

ORGANIZATIONAL COMMUNICATION AND DECISION MAKING IN HURRICANE EMERGENCIES

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by

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ABSTRACT

This paper reviews research and theory on the processes by which emergency relevant organizations communicate with each other and with the population at risk from a hurricane strike. The technology for hurricane forecast, warning, and protective action has made significant advances in the past 20 years, but there is a disturbing potential for hurricane strikes that cause a large number of casualties in addition to the predictably large economic cost from property destruction. Consequently, social science research is needed to expand the existing knowledge base on the response of households, businesses, and special facilities to hurricane warnings. Available research suggests local officials need better information about evacuation time estimates, evacuation costs, and the potential loss of life in a late evacuation. They also need improved decision support systems that will facilitate the choice of appropriate protective actions when hurricanes threaten their jurisdictions.

INTRODUCTION

Since the Galveston hurricane of 1900 killed approximately one-third of the population of that city, the annual death toll from hurricanes striking the United States has continually decreased. This decrease in casualties is not due to a decrease in the population at risk—on the contrary, there has been a major increase in the population of the coastal counties along the Atlantic and Gulf coasts (Pielke and Pielke 1997). Nor can the decrease be attributed to increased hazard mitigation; few local jurisdictions have adopted more effective land use practices and building construction practices (Mileti 1998). Instead, the vast majority of coastal cities and counties continue to permit development in vulnerable areas and to allow low-rise wood frame structures to be constructed at grade level. The reduction in U.S. hurricane casualties, then, can be attributed to improved forecast and warning coupled with timely and effective evacuations implemented in response to imminent threats. Indeed, recent years have seen steady reductions in the hurricane forecast error of prediction for the point of landfall, time at which the storm arrives, and size and intensity. Nonetheless, the probability of a repeat of the Galveston disaster will increase if the National Weather Service's improvements in forecast accuracy cannot keep up with increasing evacuation times for the largest coastal cities.

To understand why vulnerability to a catastrophic loss of life might be increasing despite improvements in forecast accuracy and what can be done to avoid future catastrophes, it is helpful to adopt a systems perspective that examines the process by which the population at risk responds to hurricane forecasts. The following sections describe an integrated model of the population protection process, which is based on the systems prospective proposed by Mileti, Drabek, and Haas (1975) and Perry, Lindell, and Greene (1980) and extended by research conducted over the intervening 25 years (see summaries by Lindell and Perry 1992, 2004; Sorensen 2000; and Tierney, Lindell, and Perry 2001). This research has shown that the units of the emergency management system perform four basic functions in any emergency—emergency assessment, expedient hazard mitigation, population protection, and incident management. *Emergency assessment* consists of diagnoses of past and present conditions and prognoses of future conditions that guide emergency personnel in their efforts to mitigate damage and prevent—or at least limit the magnitude of—the hazard to persons and property. *Expedient hazard mitigation* refers to those activities performed to limit the magnitude of hazard impact, whereas *population protection* refers to actions taken to prevent or minimize exposure of individuals to these hazards. *Incident management* consists of activities by which the human and physical resources used to respond to the emergency are maintained and controlled to accomplish the goals of the emergency response effort.

As Table 1 shows, these four emergency response functions are performed by a variety of parties—the National Hurricane Center (NHC), state and local emergency management agencies, the news media, and the risk area population (households, businesses, and special facilities). However, some of the parties play unofficial roles in the process, as is the case where the news media, households, businesses, and special facilities engage in the informal process of risk perception (designated in Figure 1 by parentheses around this activity) rather than the more formal role of emergency classification. In addition, some of the parties have no responsibility for some of the functions. For example, only households, businesses, and special facilities are responsible for performing tasks associated with the expedient hazard mitigation function. Similarly, the NHC has no *direct* role in the population protection function.

Table 1. Emergency response function allocation

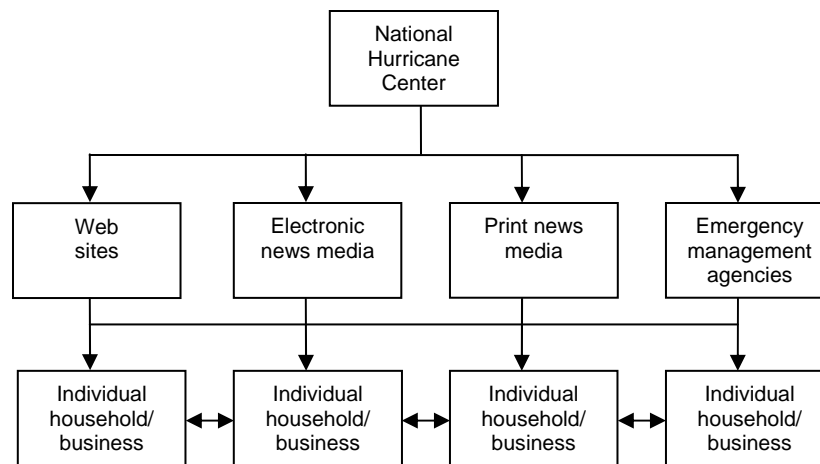
Social unit	Emergency assessment	Expedient hazard mitigation	Population protection	Incident management
National Hurricane Center	<ul style="list-style-type: none"> • Threat detection • Impact projection • Emergency classification 			<ul style="list-style-type: none"> • Activation • Notification • Internal and external coordination • Public information
State emergency management agencies	<ul style="list-style-type: none"> • Emergency classification 		<ul style="list-style-type: none"> • Protective action selection (some states) 	<ul style="list-style-type: none"> • Activation • Notification • Internal and external coordination • Public information
Local emergency management agencies	<ul style="list-style-type: none"> • Emergency classification 		<ul style="list-style-type: none"> • Protective action selection (some states) • Warning • Protective action implementation 	<ul style="list-style-type: none"> • Activation • Notification • Internal and external coordination • Public information
News media	<ul style="list-style-type: none"> • (Risk perception) 		<ul style="list-style-type: none"> • Warning 	<ul style="list-style-type: none"> • Activation • Notification • Public information
Households/ businesses/ special facilities	<ul style="list-style-type: none"> • (Risk perception) 	<ul style="list-style-type: none"> • Area protection • Debris control • Contents protection • Structural protection 	<ul style="list-style-type: none"> • Warning • Protective action implementation 	<ul style="list-style-type: none"> • Activation • Internal and external coordination

Past research has identified the interrelationships among these parties, and a simplified representation is depicted in Figure 1. Specifically, hurricane information flows from the primary initial source (the NHC) through intermediate links (Web sites, print media, electronic media, and state and local emergency management agencies) to the ultimate receivers (households, businesses, and special facilities) in threatened communities. In addition to identifying the sources, channels, and receivers, previous research has also identified the message content that flows along the channels from sources to receivers—especially from the news media and emergency management agencies to the risk area population. Less is known, however, about the ability of receivers at different stages to utilize the necessary information or the speed at which information is received at intermediate and end points in the network. Nor is there a good understanding of the consequences of information from additional sources, such as commercial weather forecast providers, that interpret NHC data or even generate their own data and models to produce alternative forecasts. These issues will be discussed later in the context of each of the parties in the warning network.

The National Hurricane Center

As noted earlier, the NHC is the principal source of hurricane emergency assessment, although commercial weather forecasting services also disseminate information to some news media and certain businesses (e.g., oil pumping platforms and refineries along the coast). The NHC accomplishes this function by monitoring data from satellite images, radar images, and telemetry from “hurricane hunter” aircraft. These data are processed by storm forecasting models and

evaluated by NHC staff, who assess the need to declare hurricane watches and warnings in addition to projecting hurricane intensities and formulating strike probabilities for specific coastal locations (see *Forecasting Models* on the National Hurricane Center Web site; <http://nhc.noaa.gov>).



NHC staff generate Tropical Cyclone Forecast/Advisories, Tropical Cyclone Public Advisories, Tropical Cyclone Discussions, Tropical Cyclone Strike Probabilities, Tropical Cyclone Updates, and Tropical Cyclone Position Estimates. A Tropical Cyclone Forecast/Advisory contains a list of all current watches and warnings about a tropical or subtropical cyclone, as well as the current latitude and longitude coordinates, intensity, and system motion. The Forecast/Advisory contains forecasts of the cyclone positions, intensities, and wind fields for 12, 24, 36, 48, and 72 hours from the time the information is released. The Forecast/Advisory may also include information on any pertinent storm tides associated with the cyclone. Forecast/Advisories are routinely issued every 6 hours, but Special Forecast/Advisory messages are issued any time there is a significant change in storm behavior. The first Forecast/Advisory is normally issued when meteorological data indicate that a tropical or subtropical cyclone has formed, and subsequent advisories are issued every 6 hours (at 0300, 0900, 1500, and 2100 UTC). Even though it is possible that there could be almost a 6-hour lag if a storm escalated to hurricane status just after the previous Forecast Advisory was released, most tropical cyclones originate far from the U.S. coast and are tracked as Tropical Depressions or Tropical Storms before they intensify to hurricane status. Moreover, the average forward movement speed of tropical cyclones is about 12 mph (27 m/s), so even a 6-hour time lag would not be an especially problematic delay. A hurricane can vary significantly over time in its track, forward movement speed, intensity (maximum wind speed), and size (radius of maximum wind). Finally, the NHC's incident management function is to notify state and local emergency management agencies, the news media, and the public of the impending danger and to provide a continuing stream of information about its emergency assessment to these parties. This essential information is released to its Web site and news media, as well as to state and local emergency managers via briefings, conference calls, and uploads to HURREVAC (Federal Emergency Management Agency 2000) and HURRTRAK (PC Weather Products, Inc. 1996).

State and Local Emergency Management Agencies

State and local emergency management agencies perform an incident management function by activating in response to the threat and by monitoring the impact projections (e.g., strike

probabilities and hurricane intensities) and emergency classifications (e.g., watches and warnings). Although there are some cases in which hurricanes form rapidly in the Gulf of Mexico only a few hundred miles from the U.S. coast, state and local emergency management agencies are usually activated days before a hurricane makes landfall. Consequently, a major element of these agencies' incident management function is to monitor the continuing stream of information from the NHC about storm behavior. This information allows state and local emergency managers to monitor the storm track and hurricane intensity and to forecast the storm's future path and wind swath. Storm tracking software such as HURREVAC and HURRTRAK has the capability of plotting uncertainty bounds so future storm behavior is mapped in terms of cones (of increasing width over time) rather than point estimates.

State and local emergency management agencies serve a population protection function by selecting and recommending protective actions for areas determined to be at risk from hurricane impact. Depending on state law, protective action recommendations are made either at the state or local level. Warning and protective action implementation, however, are performed at the local level. Each of these subfunctions is discussed in more detail in the sections that follow.

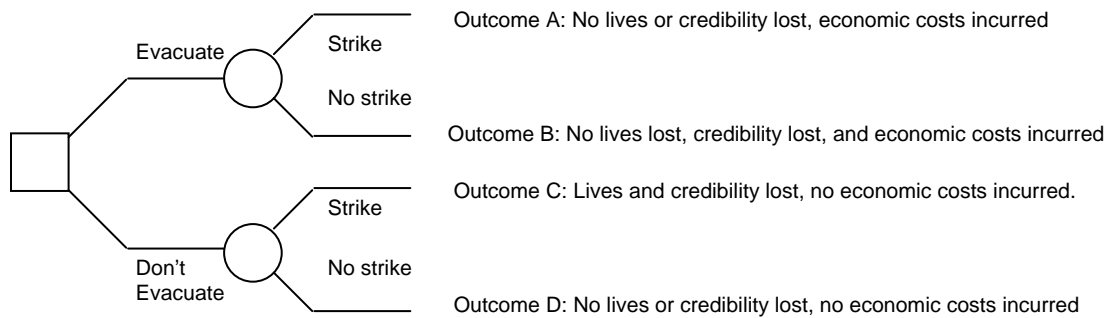
Protective Action Decision Making

As noted earlier, most coastal structures are low-rise wood frame structures constructed at grade level, making them highly vulnerable to hurricane damage. As a result, the appropriate population protective action for areas at risk from a hurricane is almost always evacuation. However, there usually is a substantial amount of uncertainty about where and when evacuation will be needed. A major problem is that there sometimes is only a small probability of a hurricane strike when an evacuation decision must be made. This occurs when evacuation time estimates for the general population exceed 36 hours, as is the case in some urban jurisdictions. When a hurricane is 36 hours from landfall, the NHC can issue only a maximum strike probability of 25%. If the storm has an erratic path, the strike probabilities could be even lower. Emergency managers are understandably reluctant to initiate evacuations when the strike probability is this low because their jurisdictions are certain to incur significant costs in an evacuation. Specifically, household costs for gas, food, and lodging costs averaged \$262.57 per household in Hurricane Lili (Lu, Lindell, and Prater 2004). In addition, businesses will incur significant losses because of lost revenues while residents are gone or when tourists evacuate after hotels close (Drabek 1996), and by local government for overtime and other expenses that accrue during management of the evacuation. All of these costs will be incurred even if there is no hurricane damage. Unfortunately, the data on household evacuation costs are quite limited and data on business and government costs are virtually nonexistent. Because of the inadequate data, local officials currently must either guess what these costs will be or ignore them altogether. In addition, local officials should consider the likely loss of life if they delay too long before making an evacuation recommendation. Here also, there appear to be no data or methods for estimating what would be the loss of life in a late evacuation, and local officials must either guess what the casualties would be or ignore them altogether.

The previous discussion indicates that hurricane evacuation decisions inherently involve a choice between alternatives that differ on a number of criteria with different units of measurement (i.e., incommensurable) that are characterized by a significant amount of uncertainty. The most appropriate technology for coping with this type of situation is decision analysis (Raiffa 1968), and the decision to initiate a hurricane evacuation can be represented pictorially with a decision

tree (e.g., Clemen 1996, p. 58). Figure 2 represents the choice of whether or not to recommend an evacuation by the square on the left side of the decision tree and two alternative courses of action that branch the right. Each of the branches from the decision intersects a circle that represents an uncontrollable event—whether or not a hurricane strikes the official’s jurisdiction. Because the hurricane either will or will not strike, two branches emanate from each of the circles. Each of the four branches on the right-hand side of the diagram represents one of the four outcomes that can occur when there are two decision alternatives and the uncontrollable environmental event can have two states. Each of the four outcomes can be evaluated in terms of the number of lives lost, the source credibility lost, and the economic costs incurred. Note that in making an evacuation decision, the only cost to consider is that of the evacuation itself, not the cost of a hurricane impact (should it occur). This is because the cost of the evacuation is the only economic cost that can be avoided by withholding an evacuation recommendation.

Figure 2. Evacuation decision tree



Outcome A is a correct decision because the evacuation saved lives and maintained credibility that would have been lost if the storm had not struck. Nonetheless, evacuation costs are incurred. Outcome D is also a correct decision, but this is because no lives turn out to have been at risk, no credibility is lost, and no evacuation costs are incurred. By contrast, Outcome B is a decision error (a “false positive”) because evacuation costs are incurred even though no lives are lost. Outcome B reduces credibility and decreases future warning compliance. Outcome C is also a decision error (a “false negative”), but for the opposite reason. No evacuation costs are incurred, but lives are lost because of the failure to recommend an evacuation and lost credibility is likely to increase spontaneous evacuation in future hurricanes.

The difficulty in making an evacuation decision is derived from the fact that the NHC’s maximum strike probability is 25% at 36 hours, but evacuation time estimates (ETEs) exceed 30 hours for major urban areas along the Gulf and Atlantic coasts. Consequently, local officials in these jurisdictions must decide whether to implement an evacuation when there is only about a one-in-four chance that they will be struck by the hurricane. If a decision maker’s jurisdiction is directly on the hurricane track, this uncertainty will not cause problems because most decision makers would opt to evacuate. Conversely, if the strike probability is less than 1%, most decision makers would choose not to evacuate. There is a range of probabilities between these two extremes, however, in which an evacuation decision will be extremely difficult to make, but existing hurricane decision support systems provide no guidance on how to address this uncertainty. Moreover, existing decision support systems are limited to treating the time at which

the decision must be made as a deterministic value. In other words, the ETE for a given jurisdiction is provided as a point estimate (e.g., “27 hours”) even though the data on which the ETEs are based should be characterized by distributions of values (e.g., 10% certain to be less than 22 hours; 50% certain to be less than 27 hours; and 90% certain to be less than 33 hours). Finally, existing hurricane decision support systems ignore evacuation costs (the consequence of a false positive) and lives lost (the consequence of a false negative). The complexity of these considerations indicates a need to better understand how state and local emergency managers evaluate and integrate the available information, and indeed, if they are receiving all the relevant information. Unfortunately, there appears to be little or no research on the process by which state and local emergency managers decide when and where to recommend evacuation.

Warning

Warning those at risk involves a number of issues, many of which are well researched and understood (Drabek 1986; Lindell and Perry 1992, 2004; Sorensen 2000; Tierney, Lindell, and Perry 2001). First, local government authorities (e.g., emergency management, fire, and police) are only one source of warning; those at risk usually receive many warnings from the news media and peers (friends, relatives, neighbors, and coworkers). Warning recipients also attempt to obtain confirmation and additional information from sources other than the one from which they received the initial warning. Second, emergency managers can disseminate warnings via many different mechanisms that vary significantly in characteristics such as precision of dissemination, penetration of normal activities, specificity of the message, susceptibility to message distortion, rate of dissemination over time, receiver requirements, sender requirements, and feedback from recipients (Lindell and Perry 1987, 1992; Sorensen 2000). Third, warning messages should clearly describe the threat and its personal consequences to those at risk, provide guidance about a protective action, and indicate sources of additional information (Mileti & Sorensen 1987; Mileti and Peek 2001). Fourth, emergency managers should be aware of differences among population segments, especially ethnic groups, in their access to warning mechanisms and perceptions of warning source credibility (Perry and Mushkatel 1986; Lindell and Perry 2004). Finally, emergency managers should attempt to obtain feedback by monitoring the news media and providing “hotlines” where citizens can obtain additional information (Perry, Lindell, and Greene 1981).

Protective Action Implementation

The past 25 years have seen major advances in techniques for modeling protective action implementation. At one extreme are macroanalytic models such as EMBLEM (Lindell et al. 2002) that are used to provide approximate ETEs for multicounty hurricane evacuations taking from 8 to more than 40 hours to implement. At the other extreme are microanalytic models such as OREMS (Oak Ridge National Laboratory, n.d.) that are designed to generate ETEs for small areas threatened by rapid onset threats (e.g., toxic chemical releases). There are many published ETE models (Tweedie et al. 1986; Urbanik, Moeller, and Barnes 1988a, 1988b; Safwat and Youssef 1997; Hobeika and Kim 1998; Barrett, Ran, and Pillai 2000) and they vary significantly in their mathematical sophistication and the apparent precision of their estimates. There has been little effort, however, to validate either the trip generation times used as inputs or the mathematical models of evacuees’ assumed behavior to determine if these correspond to the findings from empirical research. One major uncertainty concerns the rate of traffic flow when the demand on evacuation routes in the risk area exceeds their capacity—especially when queues

take many hours to clear. The importance of knowing more about the duration of the queues (and their effect on flow rates) is widely recognized because it raises significant uncertainties about average vehicle speeds and, thus, evacuation route capacity. It also is important to learn about the *location* of the queues because those inside the risk area are potentially life threatening whereas those outside the risk area are merely inconvenient and annoying.

Although the household is the principal unit of analysis in modeling protective action implementation, local government agencies play an important role in this process—especially in the evacuation of densely populated areas. First, local government agencies must provide *traffic management* when a large number of households is likely to exceed the capacity of the evacuation route system. In particular, traffic management actions can have a significant effect on the time it takes to clear the risk area by maintaining maximum traffic flows on individual segments in the evacuation route system or by equalizing the traffic load on parallel routes. Second, local government agencies provide *transportation support* for those who lack physical mobility or rely on public transportation. Such actions can ensure that all households in the risk area are able to evacuate.

News Media

One important official functions of the news media is incident management, which consists of activating in response to the threat, coordinating with the NHC and state and local emergency management agencies by monitoring the impact projections (e.g., strike probabilities and hurricane intensities) and emergency classifications (e.g., watches and warnings), and providing public information to those who are not at risk. In addition, the news media provide a population protection function by disseminating warnings to those in the risk area. However, the news media also play an unofficial role by interpreting storm data to develop their own independent emergency assessments. Table 1 lists this activity as *risk perception* rather than *emergency classification* because the emergency assessment capabilities of news media personnel tend to be more similar to those of the public than to those of NHC personnel and state/local emergency managers.

Households, Businesses, and Special Facilities

Households, businesses, and special facilities perform an incident management function by activating in response to the threat and by monitoring the available information disseminated by the NHC, state and local emergency management agencies, the news media, and peers (friends, relatives, neighbors, and coworkers). Like the news media, these entities play an unofficial role by interpreting storm data to develop their own independent emergency assessments (i.e., risk perceptions). However, they also engage in expedient hazard mitigation by taking last-minute actions to protect structures from flooding (e.g., by sandbagging) and to control debris that might become missiles in high wind. In addition, they attempt to protect building contents by elevating them beyond the expected water level of inland flood or storm surge and protect structures by actions such as installing shutters.

Finally, households, businesses, and special facilities serve a protective action function in two ways. First, they relay warnings to those they think might not have received them. This informal warning network supplements the official warning network and increases the rate at which warnings are received by those in the risk area (Lindell et al. 1984; Lindell and Perry 1987; Rogers and Sorensen 1988, 1989). Second, households, businesses, and special facilities

implement protective action—especially evacuation—when the threat reaches an unacceptable level. However, there is almost always a significant time delay after warning receipt before protective action is initiated. This delay is produced by *psychological preparation* (seeking and processing additional information until they are certain evacuation is necessary) and *logistical preparation* (uniting household members, protecting property, and collecting clothing and other materials needed while away from home). The significance of logistical preparation is obvious, but the role of psychological preparation is usually not so obvious. Research on warning response (Drabek 1986; Lindell and Perry 2004) does clearly indicate that people engage in *milling*, during which they seek confirmation that a danger exists, obtain further information about the threat and alternative protective actions, and relay warnings to peers. The broad outlines of this process are understood (Gladwin and Peacock 1997; Gladwin, Gladwin, and Peacock 2001; Lindell and Perry 2004), but insufficient information is available to accurately forecast the timing of the risk area population's protective response.

Warning Time Distributions

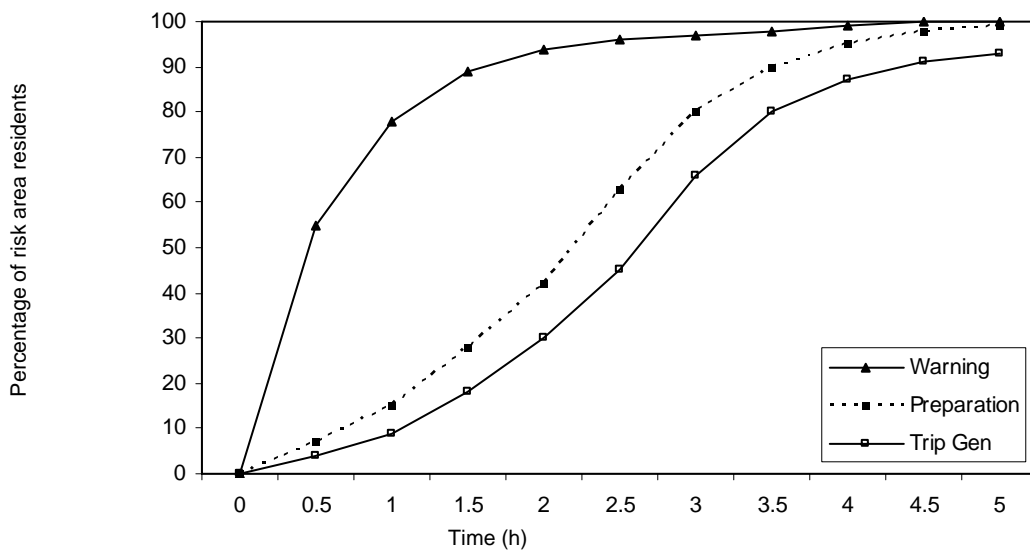
Previous research has found that risk area residents receive warnings from the official warning network of authorities and the news media (mostly radio and television) and also from an informal warning network of peers (Drabek 1986). In some instances, the informal warning network can account for a significant proportion of all first warnings (Lindell and Perry 1987). This finding suggests that warnings can be modeled as a process comprising two components: (1) the official (“broadcast”) component and (2) the informal (“contagion”) component (Rogers and Sorensen 1988). Unlike the official warning network, which is organized and planned in advance, the informal warning network emerges during the incident from proximity (neighbors), kin (relatives), and other social ties (friends and coworkers). It is thus possible for planners to identify the components of the formal warning network, estimate the cumulative distribution of warning reception times, and modify the network design if the resulting warning reception distribution is inadequate. However, the diffuse and emergent nature of the informal network precludes modeling the individual elements, so the contribution of this source to the overall warning reception distribution has usually been ignored. Unfortunately, ignoring the contribution of the informal warning network can cause a systematic downward bias in the warning reception distribution, leading to overestimates of the amount of time needed to warn the risk area population. This is obviously a problem for rapid onset incidents such as flash floods and tsunamis, but can also be a problem if a hurricane makes a late change in track toward a densely populated area.

Sorensen (1991) sought to identify predictors of household warning reception times in the Nanticoke chemical incident, but did not report the overall distribution of warning times. Some recent research has attempted to model the time dependence of the warning reception process for hurricanes. Lindell et al. (2002; see also Lindell and Perry 2004) used data from the eruption of Mt. St. Helens to assess the expected time distribution for warning diffusion in a hurricane making a late change in track (see Figure 3). However, one problem in assessing warning reception times for many hurricanes is that households receive many different messages that might be interpreted as warnings, and some of these are received before an official warning is issued. Indeed, a significant proportion of the households threatened by Hurricane Lili decided to evacuate before authorities issued an official evacuation warning (Lu, Lindell, and Prater 2004).

Preparation Time Distributions

Only a limited amount of research has been conducted on preparation time distributions. Lindell et al. (2002) estimated hurricane evacuation preparation times by summing Texas coastal residents' expectations about the time they would need to perform six evacuation preparation tasks: prepare to leave work; travel from work to home; gather all persons who would evacuate with the household; pack items needed while gone; protect property from storm damage; and shut off utilities, secure the home, and leave. Lu et al. (2004) reported the overall trip generation time distribution derived from data collected from evacuees' reports after their evacuation because of Hurricane Lili. These researchers found the aggregate preparation time distribution from the Lindell et al. (2002) hurricane expectations data collected 2 years earlier was quite similar to the aggregate preparation time distribution from the Hurricane Lili data. Moreover, Kang, Lindell, and Prater (2004) examined data from a group of 51 respondents who had replied to both questionnaires. These investigators found the individual expectations of preparation times significantly predicted respondents' later reports of the times actually required to perform these tasks. However, the preparation time components used in this research were limited to logistical preparation and did not specifically address psychological preparation. Consequently, there are no available estimates of the amount of time spent in each of these two types of activities. The available qualitative data (Baker 1991; Gladwin and Peacock 1997) suggest that the amount of time spent in either type of preparation will depend on the characteristics of the warning source (especially its credibility); the nature of the threat described in the warning message (especially its likelihood, severity, and imminence); and personal circumstances (especially separation of the family). Thus, the shape of the preparation time distribution can be expected to vary by type of hazard agent (e.g., hurricane, flash flood, or tsunami), incident-specific conditions (e.g., hurricane track and forward movement speed stability), and location-specific conditions (e.g., population size and cohesiveness, evacuation route system). As a result, additional research is needed to assess the effects of these factors on the distribution of preparation times.

Figure 3. Sample warning reception, preparation time, and trip generation time distributions



RESEARCH NEEDS

Further research is needed to improve organizational communication and decision making by refining existing models of warning and evacuation models. This goal can be achieved by improving the methods of estimating the time distributions for warning reception, evacuation preparation, and evacuation response. In addition, research is needed on evacuation transportation support and traffic management. Finally, research is needed on the processes by which state and local emergency managers make evacuation decisions and the ways in which decision support systems can be developed to assist them.

Warning

Estimates of warning reception time distribution can be improved by developing a comprehensive model of the formal and informal warning networks. The difficulty is that the formal warning network consists of linkages among the individual identifiable warning sources but the informal warning network's elements are numerous and can be modeled only in aggregate rather than identified individually. In addition to modeling the linkages among the warning sources, the model must be able to integrate the distribution of warning reception times for each of the warning sources in order to produce an overall distribution of warning reception times. Preliminary analysis of this problem suggests that it can be modeled by constructing an event tree to model the principal types of linkages among warning sources (initial and intermediate) that ultimately link to the final receivers. That is, instead of trying to model linkages among all of the elements of the network, it is necessary to model only the principal types of linkages and estimate their relative frequency. As noted earlier, Figure 1 depicts a very broad schematic model of the principal warning paths from the NHC to the population at risk that could be extended to encompass specific types of warning recipients. In such a model, the arc connecting any two elements that are directly linked can be represented by a weight indicating the importance of that arc in propagating the warnings to the ultimate receivers. Each successive stage would have its own importance weights, so multiplication of the weights would indicate the proportion of the receivers who receive a warning via that path. The warning reception time distribution for each path could be weighted by its likelihood and integrated with the warning reception time distributions for the other paths to produce the overall warning reception time distribution. Such a model would be an improvement over previous work in this area that has modeled either the formal warning network only (usually by assuming a deterministic delay; Ruch and Schumann 1997, 1998; Safwat and Youssef 1997) or some unknown composite of the formal and informal warning networks (Lindell et al. 1985; Lindell and Perry 1987; Rogers and Sorensen 1988, 1989). Specifically, the latter researchers modeled the time-dependent warning process in terms of a diffusion process that can be expressed as

$$dn/dt = k[a_b(1 - n_t)] + (1 - k)[a_c n_t(1 - n_t)], \quad (1)$$

and computed more directly as

$$B_{t+1} = B_t + [a_b(1 - n_t)], \quad (2)$$

$$C_{t+1} = C_t + [a_c n_t(1 - n_t)], \text{ and} \quad (3)$$

$$T_{t+1} = kB_{t+1} + (1 - k)C_{t+1}, \quad (4)$$

where dn/dt is the total proportion of households warned at time t ; k is the proportion warned by the broadcast process; a_b is the efficacy of the broadcast process; a_c is the efficacy of the peer warning process; n_t is the proportion warned at time t ; B_t is the cumulative proportion warned by the broadcast process at time t ; C_t is the cumulative proportion warned by the peer warning process at time t ; and T_t is the cumulative proportion of all households warned at time t . Rogers and Sorensen (1988) concluded from the limited evidence available that the parameters of the warning diffusion process varied across warning mechanisms (e.g., sirens, tone alert radio, or telephone), but refers only to the broadcast component of the warning diffusion process. The findings of previous warning studies suggest there is likely to be variation in the peer warning process attributable to community characteristics such as social integration, which, in turn, is related to demographic characteristics such as ethnicity. There appear to be insufficient warning time data, however, to estimate the parameters of the mathematical diffusion model.

Household Preparation and Response

Additional data need to be collected after future hurricanes to assess the generalizability of the preparation data from Hurricane Lili reported by Kang, Lindell, and Prater (2004) and Lu, Lindell, and Prater (2004). In addition, response time estimation procedures need to be improved by examining reports of other evacuations to determine if evidence exists on evacuee behavior in transit from home to a shelter destination. Specific issues should include evacuees' choice of routes (how many vehicles are taken per household, what percentage take unofficial evacuation routes, whether demand is distributed over all of the official evacuation routes, and what is the evacuation rate in vehicles per hour). In addition, future research should compare these models in terms of

- Their assumed trip generation time distributions
- Their time requirements for modeling a jurisdiction's evacuation route system
- Their training time requirements for operational use by emergency managers
- Their utility for guiding the emergency preparedness/hazard mitigation decisions about the redesign of the evacuation route system (e.g., link capacity and system reconfiguration)
- The adequacy of their support for emergency managers' operational decisions about when and where to evacuate
- The ETEs they produce (Urbanik 2000)

The development of these models will require the collection of large-scale (e.g., sample sizes exceeding 250 respondents) survey data from many hurricane evacuations that vary in the characteristics of the incidents (e.g., Saffir-Simpson intensity and track stability) and communities affected (population size and cohesiveness, evacuation route system capacity, and level of state and local emergency preparedness). The surveys should also collect data from areas adjacent to the evacuation area, to allow assessment of the extent of evacuation shadow. This data collection effort will provide the foundation for comprehensive spatial models predicting patterns of population protective response at various levels of resolution (e.g., census block, block-group, or tract) that can be used in GIS-based spatial models designed to predict evacuation response rates and times (Wilmot and Mei 2004).

Evacuation Management Decision Support Systems

Recently, Lindell et al. (2002) proposed an ETE model, called EMBLEM, that integrates empirically based trip generation times with a simple one-stage traffic flow model. This model was subsequently used to compute the ETEs for hurricane evacuations in all 22 Texas coastal counties (Lindell et al. 2002). The original version of the model, which was implemented as a spreadsheet, has been upgraded to a Visual Basic program based on a Microsoft Access™ database (Lindell, Naik, Agrawal & Veluswami, 2004). The current version, known as the evacuation management decision support system (EMDSS), combines an ETE module and a storm tracking module with a graphical user interface. The ETE module allows emergency managers to conduct ETE analyses in real time, thus allowing them to vary nine evacuation parameters: (1) evacuation scope (the number of risk areas evacuated); (2) evacuation phasing (the time at which each risk area is evacuated); (3) evacuation route system capacity; (4) number of vehicles per household; (5) number of trailers per household; (6) transit dependent population percentage; (7) number of persons per household; (8) hotel occupancy percentage; and (9) trip generation time distribution to examine the effects of updated information on the ETE for a given set of situational conditions. The values for the minimum probable, most probable, and maximum probable ETEs are displayed along with data on hurricane parameters (Saffir-Simpson category, forward movement speed, track, and strike probability).

The hurricane data (which are currently drawn from scenarios in research and training applications, but would be obtained from the NHC in operational applications) are used together with ETE data to construct two groups of decision arcs. Evacuation arcs are circles around the decision maker's jurisdiction whose radius (distance) is calculated by multiplying the forward movement speed of the hurricane (rate) by the ETE (time). Three evacuation arcs correspond to the minimum probable, most probable, and maximum probable ETEs. Similarly, there are three storm arrival arcs, which are circles around the eye of the hurricane whose radii (distances) are calculated from NHC data on the radius of Tropical Storm force (30 kt; 77 m/s), high-profile vehicle tipping (50 kt; 129 m/s), or hurricane force (64 kt; 165 m/s) wind. The evacuation and storm arrival arcs are plotted along with successive hurricane locations on a screen image of a Gulf of Mexico hurricane tracking map. This allows users to decide when to evacuate their jurisdictions, how large to make the evacuation scope (the number of risk areas evacuated), and whether to implement a phased evacuation (evacuating different risk areas at different times).

In addition, the multistage flow model of evacuation in EMDSS can be used in emergency preparedness to identify the locations of bottlenecks in the evacuation route system. Such problems can be reduced by (1) adopting a strategy of phased evacuations, (2) increasing evacuation route system capacity by adding lanes or new links, or (3) reducing demand by providing safe havens in strategic locations. In addition, EMDSS could be used to support hazard mitigation by identifying limits to development densities or by establishing a need for building code provisions such as elevation out of the flood plain or increased resistance to hydraulic pressures.

The existing version of EMDSS is about to begin usability testing. In the first phase, users will be given 1 hour of training on hurricane evacuation decision making before their first scenario. Although this might seem to be an inadequate amount of time, it actually is comparable to the amount of training received by many local elected officials in Texas who are faced with the responsibility for making hurricane evacuation decisions. The users will be given written training

materials, followed by a *walkthrough* demonstration in which the interface displays and controls are explained. Following the walkthrough they will be presented with a simple scenario and asked to *think aloud* as they monitor the screen, manipulate the controls, and decide when (if at all) to recommend an evacuation. The think-aloud procedure has been used extensively in psychological research and there is compelling evidence of its ability to yield a relatively accurate and complete representation of the subject's thought processes without significantly altering them (Erickson and Simon 1993). After the first scenario, users will be presented with more complex scenarios. Each user will be given only one complex scenario, but multiple scenarios will be used to test all features of the system.

Evacuation Transportation Support and Traffic Management

The emergency management profession, as a whole, has a good understanding of the need to provide transportation support for those who lack physical mobility or who rely on public transportation (e.g., Daines 1991; Texas Governor's Division of Emergency Management 2002). However, it is unclear what percentage of local jurisdictions have adequate plans to address these needs or whether the local emergency managers know how long it would take to evacuate all of these people. Similarly, emergency management professionals understand the need to provide traffic management for the large number of vehicles that will exceed the capacity of the evacuation route system (e.g., Daines 1991; Texas Governor's Division of Emergency Management 2002). However, the quality of evacuation management plans varies significantly. For example, only one of the five Texas Study Areas (coastal regions) has a written regional evacuation plan that coordinates traffic throughout all the counties in the region. There appears to be little data on the quality of the plans and procedures for evacuation transportation support and traffic management in counties that are vulnerable to hurricanes.

Moreover, it is unclear how many jurisdictions have ETEs to use in judging the amount of time needed to evacuate threatened areas or, if they do have ETEs, how many of them are based on empirical data and sound models of the evacuation process. Indeed, perhaps the most significant deficiency in the existing literature on population protective action is the limited amount of empirical research on the timing of warning and evacuation.

SUMMARY AND CONCLUSIONS

The technology for hurricane forecast, warning, and protective action has made significant advances in the past 20 years (Sorensen 2000), but there is a disturbing potential for hurricane strikes that cause a large number of casualties in addition to the predictably large economic cost from property destruction. Consequently, social science research is needed to expand the existing knowledge base on the response of households, businesses, and special facilities to hurricane warnings. As noted earlier, a series of large-scale surveys should be conducted on hurricane evacuations that vary in the characteristics of the storms (e.g., Saffir-Simpson intensity and track stability) and communities affected (population size and cohesiveness, evacuation route system capacity, and level of state and local emergency preparedness). These surveys should collect data from households on warning sources (e.g., source and time of first warning), evacuation decision criteria (e.g., time of evacuation decision and evacuation preparation time components), logistics of evacuation (e.g., number of vehicles taken, evacuation route, and destination), and costs incurred during evacuation. The household surveys should also collect data from areas adjacent to the evacuation area to facilitate assessment of the extent of evacuation shadow and any ways

in which the behavior of spontaneous evacuees differs from those in the area warned to evacuate. Businesses should be surveyed to assess the lost revenue from the evacuation of local residents, as well as tourists and other transients. Local governments should be interviewed to assess the costs these organizations incur (e.g., overtime pay for staffing emergency operations centers and traffic control points on the evacuation routes).

A systematic evaluation of the procedures used for determining hurricane ETEs is also needed. Since early work by Urbanik (1979), a variety of models have been developed and criteria for evaluating them have been identified (Urbanik 1994, 2000). Future research is needed to determine if macroanalytic flow models yield adequate data or if meso- or microanalytic models must be used instead. Research is also needed to determine if these models' assumptions about evacuee behavior (e.g., dynamic traffic assignment) are compatible with the findings of empirical social science research. If, as the available evidence indicates, there are significant errors in modeling assumptions, studies will be needed to determine whether these incorrect assumptions have a significant impact on ETEs.

There is also a need for systematic research on decision support systems and the ways in which state and local officials use these systems in determining where and when to initiate hurricane evacuations. Existing decision support systems such as HURREVAC and HURRTRAK have strong capabilities for tracking storm behavior but more limited capabilities for projecting and monitoring population response. Future decision support systems should incorporate a real-time capability for reassessing ETEs in response to last-minute changes in variables such as hotel occupancy and evacuation route capacity. New decision support systems should be subjected to thorough usability testing to ensure they are compatible with state and local decision makers' cognitive models of the hurricane evacuation process. In addition, these decision support systems should include a variety of training scenarios that give state and local authorities the opportunity to develop their skills in making evacuation decisions. One possibility would be to develop Web-based decision support system that would record users' inputs during training sessions. Such data could be analyzed to identify systematic patterns of user errors and thus guide system designers toward ways to improve the decision support system.

The development of these decision support systems will provide a critical foundation for evacuation decisions, but the development of such tools must be guided by a better understanding of the context in which these decisions are made at the state and local levels. For example, states differ in their statutory authority in terms of which level of government has the authority to initiate evacuations and whether compliance is mandatory. In addition, there can also be considerable variations in how those statutes are implemented. Consequently, the nature of the legal structures and organizational processes can significantly affect the timeliness of evacuation decisions—especially when a rapid decision is needed because of a sudden change in storm behavior. Future research is needed to identify the ways in which the governmental context affects the timing of evacuation decisions.

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