of the threatened population remaining in the risk area when the flood wave arrives (Volume I, Southworth et al., 1986a). This variable was not explicitly used in the empirical function because no data were available on evacuation traffic in past floods.

(i) Size of Population, and Urban Versus Rural Situation. It was suggested that in urban areas the evacuation process will be more efficient because of the greater number of public agencies and officials available to disseminate the warning. Also, the greater population density would make it easier for the people who are warning the population to spread the warning more quickly, as well as for the population to be able to observe evacuation actions by their neighbors. Conversely, it was suggested that in rural areas, the proportion of the threatened population relative to the population at risk would be greater. The population at risk was used as a surrogate for all of these factors. Population density may be used as a surrogate variable for the existence of an urban area. However, no data were available for population density in past floods. In any event, an urban-area dummy variable may still be preferred if it is assumed that urban services, media for communication, and

social networking are the important factors affecting the effectiveness of warning dissemination, rather than population density, per se.

In terms of being consistent with the formulation in Equation (13), which separates the factors affecting the size of the threatened population from those affecting the lethality of the flood for a given size of threatened population, two separate lists of variables have been compiled representing those in the vector $\underline{y}$ (which relate to the warning and evacuation) and those in the vector $\underline{x}$ (which relate to flood lethality). The variables listed above represented those in $\underline{y}$, and they are mainly related to the extent and effectiveness of warning, and to public response. The variables listed below, on the other hand, are those that reflect the lethality of the flood, either in terms of the hydraulic characteristics or in terms of characteristics of the environment or population that may affect the probability of loss of life for a threatened individual. Clearly, however, many of the variables affect both the effectiveness of warning and evacuation, as well as the lethality of the flood. This is exactly the premise reflected in Equation (12).

(2) <u>x -- Flood Lethality Factors</u>

(a) Number of Residences Damaged and the Extent of the Economic Damage. These variables may be used to reflect the possibility of deaths associated with the collapse or destruction of structures. The extent of economic destruction is a surrogate for the severity of the flood. Data on this variable was

generally unavailable on past floods, so that it was not used in the empirical function.

(b) Depth of the Flood. The deeper the water the greater the likelihood of death. This may be measured in terms of the maximum flood stage for a representative, heavily populated zone in a given reach. This variable may also be regarded as a surrogate for environmental cues, which affect the likelihood and speed of evacuation (i.e, a variable in the y list above). Data on depth of flood were available for only about one half of the past events, but they were included in the statistical analysis.

(c) Velocity of the Flood Wave. Not only is this a factor that affects the warning time, it is also suggested that floods with high velocity are more likely to cause a greater number of deaths. Data were generally unavailable for this variable.

(d) Discharge (as measured in cubic feet per second). It was postulated that floods with a greater volume and intensity of flooding as measured in cubic feet per second are more likely to result in a greater number of deaths. The status of the data for this variable is similar to that for flood depth.

(e) Breach of Dam. This binary variable (1 = breach) was used as a surrogate for the lethality of the flood. It may also be regarded as an environmental cue.

(f) Topography of Inundation Area: This was a dummy variable (1 = a wider flood plain, 0 = a narrow canyon). It was used to provide a descriptive measure of the topography of the

inundation area which may affect the possibility of escaping the flood for different members of the threatened population. It may also affect the size of the threatened population relative to the size of the population at risk.

(g) Special Characteristics of the Population such as the Very Elderly or Very Young. Not only may these people react differently from the rest of the population in terms of responding to an evacuation warning, they may be physically weaker and less likely to survive if exposed to the flood.

(h) Unique Facilities Such as Hospitals, Retirement Homes, Schools, Recreation Areas, or Unique Facilities or Institutions. For those people who remain behind and who are caught by the flood wave, the people in these special institutions may be more vulnerable, with a greater probability of loss of life.

(i) Type of Structures. It was suggested that particular types of structures such as mobile homes and adobes would be more vulnerable to flood wave action, and would be associated with a greater likelihood of loss of life. The hypothesis is similar to that presented in Item (a). Data were generally unavailable for types of structures in past flood events, and this variable was not used.

(j) Number of Roads and Bridges Crossing the River in the Inundated Area. Study of past floods has identified that many flood drownings are vehicle-related. Frequently, they resulted from vehicles converging to a stream or river crossing and being washed away from a bridge or from a road where the water was

too deep. Unfortunately, data were unavailable for this variable and it was not included in the empirical function. However, a discussion of how the traffic evacuation simulation model may be used to estimate the size of the threatened population is given in Section 5.4.

3.4 Identification of Recent Floods

Past floods were identified based on review of the literature and on previous experience of ORNL researchers. The goal was to develop a set of historical cases that would be representative of future severe flood events, to the extent possible. The empirical relationship derived from historical cases can be used to predict loss of life from hypothetical future flood events, as described in Sections 4.0, 5.2 and 5.3. The historical events that were considered were generally those that: (a) were in areas where there were persons at risk; (b) involved severe flooding that had the potential for loss of life; and (c) were fairly recent and in the United States so as to provide comparability in terms of the structural design of the dams and in the communications available for the warning process.

The complete list of historical cases and data is tabulated in Table 6. The cases do not constitute a statistically random sample, but rather were determined by the availability of data. The cases included those identified in the Bureau of Reclamation (1985) study as well as other cases identified as a part of this study. The Bureau of Reclamation (1985) study provided a tabulation of data for each case: an estimate of the warning time, the existence of a dam breach, year of

Table 6. Loss of Life Data

No	Location	Deaths	Exp. 1/0	Hosp 1/0	Ret. 1/0	Sch. 1/0
1	Teton (to Wilford) - June 76	7	0	0	0	1
2	Teton (Rex-Amer Falls) - June 76	4	0	0	0	0
3	Gainesville, AL - April 79	5	0	-9	-9	-9
4	Jackson, MS - April 79	4	0	1	1	1
5	Buffalo Creek, WV - Feb. 72	139	0	0	0	1
6	Big Thompson, CO - July 76	139	0	0	0	0
7	San Francisco, CA - June 82	9	1	0	0	0
8	Little Dear Creek, UT - June 63	1	0	0	0	0
9	Pike Co, KY - July 79	3	1	0	0	1
10	Toccoa Falls, GA - Nov. 77	38	1	0	0	1
11	Austin, TX - May 81	13	1	0	0	0
12	Bearwallow, NC - Feb. 76	4	0	0	0	0
13	SW Virginia - April 77	4	0	1	1	1
14	Cheyenne, WY - Aug. 85	11	0	1	0	1
15	Hill Country, TX - Aug. 78	27	1	0	0	0
16	Big Country, TX - Aug. 78	6	0	0	0	0
17	Mohegan Park, CT - March 63	6	0	0	0	0
18	Denver, CO - June 65	6	1	1	1	1
19	Millard CO, UT - June 83	1	0	0	0	0
20	Schuylkill River Basin - June 72	5	1	-9	-9	-9
21	Potomac River, D.C. Area - June 72	27	1	1	1	1
22	Wilkes Barre, PA - June 72	1	1	1	1	1
23	Harrisburg, PA - June 72	1	1	1	1	1
24	Johnstown, PA - July 77	85	1	1	0	1
25	S. California - Feb. 80	18	1	1	0	0
26	Santa Barbara, CA - Feb. 80	20	1	0	0	0
27	S. California - Feb./Mar. 78	18	1	0	0	0
28	Kansas City, KC,MO - Sept. 77	12	0	0	1	0
29	Old Creek Canyon, AZ - Feb. 80	3	1	0	0	0
30	Phoenix, AZ - Dec. 78	10	1	1	0	0
31	Tri-County Area, PA - Aug. 80	9	1	0	0	0
32	Connecticut Flood, CT - June 82	11	1	0	0	0
33	Baldwin Hills Dam, CA - Dec. 63	5	0	0	0	1
34	Honolulu - May 63	4	1	1	1	1
35	Four Mile Run (Fairfax Co.), VA - Aug. 63	1	1	0	0	0
36	Tekamah Creek, NE - June 63	3	1	0	0	0
37	North Hills, PA - June 86	8	1	-9	-9	-9
38	Black Hills (Rapid City), SD - June 72	245	1	1	1	1
39	Tonto Creek, AZ - Sept. 70	23	1	0	0	0
40	James River, VA - June 72	5	1	1	1	1
41	Brushy Hill Pond, CT - June 82	0	0	-9	-9	-9
42	Lawn Lake, CO - 1982	3	1	0	0	0
43	Northern New Jersey - 1984	2	1	0	1	1
44	Phoenix, AZ - Feb. 80	0	1	0	0	0
45	Harrison Co, WV - Aug. 80	2	1	0	0	0
46	Lee Lake, MA	2	0	0	0	0
47	El Dorado, NV	9	1	0	0	0

Table 6. Loss of Life Data (continued)

No	Rec Area 1/0	Oth 1/0	Can/ Fl P 1/0	Warning Time Information: Timely 1/0	Adequ.? 1/0	Overall 1-3	Time	Occur? 1/0	When 1/0	When 1-4
1	0	0	1	0	1	1	45	1	1	2
2	0	0	0	1	0	2	105	1	1	2
3	-9	-9	0	1	0	2	120	1	1	2
4	1	0	0	1	0	2	120	1	1	2
5	0	0	1	0	0	1	0	0	1	1
6	1	0	1	0	0	1	45	0	1	3
7	0	0	0	1	0	1	60	1	1	2
8	1	0	1	0	0	1	0	0	1	2
9	1	0	1	0	0	1	0	0	0	4
10	1	0	1	0	0	1	0	0	0	4
11	0	0	0	1	1	2	60	1	0	4
12	0	0	1	0	0	1	0	0	0	4
13	1	0	1	1	0	2	120	1	1	1
14	1	0	0	0	0	1	30	1	0	3
15	0	0	0	1	1	3	240	1	0	4
16	0	0	0	1	1	3	240	1	0	3
17	1	0	0	1	0	2	300	1	0	3
18	1	0	0	1	0	2	120	1	0	3
19	0	0	0	1	1	3	180	1	1	2
20	-9	-9	0	1	0	2	1000	1	1	1
21	1	0	0	1	1	2	600	1	1	2
22	1	0	0	1	1	3	1000	1	0	3
23	1	0	0	0	1	2	120	1	0	3
24	1	0	1	0	0	1	50	0	0	4
25	0	0	0	1	1	2	1440	1	1	3
26	0	0	1	1	1	2	120	1	3	5
27	0	0	1	1	1	2	120	1	3	5
28	1	0	0	0	0	1	60	1	0	4
29	1	0	1	1	1	1	30	1	1	2
30	0	0	0	1	1	2	180	1	3	5
31	0	0	0	1	0	1	180	1	0	4
32	1	0	0	1	0	1	150	1	0	4
33	0	0	1	1	1	3	90	1	1	2
34	1	0	0	0	0	1	60	1	-9	-9
35	0	0	0	0	0	1	60	1	1	3
36	0	0	0	0	0	1	60	1	0	4
37	-9	-9	0	0	0	1	60	1	1	8
38	1	0	0	0	0	1	90	1	1	3
39	1	0	1	0	0	1	60	1	0	3
40	1	0	0	1	1	3	840	1	1	1
41	-9	-9	0	1	1	3	150	1	1	1
42	1	0	1	1	1	2	90	1	1	1
43	1	0	0	1	1	3	600	1	0	3
44	1	0	0	1	1	3	120	1	-9	-9
45	0	0	1	1	1	1	60	1	1	2
46	0	0	1	0	1	1	60	1	1	2
47	1	0	1	0	0	1	0	0	-9	-9

Table 6. Loss of Life Data (continued)

No	PAR	Year	Dam Break	Recurr. Interval (Year)	cfs	Ft above Fl Stage	Crest to Bottom (Ft)	Urb/ Rur 1/0
1	2000	1976	1	-9	2300000	-9	275	0
2	23000	1976	1	-9	67300	-9	-9	0
3	1000	1976	0	-9	-9	20.2	56	1
4	25000	1976	0	-9	-9	25	43	1
5	4000	1972	1	5000	50000	-9	46	0
6	2500	1976	0	2000	31200	-9	-9	0
7	30000	1982	0	25	-9	-9	-9	1
8	50	1963	1	-9	47000	-9	70	0
9	250	1977	1	25	-9	-9	-9	0
10	250	1977	1	-9	24000	-9	34	0
11	3000	1981	0	25	-9	-9	-9	1
12	4	1976	0	-9	-9	-9	-9	0
13	1000	1977	0	100	-9	20	-9	0
14	200	1985	0	100	-9	-9	-9	1
15	1500	1978	0	250	240000	15	41	0
16	1000	1978	0	400	280000	37	47	0
17	500	1963	0	-9	-9	15	-9	0
18	22000	1965	0	-9	40300	18	-9	1
19	400	1983	1	-9	10000	-9	-9	0
20	10000	1972	0	-9	-9	18.5	47	1
21	2000	1972	0	-9	-9	10	22	1
22	100000	1972	0	-9	-9	18.6	40.6	1
23	10000	1972	0	-9	-9	15.6	40	1
24	50000	1977	1	500	250000	-9	72	1
25	5000	1980	0	50	-9	-9	-9	1
26	500	1978	1	10	-9	7.6	18.6	1
27	10000	1978	0	10	-9	10	28	1
28	5000	1977	0	350	-9	10	28	1
29	500	1980	0	-9	30000	15	-9	0
30	5000	1978	1	-9	130000	10	-9	1
31	1500	1977	0	-9	-9	10	-9	0
32	4000	1982	0	500	-9	-9	-9	-9
33	16500	1963	1	-9	35000	-9	59	1
34	1000	1963	0	-9	16500	-9	19	1
35	500	1963	0	100	11700	-9	-9	1
36	3000	1963	0	150	74000	-9	32	0
37	10000	1986	0	-9	-9	-9	-9	1
38	17000	1972	1	100	50000	12	-9	1
39	1500	1970	0	-9	53000	-9	30	1
40	50000	1972	0	-9	-9	15	36.5	1
41	400	1982	1	500	27815	-9	-9	0
42	5000	1982	1	250	18000	-9	26	0
43	25000	1984	0	100	-9	-9	-9	1
44	6000	1980	0	-9	170000	-9	-9	1
45	2000	1980	0	-9	-9	13	-9	0
46	80	1980	0	-9	-9	13	-9	0
47	100	1974	2	500	7600	-9	-9	0

Notation for Table 6
Loss of Life Data

-9	Missing Information
Deaths	Number of Flood-Related Deaths
Exp. 1/0	Inundation Area Experienced Flooding in the Last 10 Years (1=Yes, 0=No)
Hosp 1/0	Hospital in Inundation Area (1=Yes, 0=No)
Ret. 1/0	Retirement Home in Inundation Area (1=Yes, 0=No)
Sch. 1/0	School in Inundation Area (1=Yes, 0=No)
Rec Area 1/0	Recreation Area in Inundation Area (1=Yes, 0=No)
Oth 1/0	Other Special Institution in Inundation Area (1=Yes, 0=No)
Can/Fl P 1/0	Inundation Area Topography (1=Canyon, 0=Wider Floodplain)
Timely? 1/0	Timely Warning? (1=Yes, 0=No)
Adequate? 1/0	Quality of Warning Adequate? (1=Yes, 0=No)
Overall	Overall Subjective Evaluation of Effectiveness of Evacuation Warning (1=Poor, 2=Fair, 3=Good)
Time	Warning Time (Minutes). The interval between issuance of the evacuation warning to the public and the arrival of the flood wave to where most of the population at risk was located and/or loss of life occurred.
Occur? 1/0	Was There a Warning? (1=Yes, 0=No)
When 1/0	Time of Day of the Flood (1=Day (light), 0=Night (dark)
When	Time of Day of the Flood (1=6am to 11am, 2=11am to 5pm, 3=5pm to 6am, other=spanned several parts of the day)
PAR	Population at Risk. Number of people who would have been exposed to flood water if they did not evacuate
Year	Year of the Flood
Dam Break	1=Dam Breach, 0=No Breach
Recurr. Interval	Recurrence Interval (years). For example, a "100 year flood."
cfs	Peak Flow (measured in cubic feet per second)
Ft above Fl Stage	Number of Feet Peak Flood Stage was Above the Stage at Which Population Would be Exposed to Flood
Crest to Bottom (ft)	Distance from Crest of Dam to Bottom of Riverbed (feet)
Urb/Rur 1/0	1=Urban Area of ≥ 10,000 population; 0=otherwise

event, population at risk, and number of deaths. The data for this study was compiled independently of the Bureau of Reclamation data, although there were several source documents in common. The Bureau data were also used to supplement the data in a few cases. A complete list of all documents and sources used in the data collection effort is given in Appendix A. Interested readers may wish to consult the original documents for further information on specific flood events, in addition to the data provided in Table 6. A major obstacle to compiling the data was that there was no standard, reference source of information. Data sources included government reports, research reports, newspaper articles, and personal communications.

In many cases, a considerable degree of subjective judgement was used in interpreting the information in the source documents. In particular, the population at risk and warning time were usually not explicitly defined in terms of how they were measured. For example, if a statement is made in a report that "there was no warning," it is unclear if it was defined in the same manner as in the Corps' Guidelines (IWR, 1986b) -- the time between issuance of the evacuation warning to the public, and the arrival of the flood so that the population at risk is exposed (even minimally) to water. Certain individuals may literally have had "no warning." Perhaps this may have been due to incomplete dissemination of the warning; but if a public warning was issued (even if it was not received by some of the public) before arrival of floodwater then the Corps' Guidelines (IWR, 1986b) would state that there was still some warning time. These issues were not fully considered in the source documents.

Another major drawback of the data sources is that information was usually given for the event as a whole. If there was a dam breach, for example, data were not given separately for the population at risk and warning time associated with the spillway flood prior to breach, and for the population at risk and warning time after the breach. Also, data were not given for individual flood stage zones or river reaches. A statement may be made in the source document that "two people died when their vehicle was swept off a bridge," but no further information is given on where (i.e. the reach and flood zone) it occurred, on the population at risk, or on the warning time at that particular location.

This latter point raises a significant issue. Data limitations dictate that an observation in our data set for the empirical analysis is a single flood event for the whole inundation area, rather than for individual flood zones and reaches. Even though the inundation area may cover several hundred square miles and contain several communities at different locations along the river, data are available for only an aggregate population at risk and some "representative" or "important" warning time (its exact meaning usually being undefined).

This imprecision in the information in the source documents raises two general problems. The first is the uncertainty and aggregation error in the empirical data and the effect that this will have on the accuracy and precision of the statistical results. The second problem is that the lack of precision in the data on past flood events limits the type of detailed analysis, by reach and by zone, which is described in Section 2.9. Equations which are calibrated to explain the variance in loss of life among flood events throughout the country may be applied to estimate

loss of life in individual reaches within an inundation area for a single flood event. However, one should realize that the equations were not calibrated to account for differences between reaches and zones, but rather between many flood events in various parts of the country that occurred at different times.

The loss of life models presented in Sections 5.2 and 5.3 use the empirical function derived in this Section. The aggregate-empirical model described in Section 5.2 is a reach-by-reach computation; and the empirical-travel-time model described in Section 5.3 is a more disaggregate, zone-within-reach computation. In viewing any loss of life predictions from either of these models, one must be aware of the caveat that they are based on an empirical loss of life function that is calibrated at a geographical scale that is much more aggregate than the scale at which it is being applied.

3.5 Exploratory Data Analysis

Notwithstanding the data quality limitations mentioned previously, the data listed in Table 6 were subjected to a series of exploratory data analyses:

(a) Scatter diagrams were plotted with the explanatory variables and the number of deaths.

(b) Correlation coefficients were computed.

(c) The number of deaths expressed as a proportion of the population at risk was also used as the dependent variable, in place of the number of deaths.

(d) The logarithm of this proportion was plotted against warning time; and regression analyses were run for different subsets of observations, based on different warning time thresholds (e.g. warning time less than 90 minutes or warning time less than 120 minutes).

(e) Stepwise regression analyses were run.

(f) Different functional forms, transformations, and error structures (i.e., additive and multiplicative) were considered.

The purpose of these analyses was to gain a better understanding of the data and of any data errors, to identify key explanatory variables and their possible relationships with loss of life, and to lay the foundation for the more detailed statistical analysis presented in Section 3.6.

The result of these initial analyses was that there was no statistically significant (at the .05 level) relationship between most of the hypothesized explanatory variables and the dependent variable, either loss of life or loss of life as a proportion of the population at risk. Thus the only variables retained for further analyses were the loss of life itself, population at risk, warning time, a dummy variable to indicate previous experience with flooding in the last ten years, a dummy variable to indicate whether the inundated area was urbanized, and the depth of flooding at peak stage.

There are several reasons why the statistical results involving most of the variables were insignificant. One primary reason is the extremely small sample size. There were only forty-seven observations and in many of these observations there were missing data, information that was not

available in the original source documents. Consequently, the sample size used in the statistical analyses was often much less than forty-seven. This was particularly the case for the hydraulic and hydrologic variables such as peak depth of flooding, probability and severity of flood as represented by its recurrence time, velocity, and peak discharge. Also, many of the analyses were done separately for two smaller sub-samples -- those cases with warning time less than 120 minutes, and those with warning time equal to or greater than 120 minutes. This reduced the effective sample sizes and degrees of freedom even further.

A second reason why most of the variables were not significant is that many of the preliminary analyses were bivariate correlation analyses. It is extremely difficult to apportion a part of the overall contribution to loss of life to one specific factor. This is especially compounded with a small sample size. There are so many possible factors that interact that it is difficult to identify a statistically significant relationship with loss of life involving only one of them, except for the dominant variables that were retained for further analysis. Stepwise regression analyses were done to help address this problem. Yet, multicollinearity among the variables may have caused some of their explanatory power to be hidden by the dominant variables.

Another possible explanation is that some of these variables, such as the existence of some unique institution or facility, may have been a significant factor in the loss of life for a particular flood event, but that they have no general significance when one looks at the overall picture in all flood events in the United States. This points out the

importance of considering local factors and circumstances in trying to explain or predict loss of life.

In certain instances, a canyon may have been a contributing factor in that the population trying to escape the flood wave may have tried foolishly to drive along the road through the canyon instead of simply abandoning their vehicles and climbing up the hillside. This occurred in the Big Thompson flood, in which the topography and the geography of the road networks contributed to the loss of life (Gruntfest, 1977). But in other flood events, perhaps the action of the people or the nature of the flood was such that the canyon was really of no significance. These possibilities create problems for the analysis. They make it very difficult to construct a general model that can be used to predict loss of life in specific areas of the United States based on historical evidence from the country as a whole. This observation suggests that given the current ensemble of information available, only dominant variables, such as the population at risk and the warning time, could be statistically significant in discerning variations in historical flood events on a country-wide basis and that only these variable could be used in any predictive model. The positive aspect about this problem is that if a lot of the variation in loss of life may be predicted by these few, dominant variables, then this would provide a succinct and easily understandable explanation of the major factors affecting loss of life. It also means that data requirements, in terms of collecting information to consider hypothetical future flood events, are reduced and require less subjective judgement.

3.6 Statistical Analysis and Results

The data in Table 6 were used to develop an empirical function for loss of life estimates. Various equations were considered in which loss of life was expressed as a function of the population at risk, warning time, existence of a dam breach (even though it was not significant in the exploratory data analyses), the previous experience with flooding, the urban/rural dummy variable, and depth of flood at peak stage. The functional forms for the equations included linear, log linear, log-log, and group logit formulations, as well as more complicated non-linear forms. The equation that gave the best statistical and logical explanation of the variation in loss of life was selected. The major criteria used in this assessment were a comparison of the log likelihood values for each of the alternative equations, and the significance and signs of the coefficients of the explanatory variables.

In some preliminary analyses, two different loss of life equations were derived: one was for cases in which warning time was adequate, and the other was for cases in which the warning time was low or non-existent. This was much like the Bureau of Reclamation (1985) approach except that the statistical analysis found that the optimal cutoff boundary between the two sets of warning situations was 120 minutes rather than 90 minutes, and that warning time itself was a statistically significant variable in situations with low warning time. The major results in this preliminary analysis were that:

(a) the greater the population at risk, then the lower the loss of life as a proportion of population at risk

(b) the greater the warning time, then the lower the loss of life as a proportion of population at risk (especially if warning time is less than 120 minutes)

(c) if the inundation area had experienced flooding in the last ten years, then the loss of life as a proportion of the population at risk is higher than otherwise expected (especially is warning time is greater than 120 minutes).

These preliminary results were suggestive, but they had one major drawback. The problem was that there is a "dislocation" in loss of life estimates as one goes from a warning situation in which there is less than 120 minutes to one in which there is greater than 120 minutes. Although the two equations were rather similar, they were nevertheless quantitatively different and this led to some counter-intuitive predictions when these two equations were used to predict loss of life in two case studies (Volumes II and III, Lee et al., 1986a, 1986b).

Because of the drawbacks of the 2-equation formulation for the empirical loss of life functions, a single-equation formulation was calibrated. This took the form of a group logit model in which the probability that an individual at risk dies is represented by a logistic equation:

$$L/P = \exp(\underline{\beta}'\underline{x}) \;/\; (1+\exp(\underline{\beta}'\underline{x})) \;. \qquad (14)$$

The parameters, $\underline{\beta}$, were estimated by maximum likelihood methods. The estimated coefficients (with their t-statistics and levels of significance in parentheses) and the variables were given by

$$\underline{\beta}'\underline{x} = -\ \underset{\substack{(-31.5)\\(.0000)}}{6.2} \qquad (15)$$

$$+ \underset{\substack{(20.7)\\(.0000)}}{3.1} \quad [1/(1+W)]$$

$$- \underset{\substack{(-6.6)\\(.0000)}}{0.00034} \quad (WP)^{1/2}$$

$$- \underset{\substack{(-7.4)\\(.0000)}}{0.0077} \quad P^{1/2}$$

$$+ \underset{\substack{(9.9)\\(.0000)}}{1.4} \quad E$$

$$+ \underset{\substack{(2.6)\\(.0099)}}{0.0039} \quad D \quad ,$$

where

L = loss of life

P = population at risk

W = warning time (minutes)

E = dummy variable to denote previous experience with floods in the last ten years

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

Only 22 observations were used in the statistical calibration of Equations (14) and (15) because of missing information on the flooding depth variable in most of the cases (refer to Table 6).

An alternative to Equations (14) and (15) was estimated, omitting the depth variable but including a dummy variable to denote whether the inundation are is urbanized. A group logit model was used, as in Equation (14). The coefficients were obtained by maximum likelihood methods and were estimated as follows:

$$\underline{\beta}'\underline{x} = - \underset{\substack{(-1.8)\\(.0624)}}{0.18} \tag{16}$$

+	1.7 (15.3) (.0000)	$[1/(1+W)]$
-	0.00044 (-8.3) (.0000)	$(WP)^{1/2}$
-	0.0092 (-10.6) (.0000)	$p^{1/2}$
+	0.26 (3.2) (.0014)	E
-	0.18 (-1.86) (.0624)	U

,

where

U = dummy variable to denote an urbanized area

and the rest of the notation is as given in Equation (15).

There are several advantages to using a group logit model, as given in Equation (14):

(a) The dependent variable, L/P, is explicitly treated as a probability with values between zero and one. Other formulations such as the standard ordinary least squares regression approach, may use the same dependent variable, but it would be treated as a proportion whose predicted value could be outside the range (0,1), depending on the values of the coefficients and the values of the independent variables. If this were to occur, the predicted loss of life would be a negative number or a magnitude which is greater than the population at risk. The group logit formulation, on the other hand, insures that the probability that an individual (who is

in the area at risk) will die is between zero and one, and that the total estimated loss of life will be between zero and the overall population at risk. The group logit formulation in effect considers each individual as an observation in the statistical analysis, rather than a whole inundation area or flood event as the statistical observation.

(b) 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. For example, in an ordinary regression approach, a flood event in which four people died out of the four people at risk in a flood event would be treated the same statistically as a situation with which the population at risk and the loss of life were both 10,000. The regression approach would treat these as conveying the same amount of statistical information. In contrast, the group logit approach would consider the 10,000 LOL-10,000 PAR case as conveying more information than the 4 LOL-4 PAR event. Computationally, each individual, rather than each flood event, would carry equal statistical weight.

(c) Although this is not unique to a group logit formulation, the estimated equation(s) provided a single empirical function for loss of life. The form of the group logit equation is highly flexible in that the x's in Equation (14) can take on any

suitable transformation of explanatory variables, as shown in Equation (15).

(d) The formulation in Equation (14) is consistent with the general explanatory model for loss of life given by Equation (13) with the probability function being $p=\exp(\underline{\beta}'\underline{x})/(1+\exp(\underline{\beta}'\underline{x}))$.

Examination of Equations (14), (15), and (16) suggests some interesting factors affecting loss of life in past flood events. The most significant factor that affects the probability of loss of life for an individual in a flood was the warning time. This is reflected in the very high t-statistics for the 1/(1+W) terms in Equations (15) and (16). The positive-value coefficient for the 1/(1+W) terms and the negative-value coefficient for the $(WP)^{1/2}$ term in both Equations (15) and (16) confirm that the greater the warning time, the lower the probability of loss of life. The 1/(1+W) function suggests that warning time was extremely important for the population at risk directly below the dam, where W is small, and that its importance to the probability of loss of life diminished the greater the warning time or distance from the dam. Thus, with little warning time, "every minute counted." Differences in warning time of only a few minutes made a significant difference in loss of life. However, if warning time was relatively great, the difference of a few minutes had a much smaller effect. In general, the empirical results confirm that the greater the warning time, the greater the number of people who will evacuate, so that the threatened population is smaller, and the probable loss of life is less. When the warning time became greater (for example, greater than 2 hours), then the total warning time was generally great enough for most of most of the

population at risk to evacuate the inundation area and warning time had a much smaller quantitative influence on loss of life relative to the population at risk.

The coefficients of the $(WP)^{1/2}$ and $P^{1/2}$ terms in Equations (15) and (16) indicate that loss of life was less probable for individuals living in an inundation area that is highly populated (though more populated areas will, of course, likely have a greater total loss of life). This is even more the case if the warning time was very great, as reflected in the interaction between warning time and population at risk in the $(WP)^{1/2}$ term. The negative-coefficient for the urban variable in Equation (16) provides further corroborative empirical evidence that the probability of loss of life for a given individual was lower in more populated, urban areas. The results suggest that in urban areas there are more public officials to disseminate evacuation warning and to direct the evacuation, better communication systems, and better rescue operations so that the likelihood of loss of life for a given individual is less. Conversely, the results indicate that in less populated, rural areas, it is more difficult to disseminate the warning and to notify all of the people affected. In rural areas, the people are sparsely settled or may be transient visitors to a recreation area. Also, in rural areas the warning process may not be as efficient because of the lack of public officials and resources to disseminate the warning, as well as the larger areal extent that would have to be covered relative to the number of people available to disseminate the warning.

The negative relationship between the probability of loss of life (for a given individual) and the size of the population at risk suggests

further that the problems of traffic congestion, in terms of increasing the size of the threatened population through traffic accidents or delays in evacuation time because of traffic congestion, were over-shadowed by the positive influences of more efficient evacuation-warning dissemination. In addition, individuals observing the actions of neighbors and others in the process of evacuation may have been more likely to evacuate. In general, being in a highly populated, urban area had a positive influence in terms of reducing the probability of loss of life, though the magnitude of the impact diminished as the size of the population increases. This is reflected in the square root term for the population at risk in Equations (15) and (16).

Another important result is the significance of the E term, representing the prior experience factor. The empirical results suggest that areas with previous flood experience in the last ten years actually had a greater loss of life other things being equal. An intuitive explanation of this is that people living in areas that have recently experienced flood events have developed some skepticism towards the necessity of evacuation and a degree of over-confidence in their ability to survive the flood. The impact is that fewer of them evacuate. This leads to an increase in the threatened population exposed to the flood, thus increasing the probability of loss of life. This previous experience factor was somewhat less important when the urban variable was included as in Equation (16), rather than the depth variable, which was used in Equation (15). However, this is not necessarily to suggest that this experience factor becomes less important in urbanized areas. The "previous experience" factor provides some interesting evidence about

disaster response behavior. Moore (1963, 1964) first explicitly noted the role of a "disaster subculture" affecting disaster response. Moore noted that communities occasionally affected by disasters build into their systems ways of responding to a disaster. Moore (1964) and Wenger (1978), among others, have noted both the positive and negative effects of a disaster subculture.

First, a disaster subculture may lessen the ambiguity and difficulty in coordinating response. Second, fewer organizational adaptations are necessary to facilitate emergency response. In the words of Wenger, "the community can utilize a traditional (sometimes latent) disaster structure (Wenger, 1978, p. 42).

However, not all aspects of an existing disaster subculture are positive. The experience of one disaster may not totally translate into the needs and response for another. Specifically, a community, having recently experienced and responded to one impact, may not regard the next threat as severely as the previous experience. Organizations may not respond to the threat as if there was a crisis. In fact, some people and organizations develop levels of overconfidence that may inhibit the appropriate disaster response (Wenger, 1978).

Therefore, the positive relationship between probability of loss of life and previous flood experience is not totally surprising. These data suggest that most communities, after having experienced a recent severe flood, believed that nothing could be as worse as the recent flood. Wenger (1978, p. 44) surmises the situation as follows:

> The consequences of disaster subcultures for effective response are both facilitative and debilitative. However, to the extent that they reduce or delay the development of a crisis definition, they may debilitate a community's response to an

impact that exceeds the experience upon which the subcultural patterns have developed.

The flood depth is the only variable in the empirical functions which explicitly represents the hydraulics and hydrology of the flood event. The results in Equations (14) and (15) show that the probability of loss of life for an individual was greater the greater the depth of the flood at peak stage. This provides an empirical basis for what may be an intuitively reasonable assumption that the lethality of the flood may be represented by its depth. Other variables, such as velocity and discharge, were not included because of data limitations.

When the depth variable was used in the statistical analysis, there were a great number of missing observations. An alternative formulation that did not include the depth variable was considered. The result was Equation (16). The urban variable in Equation (16) confirms the hypothesis that the probability of loss of life was lower in urban areas, holding constant the size of the population at risk. Another related variable that was considered for the empirical functions was the population density. However, data on this variable were unavailable in the reports and documents that were used as the sources of information on the past floods. Nevertheless it may be appropriate to direct future research to estimate the population density, which is simply defined as the population at risk divided by the area of the inundated zones. This would require a detailed case-by-case estimate of the areas of the inundated zones in each of the past floods. In any event, the population at risk and the urban variable may sufficiently reflect the factors affecting loss of life that would be embodied in a population density variable. These include such factors as the quality of warning

dissemination, communications systems, emergency response personnel, and other factors that may affect loss of life. However, the population density variable may be important if it is postulated that an area with high population density would be expected to have significantly lower loss of life than an equally highly populated urban area with low population density.

The recommended empirical function to be used in the loss of life models, that are discussed in Sections 4 and 5, is the one given by Equations (14) and (15). Even though few observations were available for the statistical calibration, the presence of the depth variable is very appealing as a logical explanation of loss of life. The flood depth represents directly the hydraulics, hydrology, and overall lethality of the flood. An empirical function in which the depth and urban variables were combined with the other terms was also considered. However, the results of the statistical analysis was that the urban variable was only marginally significant and that it had a surprisingly positive valued coefficient.

3.7 Comparison Among Loss of Life Formulations

A numerical comparison among the Bureau of Reclamation (1985) model, the Stanford/FEMA/IWR (1986) formulation, and the empirical functions derived in this study is summarized in Table 7. For each of the historical cases, Table 7 lists the actual loss of life, the estimated numbers based on the two different empirical functions in Section 3.6,

Table 7. Comparison of Loss of Life Predictions

Obs	Location	Actual	ORNL Pred #1	ORNL Pred #2	BuRec Pred	BuRec Lower 95%	BuRec Upper 95%	IWR Pred
1	Teton (to Wilford)	7	3	15	96	45	205	1360
2	Teton (Rex-Amer Falls)	4	10	34	5	3	5	3910
3	Gainesville, AL	5	2	7	0	0	0	2
4	Jackson, MS	4	10	27	5	3	6	43
5	Buffalo Creek, WV	139	120	142	145	63	332	3400
6	Big Thompson, CO	139	4	18	109	50	239	1700
7	San Francisco, CA	9	47	43	486	173	1361	6375
8	Little Dear Creek, UT	1	2	3	10	7	15	43
9	Pike Co, KY	3	38	18	27	16	48	213
10	Toccoa Falls, GA	38	38	18	27	16	48	213
11	Austin, TX	13	16	21	122	55	272	128
12	Bearwallow, NC	4	0	0	2	2	3	3
13	SW Virginia	4	2	8	0	0	0	68
14	Cheyenne, WY	11	0	2	24	14	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	4	3	5	37
19	Millard CO, UT	1	1	4	0	0	0	2
20	Schuylkill River Basin	5	14	13	2	1	2	0
21	Potomac River, D.C. Area	27	8	11	0	0	0	0
22	Wilkes Barre, PA	1	3	1	20	14	22	0
23	Harrisburg, PA	1	29	33	2	1	2	17
24	Johnstown, PA	85	49	39	660	224	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	2	1	2	12
28	Kansas City, KC,MO	12	6	22	166	71	388	750
29	Old Creek Canyon, AZ	3	4	7	42	22	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	3	2	4	140
34	Honolulu	4	7	9	63	32	126	213
35	Four Mile Run (Fairfax), VA	1	4	5	42	22	77	106
36	Tekamah Creek, NE	3	16	25	122	55	272	255
37	North Hills, PA	8	33	38	251	100	631	2125
38	Black Hills (Rapid City), SD	245	37	39	3	2	4	2040
39	Tonto Creek, AZ	23	9	13	80	39	167	319
40	James River, VA	5	9	4	10	7	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	5	3	6	0
44	Phoenix, AZ	0	22	27	1	1	1	10
45	Harrison Co, WV	2	12	19	96	45	205	170
46	Lee Lake, MA	2	0	1	14	9	21	7
47	El Dorado, NV	9	16	7	16	10	25	85
	Root Mean Square Error		22	25	133	47	374	2810

the estimated loss of life using the Bureau of Reclamation's (1985) model, lower and upper 95% confidence levels using data provided in the Bureau of Reclamation (1985) report, and estimates based on the IWR (1986a) formulation. Estimates were expressed to the nearest integer value, any negative values in the estimated loss of life were set to be zero, and any estimates greater than the population at risk were set equal to the population at risk. The root mean square errors are tabulated at the bottom of Table 7. These indicate the overall fits of each of the estimators to the actual loss of life data.

For each case, the loss of life was predicted by substituting the values of the population at risk, warning time, previous experience factor (1=previous experience), the urbanized-area dummy variable (1=urban area), and depth from Table 6 into Equations (14) and (15), and into Equations (14) and (16). Equations (14) and (15) are designated as ORNL #1 in Table 7, and Equations (14) and (16) are designated as ORNL #2. For the empirical function which includes the depth of the peak flood stage, about one-half of the past cases had missing information on that variable. For these cases, the average flood depth of all other cases was used in Equation (15). For the case in which past data were unavailable on the urban-area dummy variable, the estimate is the average of the estimates with the urban variable=1, and with the urban variable=0.

The predicted loss of life for the Bureau of Reclamation (1985) model was calculated from Equations (1) and (2), by using a warning time of 90 minutes as the point at which Equation (1) or (2) is used, and by substituting the value of population at risk which is given in Table 6.

The 95% bands for the Bureau of Reclamation estimates were obtained by using the coefficients 0.5 and 0.7 in place of 0.6 in Equation (1), and 0.00014 and 0.00022 instead of 0.0002 in Equation (2). These values were provided in the Bureau of Reclamation (1985, p. 54) report.

The last column in Table 7 represents a best-guess estimate of the loss of life for each historical case, using information on population at risk, warning time, warning quality, urban or rural nature of the area, and flood depth. The IWR (1986a) procedure was used, as given by Equation (6), with the coefficients tabulated in Tables 1 and 3. For cases with missing observations on flood depths, the average of all other cases was used. For the case with missing information on the urban versus rural nature of the area, an average value was used. For the quality of the warning system, data tabulated in Table 6 were used.

An examination of the results in Table 7 reveals that both of the loss of life functions derived in the study provided more accurate predictions of actual loss of life in past floods than either the Bureau of Reclamation model or the Stanford/FEMA/IWR model. The root mean square error provides a summary indicator of the accuracy of the predictions of the models. A lower root mean square error indicates a better fit. The empirical function which includes the depth of the water as one of the predictor variables affecting the probability of loss of life provided a slightly better prediction of actual loss of life than the alternative function which had the urban-area indicator. In looking at the individual cases, the predictions of these two empirical functions were approximately comparable. They did not deviate significantly from one another.

While the loss of life was predicted rather well in many of the cases, such as the Buffalo Creek, West Virginia flood, the empirical function generally did not predict the great variations in loss of life which were actually observed. 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. In the latter two cases, the empirical functions predicted relatively great loss of life, compared to the range of estimates in the "ORNL Pred # 1" column in Table 7, but the predictions were nevertheless below the actual numbers. 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.

The Bureau of Reclamation model tended to significantly over-predict loss of life on average. In fact, the Bureau of Reclamation lower 95% confidence band provided a better estimate than the Bureau of Reclamation best-guess equation. The Stanford/FEMA/IWR model resulted in extremely large predicted loss of life, over-predicting actual loss of life in many cases by orders of magnitude. The major reason for this was that the f(x) coefficient in Table 1 specified a .85 proportional loss of life relative to the threatened population when flood depths exceed 12 feet. In most of the historical floods, peak depths of flooding were greater than 12 feet, so that the .85 coefficient was used in the calculations. This resulted in very high values for the estimated loss of life. Empirical evidence suggests that the flood lethality coefficients in

Table 1, and possibly the evacuation effectiveness coefficients in Table 3, should be reduced significantly.

3.8 Uncertainty in Loss of Life Estimates

The sizeable errors in the estimates in Table 7 point to the fact that there is indeed considerable uncertainty in predicting loss of life. There are several reasons for this:

(a) The empirically calibrated functions may be misspecified in terms of missing or inaccurately defined variables. Thus, the empirical equations may be inaccurate and factors not included in the equations may cause the loss of life to be very different from those predicted by the equations.

(b) Even if all of the general factors affecting loss of life are included in the models, there are many unique local circumstances or conditions whose effects on loss of life are difficult to generalize in a statistical sense, but which may nevertheless have a major influence in some situations.

(c) There are unpredictable occurrences that happen by chance.

(d) Several approximations were made to estimate missing information for several of the cases.

(e) The independent variables, i.e. the factors that affect the likelihood of loss of life, may not have been estimated accurately; for example, the actual warning time will be different for different individuals living in different zones at risk. Also, information on warning time is often difficult to find in source documents on historical flood events. In

addition, even after study of warning and evacuation procedures for an inundation area, as well as experience from test exercises in the area, it may still be difficult to estimate the actual warning time and behavior of the population should a flood actually occur.

Because of these reasons, a large range in the estimated loss of life is to be expected. In fact it is prudent to express loss of life estimates as a range such as that defined by 95% confidence limits, or possibly by 67% confidence limits which give a narrower band. Also, in any study, it seems useful to perform sensitivity analyses by varying the values of the population and warning time within reasonable limits, particularly if these variables are difficult to estimate.

4.0 DATA INPUTS FOR ESTIMATING LOSS OF LIFE IN CASE STUDIES

The general procedure for predicting loss of life is presented in the Interim Procedures and in the Guidelines for Evaluating Modifications of Existing Dams Related to Hydrologic Deficiencies (Institute for Water Resources, 1986a,b). The procedure can be summarized as consisting of four steps:

1) Establish the flood scenario,
2) Estimate the population at risk,
3) Estimate warning time,
4) Use loss of life models to estimate the number of deaths, and compare results of models.

The first three steps involve key input variables that are used in the loss of life models. The rest of this section discusses these

variables and methods for estimating their values in case studies. Section 5 discusses the loss of life models for estimating the number of deaths.

4.1 Establish the Flood Scenario

The flood scenario is established by assuming a flood event, which is specified for a particular inundation area. The flood event is expressed as a proportion of the Probable Maximum Flood (PMF), and a dam breach is considered as a possibility.

For a given event, information on the flood stage and geographical extent of the inundation area are provided through a set of models maintained by the Hydrologic Engineering Center (HEC). There are three commonly used and readily available computer models that are useful in predicting dam failure breach flows and downstream inundation (Institute for Water Resources, 1986b). These are:

(1) simplified dam-break (SMPDBK),

(2) HEC-1,

(3) National Weather Service Dam Break (DAMBRK).

The most sophisticated and potentially most accurate is DAMBRK. It provides a complete solution to the breach and flow hydraulics. However, it does not have the capability to generate inflow hydrographs, so that a watershed model, such as HEC-1, is needed to compute the reservoir and tributary inflow. DAMBRK is considered by the Corps of Engineers to be the preferred model for dam failure analysis (IWR, 1986b). HEC-1 has somewhat less sophisticated hydraulic calculations than DAMBRK and should not be used for dam failure analysis where significant backwater problems

occur. HEC-1 is probably more familiar to most dam designers and dam safety analysts and has the advantage of integrating the hydraulic and hydrologic analyses. SMPDBK is less sophisticated and less accurate compared to DAMBRK but may be more accurate for dam failure analysis than HEC-1. SMPDBK, however, should be used only for a preliminary estimate of the flood wave.

To begin the analysis, the DAMBRK model is applied to a set of hypothetical flood events such as:

1) Probable maximum flood (PMF) with dam breach,
2) Probable maximum flood (PMF) without dam breach,
3) 0.8 PMF with breach,
4) 0.8 PMF without breach,
5) Spillway design flood (e.g., 0.64 PMF) of existing dam, with breach,
6) Spillway design flood (e.g., 0.64 PMF) of existing dam, without breach,
7) .37 PMF.

The choice of events is somewhat arbitrary, although "with" and "without" breach scenarios should be included for the PMF, for the threshold flood at which failure may occur, and for a lesser flood (without breach). To compare dam modification alternatives the same set of events would be selected (except that the modification may eliminate some breach scenarios), and the complete loss of life analyses would be repeated.

The key considerations to be considered in determining flows and inundation from flood events are discussed in Step 2 ("Determination of the Existing Threshold Flood"), Step 3 ("Determine Total Flows and

Downstream Inundation from the Threshold Flood With and Without Dam Failure and from Lesser Floods") and Step 4 ("Compute the Hypothetical Maximum Dam - Failure Flows and Downstream Inundation") of the Corps' Guidelines (IWR, 1986b). An antecedent flood is generally assumed to begin five days prior to the onset of the flood event under consideration. The antecedent event is assumed to be 50% of the succeeding, full flood event. The initial level of the reservoir for the succeeding flood is determined by routing the antecedent event through the reservoir.

The freeboard should be computed according to the guidelines referenced in the Corp Guidelines (IWR, 1986b). Freeboard is indicated to provide overtopping protection against wave and wind effects on a full reservoir, and should always be at least three feet. The operation of the outlet works and spillway gates, if any, should follow the regulations set forth in "Water Control Manual" or historical operating criteria for the project. In using the DAMBRK model, a range of different breach formation parameters should be used, as discussed in the Corps' Guidelines (IWR, 1986b).

The cross-sectional profiles are a key set of input to the DAMBRK model. Downstream cross-section points should be selected judiciously to reflect not only important river valley and off-channel storage considerations, but also the locations of economic development and the population centers. This is especially important since estimates of inundation for the zones within each reach are calculated by interpolating the DAMBRK data. These inundation estimates are a key factor in the depth-damage functions that are used to estimate the stage-

damages and economic losses (Volume I, Das et al., 1986), as well as the size of the population at risk. Output from the DAMBRK model is used to identify the extent of the inundation area and to estimate the depth of the flood at downstream cross-sections along the river. The inundation boundary is used to delineate the areas that would be exposed to potentially life-threatening flooding.

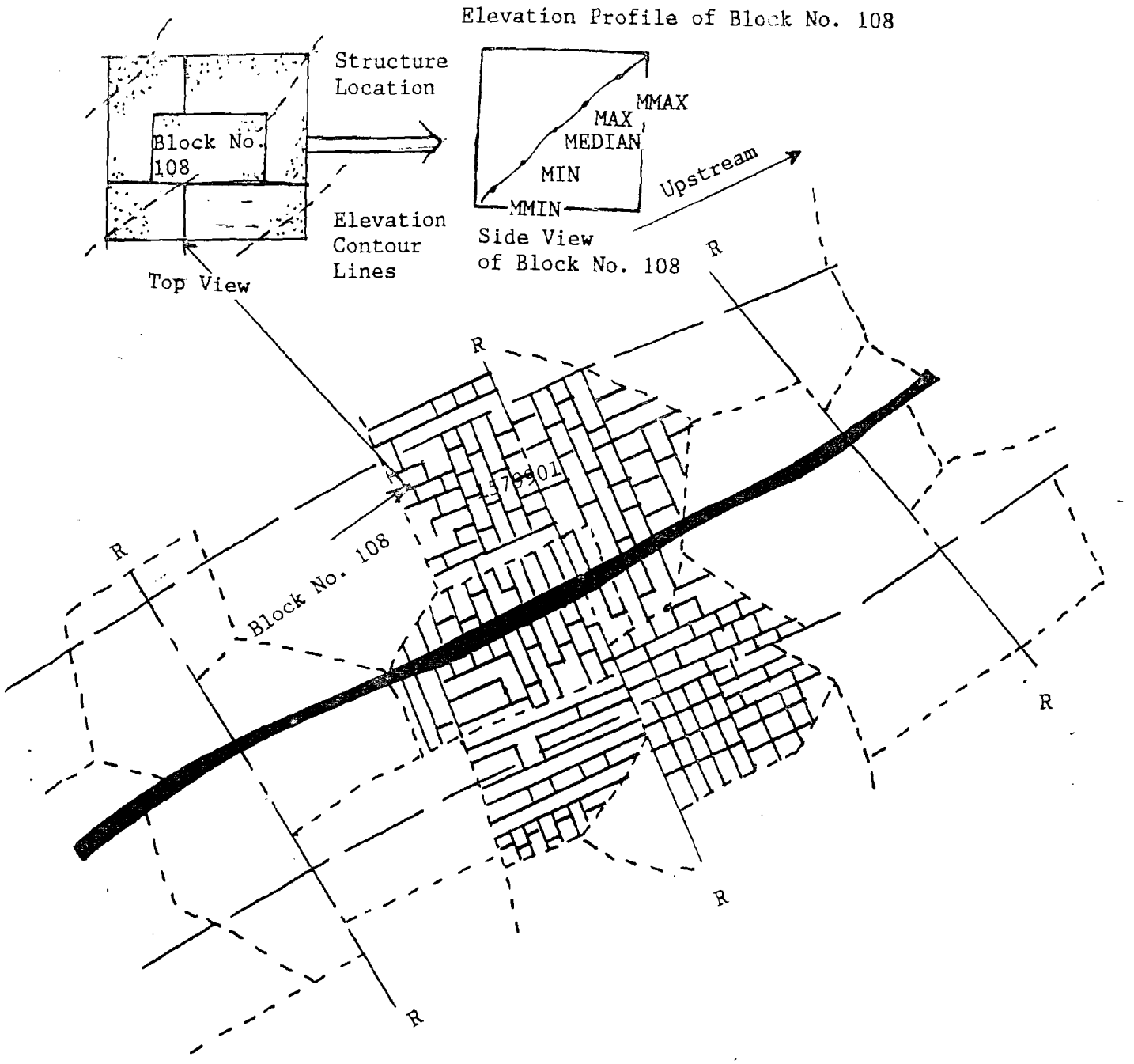
The scenario that results in the hypothetical maximum flow and greatest downstream inundation is termed the "Reference Flood." It results from the PMF with a breach of a dam designed to hold the PMF. Flood stages for other hypothetical events are expressed as an incremental difference below the Reference Flood stage along each downstream cross-section. These cross-sections are those defined for the DAMBRK input profiles. Estimates of the Reference Flood stages at each of the cross-sections are used to interpolate flood stages for each unit area throughout the reach. This is done by visual inspection of maps of the area. The unit areas are defined in terms of city blocks in urbanized areas, and Census tracts and enumeration districts in rural areas. Microcomputer software may be used to delineate the inundation area, and to estimate zonal flood depths and populations at risk on a Census Tract/Enumeration District/Block basis. This is accomplished by an automated comparison of flood stages and land elevations for each of the areal units throughout the overall area at risk. The terrain in each areal unit (which is as small as a city block) is represented by three elevation values. For the lowest ("MIN") of the three elevations, three-quarters of the structures (and presumably of the population at risk) within the unit area are at elevations greater than or equal to the

designated MIN elevation. The second elevation is a median ("MEDIAN") elevation, and the third is an upper quartile ("MAX") elevation. The MIN and MAX elevations are extrapolated to estimate two additional elevations, MMIN and MMAX, in each Census Tract/Enumeration District/Block. Consequently, the population in each areal unit is estimated to be at one of five zones, as illustrated in Figure 2.

4.2 Estimate the Population at Risk

The second step of the analysis is to estimate the population at risk. It is defined as the number of people who would be exposed to flooding if they took no action to evacuate. The population at risk is identified for each of the areal units in the inundation area. These areal units consist of city blocks, Census tracts, and enumeration districts; and the populations at risk in these areal units are added to compute the total population at risk in each of several pre-defined reaches. The reaches are defined arbitrarily and correspond to individual communities or large concentrations of population. The number of reaches may, for example, number around eight or nine. The specification of population on a reach by reach basis appears to offer a reasonable spatial compromise given the inherent uncertainty and inaccuracies in measuring the size of the population, flood travel times, flood depths, and evacuation notification times on a unit area basis.

The procedures that were developed to estimate unit area populations are documented elsewhere in Volume I (Evans et al., 1986). The procedures rely largely on Census data as provided in Summary Tape Files 1B and 3A of the Census of Population and Housing, 1980 (the most recent



River

River Reach (RR) Boundary

Inundation Zone for the Reference Flood

Political Boundaries (e.g., Census Tract)

Block Boundaries

Figure 2 . Schematic Representation of the Process of Elevation Determination

Census should be used). These data provide estimates of the number of people, by place of residence, for each Census area. In the cities, the smallest Census area is at the city block level. The level of geographic aggregation in the Census data increases to block groups, Census tracts, and enumeration districts as one shifts to more rural areas. The location and elevations of each Census area are identified by inspection of Census and U.S. Geological Survey maps, which have Census area boundaries and elevation contour lines, respectively. Since the Census data are by place of residence, the population estimates compiled directly from the Census data are interpreted as estimates of the population at night, when most people are at home.

These estimates do not provide as accurate a picture of the population at risk during daytime or working hours, however, and a method was developed to estimate population during work hours by using several other secondary sources of data (Volume I, Evans et al., 1986). The most important of these was County Business Patterns, which was used to estimate levels of employment in each area. The equation used to calculate the daytime population is:

$$P_j = Q_j - T_j + E_j \tag{17}$$

where

P_j = the population in area j during the working hours,

Q_j = the Census population, by place of residence,

T_j = an estimate of workers, students, and others who would likely not be at home during working hours (estimated from Census data),

E_j = level of employment and associated activity in area j, estimated from County Business Patterns.

The estimate of T_j is the sum of the number who are employed (and who live in j), the number who reside in j who are of school age, and some proportion of the rest of the people in j who are assumed to be away from the residence at the time of the flood (e.g., shopping). The value of E_j can be defined to include not only employment, but other activity such as the number of shoppers, expressed as a proportion of retail employment. In general, employment data are unavailable at the city block level, so that estimates of daytime population at risk are at the more aggregate Census Tract/Enumeration District level, and are thus less precise than the estimates of the night-time PAR.

For the evening, which spans the time between work hours and the late night hours, some of the population are not at home and may be at retail centers or recreation facilities, as well as at some work areas. For these evening hours, however, published population estimates are usually unavailable. In general, estimates of population for these hours would be subjective and based on the Census information; on knowledge of special events; and on the locations of buildings, retail areas, arenas, and motel/hotels that would attract population during the evening hours.

In certain parts of the country, the number of people in an inundation area will vary significantly depending on the time of day, week, and season. Thus estimates of the transient population such as tourists, travelers, and other visitors must be taken into account. This includes people residing in the area who may not be in town and who would not be at risk, as well as visitors from outside the area who would be

exposed to the flood. The transient population should be a net figure that includes both groups. Data on visitors to an area may, in some cases, be obtained from the local Chamber of Commerce, Visitors' Bureau, Tourism Office, registries of visitors at recreation and tourist sites, and other similar sources.

Further discussion on estimating the population and threatened population are given in the Corps' Guidelines (IWR, 1986b): Steps 7 ("Determine Population at Risk from the Threshold Flood and Lesser Events") and Step 10 ("Estimate the Baseline Probable PAR, Probable TP, and Probable LOL from the Threshold Flood and Specified Lesser Floods").

4.3 Estimate the Warning Time

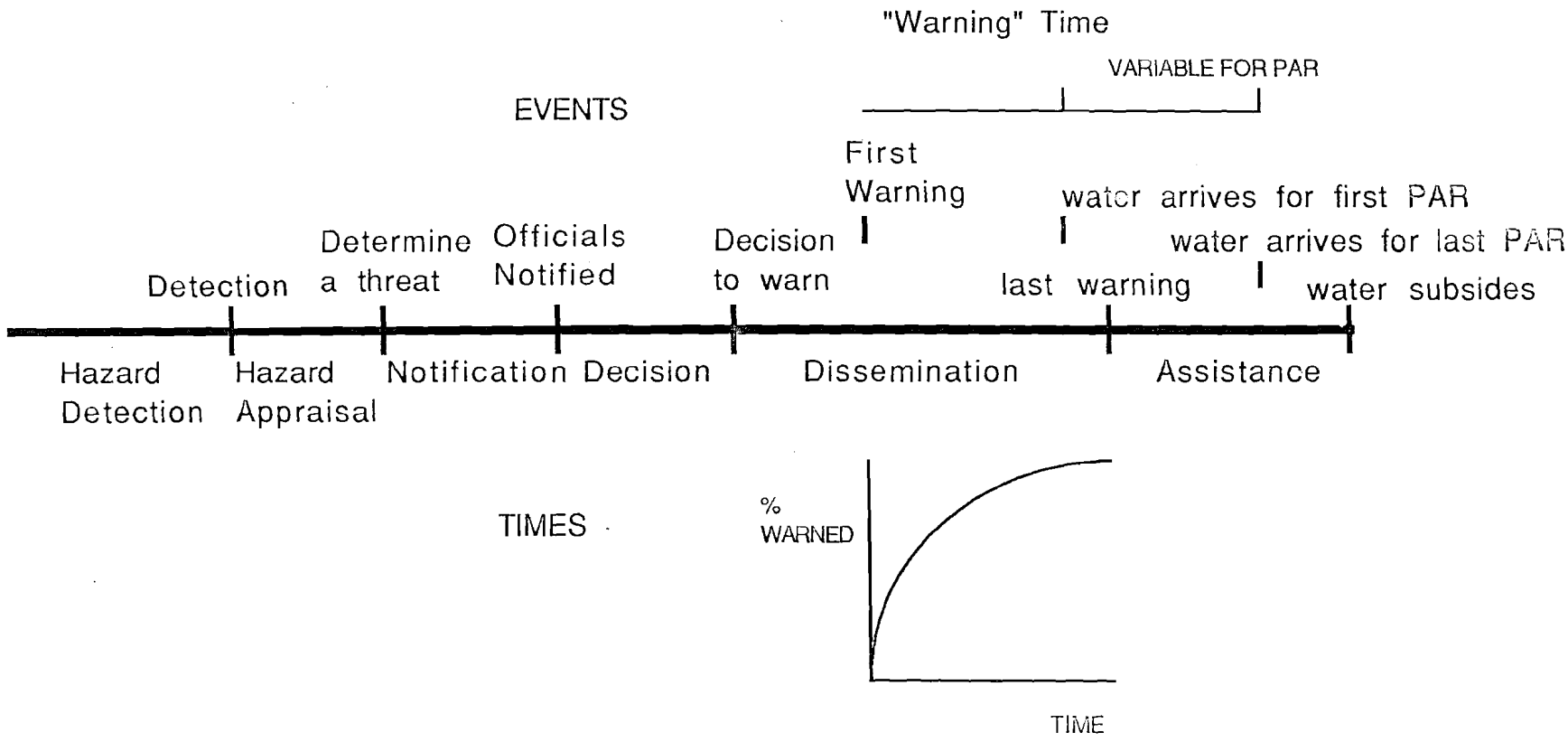
After population at risk is estimated for each reach, it is necessary to estimate the warning time for each reach. This is defined as the interval between the first official notification of the evacuation warning and the time of flooding at that reach. For any given flood event and dam modification alternative, there is a different warning time for each location within any reach.

To estimate the warning time, one should consider two separate time lines. One of the time lines encompasses the warning and evacuation process. The second time line is associated with the physical events of the flood in terms of the rise in flood elevation as a function of time and location downstream (and upstream) from the dam.

Major segments of the warning and evacuation system have been discussed in detail elsewhere in Volume I (Sorensen and Neal, 1986; Southworth, et al., 1986). Sorensen and Neal (1986) identified a

sequence of evacuation warning activities. These are illustrated in Figure 3. The labels on top of the time line refer to specific points in time at which events occur (e.g., detection of the hazard). The labels on the bottom of the time line refer to time intervals in which various warning-related activities occur. The first time interval is the hazard detection time. Because of the severe flood events being considered, this would be an ongoing process with continual monitoring at the dam. The first significant event in the time line in Figure 3 is the detection of a possible hazard. After this determination, there is a period during which the potential magnitude of the hazard is appraised. This corresponds to the next time interval along the time line. At a certain point, it is decided that there is a significant threat. At this point, the Corps staff begins the notification process. The time interval for notification of the threat among public agencies includes the time for the required officials within the Corps to be notified, as well as for inter-organizational communications to notify officials in other public agencies such the local sheriff's office, the governor's office, and others. Once the officials are notified, some period of time is required to make the decision on whether to issue the evacuation warning. This is the next time interval on the time line in Figure 3. Once a decision is made to issue the warning, it is then issued to the media and to the public at large. The time at which the first official notification is issued to the public to evacuate the inundation area is the next significant event. This event is identified in the Figure 3 time line, and it is the beginning of the "warning time". The dissemination of the evacuation warning to the public continues over a period of time, as

Figure 3. Events and time intervals associated with evacuation warning process

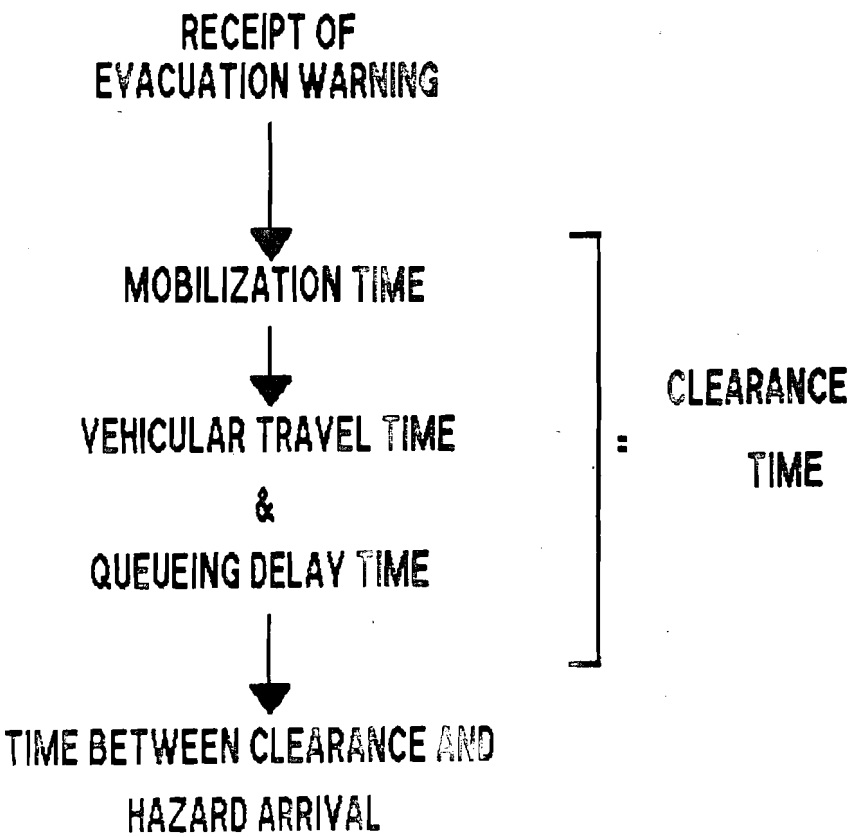


indicated on the bottom of the time line in Figure 3. At some point in time, the flood wave arrives at a particular location rising to a specific flood zone or elevation. The interval between the beginning of the warning time (i.e., the time at which the first notification was issued to the public) and the arrival of the flood at that location in the specific elevation zone marks the length of the warning time for the population at risk in that zone. Any population at risk remaining in the zone at the time the flood arrives constitutes part of the threatened population. The flood may arrive and impact some of the population at risk while the evacuation warning is still being disseminated to portions of the public. This is illustrated in the time line in Figure 3 in which the time interval for dissemination spans some of the flood impact times. At some point, the evacuation warning is disseminated to as much of the population at risk as possible, and this time of "last warning" is identified in the time line. As the flood progresses, the size of the threatened population increases as more of the area at risk becomes inundated. Finally, the flood reaches peak stage, which is the maximum, last zone of impact.

It is important to emphasize that the time at which the first notification is made to the public to evacuate the area is the beginning of the warning time (i.e., warning time = 0 at this point). The warning time does not take into account the time for dissemination of the warning to all members of the public or to any single individual.

Once the warning is disseminated, the evacuation response of the population at risk affects the size of the threatened population. Figure 4 illustrates the major time components of the transportation evacuation

Figure 4. Time intervals associated with evacuation of vehicular traffic from inundation area



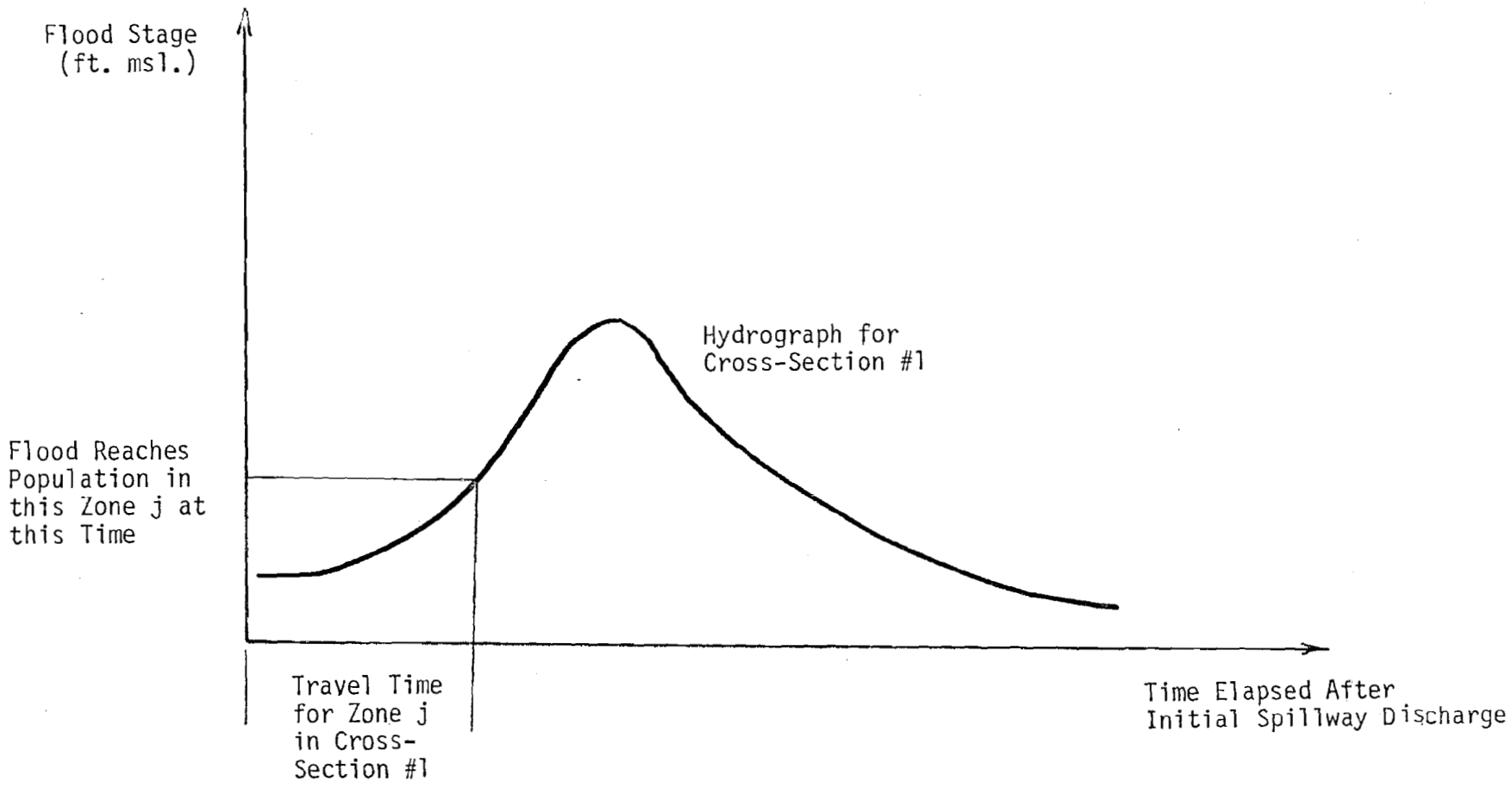
process. Once the evacuation warning is received by the population at risk, it takes some "mobilization time" for the population to assess the situation, decide on a plan of action, load the vehicles with important household possessions, and begin to evacuate. Once a vehicle is on the street or highway, it will take some "vehicular travel time" for the vehicle to travel from the place of origin to a shelter or to some other point outside the inundation area. Part of the total time required to evacuate the area may include "queuing delay time" due to traffic congestion and bottlenecks. The total of mobilization time, vehicular travel time, and queuing delay time is termed the "clearance time" or the evacuation time. The "network clearance time" is the total time for mobilization, vehicular travel, and any queuing delays for all vehicles evacuating the inundation area to shelters or other locations outside the inundation area. Depending on the time at which the evacuation warning is received by the public at risk, the network clearance time, and the travel time of the flood wave, some of the population at risk will evacuate the inundation area while others may be reached by the flood. Individuals in vehicles reached by the flood become part of the threatened population. Further discussion of a evacuation traffic simulation model that may be used to estimate the clearance time is provided elsewhere in Volume I (Southworth et al., 1986).

The discussion up to this point has concentrated on the one time line which involves the threat assessment, decision making, and evacuation response on the part of individuals. As evacuation warning activities are progressing, a series of flood events is unfolding. Whereas the first time line is associated solely with decision making and

communication activities, response to evacuation warning, and evacuation actions, the second time line is associated with the physical events of the flood. The key concept in this second time line is the flood "travel time". According to the Corps Guidelines (IWR, 1986b), for non-failure floods, the travel times should be measured from the time of initial spillway discharge until the time at which the flood water reaches the specified stage at which the population at risk is located in each downstream reach. For the threshold flood, i.e., the flood capable of overtopping a dam, the travel time should be measured from the time the dam overtops until the flood water reaches the specified stage in the reach downstream. Thus, the flood travel time for the failure cases includes the time that it takes for the breach to form. Under either scenario, failure or non-failure, the end of the travel time also marks the end of the warning time for the population at risk that is located at a specified elevation and reach. Thus, the starting point for the warning time to a population at risk is determined by the sequence of activities relating to the decision to notify the public to evacuate, and the end point for the warning time is established by the arrival of the flood.

The concept of travel time is illustrated in Figure 5. This is a hypothetical hydrograph for a particular cross-section downstream from the dam, similar to the hydrograph that is printed in the DAMBRK output. The horizontal axis in Figure 5 is "Time", which is usually given along the vertical axis in the DAMBRK output in multiple-hour increments. The vertical axis is the elevation of the flood water at each given point in time, for that particular cross-section. In the DAMBRK output, the flood

Figure 5. Hydrograph for a river cross-section



elevation is given as a stage (in feet) above the river bed gauge elevation, itself a user input. Each flood elevation corresponds to a discharge at the cross-section, which is measured in cubic feet per second (cfs). For rather severe flood events, the water level from the antecedent event would commonly be above flood stage, before the full event begins inundating some of the zones at risk. In the DAMBRK hydrograph, this is reflected in spillway discharge at the beginning of the hydrograph. The flood level recedes somewhat before the ensuing full event. The "Reservoir Depletion Table" in the DAMBRK output indicates the time at which there is renewed flooding from spillway discharge due to the second, larger flood event. This point in time marks the beginning of the non-failure flood travel time for all populations at risk.

Downstream from the dam, there is a time lag before this renewed spillway discharge reaches the cross-section. When spillway discharges initially flow from the dam, water is still receding downstream. After a period of time, the discharge at the cross-section begins to increase, first slowly, then very rapidly, as illustrated in Figure 5. As discharge increases, so does the stage of the flood. After reaching peak flow, the discharge diminishes and the stage begins to recede.

As the stage of the flood increases, it progresses up in elevation, zone by zone, and begins to inundate areas at which the population at risk are located. Any populations at risk remaining at the time their zone is inundated become part of the threatened population. The time at which the flood arrives at a particular zone and cross-section, minus the time of initial spillway discharge from the full event, is the travel

Figure 6. Hydrograph for a river cross-section that is downstream from Cross-Section #1

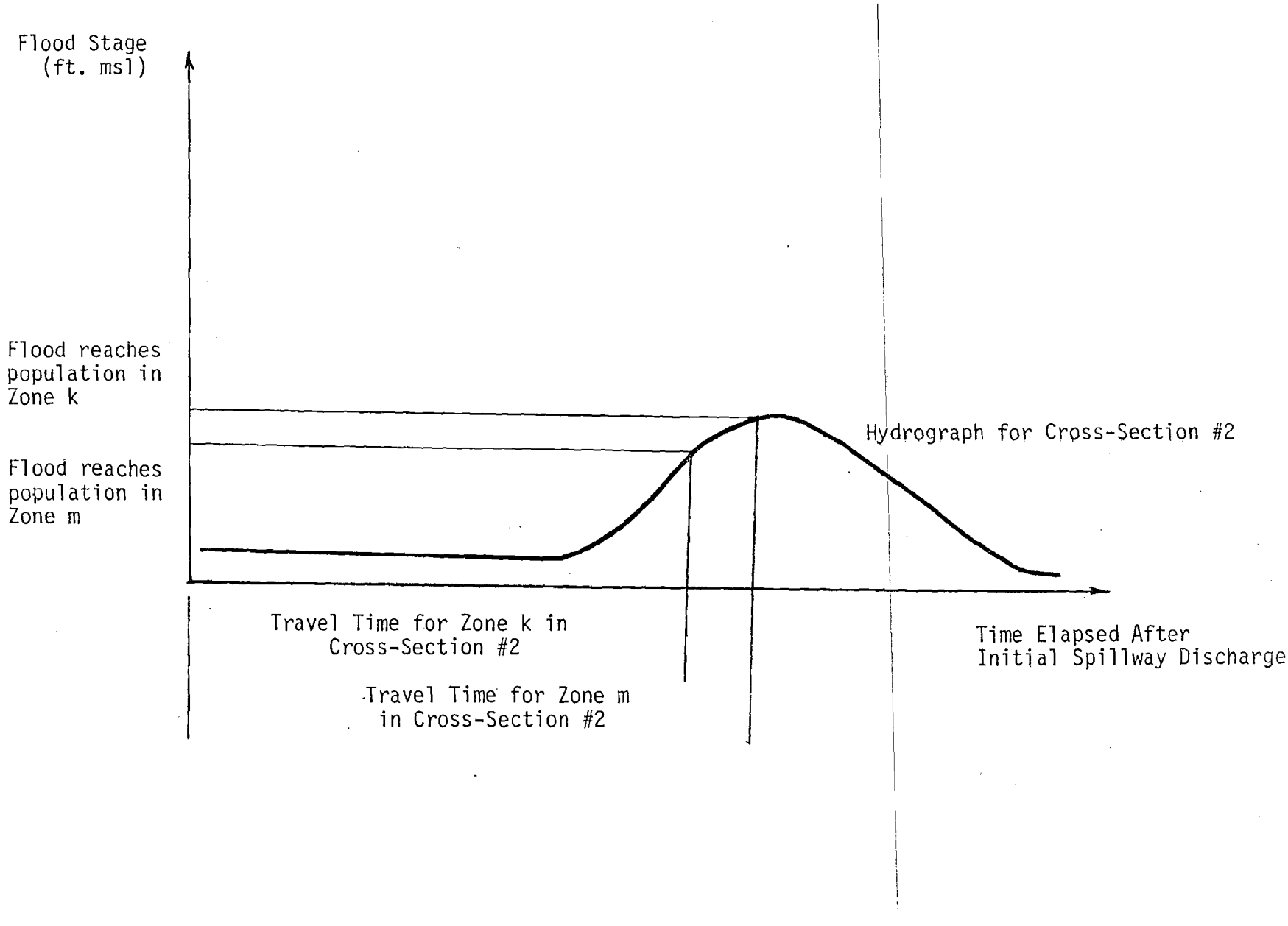
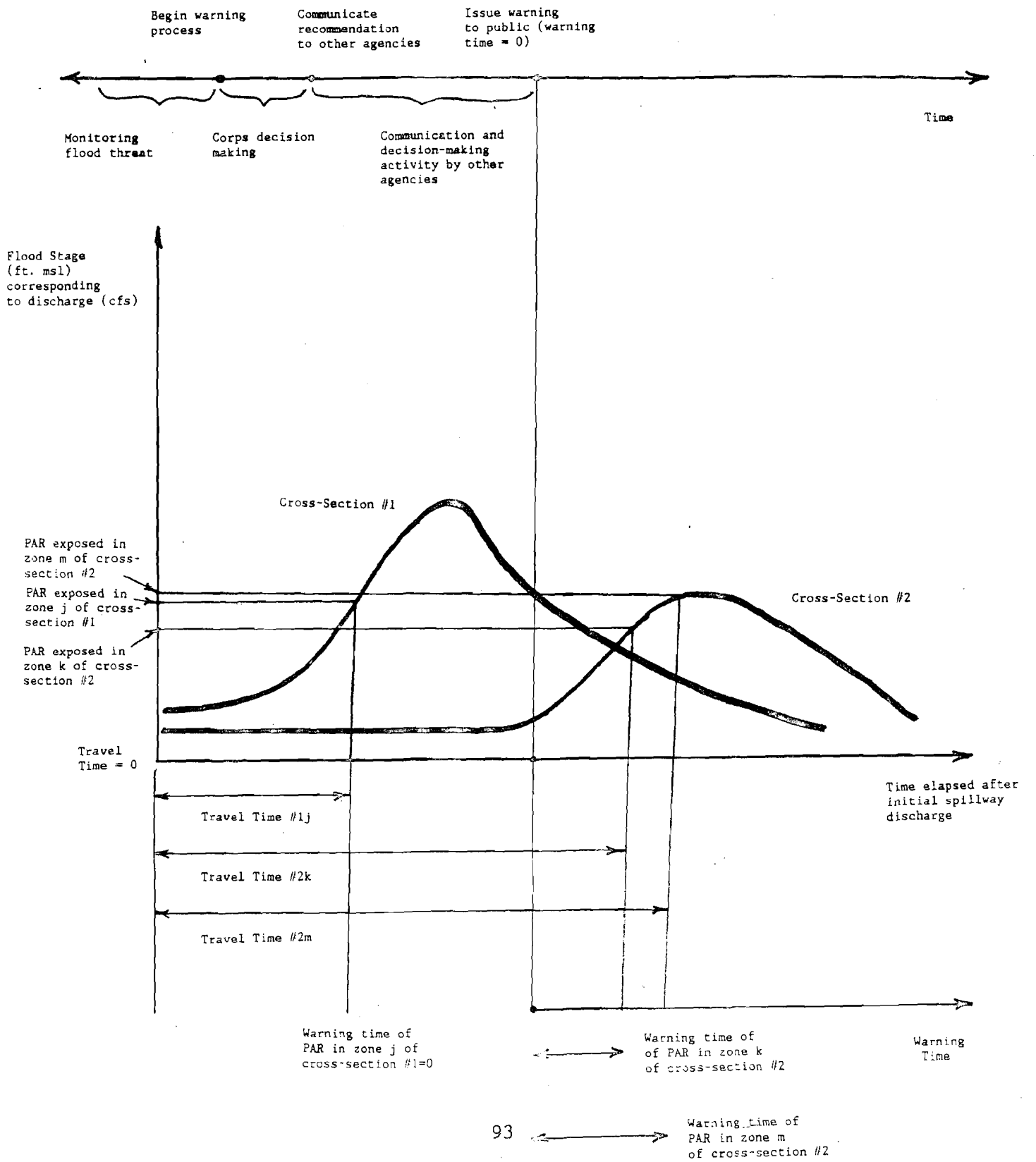


Figure 7. Estimation of Warning Time



time frames. The second time line combines Figures 5 and 6, and shows two representative hydrographs on the same time scale as the first time line, so that time=0 is the beginning of the full inflow event in both cases. The third time line is a combination of the first two and it illustrates how the warning time for the population at risk in a particular zone and cross-section is the time between the first official evacuation notification to the public and the time of arrival of the flood at that zone. When flooding reaches the indicated stage, then the population at risk in a given zone and cross-section is potentially exposed to the flood. Thus, travel time will differ not only between cross-sections within the reach, but also between different elevations at each cross-section. At a given cross-section, travel time to a low-lying area is shorter and warning time for the population at risk is less than for those at higher elevations.

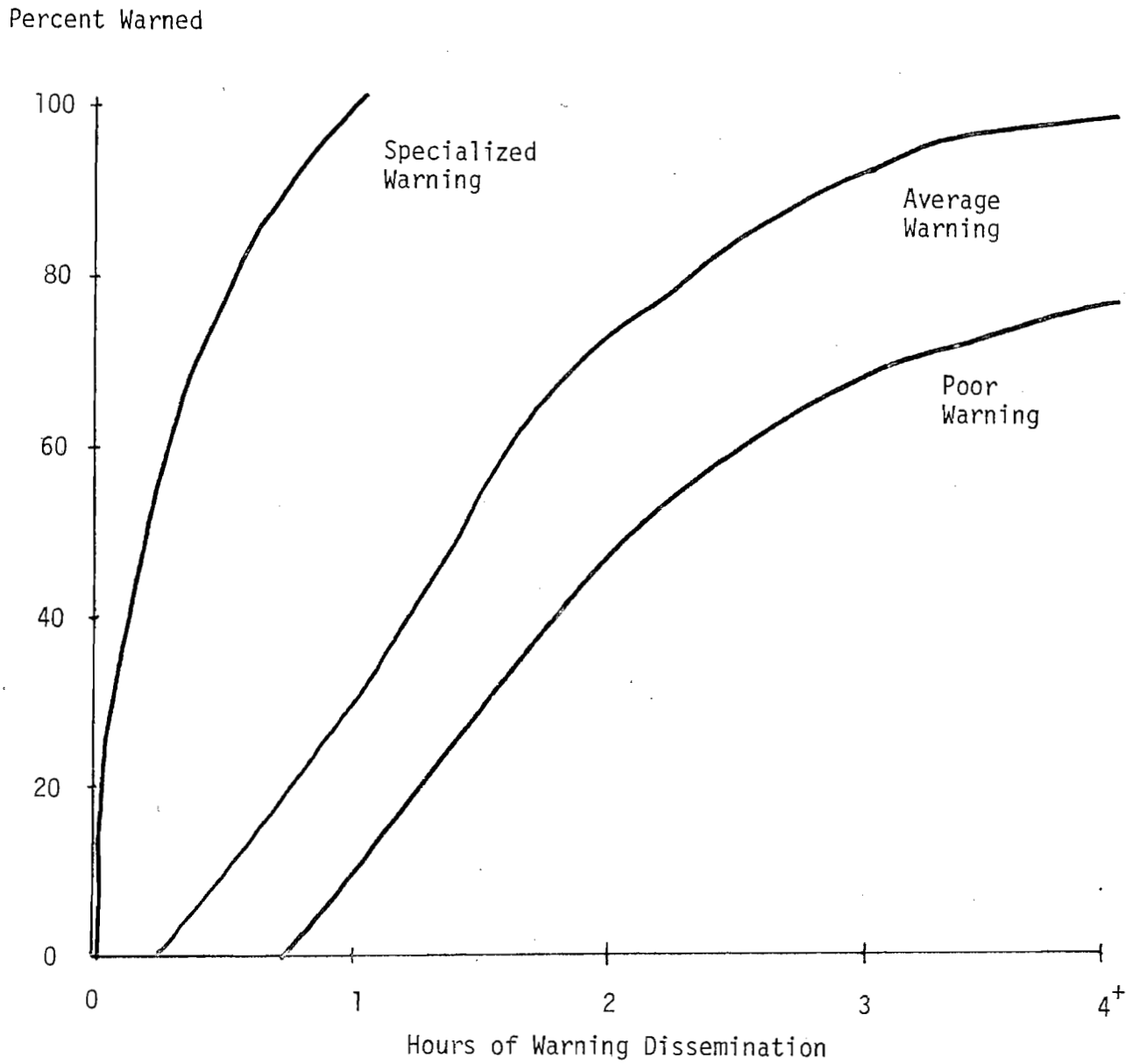
Figure 7 also illustrates the crucial comparison between the time intervals required for the various threat-identification, communication, and decision-making activities against the time of the initial spillway discharge and the movement of the flood and its travel time downstream. For reaches that are immediately downstream from the dam, travel times may be so short that many of the zones are inundated soon after any official evacuation warning, before the population at risk has the opportunity to evacuate. On the other hand, for reaches which are well downstream, for example greater than 50 miles from the dam, the travel time should be sufficiently long that the population at risk in those locations should have ample time to evacuate. For the reaches between

these two extremes, however, the time for evacuation relative to the spread and rise of the flood water becomes more crucial.

It is expected that most evacuation from the area at risk will be in automobiles and light trucks. The traffic evacuation simulation model can provide a useful tool for estimating the size of the threatened population, as well as for evacuation traffic planning and control (Volume I, Southworth et al., 1986). The model encompasses the concepts illustrated in Figure 4. After they receive the evacuation warning (or possibly as it is still being disseminated), households who are potentially at risk will make appraisals of the situation, load their vehicles, and begin to evacuate. This is the "mobilization time" in Figure 4. In the MASSVAC2 simulation model used in Volume I (Southworth et al., 1986), mobilization time was represented as a logistic function. This function conforms with the limited quantitative empirical observations available on evacuation in past natural disasters. Typical mobilization curves are illustrated in Figure 8 adapted from elsewhere in Volume I (Sorensen, 1986).

The simulation model loads vehicles onto the road network, which is represented in a data file obtained from digitizing road maps of the inundation area. Next, it simulates the movement of the vehicles from their points of origin to destinations outside of the inundation area. Various kinds of vehicular travel behavior can be assumed in the model: the vehicles may be assumed to go to the nearest shelter, they may go to various shelters according to a probability distribution which is a distance-decay function of distance of the destination from the origin, or they may go to a pre-specified destination. There is also some

Figure 8. Generalized relationships between warning time and percent at risk warned



flexibility in the selection of routes taken by the vehicles. Optimizing (i.e., time-minimizing) as well as non-optimizing vehicular route selections and travel behavior may be used.

After these behavioral assumptions are inputted into the traffic simulation model, it is necessary to select other parameters so as to optimize (i.e., minimize) the total clearance time of the vehicles from the network. It is important to realize that this optimal selection of parameters does not necessarily imply optimal behavior on the part of motorists or evacuation planners, since those assumptions are imbedded in the value of the other behavioral and network parameters which are also input into the model. Output from the MASSVAC traffic simulation model provides data for plotting the percentage of the population at risk which is evacuated from a given reach as a function of time. Some typical curves (taken from elsewhere in Volume I, Southworth et al., 1986) are shown in Figure 9.

The hydrograph output from the DAMBRK flood routing model can be used with the population data base compiled in Volume I (Evans et al., 1986), which is described in Section 4.2, to estimate the percentage of the population at risk which would be inundated if they took no evacuation measures, as a function of time. This function is illustrated in Figure 10. It can be compared with the mobilization time in Figure 8 and the network clearance time (which encompasses the mobilization time) which is given in Figure 9. Figure 11 combines Figures 9 and 10. The graphs in Figures 11 provide an indication of the severity of the flood event. A situation in which the flood travel time curve quickly overtakes the network clearance or evacuation curve suggests a situation

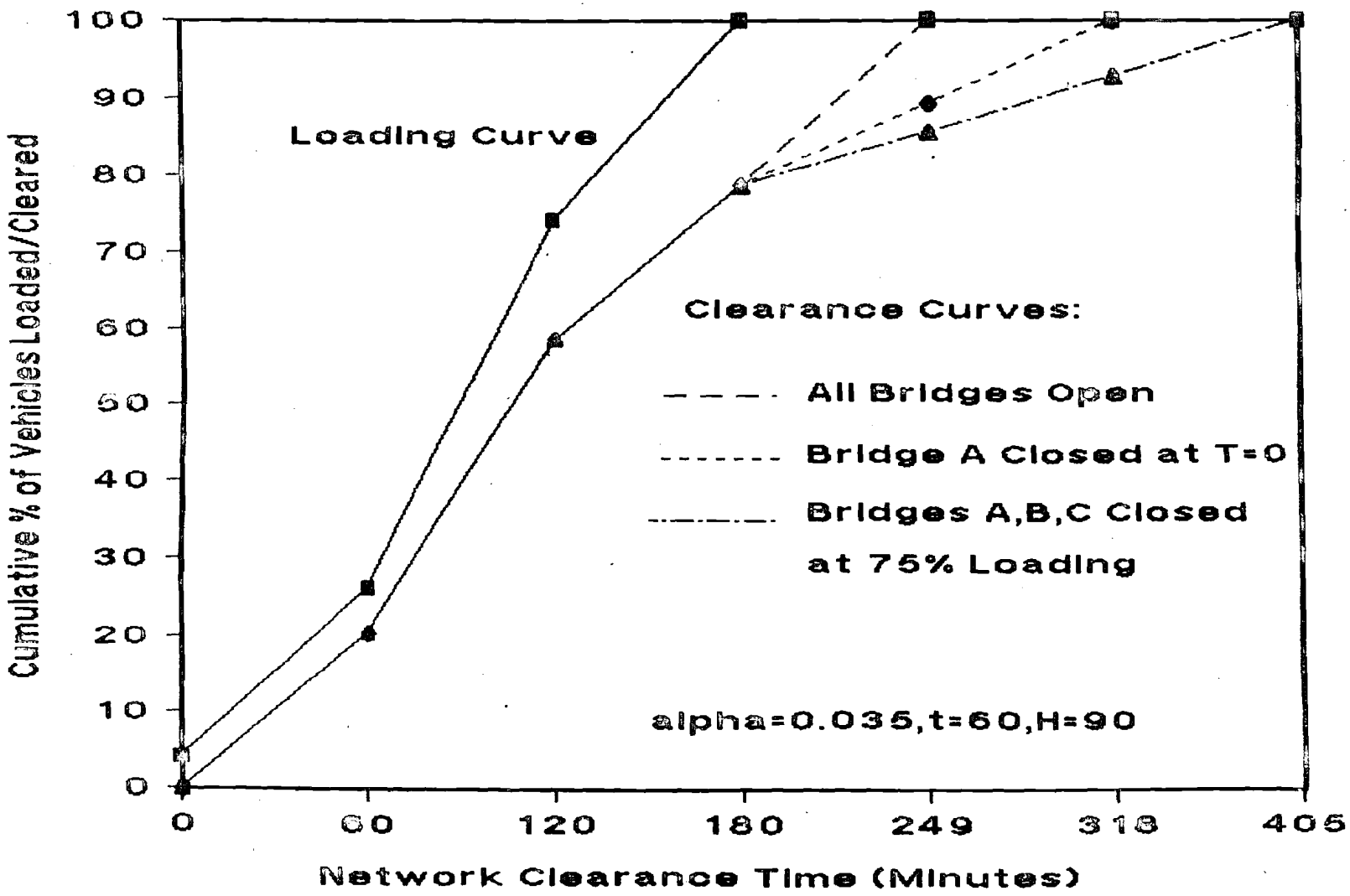


Figure 9. Clearance Curves Setting 100% Green Time For Major East-West Arterials.

Figure 10. Inundated population at risk if no action taken to evacuate, as a function of flood travel time

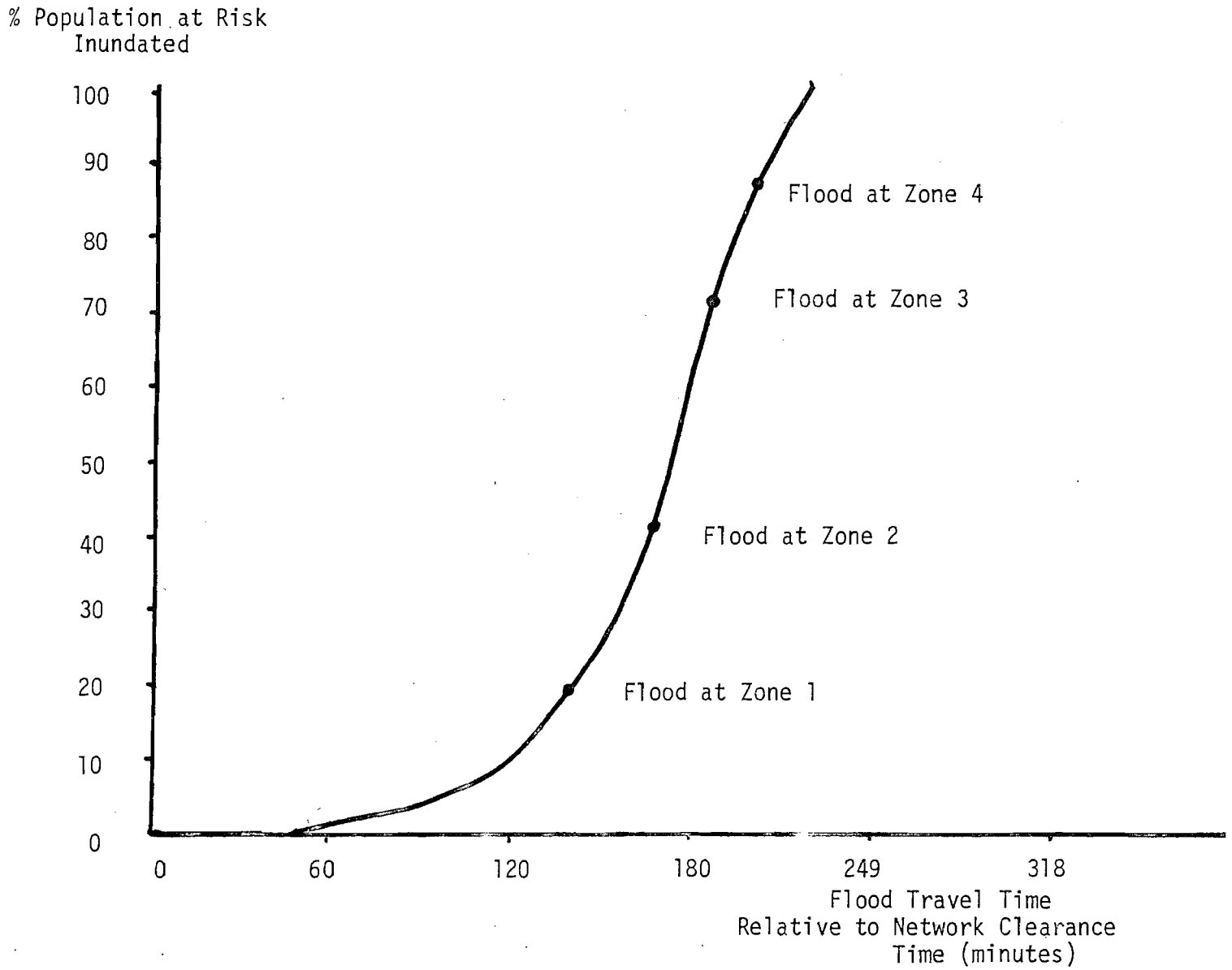
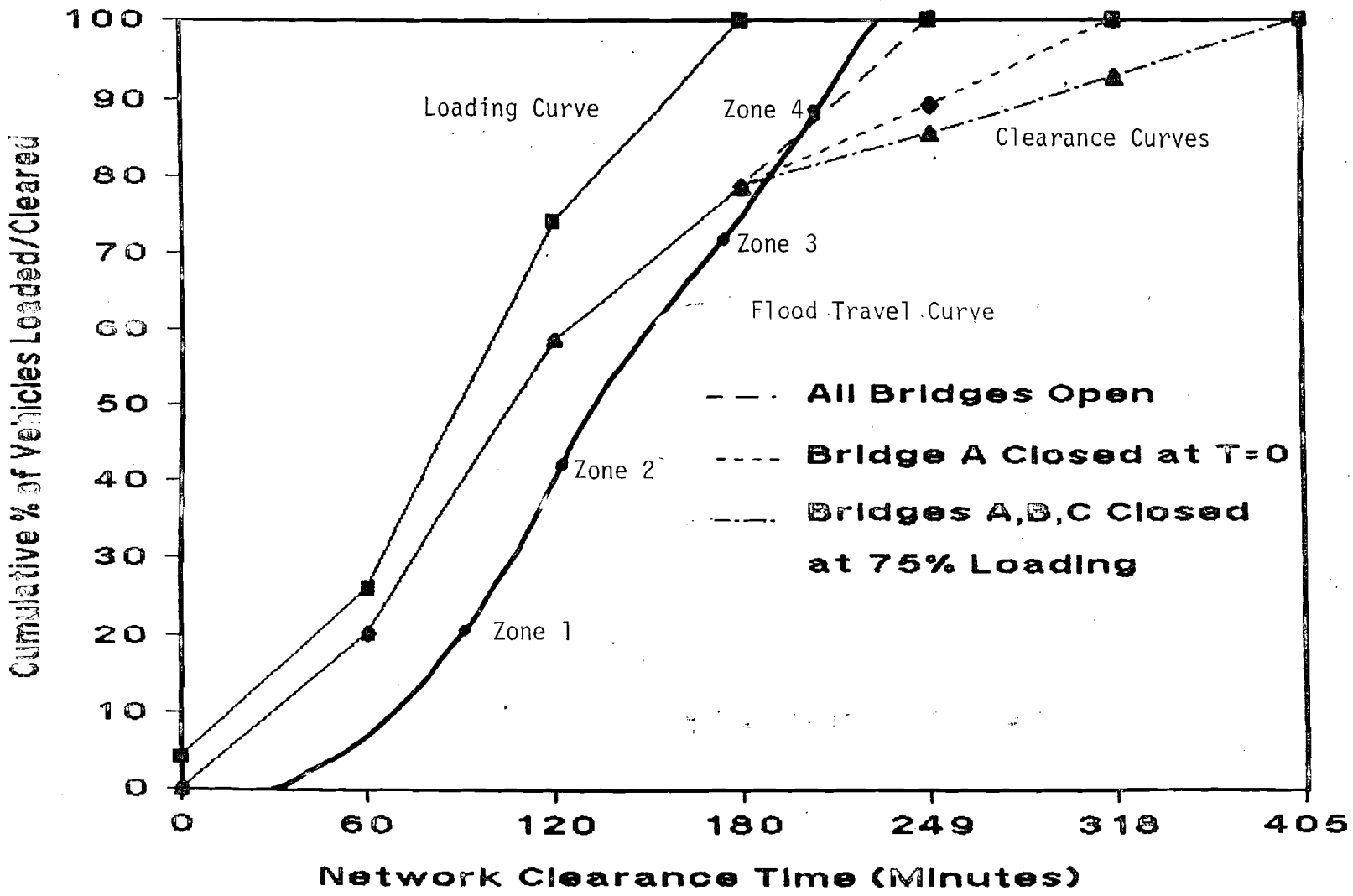


Figure 11. Comparison of Flood Travel and Network Clearance Time Curves



in which the size of the threatened population relative to the population at risk will be greater.

It is important to realize that Figure 11 should be interpreted only in a qualitative sense. The curves do not provide any quantitative estimate of the threatened population. The "% PAR" values for the flood travel time and for the evacuation time are not directly comparable. In the flood travel time curve, % PAR is measured by place of residence or origin. In the evacuation time curve, % PAR is measured as the proportion evacuated from the area. For example, if the evacuation time curve intersects the flood travel time curve at Zone 4, as illustrated in Figure 11, it does not necessarily imply that all of the population in Zone 4 becomes inundated. The reason is that populations at risk in this zone may well have begun to evacuate soon after the evacuation warning was issued. Zone 4 may be very close to a shelter outside of the inundation area and it may not take very long to travel the distance from Zone 4 to a point outside the inundation area. Conversely, the intersection of the evacuation and travel time curves in Figure 11 does not necessarily imply that all of the population at risk in Zones 1, 2, and 3 are able to evacuate the inundation area before being overtaken by the flood. Some of the population at risk in Zone 1 may delay their departure from their residences or they may encounter traffic problems. Consequently, they may still be at a relatively low-elevation location when the flood arrives. In general, the evacuation time curve depicts the total percentage of the population at risk that has evacuated the inundation area as a function of time, regardless of their origin and

regardless where vehicles may be located on the road system relative to the elevation of the flood.

5.0 METHODS FOR ESTIMATING LOSS OF LIFE

5.1 Introduction

This section provides step by step descriptions of three methods for estimating loss of life in hypothetical, extreme flood events.

Section 5.2 describes the aggregate-empirical model. This approach is the most aggregate of the three models in that each reach is treated as a single entity. The population at risk, a representative estimate of the travel time, and a representative warning time are estimated for each reach as a whole. The empirical loss of life function, derived in Section 4.0, is used on a separate reach by reach basis.

Section 5.3 describes the empirical-flood-travel method. As before, the empirical function is used on a reach by reach basis. However, unlike the aggregate-empirical model, distinctions are made among the populations at risk that are located at different places and at different elevations within each reach. Because of these distinctions, the populations at risk will have different warning times based on the different travel times to reach the different individuals.

Section 5.4 describes the flood-travel-evacuation method. This is the most disaggregate of the three methods. The empirical function is not used in this method. Rather, estimates are computed for the threatened population in each reach by comparing the flood travel times with the times for evacuation of the population at risk. The MASSVAC2 traffic simulation model is used to predict the evacuation of vehicles in

the street and highway network. Consequently, this is a dynamic process in which the elevation of the flood is compared to the elevations of the evacuating vehicles, in discrete time increments until the peak flood stage is reached.

5.2 Aggregate-Empirical Model

The aggregate-empirical method uses aggregate reach-by-reach data on the population at risk, warning time, and depth of flooding in the empirical function derived in Section 3.6. The method is the easiest of the three to use. However, because of its aggregate spatial nature and its use of a composite surrogate measure for the flood travel time, the method is also the least precise and probably the least accurate of the methods. On the other hand, its simplicity allows quick comparisons of loss of life for different flood event scenarios and dam remedial alternatives.

The steps in this method are as follows:

(1) Follow the procedure discussed in Section 4.1 to establish the flood event scenarios. A range of hypothetical flood events should be selected. They should include severe events as well as lesser events below the threshold flood. Also, both failure and non-failure scenarios should be considered for both the existing dam as well as for an alternative dam remedial measure(s).

The DAMBRK model should be used to route the flood. The DAMBRK model provides the output that is used in subsequent steps to

identify the population at risk and to estimate the travel times, by reach.

Flood depths are estimated on a Census Tract/Enumeration District/Block basis. For urbanized areas, block-level # data are available from the Census for population. For less urbanized areas, Census data are compiled by Census Tract or by Enumeration District. DAMBRK estimates of Reference Flood stages at each river cross-section are interpolated to estimate Reference Flood stages for each Census Tract/Enumeration District/Block.

Estimates of flood stages for the other events are based on the detailed Reference Flood estimates at the Census Tract/Enumeration District/Block level. The Reference Flood levels are adjusted by subtracting an incremental difference so that, for example, the .80 PMF flood level for a given block may be four feet less than its Reference Flood level. A different incremental difference should be calculated for each reach, for each flood event.

The incremental difference is computed by comparing a representative, weighted average flood stage for the Reference Flood with that for another flood (e.g., .80 PMF). For each reach, the representative flood elevation is calculated by means of a weighted average of the flood elevations at the

appropriate, representative cross-sections for each reach. The weights assigned to the different cross-sections lying in (or spanning) that reach are proportional to the size of the population in the reach that was located around that cross-section. The relative locations of the river cross-sections, populated areas, and river reaches can be identified in a flood scenario map of the area.

(2) Compile the estimates of the population at risk (PAR), by reach, as outlined in Section 4.2. The PAR is estimated for each areal unit (i.e., city blocks, Enumeration Districts, and Census Tracts) within the inundation area. Each areal unit has a unique numerical identifier, which is given on Census-boundary maps and which is also specified in the Census data used to compile the population estimates. The PAR data are merged with data on the corresponding land elevations for each of these areal units. The land elevations are estimated through a manual process by visual inspection of topographic maps and interpolation of the contour lines on those maps. Five representative elevations, which span the geographical distribution of the population within an areal unit, are derived for each Census Tract/Enumeration District/Block.

Software is used for an automated comparison of the land elevations (and their corresponding populations at risk) with the flood elevations (which were estimated from the DAMBRK

output in Step (1)). Any land elevations which are less than the flood elevation estimated for that portion of the Census Tract/Enumeration District/Block are assumed to be inundated, and the population located at that land elevation within the Census Tract/Enumeration District/Block is assumed to be population at risk. This automated comparison is done for each of the five elevation zones within an areal unit, and the estimates of PAR are aggregated by reach, for each of the flood events.

(3) Estimate warning times. The warning time is defined as the time between the initial official notification to the public to evacuate and the time of arrival of the flood. The warning time consists of two major components: decision making associated with the warning process and public evacuation response, and flood travel time. If quantitative estimates are available for the times taken in the various warning and evacuation activities, then these may be used to establish the time at which the first official notification to the public would be issued. This point in time is the beginning of the warning time for all of the population at risk. The various time intervals that should be taken into account are:

- hazard detection -- the time interval required to detect a possible threatening hazard
- hazard appraisal -- the interval required for the Corps to fully appraise the situation

- notification -- the interval for the Corps to notify the appropriate, responsible agencies, and for those agencies in turn to notify other agencies as required in the official evacuation plans
- decision making -- the interval required to make a decision on an appropriate announcement to the public
- dissemination of the warning -- the time interval required to disseminate the public evacuation warning so that it is received by a member of the public.

In practice, it is extremely difficult to estimate the length of each time interval. Thus, the warning time may be assumed arbitrarily to start at some specified time relative to the beginning of discharge (i.e., relative to the beginning of the flood travel time). Sensitivity analyses should be considered here so as to calculate estimates of loss of life for a range of warning time scenarios. For example, it can be assumed that the evacuation warning is first issued sixty minutes before the beginning of discharge, sixty minutes after, or exactly at the same time of the initial discharge.

Flood travel time is estimated for a representative location, on a reach-by-reach basis. A surrogate is used for the flood travel time. This surrogate is defined as the difference between the peak stage at the dam and the time of peak stage at a representative location in the reach. The times of peak

stages are given in the DAMBRK output for individual cross-sections, as well as interpolated between cross-sections. A representative location within each reach should be selected based on the population distribution within the reach. The representative point is essentially the centroid of the population distribution.

It should be realized that this surrogate measure is not the travel time, as defined in the Corps' Guidelines (1986b). In the strictest sense, as specified in those Guidelines, travel time is different for each individual depending on his or her location and elevation in the inundation level. Since the analysis in this approach is at a reach-by-reach scale, individual travel times are combined into a single, representative measure. In addition, the further simplification is made that the flood travel times associated with the antecedent event, the non-failure flow, and the failure discharge are all combined in a single composite surrogate for the flood travel times. The use of this single surrogate measure has obvious limitations in terms of its aggregate scale. In addition, it should be noted that because of the great computational burden, flood travel times for individuals are not estimated and averaged for the reach as a whole. (This more detailed method is suggested in Section 5.3.) In contrast, the times between peak flood stages at the

dam and at downstream cross-sections can be read directly from the DAMBRK output.

Even with the simplification of calculating one travel time for the reach, the DAMBRK output may result in "inconsistent" estimates of travel times. Thus, some subjective adjustments are required (especially for reaches directly below the dam) so as to develop a set of travel time estimates that are "consistent" in the following ways: (a) travel time to a reach should be less than that for a reach downstream from it, (b) travel time for a given flood event should be less than that for a lesser event, assuming the same dam modification alternative, (c) the travel time for a dam failure event is less than that for a non-failure, (d) travel time for upstream reaches are not available from the DAMBRK output and must be estimated subjectively.

These are general guidelines to insure "consistency" in the estimated travel times. In reality, these rules are not always met. But they are qualitatively reasonable and offer a simple means of approximating travel time.

(4) Use empirical loss of life function. The data compiled in the three previous steps are used in an empirical loss of life function, such as that given in Equations (14) and (15), or Equations (14) and (16). The data are compiled on a reach-by-

reach basis, and are substituted into the empirical loss of life function to estimate loss of life within each reach. The variable W for warning time is calculated as discussed in the previous step. The population at risk is compiled on a reach-by-reach basis and is described in Step (2). The depth of flooding is estimated for the reach as described in Step (1). The previous experience factor is assigned a value of one or zero depending on whether the area had experienced severe flooding within the last ten years. The probability that an individual within a given reach will die is represented by a logistic function, as given in Equation (14). The estimated total loss of life in reach i is given by Equation 17: $L_i = P_i \exp(\underline{\beta}'\underline{x}_i) / (1 + \exp(\underline{\beta}'\underline{x}_i))$ (17)

5.3 Empirical-Flood-Travel Method

This method is more disaggregate than the aggregate-empirical method. Travel times and populations at risk are defined within each zone of a reach, rather than compiled for the reach as a whole. Thus, the major advantage of this method is its more accurate representation of the flood as it spreads downstream and rises to higher elevations. Computer software has not yet been written to implement this method, though in principal it is preferred to the first method.

The empirical--flood-travel method consists of the following steps:

(1) Consider a range of inflow flood event and dam modification scenarios, as before in Step (1) of Section 5.2. Use the DAMBRK model to simulate dam breach and flood routing for each

inflow event and dam modification alternative. For each combination of flood event and dam alternative, both the antecedent event and the ensuing, full event should be routed. Before doing the DAMBRK runs, select a representative river cross-section for each reach. This cross-section should correspond as closely as possible to the location of the greatest population within the reach. Hydrographs should be plotted in the DAMBRK output for each of these selected cross-sections. Thus, there is a representative hydrograph for each reach.

(2) Compile the population at risk for the whole inundation area, as described previously. The population at risk is tabulated for each Census Tract/Enumeration District/Block within each reach. The population within each areal unit is further separated into five land elevations and a flood depth is calculated for each of the five land elevations within each areal unit.

Identify the population at risk from the antecedent event alone. This is done by comparing the peak stage elevation with the land elevations within each Census Tract/Enumeration District/Block.

(3) For each reach i and zone j, compute an average depth of inundation for the (i,j). Populations at risk in the same zone will generally experience different depths of flooding,

depending on their locations (i.e., upstream or downstream) within the reach. An average depth of flooding is required for the empirical function. This should be a weighted average, with the weights expressed relative to the sizes of the respective populations.

(4) From the DAMBRK output for the antecedent flood, identify the time of initial spillway discharge (from the DAMBRK Reservoir Depletion Table). This time marks the beginning of the flood travel time.

(5) From the hydrograph plotted at the end of the DAMBRK output, inspect the hydrograph and identify the time of arrival of the flood, by zone. This is a representative flood travel time for each reach i and zone j. Note that this arrival time is not specified for each Census Tract/Enumeration District/Block within the reach, since a DAMBRK hydrograph is plotted for only a single cross-section within each reach. This representative arrival time is used for all of the population at risk within zone j in reach i.

(6) Calculate a representative flood travel time for reach i, zone j. This is obtained from the representative arrival time for zone j in reach i, which was calculated in Step (5), minus the time at which spillway discharge commenced, which was given in Step (4). As with the arrival time, it should be noted that

the travel time is representative for all locations within an elevation Zone j in a given Reach i.

(7) In order to perform sensitivity analyses, set the time of the initial official evacuation warning to the public at a time relative to the start of the flood. For example, some possible values may be 60 minutes before the start of the flood, 60 minutes after, and at the same time of the initial spillway discharge. Compute the warning time as equaling travel time (from Step (6)) plus/minus some adjustment for the evacuation notification time.

(8) Compile any other data such as the previous experience factor or urban-area identifier. Substitute these values of E_i (or U_i), P_{ij} from Step (2), W_{ij} from Step (7), and D_{ij} from Step (3) into a loss of life empirical function. Using the function given by Equations (14) and (15), one obtains:

$$\text{Probability}(L_{ij})=\exp(\underline{\beta}'\underline{x})/(1+\exp(\underline{\beta}'\underline{x})),$$

where

$\underline{x} = [P_{ij}, W_{ij}, D_{ij}, E_i]$

$\underline{\beta}'$ = a set of coefficients as given in Equation (15) (the ' denotes the transpose of the vector).

(9) Compute L_{ij} = Probability(L_{ij}) P_{ij}.

$\Sigma L_{ij} = L_i$, the estimated loss of life in Reach i due to the j antecedent event.

(10) Complete the flood routing for the full flood event. Step (2) through Step (9) were computed for the antecedent flood event. Repeat these steps for the spillway flood for the full event. The time of renewed discharge, or increase in discharge, from the spillway is designated as the start of the travel time. As before, the hydrographs may be used to estimate the times of arrival for each Zone j and Reach i. The populations at risk in the spillway flood in the full event should not include those that were already taken into account in the antecedent flood. Thus, Zones j in Reaches i, which were already flooded from the antecedent event should not be included in the in calculations for the spillway flood for the full event. For a failure flood, a separate DAMBRK run is required for a non-failure situation so as to identify the population at risk under a non-failure scenario. The result of repeating the calculations in Steps (2)-(9) is an estimate of loss of life in Reach i due to the spillway flood in the full event that follows the antecedent event.

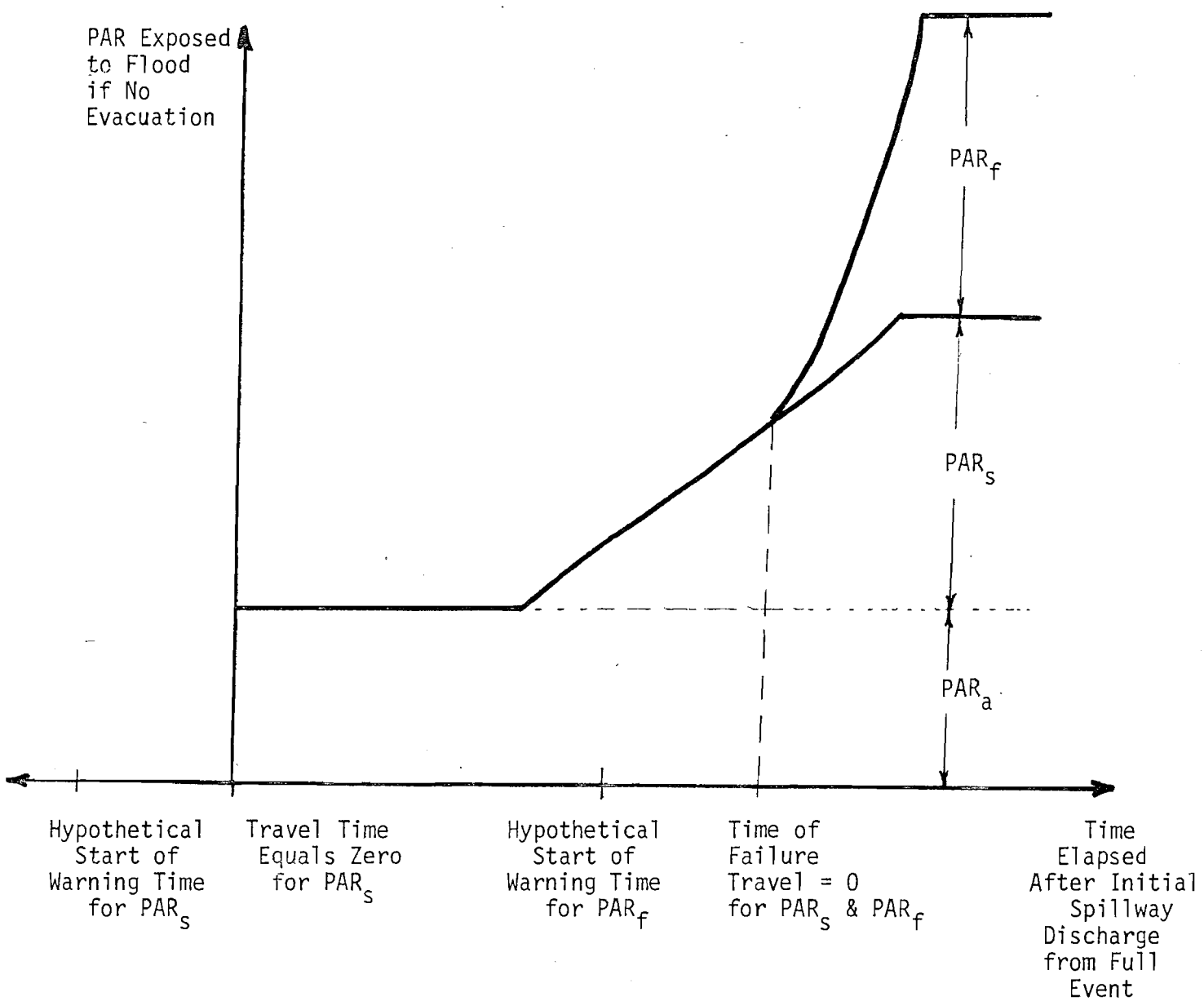
(11) Analogous to Step (10), repeat Steps (2) to (9) for the populations at risk and travel times associated with the failure flood. The failure flood starts with initial discharge from a breach or from dam overtopping. This point in time can be identified in the Reservoir Depletion Table in the DAMBRK output. Following the approach for the spillway flood, the populations at risk due to the failure flood should include

only those in Zones j and Reaches i that are not inundated by the antecedent event or by the spillway flood from the full event, but rather are reached only by the failure flood. As mentioned in Step (10), a separate DAMBRK run is required for a non-failure situation so as to calculate the population at risk from the non-failure flood. Any remaining population at risk is only at risk in the failure flood. The result of the calculations is an estimate of the loss of life (in Reach i) which is due to the failure flood.

(12) For each Reach i, add the loss of life estimates which were calculated in Steps (9), (10), and (11). This loss of life estimate includes fatalities that result from the antecedent event prior to the full flood, the spillway flood resulting from the full event, and the failure flood.

Figure 12 illustrates that for a given reach or cross-section, there are different populations at risk: those at risk from the antecedent event, the additional increment which is at risk due to the spillway flood from the ensuing full event, and the final increment which is at risk because of dam failure. In calculating the time of arrival of the full flood, for a given Zone j within Reach i, the same DAMBRK output is used for the spillway flood that precedes the failure, as well as for the failure event. The population at risk from the non-failure flood may experience an earlier arrival time than expected, due to failure. Some of these people, as well as those at risk solely from the failure, would appear to be the most vulnerable to loss of life. The reason is that the

Figure 12. Population at risk and travel time for the antecedent event, spillway flood of the full event, and failure flood of the full event



flood travel times and the resulting warning times are the least for these segments of the population. In contrast, populations at risk in the antecedent event as well as many of the populations at risk from the spillway flood, will have substantial warning time because flooding in these cases rises rather slowly, taking several hours for one foot in elevation.

This method for estimating loss of life combines the empirical function calibrated from historical floods with a representation of flood travel dynamics and rise in the water elevation. The method provides a more precise spatial representation of the flooding events than the aggregate-empirical method. The antecedent event, the spillway flood from the full event, and the failure flood in the full event are distinguished and treated separately. Because of this, travel times for the populations at risk in each Zone j within a Reach i are estimated more accurately. This should help alleviate the bias in the aggregate-empirical approach in which the use of a single composite flood travel time for a reach results in a possible under-estimation of the spillway flood travel time (and thus an over-estimation of the associated loss of life) and an over-estimation of travel time associated with dam failure (thus resulting in an under-estimation of loss of life due to failure).

5.4 Flood-Travel-Evacuation Model

Unlike the other two approaches, this method explicitly takes into account the evacuation of the population at risk, the time required for vehicles to escape the inundation area, and a comparison of evacuation

times and flood travel times. The procedure consists of the following steps:

(1) Use the DAMBRK model to do the flood routing for the antecedent flood. Select representative cross-sections for each reach and plot the hydrographs in the DAMBRK output.

(2) Determine the population at risk for the antecedent event by comparing the elevations of the populations at risk, which are defined by Census Tract/Enumeration District/Block, with the depth of flood at peak stage. Population data are compiled from Census data as described in Section 5.2. Flood elevations are given for each river cross-section in the DAMBRK output, and are interpolated to provide estimates for each areal unit, as discussed in Section 4.

(3) Identify the time of the initial spillway discharge in the antecedent event. This is determined from the Reservoir Depletion Table in the DAMBRK output.

(4) From the hydrographs, identify the times of arrival of the flood, by zone (elevation) at each given cross-section.

(5) Establish a specific time for receipt of the evacuation warning; and set the flood travel times and the evacuation times to be calculated in the traffic simulation model on the same time scale.

(6) Estimate the elevations of the origin nodes and road links in the transportation network. This is a manual process involving visual inspection of topographic maps. Enter the data into the network data base.

(7) Run the MASSVAC2 traffic evacuation simulation model (refer to Volume I, Southworth et al., 1986) for only the population at risk from the antecedent event. Run the traffic model for only a single time increment, such as 15 minutes. Use the DAMBRK hydrographs to check the elevation of the flood at the cross-section for the time corresponding to the time after the traffic simulation run. These times are "clock times" as set in Step (5). Close any roads which are inundated. Any population left at origin nodes that are inundated (i.e., elevation of the node is less than elevation of the flood) are part of the threatened population.

(8) Re-run the traffic simulation model for another time increment and repeat Step (7).

(9) Continue running the traffic simulation model until the evacuated population approaches some asymptote. This signifies that there are populations at risk that do not evacuate, on that cannot evacuate because of roads which are closed due to inundation. Any population not evacuated, including populations at risk which are left at the origin nodes when the flood arrives, constitutes the threatened population.

(10) Multiply the threatened population by a fractional coefficient to provide a subjective estimate of the loss of life, calculated as a proportion of the threatened population.

(11) Repeat all of the prior steps for the full event, that follows the antecedent event. The population at risk in the full event excludes those at risk from the antecedent event. After

repeating all of the steps above, an estimate of loss of life can be computed for the full event.

As in the empirical-flood-travel method described in Section 5.3, it is an approximation to use a cross-section as being representative of a reach. If a reach contains several populated towns, then separate cross-sections would be required to represent each of those towns. As with the empirical-flood-travel method, software for the flood-travel-evacuation method has not yet been written. Both methods are much more complicated than the aggregate-empirical method, and the flood-travel-evacuation method would require some re-coding of the MASSVAC2 model which is used for the evacuation traffic simulation.

5.5 Discussion of Sources of Errors in Loss of Life Predictions

It is important to stress that any numerical predictions of loss of life should be interpreted in terms of qualitative or relative differences and trends as a function of alternative scenarios rather than as absolute, precise estimates. There are many sources of uncertainty when trying to develop estimates of loss of life. Most of these have been covered in previous sections of this report and are summarized here:

(a) Estimates of the population at risk

(b) Flood travel time

(c) Time for the official notification process to issue the evacuation warning, and time for the dissemination of the public warning

(d) Minimum depth of flooding required to have a potentially lethal situation

(e) Spatial aggregation

(f) Inherent uncertainty in the calibrated empirical functions

(g) The importance of unique site-specific and circumstance-specific factors and events (such as the road network, topography, etc.)

The analytical methods used to estimate the population at risk have some inherent inaccuracies. One problem is that the 1980 Census was used to estimate the population at risk for the current year (1986). In the Cochiti Dam case study (Volume III, Lee et al., 1986b), this was somewhat less of a problem than that expected for other areas because most of the new development in Albuquerque occurred on higher ground outside the inundation area. In the other reaches, north and south of Albuquerque, residential development has been rather stable. Thus, there was relatively little change in population between 1980 and the present time. If anything, there has probably been a decline in the population in the inundation area. This is particularly true in the downtown Albuquerque area, as there has been a transition in land use from older residential structures to commercial establishments. In other parts of the country, however, the situation may be different. Each situation should be considered on a case by case basis.

There is also uncertainty in terms of estimating the night-time population directly from the Census data on place of residence, and estimating the daytime population strictly in terms of Census and secondary employment data. However, it seems that from results in case studies, errors in measuring population at risk will not be a major problem in the reaches well downstream from the dam. From these previous

numerical results, one can infer that errors in estimating the population at risk, which are expected to be about 25%, will have almost no impact for reaches with warning times of at least two hours.

Discussions in the previous sections alluded to some of the complications in attempting to measure travel time. The estimation of travel time using the DAMBRK model is a rather mechanical process. It provides estimates of dam overtopping and travel times from user-specified parameters such as the inflow hydrograph, the antecedent condition of the reservoir, the time for a complete breach to develop, minimum elevation of breach bottom, breach bottom width, and breach side slope. Thus, travel times can be estimated relatively precisely. However, many of the user-specified parameters are arbitrary and this results in considerable uncertainty in the accuracy of the calculated travel times.

Another problem with measuring travel time is the estimate used in the aggregate-empirical method. The time between peak stage at the reach and peak stage at the dam is used as a surrogate variable for travel time. However, the surrogate is far from completely satisfactory, and is in some cases a rather inaccurate measure of actual travel time. In addition, the use of a single composite time for the whole reach may very well result in a consistent over-estimation of travel times associated with failure flooding and an under-estimation of non-failure travel times.

The time at which the official evacuation warning is initially disseminated to the public presents another source of uncertainty in predicting loss of life. The timing of the warning reflects the

activities, actions, and decisions of several agencies and individuals. Because of this, it is difficult to estimate precisely when the decision making process begins, and how long it takes the various agencies and offices to make decisions. The optimistic case is one in which many of the steps in the decision making process have already been carried out as a result of the severe precipitation and threatening situation. Under this scenario, it is a case of the officials at the dam site monitoring the developments carefully and then informing the agency, that is to make the announcement, at some agreed upon designated water level in the reservoir. Under these circumstances, all of the prior arrangements and communications have already taken place, so that the final decision point reduces to a very streamlined procedure that all responsible parties have agreed upon in advance in the days or hours before the threatening situation reaches a critical level and before an evacuation warning is deemed to be necessary. Under these optimistic circumstances, the notification time may occur before any severe flooding and certainly well before a dam breach.

Examination of results in the case studies suggests that the estimates of travel time and of the time at which the evacuation warning is received have a major bearing on the estimated loss of life. For example, in the Beach City Dam case study, estimated loss of life in Strasburg for a PMF with breach increases from 2 to 60 if the evacuation warning is issued 60 minutes after the beginning of flooding rather than 60 minutes before flooding. By extrapolation, it is easy to see that if warning dissemination begins before the start of the travel time, then loss of life would be decreased dramatically. With such early warning

two important factors come into play. One of these is the time that it takes the population at risk to evacuate the risk area after the evacuation warning is made (i.e., evacuation time). This depends on the haste with which families will begin to evacuate (i.e., mobilization time) as well as on the traffic flow conditions for the local transportation network (i.e., vehicular travel time and queuing delay time). Evacuation traffic simulation models that have been applied to the Cochiti Dam inundation area suggest total evacuation time for most reaches to be between 1 and 2 hours, with the Albuquerque urbanized area requiring much greater evacuation times of around 5-6 hours (Southworth et al., 1986). These times are extremely important for the first reach below a dam where warning times are of the essence, but much less important for the other downstream reaches since flood travel time and the resulting warning time under any reasonable notification scenario is hypothetically great enough to allow for full evacuation of the population at risk.

Another source of uncertainty is in the depth of flooding. This can be regarded in two ways. One consideration is the flood stage that results from a given flood event. Once the DAMBRK input parameters have been established, then the hydraulic and hydrologic models are able to predict flood stages reasonably precisely, though not necessarily accurately. A second issue raised by the question of flood stage is the depth of flooding that is regarded as posing a serious and potentially lethal situation. If the presence of flood water at any level more than zero feet is assumed to subject the population to risk, then this will

obviously result in a very large population at risk. This is the definition used in the Corps' (1986b) Guidelines.

The issue of spatial aggregation is another source of uncertainty in the loss of life predictions. Although population and flood stage information was estimated on a unit area basis, the population estimates were aggregated to a reach level, with for example, nine reaches for an inundation area. Not only are the PAR aggregated laterally along a reach, they are also grouped vertically (i.e., in zones of, for example, 4 foot increments of elevation). The main problem with this is that warning time estimates will be imprecise. To alleviate this shortcoming, a detailed analysis could use unit areas as specific as the city block level in urban areas, though this would be unnecessary. The reason is that frequently the warning time is not a crucial factor for many areas well downstream from the dam. Warning time is great enough that it hypothetically allows for full evacuation. Thus, it is unnecessary to specify population at risk and warning times for individual city blocks. On the other hand, warning time is usually very crucial for the first reach closest to the dam. Even for this situation, however, it is difficult to justify a level of aggregation finer than the four subreaches identified in the Cochiti Dam case study. This is mainly because of the uncertainty in estimating the warning times and the inherent limitation in using an aggregate loss of life model, that was calibrated for comparisons of flood events across the country, to highly disaggregate reaches within a single inundation area.

Another spatial aggregation problem involved unit areas which were along the inundation boundary. It is straightforward, though tedious, to

partition that portion of the population within a unit area that would be exposed, from the portion that would be outside the inundation area. Inspection of maps of the Cochiti Dam area, for example, revealed that most of the population nodes in the large (in terms of area) rural Enumeration Districts are situated on the floodplain close to the Rio Grande River and would likely be at risk. For Albuquerque, on the other hand, the specific estimate of the population at risk did not affect the predicted loss of life by very much; and in any event, the level of aggregation, which is at the city block level, resulted in relatively small inaccuracies compared to the primary source of uncertainty, which is in the empirical function used to predict loss of life.

The primary source of uncertainty in predicting loss of life is undoubtedly in the empirical function that was derived from a limited sample of past flood events. Local, unique situations and circumstances are extremely important to explaining differences in loss of life among different events, but these considerations generally do not follow any consistent systematic relationship. The confidence bands for the estimates would give one a quantitative indication of the precision that is justified when using the models to estimate loss of life. Although these bands have not been computed for the group logit model, the order of magnitude of these confidence bands is reflected in a comparison of predicted and actual loss of life in Table 7.

6. NUMERICAL EXAMPLE

Table 8 gives a numerical example that summarizes an application of the aggregate-empirical method for estimating loss of life. The case

Table 8 : Summary of Loss of Life Predictions for Beach City Dam PMF with Breach - Before Modification

Nighttime Flood

Time of Evacuation Warning: 0 Minutes After Start of Flood

Obs	Reach	PAR	Travel Time* (Min.)	Warning Time* (Min.)	Pred Loss of Life	% Loss of Life
1	Beach City/Brewster	2630	320	320	3	0.11
2	Strasburg	1590	60	60	3	0.19
3	Dover	1160	320	320	2	0.17
4	New Philadelphia	3220	360	360	3	0.09
5	Urichs./Gnadenhutten	2380	920	920	2	0.08
6	Newcomerstown	3070	1730	1730	2	0.07
7	Coshocton	3220	2870	2870	2	0.06
8	Zanesville	5990	4690	4690	1	0.02
9	McConnelsville	910	5230	5230	1	0.11
		24170			19	0.08

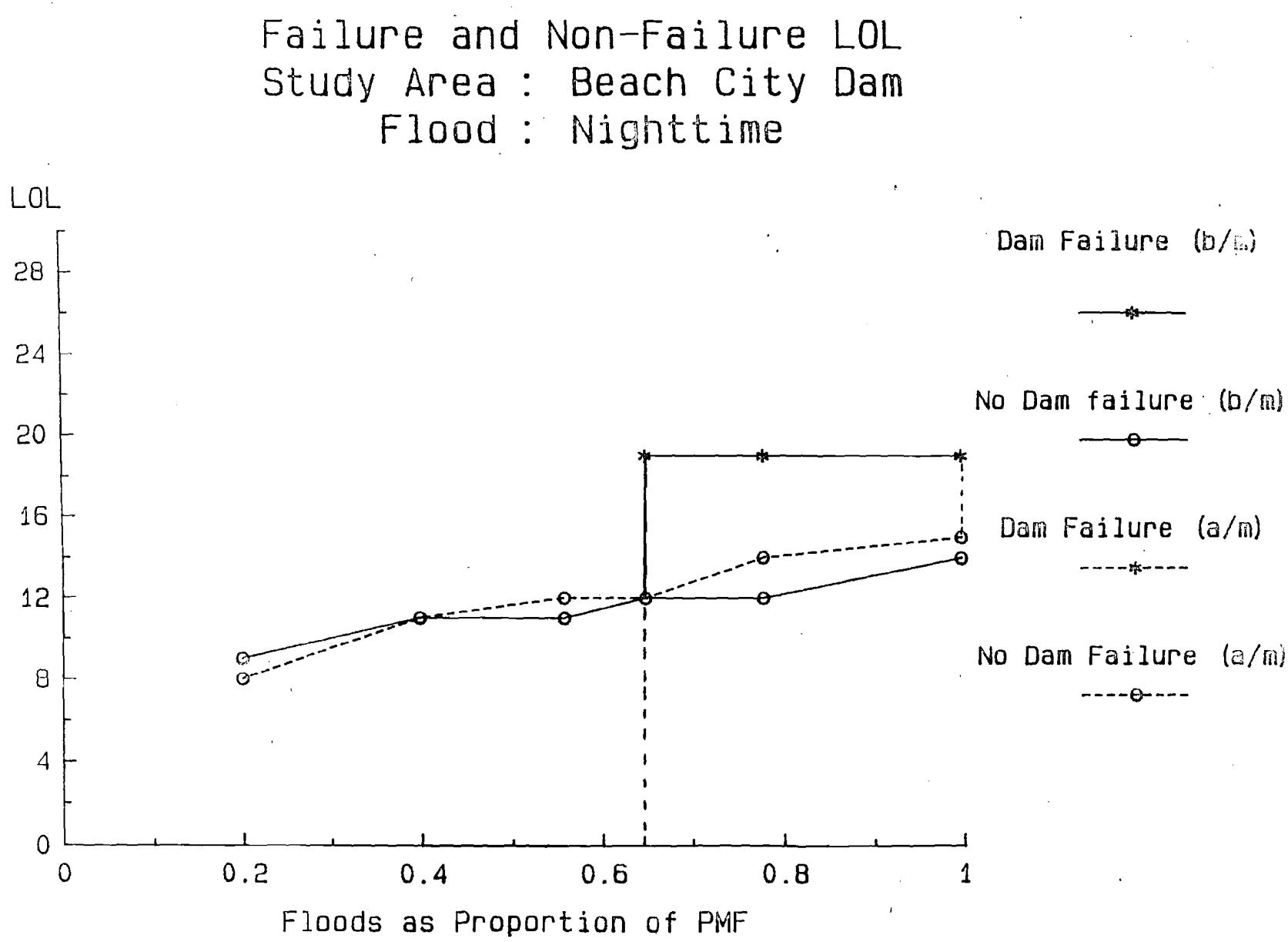
* Travel and Warning Times are representative of those for the PAR in the reach.

study was for the Beach City Dam, Ohio inundation area. The PAR estimates were aggregated from unit area data (i.e., city block, enumeration district, and tract) Census information, together with their corresponding elevations, as described in Sections 4.2 and 5.2(2). The time at which the evacuation warning is first issued was arbitrarily expressed as being at the start of the flood travel time. The travel time was calculated from the DAMBRK output by taking the differences in the times of the peak stage at the first cross-section (at the dam) and at the cross-section presenting the reach, as described in Section 5.2(3). This is an approximation of the preferred method which was described in Section 5.3. The prior experience variable in Equation (15) was set to be zero.

The resulting estimates for loss of life are tabulated in the two right columns in Table 8. Results comparing loss of life estimates among a number of flood event scenarios are summarized graphically in Figure 13.

An expanded discussion of the numerical example is given in the report on the Beach City Dam area (Volume III, Lee et al., 1986b).

Figure 13



a/m : After Modification
b/m : Before Modification
Modification : raise the top of dam 3 feet and widen spillway to 350 feet

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Being compiled and to be included in the final report.

APPENDIX A

REFERENCES FOR THE FLOOD DATA BASE

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