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A hurricane evacuation management decision support system (EMDSS)

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Abstract This article describes the challenges confronting local authorities who must decide if and when to initiate evacuations from tropical cyclones. This problem can be decomposed into the behavior of the hurricane that is relevant to evacuation and the behavior of evacuees that is relevant to the hurricane. The uncertain behavior of these two systems can be modeled in an evacuation management decision support system (EMDSS). The hurricane EMDSS described here displays information about the minimum, most, and maximum probable evacuation time estimates (ETEs) in comparison to the earliest, most, and latest probable estimated times of arrival (ETAs) for storm conditions. In addition, EMDSS calculates the cost of false positive (the economic cost of an evacuation) and false negative (lives lost in a late evacuation) decision errors. EMDSS is being used in experiments to assess different information displays, team compositions, community characteristics, and hurricane scenarios. In addition, it will be used in training and actual hurricane operations. Finally, definition of the program's requirements has identified further research needed to build a better empirical base for its input data.

Keywords Evacuation · Hurricane · Management

1 Introduction

Coastal communities in many parts of the world are vulnerable to tropical cyclones, known as hurricanes in the Atlantic and Eastern Pacific, typhoons in the Western Pacific, and cyclones in the Indian Ocean. When a hurricane threatens, those who live in areas exposed to high wind and surge must evacuate unless they live in

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elevated reinforced structures. In some cases, evacuees number in the tens or even hundreds of thousands, so the large volume of vehicular traffic involved in an evacuation can significantly exceed the capacity of local road networks unless the evacuation is carefully managed. To decide if and when to initiate an evacuation, local authorities must predict the behavior of the hurricane and evacuees, yet both systems can be predicted with only moderate accuracy. Thus, local authorities also need support from an evacuation management decision support system (EMDSS) to make the best possible decision from the data available to them.

2 Basic structure of hurricane and evacuation behavior

The basic structure of hurricane behavior that is relevant to evacuation and the basic structure of evacuation behavior that is relevant to hurricanes are represented in Fig. 1, which depicts a hurricane approaching a vulnerable coastline. The hurricane eye is surrounded by a ring representing the radius of severe storm conditions, such as the arrival of Tropical Storm wind. The hurricane follows a track toward the point of landfall at its forward movement speed (FMS). Consequently, the time until the arrival of severe storm conditions can be determined by subtracting the radius of Tropical Storm wind from the distance of the hurricane eye from the coastline and then dividing this difference by the FMS.

In order to successfully evacuate the vulnerable population, local authorities first need to decide which geographic areas are at risk. These risk areas can be defined by hurricane intensity, which is typically classified by the Saffir-Simpson Categories 1–5. For example, Risk Area 1 is the area affected by a Category 1 hurricane. Once local officials have identified which risk areas are likely to be affected, they need to know how long it would take to evacuate those risk areas. Evacuation time estimates (ETEs) are determined by assessing the risk area population's time-dependent evacuation demand and the capacity of the evacuation route system (ERS) to handle

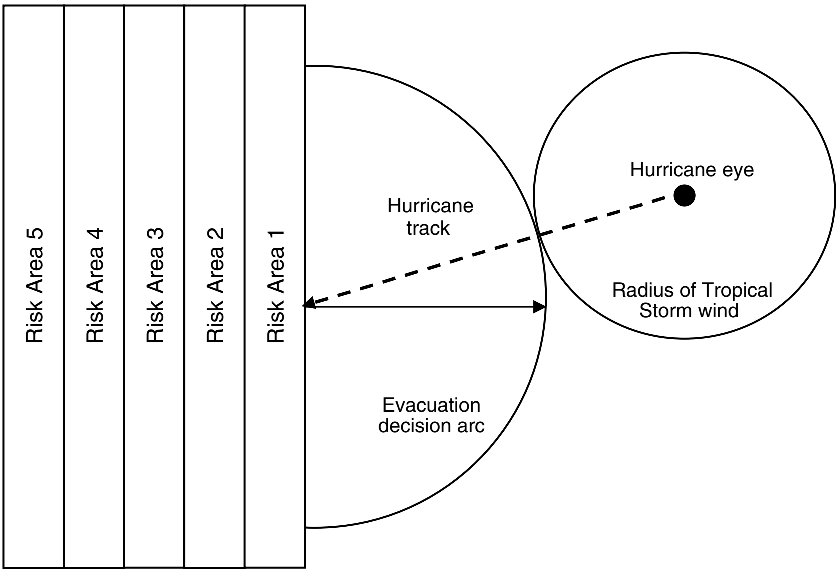

Fig. 1 Schematic drawing of the hurricane evacuation problem

that demand. The ETE (in hours) for any given set of risk areas can be represented as an equivalent distance on a map by multiplying the hurricane's FMS by the ETE for that set of risk areas. This produces a vector whose tail is located on the nearest point in the jurisdiction to the approaching hurricane and whose length is equal to the distance the hurricane is expected to travel before the evacuation is completed. This vector can be used to define an *evacuation arc* as it sweeps from its left intersection with the coastline to its right intersection (Federal Emergency Management Agency 2000). Local authorities who initiate an evacuation as soon as the radius of Tropical Storm force wind reaches the evacuation decision arc can completely clear the risk areas before the wind reaches this intensity at the coastline.

3 Making an evacuation decision in the face of uncertainty

An evacuation decision is complicated by uncertainty about the behavior of the hurricane and evacuees. Uncertainty about a hurricane includes its track (whether it will strike a given community), FMS (how fast it will approach), intensity (what category will it be at landfall), and size (the actual radius of Tropical Storm wind at landfall). Uncertainty about evacuee behavior includes 22 behavioral parameters (see Table 1 from Lindell and Prater 2005).

All these uncertainties can be incorporated into the evacuation decision by using decision analysis to construct a decision tree (Raiffa 1968; Clemen 1996). Figure 2 shows the choice of whether to recommend an evacuation, which is indicated by the square at the left, and the two alternative courses of action—evacuate and do not evacuate—which branch to the right. Each branch intersects a circle representing the uncontrollable event—whether the hurricane strikes. Because the hurricane either will or will not strike, there are two branches emanating from each of the circles.

Table 1 Uncertain evacuation behavioral parameters

1. Size and distribution of the risk area resident population
2. Size and distribution of the transit-dependent resident population
3. Number of persons per residential household
4. Number of evacuating vehicles per residential household
5. Number of evacuating trailers per residential household
6. Number of hotel rooms
7. Size and distribution of the transient population
8. Number of vehicles per evacuating transient
9. Percentage of early evacuating residential households
10. Percentage of early evacuating transients
11. Percentage of residents' protective action recommendation (PAR) compliance/spontaneous evacuation
12. Percentage of transients' PAR compliance/spontaneous evacuation
13. Residential households' trip generation time distribution
14. Transients' trip generation time distribution
15. Evacuees' utilization of the primary evacuation route system
16. Evacuees' utilization of routes within the primary evacuation route system
17. Evacuation destinations
18. Residential households' evacuation costs
19. Commercial evacuation costs
20. Governmental evacuation costs
21. Fatality rates in structures, by surge depth and wind speed
22. Fatality rates in vehicles, by surge depth and wind speed

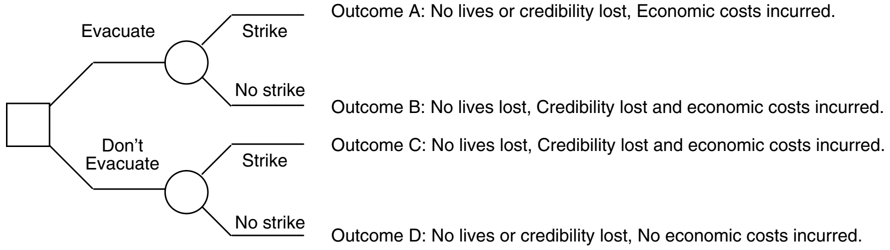

Fig. 2 Evacuation decision tree

Each branch 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 has two states. Each outcome can be evaluated in terms of the number of lives lost, the economic costs incurred, and the credibility lost by local authorities.

Outcome A is a correct decision because evacuation saves lives and maintains credibility that would have been lost if the storm had not struck. Nonetheless, evacuation costs are incurred. Outcome D also is a correct decision, but this is because no lives or credibility are 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. In addition, Outcome B reduces credibility and decreases future warning compliance. Outcome C also is a decision error (a ''false negative''), but for the opposite reason.

Although structuring the decision problem in this way is helpful, an EMDSS needs to be able to specify the problem quantitatively. That is, the decision makers need to be told the magnitude of the outcomes (deaths, economic cost, and lost credibility) and the probability of the uncontrollable event. At present, there is only limited information available on the number of deaths resulting from a failure to evacuate (Texas Governor's Division of Emergency Management 2002) and no reliable data whatsoever on economic costs and lost credibility. There are data regarding the hurricane strike probability, but these underscore the difficulty in making an evacuation decision; the National Hurricane Center's *maximum* strike probabilities are 18% at 48 h, 25% at 36 h, and 50% at 24 h. Unfortunately, ETEs exceed 30 h for major urban areas along the Gulf and Atlantic coasts (Lindell et al. 2002b), so local officials in these jurisdictions must decide whether to evacuate when there is only about a one-in-three chance that they will be struck by a hurricane. Moreover, existing hurricane DSSs such as HURREVAC (Federal Emergency Management Agency 2000) and HURRTRAK (PC Weather Products 1996) are limited to treating the time at which the decision must be made as a deterministic value. That is, the estimated time of arrival (ETA) of Tropical Storm force wind is provided as a point estimate even though a hurricane's FMS is a probabilistic variable. Thus, a hurricane's ETA should be characterized by distributions of values (for example, 10% certain to be less than *X* hours; 50% certain to be less than *Y* hours; 90% certain to be less than *Z* hours). Similarly, the ETE for a given jurisdiction is usually provided as a point estimate even though the variables upon which it is based are also uncertain. In addition, existing DSSs only provide a ETE values for a few scenarios rather then providing a capability for computing ETEs based on the conditions that exist when the evacuation decision must be made. Finally, existing hurricane DSSs ignore altogether the costs of decision errors—death rates and evacuation costs.

4 Forecasting evacuation behavior

There are many sophisticated models for predicting hurricane behavior from data collected by satellite, radar, and aircraft. National meteorological agencies use these models to generate the data on hurricane track, FMS, intensity, and size that are input to currently available storm tracking software. However, ETE models rely on local data and are much less sophisticated—in part because only limited attempts have been made to integrate the findings of research on household evacuation behavior with traffic flow models. Lindell et al. (2002a) made a step toward such integration by developing EMBLEM, which linked data on household evacuation with a single cell evacuation model. EMBLEM, which was used to produce ETEs for the 22 Texas coastal counties (Lindell et al. 2002b), has been superseded by EMBLEM2 (Lindell 2005). The latter algorithm is a multi-cell model that calculates traffic flows in m risk areas by n sectors (subdivisions of risk areas) based on input data regarding the scope of the evacuation and the parameters specified in Table 1.

ETEs are computed using a five-step procedure in which the first step is to identify risk areas for different hurricane intensities. This is accomplished by overlaying data on hurricane surge depth [produced by the National Hurricane Center's SLOSH model onto a topographical map using a Geographical Information System (GIS) to produce surge depth contours for a large sample of simulated hurricanes of a given category]. These surge contours are compared to wind intensity contours calculated using Kaplan and DeMaria's (1995) *Inland Wind Penetration Model* to define the inland boundaries for the risk areas corresponding to each of the five hurricane categories (Lindell et al. 2001b). Once the risk areas have been identified, GIS analysts can overlay them onto census tracts to estimate the population of each risk area.

The second step is to assess the capacity of the ERS within each community. This assessment is accomplished by first defining an ERS, which local police and highway department personnel define by identifying a set of roads that interconnect with each other and are relatively distinct from other sets of roads – often because of geographic barriers such as rivers and bays that prevent movement from one ERS to another. Within each ERS, local authorities define the primary evacuation route(s), usually based on the limits to their ability to staff traffic control points that manage the traffic flow. Finally, evacuation analysts examine the geometry of the ERS in order to identify the collector routes and to estimate individual route capacities based on sources such as Homberger et al. (1996) and the Transportation Research Board (1998).

The third step of the procedure is to assess evacuation demand. This is accomplished by dividing the estimated population of each risk area by the number of persons per household and multiplying by the number of vehicles per household to estimate an upper limit to the number of evacuating vehicles. This figure represents a substantial overestimate of the actual number of evacuating vehicles because evacuation rates are higher for more intense storms and for risk areas that are closer to the coast. For example, expected evacuation rates for a Category 1 hurricane range from 45% in Risk Area 1 to 36% in Risk Area 5, and those for a Category 5 hurricane range from 100% in Risk Area 1 to 93% in Risk Area 5 (Lindell et al. 2001a). The overall evacuation rates are converted to time-dependent rates by multiplying them by a normalized trip generation time (TGT) distribution that Lindell et al. (2002a) generated by performing a convolution of the probability distribution for the time for households to receive a warning with the distribution of the time for them to prepare to leave.

The fourth step is to estimate the time needed for evacuating households to clear the evacuation area (i.e., all risk areas advised to evacuate). The time required for risk area clearance is estimated using six simultaneous equations that are solved repeatedly at successive time intervals $t \geq 1$ until all transients have entered the primary evacuation route, and all households attempting to evacuate have entered the primary evacuation route (Lindell 2005). Travel time on the primary evacuation route from the access point to the edge of the area at risk is a function of the distance between these two points and the average travel speed, which typically is about 30 mph (Witzig and Shillenn 1987). EMBLEM2 produces three ETEs—minimum, most, and maximum probable—based on variation in the TGT distribution.

5 EMDSS displays

Lindell et al. (2005) have developed a hurricane EMDSS that runs in six modes: initialization, training setup, ETE analysis, experiment control, training, and operations. *Initialization mode* allows the user to review updated essential information about the community, including its population, ERS capacity, and linkage among the evacuation routes in different risk areas. *Training setup mode* allows users to construct their own training scenarios (simulated hurricanes) in addition to those that are already installed in the system. *ETE analysis mode* implements EMBLEM2 which, as noted earlier, uses the 22 behavioral parameters listed in Table 1 as input to calculate the minimum probable, most probable, and maximum probable ETEs for an evacuation of a given scope. *Experiment control mode* allows the user to control the visibility of each of the major display elements on the storm tracking page. *Training mode* allows users to develop their evacuation decision making skills by monitoring different hurricane scenarios in accelerated time (10, 20, 30, 40, or 50 real-time seconds per simulated hour). *Operations mode* allows the user to track an actual storm, recalculate ETEs using real-time data on variations in hurricane and community characteristics (especially current information about the hurricane track and intensity, hotel occupancy, and the percentage of spontaneous evacuees).

Two sets of EMDSS displays provide information about the hurricane's FMS and intensity. For both parameters, EMDSS displays the National Hurricane Center's forecast for 24, 36, 48, and 72 h. In addition, it displays historical data on the conditional probabilities of each parameter over these four time periods. One table displays conditional (on current hurricane intensity) probabilities of the hurricane being in each of the five Saffir-Simpson categories at 24, 36, 48, and 72 h. The other table displays conditional (on current FMS) probabilities of the hurricane being in each of five FMS categories (0–4 kt, 5–9 kt, 10–14 kt, 15–19 kt, 20–24 kt, and 25+ kt) at 24, 36, 48, and 72 h. From the current forecast and historical data, EMDSS allows the user to select a value for the hurricane intensity and FMS to be used in computing the scope of the evacuation and the evacuation decision arc. In addition, users select the wind speed threshold (39, 50, 65 kt) to be used for determining when to initiate an evacuation.

EMDSS displays time bars showing the minimum probable, most probable, and maximum probable ETEs as well as the earliest probable, most probable, and latest probable ETAs for the wind speed threshold (as noted earlier, this is usually the Tropical Storm wind speed). The ETE time bars are, of course, constant throughout a scenario (unless they are recomputed using a new evacuation scope or new data on the 22 behavioral parameters). However, the hurricane time bars constantly change as the wind speed threshold approaches the coast. The ETE and ETA time bars have an equivalent representation as decision arcs, with the radii of the evacuation arcs being calculated as described in connection with Fig. 1 and the hurricane arcs (distances) being calculated by multiplying the user-selected FMS by the corresponding ETAs from the time bar display.

Finally, EMDSS displays a table showing the estimated cost (to households, businesses, and local government) of the evacuation. EMDSS also displays a table showing the costs of a false negative decision error in terms of the expected percentage of the population expected to survive if an evacuation is initiated immediately. The evacuee survival table cross tabulates the earliest, most, and latest probable ETAs for storm conditions against the minimum, most, and maximum probable ETEs based on the assumption that only two-thirds of the evacuees will survive if they are still in the impact area at the time the wind condition makes landfall.

6 Discussion

EMDSS is undergoing three forms of usability testing to assess its capabilities. First, experiment control mode is being used to vary (1) hurricane behavior (e.g., track, FMS, intensity, size, and stability), (2) community characteristics (e.g., population size and distribution, ERS link capacity and geometry), (3) information displays (e.g., historical and forecast data on FMS and intensity, evacuation costs, survival probabilities), and (4) decision team characteristics (e.g., number and characteristics of team members) to identify the variables determining effective evacuation decision making. Difficulties in using EMDSS will be evaluated to determine whether emergency managers require improved training or whether modification of program features is warranted. After thorough evaluation in laboratory experiments, EMDSS's training mode will be used to allow local emergency managers to practice their evacuation decision making abilities in response to historical and hypothetical hurricanes. Feedback will be solicited regarding the user manual and the features of the program. Finally, EMDSS will be evaluated in operations mode by running it concurrently with other hurricane tracking software during response to actual hurricanes. After the incidents are over, emergency managers will be asked to evaluate the utility of EMDSS.

Another important aspect of EMDSS is its identification of a need for further research. The past 50 years have seen significant advances in the findings on household evacuation (Lindell and Perry 2004; Tierney et al. 2001), but the process of defining EMDSS's requirements has identified the need for further research. Many of the behavioral parameters have little empirical data to support them, and a substantial amount of further research is needed to fill the void.

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