ROUTLEDGE

# Large-Scale Evacuation

## The Analysis, Modeling, and Management of Emergency Relocation from Hazardous Areas

Michael K. Lindell, Pamela Murray-Tuite, Brian Wolshon, and Earl J. Baker

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*Large-Scale Evacuation* introduces the reader to the steps involved in evacuation modeling for towns and cities, from understanding the hazards that can require large-scale evacuations, through understanding how local officials decide to issue evacuation advisories and households decide whether to comply, to transportation simulation and traffic management strategies. The author team has been recognized internationally for their research and consulting experience in the field of evacuations. Collectively, they have 125 years of experience in evacuation, including more than 140 projects for federal and state agencies.

The text explains how to model evacuations that use the road transportation network by combining perspectives from social scientists and transportation engineers, fields that have commonly approached evacuation modeling from distinctly different perspectives. In doing so, it offers a step-by-step guide through the key questions needed to model an evacuation and its impacts to the evacuation route system as well as evacuation management strategies for influencing demand and expanding capacity. The authors also demonstrate how to simulate the resulting traffic and evacuation management strategies that can be used to facilitate evacuee movement and reduce unnecessary demand. Case studies, which identify key points to analyze in an evacuation plan, discuss evacuation termination and re-entry, and highlight challenges that someone developing an evacuation plan or model should expect, are also included.

This textbook will be of interest to researchers, practitioners, and advanced students.

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# List of Acronyms

| | |
|---|---|
| ACH | Air changes per hour |
| ATIS | Advanced Traveler Information System |
| CCTV | Closed Circuit Television |
| CMS | Changeable Message Sign |
| CV | Connected Vehicle |
| DMS | Dynamic Message Sign |
| DOT | Department of Transportation |
| DOT-ERG | DOT-Emergency Response Guidebook |
| DPW | Department of Public Works |
| EAS | Emergency Alert System |
| EHS | Extremely Hazardous Substance |
| EMA | Emergency Management Agency |
| EOC | Emergency Operations Center |
| EOP | Emergency Operations Plan |
| EPCRA | Emergency Planning and Community Right to Know Act |
| EPZ | Emergency Planning Zone |
| ERPA | Emergency Response Planning Area |
| ERS | Evacuation Route System |
| ETE | Evacuation Time Estimate |
| FEMA | Federal Emergency Management Agency |
| FIRM | Flood Insurance Rate Map |
| GIS | Geographic Information System |
| HAR | Highway Advisory Radio |
| HOV | High Occupancy Vehicle |
| IC | Incident Commander |
| IDLH | Immediately Dangerous to Life or Health |
| ITS | Intelligent Transportation System |
| LOC | Level of concern |
| MEOW | Maximum Envelope Of Water |
| MOM | Maximum Of MEOWs |
| MPC | Manual Police Control |
| NHC | National Hurricane Center |
| NOAA | National Oceanographic and Atmospheric Administration |
| NPP | Nuclear Power Plant |
| NRC | Nuclear Regulatory Commission |
| PADM | Protective Action Decision Model |
| PAG | Protective Action Guide |

| | |
|---|---|
| PAR | Protective Action Recommendation |
| SLOSH | Sea, Lake, and Overland Surges from Hurricanes (hurricane surge model) |
| TAZ | Traffic Analysis Zone |
| TLV | Threshold Limit Value |
| TWC | Tsunami Warning Center |
| USACE | US Army Corps of Engineers |
| V2I | Vehicle to Infrastructure communication |
| V2V | Vehicle to Vehicle communication |
| VMS | Variable Message Sign |
| VZ | Vulnerable Zone |
| WEA | Wireless Emergency Alert |

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# Chapter 1

# Introduction and Overview

Evacuation is a protective action that involves people relocating from a threatened area to a safer area. As Perry (1978) noted, evacuations can differ with respect to a number of different dimensions. These include their timing in relation to disaster impact (pre-impact or post-impact) and their duration—ranging from perhaps a few hours to permanent relocation. In addition, they differ in their degree of pre-impact planning (from completely improvised to substantially planned), the number of people involved (ranging from one person to millions of people), and the distance to safety (ranging from a few feet to many miles). The simplest evacuations—such as well practiced building fire evacuations—involve only a few people, require walking only a short distance, are well planned and exercised, take place pre-impact, and last only a short time.

At the other extreme are mass evacuations that involve millions of people evacuating tens or hundreds of miles in vehicles, require a significant amount of improvisation despite a substantial amount of planning, take place before or after disaster impact has disrupted communication and transportation systems, and displace people for weeks, months, years, or even permanently. It is these mass evacuations that are the focus of this book, particularly the need to develop evacuation plans that are based on empirical data about how households respond to environmental threats coupled with engineering models of traffic flows.

For many decades, practitioners and researchers have sought new techniques and systems to move people faster and more safely during evacuations. Some of these methods and strategies have focused on evacuees directly—using improved methods of communication to help them make faster and better informed decisions. Others have focused on transportation systems to better utilize personnel, modal, technological, and infrastructure resources to move people. Over time, this evolution has brought about major changes in the way evacuations are planned and implemented. It has also resulted in the emergence of specialized areas of emergency management study in the physical and social sciences, engineering, planning, and public administration. This book summarizes the current state of knowledge in many of these fields, with a particular focus on the practical application of this knowledge. It also highlights many of the latest emerging topics that have been identified for needed study in the aftermath of recent high profile evacuations.

Many people are surprised to learn that mass evacuations are quite common. A study of emergencies over a 10-year period showed that evacuations involving 1,000 or more persons occur, on average, about every two weeks somewhere in the United States (Dotson and Jones 2005). However, the large scale attention-grabbing evacuations that capture news headlines are considerably less frequent. In fact, of the events studied, only about 25% of them involved more than 5,000 people and only about 5% of them included 100,000 or more people. Because of their infrequent occurrence, large-scale evacuations can be extremely challenging to implement, so that is why they are the main focus of this book.

Decades of operational experience have shown that when a mass evacuation of an urban area is needed, the methods used to move people become quite complex and can require travel over long distances and over extended periods of time. Not only do such conditions increase the risk of harm in an evacuation zone, they also affect much larger areas. In extreme cases, evacuations can have regional impacts. Past hurricane evacuations in Miami and New Orleans, for example, have impacted travel conditions statewide throughout Florida and Louisiana (Wolshon 2007) and even affected bordering states.

Despite the multitude of conditions that can influence any specific evacuation, the history of prior evacuations indicates that there is actually a small set of key variables and fundamental relationships that govern all evacuation processes. These variables can be expressed in spatial and temporal terms and quantified. This book examines these concepts, describes a theoretical foundation of evacuation processes, and shows how emergency management and transportation professionals can apply evolving scientific and engineering knowledge to improve the practice of large scale mass evacuations.

## 1.1 Evacuation Fundamentals

The goal of an evacuation is to avoid injuries, loss of life and, to a lesser extent, property damage and economic loss. Thus, a primary objective is to move all evacuees outside of a threat area as safely and as quickly as possible. The time it takes to clear the last person from a danger zone after the recognition of a threat is commonly referred to as *clearance time*, which is also referred to as an *evacuation time estimate* (ETE). Clearance times for mass evacuations vary widely based on the

- characteristics of a hazard,
- size and response of the evacuating population,

- road network through which evacuees must move,
- adverse travel conditions such as heat, darkness, and precipitation.

The characteristics of these four variables effectively dictate the clearance times of all evacuations. And, although evacuations vary widely in terms of the specific attributes and scope of these four variables, they can be scaled up or down to describe, quantify, and assess all evacuations within a spatiotemporal framework. Ultimately, these four variables are used to define the demand and supply conditions of all evacuation processes.

Evacuation *demand* is, fundamentally, the number of people—and more specifically, the number of vehicles—that seek to use an evacuation route system (ERS)—the portion of the road network that authorities encourage people to use for their trips to safety. Evacuation demand is more precisely described as the number of vehicles per hour that attempt to depart from each origin via each path to each destination. Conversely, evacuation *supply* is the ability of the ERS to serve the demand placed upon it. Supply, in an evacuation context, may be described in a number of ways but, fundamentally, it is the ERS's outflow capacity in terms of the number of vehicles per hour that can exit the risk area. More specifically, supply is a function of link capacity and network geometry. Link capacity can be defined simply in terms of the number of vehicles per hour that can move through a given section of the ERS. Consequently, local authorities typically designate the highways with the greatest capacities as the ERS. However, network geometry is also an important determinant of evacuation supply because total ERS capacity is equal to the sum of the individual link capacities only if the links are *parallel* to each other. For example, if an ERS consisted of two parallel evacuation links, each with a capacity of 800 vph, it would have a capacity of 1,600 vehicles per hour (vph). However, total ERS capacity will be the smaller of the individual link capacities if the links are *serial*. For example, if an ERS consisted of two serial evacuation links, one with a capacity of 800 vph and the other with a capacity of 400 vph, it would only have a capacity of 400 vph. Transportation networks are typically more complex than this example as a given route consists of a series of links and nodes (e.g., intersections). Multiple routes need to have no common links in order for capacity to be additive across the routes.

Another important consideration in evacuation analysis is that neither demand nor supply variables remain static throughout an evacuation. Both are influenced by spatial and temporal conditions that vary during an emergency. In most emergencies, evacuation traffic demand rises over time until it reaches a peak. For example, information about changing threat conditions and phased evacuation notices produce different evacuee departure times from different origins travelling to different destinations via different paths. Evacuation supply can decrease due to bottlenecks at merging highways, lanes blocked by vehicle breakdowns, and hazards such as flooding. The dynamic nature of evacuation demand and supply adds an additional layer of complexity to evacuation planning and management.

In summary, clearance time is estimated as a function of evacuation demand and supply. When supply exceeds demand, vehicles can evacuate at the rate defined by the level of evacuation demand. However, when demand exceeds supply, the situation becomes more complex because queues will form that can decrease link capacities below their nominal values and, thus, increase clearance time—sometimes dramatically. Thus, the challenge for emergency managers and transportation officials is to employ demand management techniques such as *phased evacuations* (Zhang, Spansel, and Wolshon 2014b) and supply management techniques such as *contraflow* (Wolshon 2001) to balance demand and supply and, thus, reduce clearance time. These techniques are described in detail later in this book.

## 1.2 Evacuation Modeling

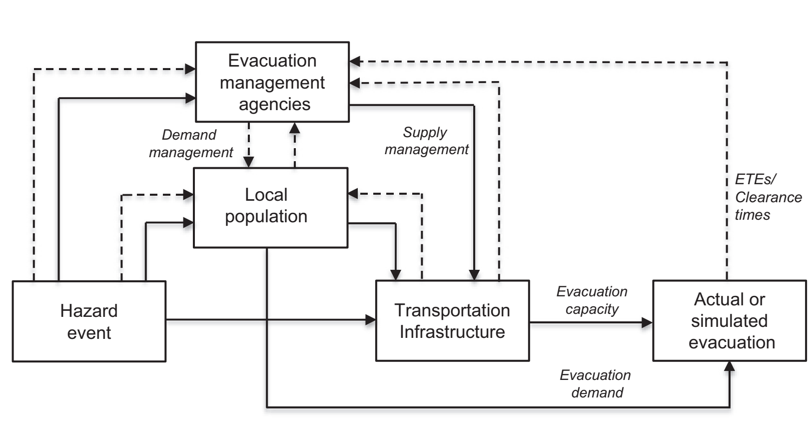
Among the most significant advances in evacuation analysis and planning over the past four decades has been the development of quantitative models of evacuation processes (see Murray-Tuite and Wolshon 2013b; Lindell 2013). One contribution has been the development of mathematical models of evacuee demand and another contribution has been the development of simulation and optimization models for computing clearance times. Mathematical models of evacuation demand have taken two forms, aggregate and microscopic. The aggregate models have been used to characterize evacuation model variables such as average evacuation rates (Baker 1991), average percentage of evacuees seeking accommodations in public shelters (Mileti, Sorensen, and O'Brien 1992), and the distributions of warning reception times (Lindell and Perry 1987). However, microscopic models are increasingly being used to predict these evacuation model variables. There has been an extensive line of research on the prediction of households' evacuation decisions with models ranging from the simple cross-tabulation of evacuation rates by hurricane category and risk area (Lindell and Prater 2007) to multi-stage, multi-equation models involving social/environmental cues; warning source, channel, and message; previous experience, social and environmental context, psychological variables, and demographic variables (see Huang et al. 2016a for an example and Huang et al. 2016b for a review). There has also been research on models to predict other evacuation model variables such as departure time (Hasan, Mesa-Arango, and Ukkusuri 2013) and evacuation destination (Mesa-Arango, Hasan, Ukkusuri, and Murray-Tuite 2013).

There has also been substantial development of simulation and optimization models that can integrate data from evacuee demand models with increasingly detailed ERS models to generate ETEs. As noted by Davidson and Nozick (2017), *optimization models* define a problem in terms of decision variables (controllable variables whose optimal values are to be determined), an objective function (the overall measure of performance to be minimized or maximized), and constraints (restrictions on the permissible values of the decision variables). By contrast, *simulation models* define a problem in terms of causal relationships among variables. Moreover, evacuation models are typically stochastic (having some element of randomness to their inputs) and dynamic (modeling the system's evolution over time).

Evacuation modeling serves numerous purposes, the most important of which is to estimate the number of people reaching safety by a given time and, conversely, to determine the time by which authorities need to issue evacuation notices in order for everyone to reach safety prior to a hazard's arrival. In addition, these models can identify traffic congestion locations, estimate the demand for space in public shelters, test scenarios that have not occurred previously, evaluate strategies that could facilitate evacuee movement, and assess the sensitivity of ETEs to plausible variations in the input parameters.

Evacuation models should take into consideration the interactions of the hazard, population, evacuation management agencies (emergency management, transportation, police, and transit agencies), and the transportation infrastructure, as displayed in Figure 1.1. This figure

**Figure 1.1 General Evacuation Modeling and Planning Framework**



not only represents the process as it unfolds in an actual evacuation, but also as it is simulated. For example, the dashed lines connecting the hazard event to evacuation management agencies and local households represent information that these community stakeholders obtain about the unfolding event. The solid lines represent impacts that the hazard can have on the ability of these community stakeholders to respond.

The dashed lines between the two stakeholder groups reflect the exchange of information between them, with evacuation management agencies seeking to influence households indirectly through the news media, but also directly through agency Internet sites and social media accounts. Households provide feedback by accessing agency rumor control centers and posting on social media. Both stakeholder groups obtain information about the transportation infrastructure—the evacuation management agencies through infrastructure monitoring devices such as CCTV and the households through the news media. In turn, the local population can degrade the transportation infrastructure through traffic incidents such as lane-blocking collisions, whereas evacuation management agencies can enhance the transportation infrastructure through supply management actions such as contraflow. The solid line from the hazard event to infrastructure represents adverse impacts that reduce ERS capacity whereas the solid line from evacuation management agencies to infrastructure represents interventions that maintain or increase ERS capacity. The solid line from households to simulated or actual evacuation represents the demand model and the solid line from the transportation infrastructure to the simulated or actual evacuation represents the supply model. Finally, the dashed line from the simulated or actual evacuation to the evacuation management agencies represents the feedback to them about clearance times and other measures of effectiveness (for actual evacuations) and ETEs (for simulations).

A long history of research in the social sciences has explored the relationships among the hazard, population (and their preferences and constraints), and warning messages. This social science research has informed further research into the development of spatiotemporal travel demand models that can be used with traffic simulation tools to produce ETEs that predict *network clearance time*. Assessing demand requires addressing the following questions:

- How many vehicles are entering the ERS?
- When are they entering the ERS?
- Where are they entering the ERS (i.e., what are their origins)?
- What are their destinations?
- What routes are they taking from their origins to their destinations?
- Where do they expect to stay when they get to their destinations?

The question of how evacuees get to their destinations has two elements. First, the mode of transportation (e.g., personal vehicle, transit) for each household is needed because the vehicle is the fundamental unit of analysis for mass evacuation traffic models. At the very least, an aggregate percentage is needed for each mode of transportation for each origin/destination/departure time triplet. Many households using personal vehicles take more than one, influencing the overall number of evacuating vehicles. Second, the paths that the evacuees use to reach the destination from the origins are needed. Some evacuation models determine these paths by making assumptions about how drivers choose among different evacuation routes, whereas others rely on data about drivers' expected routes obtained through surveys.

Some hazards also damage or otherwise make sections of the ERS unavailable; these impacts should also be incorporated into the simulation. Furthermore, the population itself can affect the transportation system through traffic incidents such as crashes and disabled vehicles. Taking into account all of these effects, emergency management agencies may consider the ETEs to be too high, leading them to try to modify the demand (e.g., by instituting staged evacuations) or supply (e.g., adopting contraflow).

When considering hazards, one needs to identify the type, severity, location, and impact timing. The detection and monitoring systems for some hazards, such as hurricanes, provide days of forewarning, and can be considered *short notice* events that allow preimpact evacuation; these hazards allow enough time to track the conditions, make decisions, and prepare for evacuation, as illustrated in the generalized timeline shown in Figure 1.2. However, each household operates on a different timeline and some evacuate prior to an official evacuation warning. Moreover, depending on how long households take to prepare, they might not evacuate until after impact.

Other hazards, such as explosions, are not detected ahead of time; these *no-notice* events trigger *postimpact* evacuations, as illustrated in Figure 1.3. (Note that some individuals or households may evacuate

**Figure 1.2 Generalized Timeline for Short Notice Events**

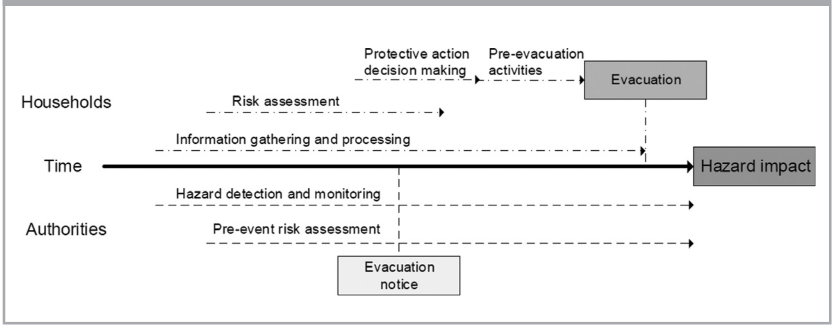
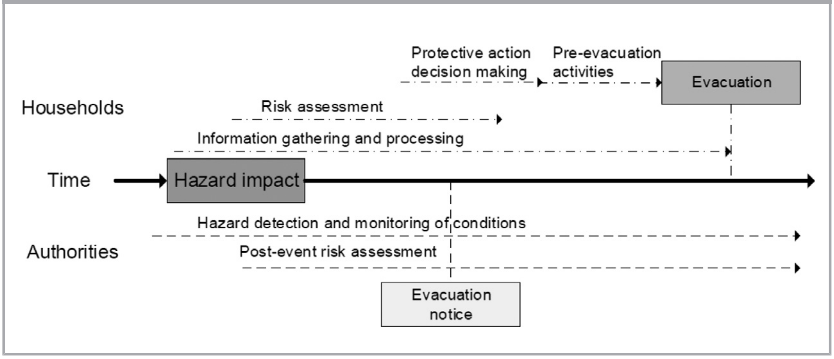


**Figure 1.3 Generalized Timeline for No-Notice Events**




before the authorities detect the hazard.) In these events, the amount of time to perform all of the activities is generally much smaller than for short notice events.

The specific hazard type (e.g., hurricane, flood, wildfire explosion, fire, hazardous material release) suggests the appropriate protective action (evacuate or shelter in-place), whether decontamination will be needed, whether law enforcement will investigate the event as a crime scene, whether infrastructure could be damaged and where, whether injuries or casualties are present, and whether transit services can be offered, among other factors (Murray-Tuite and Wolshon 2013a). Different types of hazards present different environmental cues (if any), which increase the public's and authorities' awareness of the danger and increase the likelihood of evacuation (Perry 1983). Within a given type of hazard for which evacuation is the appropriate protective action, events that affect larger areas and have more severe impacts lead to larger evacuations. A greater evacuation zone and number of evacuees generally requires a greater network clearance time. In turn, to be successful, earlier evacuation notices are needed.

These issues become more complex when other considerations are incorporated, such as background traffic already in or driving through an evacuation zone when an evacuation notice is issued. This additional traffic, which is not part of the recommended evacuation, can significantly increase clearance time. Another consideration is when persons not advised to evacuate do so anyway due to their perceived risk of remaining. These individuals, commonly referred to as *shadow evacuees*, can also increase clearance time significantly. In a well managed incident, shadow evacuees are anticipated to be 20% of the residential population within five miles of the 10 mile emergency planning zone (EPZ) of a nuclear power plant (Jones, Walton, and Wolshon 2011). However, a poorly managed incident could produce a much greater shadow evacuation, as was the case in the 1979 Three Mile Island accident. There, the Governor's evacuation recommendation for pregnant women and preschool children within five miles of the plant (no more than 10,000 people if the target population segment left with their entire families) produced an evacuation of approximately 150,000 people (Houts et al. 1984; Lindell and Perry 1983).

To help address situations in which demand is expected to exceed ERS capacity, evacuation management agencies can attempt to influence demand and modify supply. These agencies also need to consider the influence of the hazard on the infrastructure so that the evacuation management strategies do not expose the evacuees to other risks. The effect of the evacuation management strategies and the "do nothing" case (where the evacuation management agencies make no attempt to manage demand or supply) are tested through traffic simulation to produce ETEs. Comparing the evacuation time in the "do nothing" case to the hazard's anticipated arrival time indicates how long before impact authorities must issue evacuation notices. However, if they find that the estimated amount of lead time is unacceptable—over 36 hours for many hurricane-prone cities—they need to identify evacuation management strategies and determine how much these strategies can reduce the ETEs.

## 1.3 Need for Multiple Disciplines

Prior to the 1970s, many professionals in the emergency management and transportation fields assumed that evacuations "just happened" and that little could be done to facilitate vehicle movement during large scale, regional evacuations. This opinion, expressed by some state-level DOT officials, was based on the belief that ERS capacity was fixed and the massive demand generated by a large-scale evacuation would quickly overwhelm it. After all, as it was believed at the time, if it was not even possible to move routine rush hour traffic congestion-free, how would it ever be possible to move an entire city or region on the same network without enormous traffic problems? Another issue affecting evacuation planning was that few transportation agencies viewed evacuations as one of their responsibilities at that time. As professionals who were engaged in the safe and efficient movement of traffic during routine periods, transportation officials tended to see evacuations as an emergency management problem that they were willing to support, but not as a need that they could play a leading role in addressing.

Due in large part to a series of hard-learned lessons from Hurricane Floyd (1999), the terror attacks of September 11$^{th}$ 2001, Hurricanes Rita and Katrina (2005), and 2007 Southern California wildfires, it became apparent that there were many simple and effective traffic management strategies that could significantly improve evacuations. Another realization was that transportation professionals could bring enormous expertise to help assess, plan, and coordinate evacuation operations. However, the most significant advancement that occurred at this time was the linkage of transportation and emergency management officials to discuss needs and policies, share resources, and develop joint operational strategies for protecting the public. Today in the United States, strategies such as the National Response Framework (www.fema.gov/media-library/assets/documents/117791), National Incident Management System (www.fema.gov/national-incident-management-system), and Incident Command System (www.fema.gov/incident-command-system-resources) have brought a standardized approach to the command, control, and coordination of emergency response. These systems provide a common organizational structure that allows responders from agencies across government jurisdictions to collaborate more effectively. In addition to these operational efforts, the National Science Foundation (www.nsf.gov), Department of Transportation (www.ops.fhwa.dot.gov/eto_tim_pse/) and the National Cooperative Highway and Transit Research Programs (www.trb.org/securityemergencies/securityandemergencies1.aspx) have supported scores of research studies, reports, and guidance documents that have developed evidence-based solutions to emergency and security related issues within transportation. These resources are significantly enhancing the development of carefully crafted, robust evacuation plans through the collaboration of emergency management and transportation agencies in ways that were virtually unimaginable just a few decades ago (Matherly et al., 2013, 2014).

Nonetheless, some of the key findings from this research have not received the recognition they deserve, in part because they have not crossed disciplinary boundaries. This is partly because social scientists and transportation engineers have each tended to present their research findings at their own conferences and in their own journals. In addition, they tend to speak to other researchers rather than to practitioners and, when they do, they speak to different practitioner audiences—social scientists to emergency managers and transportation engineers to transportation officials.

The research described in this book is important to practitioners because it explains how households react to different types of environmental threats and the protective actions they are advised to take in response to these threats. These considerations involve understanding people's perception of a hazard (an interaction of the social environment with the natural environment), different sources of warnings and other information (interaction within the social environment), and alternative protective actions (an interaction of the social environment with the built environment). Practitioners also need to know how people's responses to an environmental threat manifest themselves in evacuation demand (social environment) and how this demand interacts with the transportation system (built environment) so that accurate ETEs can be produced.

The research described in this book is important to other researchers because interdisciplinary approaches are essential to advances in evacuation modeling. Social scientists and transportation engineers have been collaborating increasingly over the past few decades in interdisciplinary evacuation research efforts. Prior to these efforts, transportation engineers' efforts typically, albeit with a few exceptions, focused on the traffic flow models or simulation efforts whereas extensive empirical social science research focused on models for warning response (Lindell and Prater 2007). These two broad fields, each of which has several subdisciplines, took quite different, and largely nonoverlapping, approaches to evacuation studies. Social scientists approached evacuation modeling as building theories or "empirical tests that explain how people make sense of and act in situations where they are told to evacuate or may want to evacuate from a hazard on their own" (Trainor et al. 2013, p. 152). Transportation based evacuation models, on the other hand, were typically developed to address a specific planning problem and efforts were "focused on collecting information and designing processes that will allow for a solution to that problem" (Trainor et al. 2013, p. 153). This book continues the efforts to combine social science and transportation engineering perspectives to provide both practitioners and researchers with an understanding of how social and transportation systems interact to produce ETEs in the face of environmental hazards.

## 1.4 Intended Audience and Scope

The topics addressed in this book have been conceived to support the work of two primary audiences within the fields of emergency management and transportation, either of which may be practitioners or researchers. The research community primarily comprises university and government researchers but also students at the graduate and undergraduate level who seek a better understanding of the key models and strategies involved in evacuation management. The practitioner community seeks to apply research findings, as well as lessons learned in other locations and from other hazards, to protect public health and safety.

This book walks the reader step by step through the key questions needed to model an evacuation and to manage evacuations through effective demand and supply strategies. The book begins with the basic questions "to what hazards does evacuation apply?" and "how do agencies make the decision to advise evacuating?" and then addresses people's responses to evacuation advisories, including factors associated with their decisions to evacuate, activities undertaken prior to the evacuation trip (e.g., gathering family members, buying fuel), the timing of their departures, their transportation modes, and their choices of routes, destinations, and accommodations. These activities determine evacuation demand. The book then discusses methods of simulating the resulting traffic and the evacuation management strategies that can facilitate evacuee movement, especially reducing unnecessary demand.

The book continues with a largely neglected issue, organized reentry into the community after authorities determine that it is safe to do so. Finally, the book concludes with four case studies that illustrate key concepts needed to develop and analyze evacuation plans.

This book supports a planning process involving stakeholder engagement by providing assistance in evacuation modeling, which is a key component to the development of plans. The scope of this book is the vehicular evacuation of towns, cities, and metropolitan areas, rather than the pedestrian evacuation of buildings, transportation vehicles such as airplanes and ships, or mountainous areas (e.g., flash floods). Although most of the principles presented here apply to all hazards, the book does address some hazard-specific issues. Moreover, this book is also broader in scope than procedural guidance for preparing evacuation plans. Instead, it also presents the fundamental principles upon which evacuation plans should be based. That is, it describes what scientific research has revealed about people's behavior during different phases of the evacuation process. It also describes the management and operation of transportation infrastructure and evacuation assets, with illustrations of evacuation planning, evaluation, and results.

In summary, this book focuses on self-evacuation by personal vehicle. It introduces the reader to the steps involved in evacuation modeling by providing an understanding why hazards trigger evacuations, how authorities decide to issue evacuation advisories, how households respond to those warnings, and how traffic management strategies can make evacuations faster and safer. At each step, the emphasis is on the use of mathematical models for use in simulations that can be employed to assess the effectiveness of alternative evacuation management plans. The goal is to help evacuation planners learn from *simulated*, as well as *actual*, experience. Using computer simulations to identify flaws in evacuation plans before they are implemented on the road will ultimately save lives.

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Chapter 2

# Natural and Technological Hazards Requiring Evacuation Management

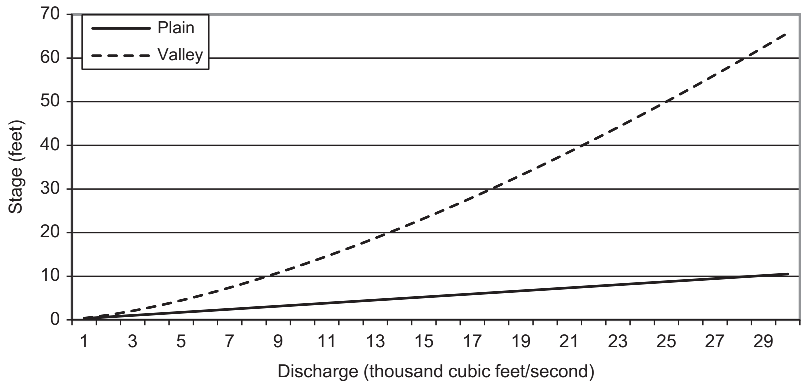
This chapter addresses a set of hazards that require evacuation management because they strike too fast for spontaneous relocation (which is possible for lava flows from effusive volcanic eruptions) but not so fast that evacuation is unsafe (as is the case for tornadoes). Section 2.1 addresses floods, Section 2.2 addresses tsunamis, Section 2.3 addresses wildfires, Section 2.4 addresses hurricanes, and Section 2.5 addresses hazardous materials releases.

## 2.1 Floods

Flooding is a widespread problem in the United States that accounts for three quarters of all Presidential Disaster Declarations. There are seven different types of flooding that are widely recognized. *Riverine (main stem) flooding* occurs when surface runoff gradually rises to flood stage and overflows its banks. *Flash flooding* is defined by runoff reaching its peak in less than six hours. This usually occurs in hilly areas with steep slopes and sparse vegetation, but also occurs in urbanized areas with rapid runoff from impermeable surfaces such as streets, parking lots, and building roofs. *Alluvial fan flooding* occurs in deposits of soil and rock found at the foot of steep valley walls in arid Western regions. *Ice/debris dam failures* result when an accumulation of downstream material raises the water surface above the stream bank. *Surface ponding/local drainage* occurs when water accumulates in areas so flat that runoff cannot carry away the precipitation fast enough. *Fluctuating lake levels* can occur over short term, seasonal, or multiyear periods, especially in lakes that have limited outlets or are entirely landlocked. *Control structure (dam or levee) failure* has many characteristics in common with flash flooding.

Floods are measured either by *discharge* or *stage*. Discharge, which is defined as the volume of water per unit of time, is the unit used by hydrologists. Stage, which is the height of water above a defined level, is the unit needed by emergency managers because flood stage determines the level of casualties and damage. Discharge is converted to stage by

**Figure 2.1** Stage Rating Curve




From Lindell et al. 2006

means of a rating curve (see Figure 2.1). The horizontal axis shows discharge in cubic feet per second and the vertical axis shows stage in feet above flood stage. Note that high rates of discharge produce much higher stages in a valley than on a plain because the valley walls confine the water.

Flooding is affected by a number of factors. The first of these, precipitation, must be considered at a given point and also across the entire watershed (basin). The total precipitation at a point is equal to its intensity of precipitation (frequently measured in inches per hour) times its duration. Total precipitation over a basin is equal to precipitation summed over all points in the surface area of the basin. The precipitation's contribution to flooding is a function of temperature because rain (a liquid) is immediately available whereas snow (a solid) must first be melted by warm air or rain. Moreover, as indicated by Figure 2.2, the precipitation from a single storm might be deposited over two or more basins and the amount of rainfall in one basin might be quite different from that in the other basin. Consequently, there might be severe flooding in a town on one river (City A) and none at all in a town on another river (City B) even if the two towns received the same amount of rainfall from a storm.

Flooding is also affected by surface runoff, which is determined by terrain and soil cover. One important aspect of terrain is its slope, with runoff increasing as slope increases. In addition to slope steepness, slope length and orientation to prevailing wind (and, thus, the accumulation of rainfall and snowfall) and sun (and, thus, the accumulation of snow) are also important determinants of flooding.

Slope geometry is also an important consideration. Divergent slopes (e.g., hills and ridges) provide rapid runoff dispersion. By contrast, convergent slopes (e.g., valleys) provide runoff storage in puddles, potholes, and ponds. Mixed slopes have combinations of these, so slope mean (the average slope angle) and variance (the variability of slope angles) determine the amount of storage. A slope with a zero mean and high variance (a plain with many potholes) will provide a larger amount of storage than a slope with a zero mean and low variance (a featureless plain). Similarly, a slope with a positive mean and high variance (a slope with many potholes) will provide a larger amount of storage than a slope with a positive mean and low variance.

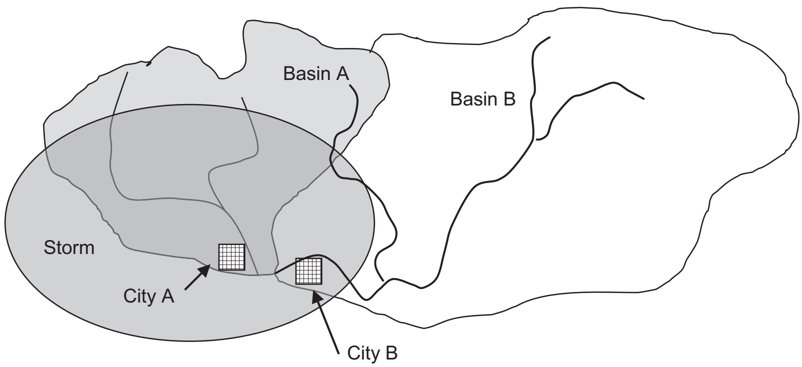
Soil cover also affects flooding because dense low plant growth slows runoff and promotes infiltration. In areas with limited vegetation, surface permeability is a major determinant of flooding. Surface permeability increases with the proportion of organic matter content because this material absorbs water like a sponge. Permeability also is affected by surface texture (particle size and shape). Clay, stone, and concrete are very impermeable because particles are small and smooth, whereas gravel and sand are very permeable—especially when the particles are large and have irregular shapes that prevent them from compacting. Finally, surface permeability is affected by soil saturation because even permeable surfaces resist infiltration when soil pores (the spaces between soil particles that ordinarily are filled with air) become filled with water. Groundwater flows via local transport to streams at the foot of hill slopes and via remote transport through aquifers. Rapid in- and outflow through valley fill increases peak flows whereas very slow in- and outflow through upland areas maintains flows between rains.

Evapotranspiration takes place via two mechanisms. First, there is direct evaporation to the atmosphere from surface storage in rivers and lakes. Second, there is uptake from soil and subsequent transpiration by plants. Transpiration draws moisture from the soil into plants' roots, up through the stem, and out through the leaves' pores (similar to people sweating). The latter mechanism is generally much higher in summer than in winter due to increased heat and plant growth, but transpiration is negligible during periods of high precipitation.

Stream channel flow is affected by channel wetting which infiltrates the stream banks (horizontally) until they are saturated as the water rises. In addition, there is seepage because porous channel bottoms allow water to infiltrate (vertically) into groundwater. Channel geometry also influences flow because a greater channel cross-section distributes the water over a greater area, as does the length of a *reach* (distinct section of river) because longer reaches provide greater water storage. High levels of discharge to downstream reaches can also affect flooding on upstream reaches because flooded downstream reaches slow flood transit by decreasing the river's elevation drop.

Flooding increases when upstream areas experience deforestation and overgrazing, which increase surface runoff to a moderate degree on

**Figure 2.2** Map of the Distribution of Precipitation From a Storm




From Lindell et al. 2006

shallow slopes and to a major degree on steep slopes as the soil erodes. The sediment is washed downstream where it can silt the channel and raise the elevation of the river bottom. These problems of agricultural development are aggravated by flood plain urbanization. Cities throughout the world have been located in flood plains because water was the most efficient means of transportation until the mid-1800s. Consequently, many cities were located at the head of navigation or at transshipment points between rivers. In addition, cities have been located in flood plains because level alluvial soil is very easy to excavate for building foundations. Finally, urban development takes place in flood plains because of the aesthetic attraction of water. People enjoy seeing lakes and rivers, and pay a premium for real estate that is located there.

One consequence of urban development for flooding is that cities involve the replacement of vegetation with *hardscape*—impermeable surfaces such as building roofs, streets, and parking lots. This hardscape decreases soil infiltration, thus increasing the speed at which flood crests rise and fall. Another factor increasing flooding is intrusion into the flood plain by developers who fill intermittently flooded areas with soil to raise the elevation of the land. This decreases the channel cross-section, forcing the river to rise in other areas to compensate for the lost space.

### 2.1.1 Flood Hazard Analysis

Flood risk areas in the US are generally defined by the 100-year flood—an event that scientists estimate to have a 1% chance of occurrence in