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Computer-based Model for Flood Evacuation Emergency Planning

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Abstract. A computerized simulation model for capturing human behavior during flood emergency evacuation is developed using a system dynamics approach. It simulates the acceptance of evacuation orders by the residents of the area under threat; number of families in the process of evacuation; and time required for all evacuees to reach safety. The model is conceptualized around the flooding conditions (physical and management) and the main set of social and mental factors that determine human behavior before and during the flood evacuation. The number of families under the flood threat, population in the process of evacuation, inundation of refuge routes, flood conditions (precipitation, river elevation, etc.), and different flood warnings and evacuation orders related variables are among the large set of variables included in the model. They are linked to the concern that leads to the danger recognition, which triggers evacuation decisions that determine the number of people being evacuated. The main purpose of the model is to assess the effectiveness of different flood emergency management procedures. Each procedure consists of the choice of flood warning method, warning consistency, timing of evacuation order, coherence of the community, upstream flooding conditions, and set of weights assigned to different warning distribution methods. Model use and effectiveness are tested through the evaluation of the effectiveness of different flood evacuation emergency options in the Red River Basin, Canada.

Key words: flooding, evacuation, behavior, simulation, system dynamics

1. Introduction

Preparation for emergency action must be taken before the crisis. Some of the reasons for early preparation are that the conditions within a disaster-affected region tend to be chaotic. Communication is difficult and command structures can break down because of logistical or communications failure. Human behavior during the emergency is hard to control and predict. Complaints during the emergency cannot normally be addressed. Experience with emergency evacuation in the Red River Basin during the flood of 1997

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unveiled an abundance of problems that the population affected by the disaster has with existing policies and their implementation (Morris-Oswald and Simonovic, 1997; IJC, 2000). Residents in the Red River Basin were not happy with the timing of the evacuation orders, evacuation process implementation, order of command and many related issues captured in the final report of the Red River Basin Task Force (IJC, 2000) that was established by the Governments of Canada and US to study the flooding in the Red River Basin immediately after the flood of 1997.

Literature confirms a very similar situation in other kinds of disasters (Quarantelli and Russell, 1977). There is an obvious need for improving (a) our understanding of the social side of emergency management processes; (b) our understanding of human behavior during the emergency; (c) the communication between the population affected by the disaster and emergency management authorities; and (d) preparedness through simulation, or investigation of "what-if" scenarios.

Subcultures, defined as group level coping mechanisms fulfilling the needs of those that are not provided for by the main society, play quite an important role in the context of disaster management (Hannigan and Kueneman, 1978). The evacuation model developed in this study took into consideration the existence of different subcultures in the Red River Basin. They are not mutually exclusive, nor uniform. In sociology subculture represents a subset of cultural patterns. Analysis on a Canadian subculture in Southeastern Manitoba show three stages as part of the disaster response: prediction, control and response. *Predictio*n: In Southern Manitoba water resource specialists are using sophisticated prediction measures. A key component of the subculture is the Provincial Water Resources Branch. *Control*: Second stage of the disaster subculture is the organizationally based attempt rationally to reduce the possibility of disaster by erecting flood mitigation structures. *Response*: is highly institutionalized and formalized. Multiple close interrelationships exist among organizations and agencies participating in the disaster subcommunity. Individual awareness and the integration into the flood subculture in Manitoba is weak. The community at large is not always supportive of the organizational subcommunity even in the high threat areas. There is limited knowledge of flood fighting agencies. General disinterest in disaster has grown significantly since the floodway was built. Residents assume that official agencies should do the flood fighting. People were split over regulating building on flood plains, or the reimbursements of flood victims.

The proper understanding of human behavior in response to a disaster and our ability to capture it in a dynamic model is a valuable addition to the emergency management policy analysis. This work develops a theoretical framework for studying flood evacuation emergency planning in a more holistic way, integrating a broad range of social and cultural responses to the evacuation process. The paper provides new insights by developing a dynamic model of the process, which is converted into a gaming format for policy analysis and for other practical applications. The model integrates empirical survey data to fit characteristics of specific communities.

This paper presents a computer-based model that simulates the evacuation process (movement of people from the region under the threat to safety) during flood emergency including the mental decision process that leads towards evacuation decisions at a family level. The dynamic interactions among model components are captured using a feedback based modeling approach called system dynamics. The main purpose of the model is to allow for the different policy options available to flood emergency managers to be evaluated before the emergency situation occurs. In this study the different policy choices related to the evacuation warning dissemination in particular are investigated using the model. Data collected after the flood of 1997 in the Red River Basin are used to demonstrate the utility of the model.

Selection of the variables for the development of the model structure used the extensive literature on social aspects of flood disasters, presented in the following section. A system dynamics approach to simulation modeling is reviewed in the follow up section.

1.1. BACKGROUND ON MODELING HUMAN BEHAVIOR DURING DISASTERS

The modeling process conducted in this research required a very detailed consideration of major factors that are affecting human behavior during disasters (like individual risk perception, disaster recognition, acceptance of the evacuation order, and similar). Hansson *et al.* (1982) found that in coping with floods the major factors are economic status and previous experience with flooding. Stress indicators were measured using fear, desperation, action, depression and family health index. Flood knowledge included flood-warning system, contributing topographical factors, contributing effects of urbanization and political trends. Both factors, the economic status and the previous experience with flooding, are incorporated in our model and will be discussed in the section describing the model structure.

The amount of human effort involved in coping with natural hazard varies from high to low (Laska, 1990). The steps involve different levels and thresholds. Movement from one level to another is cumulative and happens when a social group passes through a threshold of experiences and conditions. Awareness threshold precedes Acceptance level, which is followed by Action threshold with Modify Events and Prevent Events, and then Intolerance Threshold measured by Change Use or Change Location steps. Factors that influence movement from one level to another at the societal level are: severity of a hazard, recency of a hazard, intensity and extensiveness of human activities in the area and the wealth of the society. The Red

River Basin evacuation model uses a structure that divides the process into three phases: concern; danger recognition; and evacuation decision.

Studies of mental health (Tobin and Ollenburger, 1996) indicated that stress associated with living in hazard areas is related to income levels, status, gender, kin relationships, physical health, socio-psychological traits, community structure and familiarity or experience with the hazard. Data from the Red River Basin confirmed the findings of this study and indicated, for example, a reduced level of stress for the individuals with higher income, and an increase in level of stress for females in the disaster.

Relocation of residents after a natural disaster contributes to environmental, social and psychological stress. Study by Riad and Norris (1996) measured: (a) environmental stress (living conditions; spatial and social density at home; basic living conditions – water, food, sanitation, heat, insects; subjective crowding – too little space, too many people, too little privacy, feeling overcrowded); (b) social stress (visiting with neighbors, fear of crime, isolation, similarity to others in the neighborhood in terms of age, income, race, ethnicity.); (c) psychological stress; and (d) control and moderator variables (education, age, gender that were used as statistical controls, as well as illness/injury, threat to life, and total perceived impact on property). In our modeling effort the results of this study contributed to the better understanding of the evacuation. For example, refuge places that did not allow people from the same neighborhood to be together were not accepted very well. Therefore, the acceptance of evacuation orders that directed people from the close social environments to different temporary accommodation was very low and delayed the evacuation process in general.

The literature on human behavior during disasters indicates that the modeling of behavior is rarely attempted. The only serious modeling effort of human behavior during flood evacuation was conducted at Kyoto University, Japan (Takasao *et al.*, 1995; Hori and Takasao, 1997; Hori, 1999; Hori *et al.*, 1999). Their work was based on the use of an expert system with fuzzy inference rules to model individual's mental decision process in a flood situation.

1.2. SYSTEM DYNAMICS MODELING APPROACH

System dynamics (SD) has a long history as a modeling paradigm with its origin in the work of Forrester (1961), who developed the subject to provide an understanding of strategic problems in complex dynamic systems. SD models, by giving insight into feedback processes, provide system users with a better understanding of the dynamic behavior of systems. Complex evacuation simulation problems involve a large number of quantitative and qualitative variables, non-linear relationships between the variables and a very pronounced feedback interaction between the state of the system (for example, the number of people under threat from flooding) and action taken by the authorities responsible for the disasters evacuation (for example, timing of the evacuation orders delivery). Thus evacuation simulation problems are well suited for application of SD solution techniques.

The SD approach is based on theory of feedback processes (Sterman, 2000). A feedback system is influenced by its own past behavior. This system has a closed loop structure that brings results from past actions of the system back to control future actions. One class of feedback loops – *negative feedback* – seeks a goal and responds as a consequence of failing to achieve the goal. In the model discussed in this paper the relationship between the population under the threat of flooding and the population in the process of evacuation represents an example of negative feedback loop. The higher a number of families under the threat, the more people in the process of evacuation. In return the more people in process of evacuation will reduce the number of families under the threat. It is the negative feedback or goal seeking structure of system that causes balance and stability. A second class of feedback loops – *positive feedback* – generates growth processes where action builds a result that generates still greater action. In our model the more people in the process of evacuation, the more people will reach safety. The more people that reached safety will increase the number of people in the process of evacuation. Positive feedback structure amplifies or adds to change and thus causes the system to diverge or move away from the reference state, status quo or initial point.

Simulation of the model over time is considered essential to understand the dynamics of the system. Understanding of the system and its boundaries, identifying the key variables, representation of the physical processes or variables through mathematical relationships, mapping the structure of the model and simulating the model for understanding its behavior are some of the major steps that are carried out in the development of a system dynamics model. A system dynamics simulation environment, STELLA, is used to model the evacuation process (High Performance Systems, 1992).

2. A System Dynamics Model for Flood Emergency Evacuation Planning

Flood management is aimed at reducing the potential harmful impact of floods on people, environment and economy of the region. The flood management process in Canadian practice can be divided into three major phases: (a) planning; (b) emergency management; and (c) post-flood recovery (Simonovic, 1999). During the planning phase, different alternative measures (structural and non-structural) are analyzed and compared for possible implementation to reduce flood damage. Emergency management involves regular appraisal of the current flood situation and daily operation of flood control structures to minimize damage. Following appraisal of the current situation, decisions are made about the evacuation of different areas. Post-flood recovery involves decisions regarding the return to normal everyday life. The main concerns during this phase are provision of assistance to flood victims and rehabilitation of damaged properties. This paper is focusing on the issues related to the emergency management, provision of assistance and conduct of the evacuation process. Human behavior during evacuation, in response to a disaster warning, is captured within a system dynamics model (Ahmad and Simonovic, 2001) that allows emergency managers to develop the "best" possible response strategy in order to minimize the negative impacts of flood disaster. Theoretical knowledge collected from the relevant literature is used to conceptualize the model. Model relationships and all other necessary data are obtained through interviews conducted in the Red River Basin immediately after the flood of 1997.

The human decision making process for evacuation, in response to disaster warning, is divided into four psychological phases following the work of Laska (1990): (a) concern; (b) danger recognition; (c) acceptance and (d) evacuation decision. The factors that play an important role in the evacuation decision-making process are divided into four groups, i.e., initial conditions, social factors, external factors, and psychological factors (denoted as ID, SF, EF and PF in Figure 1). Figure 1 shows the conceptual framework of the

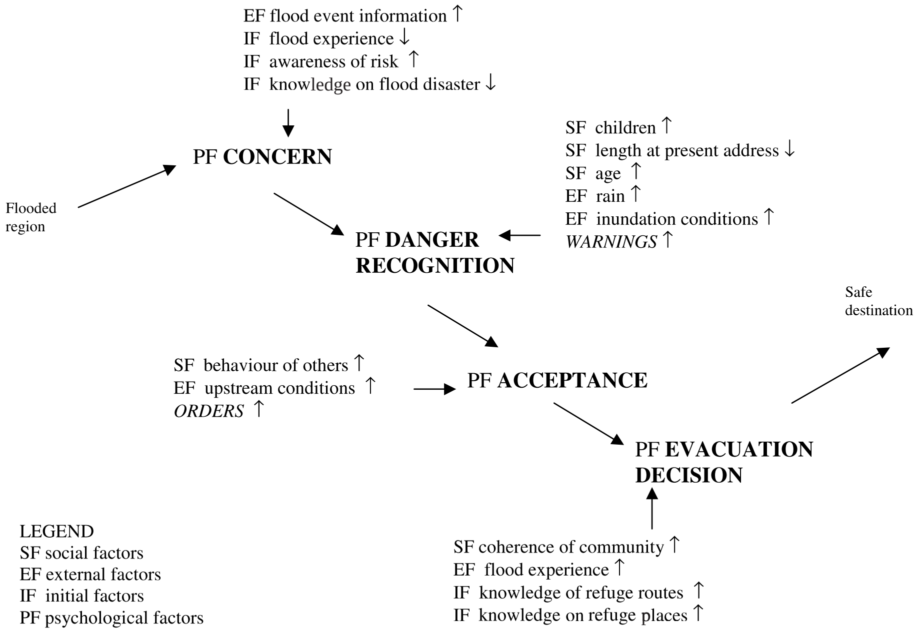


Figure 1. Conceptual framework of a behavioral model for evacuation planning.

behavioral flood evacuation model. Four groups of factors are identified with their acronyms. Vertical arrows along each of the variables indicate the direction of causal relationship between the variable and the psychological phase under consideration. For example, the concern rate of a family with previous flood experience is lower. Therefore, an arrow pointing down is shown along the variable flood experience. Variables in italics are the policy variables and can be changed by the emergency managers. Detailed discussion of the links between the phases and the main groups of factors follows.

2.1. MODEL VARIABLES

2.1.1. *Initial conditions and social factors*

They refer to the social and demographic aspects of the population such as income, age group, and daily life pattern and include attributes such as an inhabitant's experience with disaster, an awareness of being at risk, and knowledge about disasters. Each family living in a disaster-prone area has a certain degree of disaster awareness and a life pattern of its own. This disaster and risk awareness forms a set of initial conditions for that family's behavior when the disaster hits the area. Behavioral patterns of the household are further affected by the information provided about the disaster and of any variation in physical parameters of the disaster, such as intensity and the size of the area affected. Initial conditions trigger a *concern*. Based on the data collected in the Red River Basin the concern is higher if experience with flooding is missing, the sense of risk is high, and the size of the event (precipitation, flood peak, water levels, etc.) is big. In the model *concern* is defined as the first phase of the decision-making process when an individual or family is aware of risk, and has basic information on the type of disaster and its impacts (Figure 1). The *concern* is always present, even when there is no imminent threat of a disaster. Initial conditions provide a background for an individual's perception of danger.

The process through which initial conditions affect an individual's behavior is complicated and involves a chain of complex psychological reactions. The model considers two categories of households: those who have experienced disaster before, and those without this experience. Model development requires the following background information from households having previous experience with disasters: the extent of damage they experienced; whether they have evacuated in the past; whether they evacuated in the most recent disaster; the reasons why they did not evacuate (for those who did not); and the damage to their property. The information required from households without any disaster experience include: their knowledge about disasters in the area; the criteria that they would use in order to decide if evacuation is necessary; and an awareness of the risk to their property. This information in the Red River Basin has been obtained through the personal interview data collection process and used in the development of the quantitative relationships used in the model.

Depending on the severity of the situation *concern* further develops into *danger recognition*, defined as a new variable and calculated in the model using different equation as shown later in the paper. There is a positive causal relationship between these two variables shown in Figure 2. *Danger recognition* is the second phase of the evacuation decision-making process. In this stage an individual or family is aware of imminent threat and is on alert, closely watching the external factors.

2.1.2. *External factors*

Information provided on disaster situations by media, responsible emergency management authorities, and the inundation levels and rainfall that inhabitants experience themselves constitute external factors. They play a vital role in forming the inhabitant's response during a disaster. The evacuation order directly affects the evacuation decision as it initiates the evacuation action itself (Figure 1). On the other hand, effects of weather conditions are indirect; they give rise to *danger recognition*. External factors influence the evacuation decision by modifying a response to any provided information on disaster.

The evacuation decision process for each individual or household depends on their perception of danger. This perception is expressed as the *danger recognition*. The higher the recognition the more dangerous an individual feels the situation is. The *danger recognition* of each household changes with time. The *danger recognition*, which represents each household's perception of

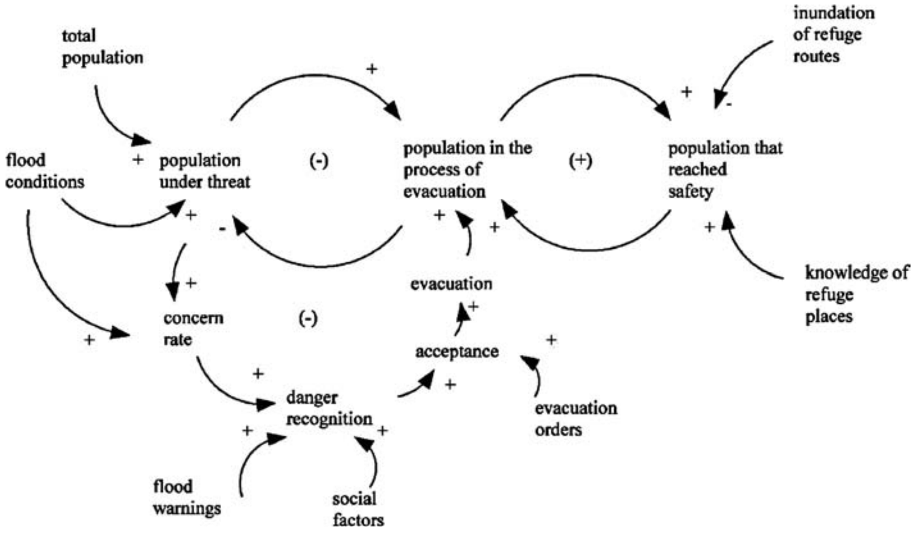


Figure 2. Causal diagram of a behavioral model for evacuation planning.

danger, affects not only the evacuation decision but also broader attitude toward the disaster. People with a high *danger recognition* rate try to get as much information as possible about a disaster event from all possible sources.

2.1.3. *Psychological factors*

Psychological factors in our modeling study are used to represent all phases of the evacuation decision-making process. They include: *concern*, *danger recognition* and *acceptance*, and *evacuation decision*. An inhabitant's decision to evacuate is a result of external factors influencing the initial conditions. Social factors such as age, presence of dependents in the family (children or elders) in combination with external factors like heavy rain and inundation conditions give rise to a *danger recognition*. Once the *danger recognition* rate reaches a certain threshold level, evacuation orders and the behavior of others can precipitate an *evacuation decision*. The reaction of each inhabitant to external factors differs based on *danger recognition*. For example, there are households that do not evacuate in spite of receipt of an evacuation order, and there are those who evacuate even before an evacuation order is issued. To incorporate these behaviors in the model, a variable called an *acceptance level* is introduced, which represents a measure of the extent that a household accepts the danger. The *evacuation decision* results from the interaction between the acceptance level and the trigger information. An evacuation order and the behavior of other households are considered the trigger information in the model.

Once a household decides to evacuate, their ability to reach safety depends on their knowledge of the refuge place and the availability of routes to that place. The information that needs to be processed by the household prior to deciding to evacuate includes: receipt of the disaster information; a comprehension of external conditions (such as rainfall and inundation); receipt of the trigger information; and a decision to take an action. After a household decides to evacuate, it has to determine a refuge place and a route. It is the knowledge about a route to an evacuation place that most likely affects the behavior of the inhabitants after they decide to evacuate. Lack of this knowledge causes a loss of valuable time in the evacuation process. The behavior of a family with little knowledge of a route may be affected by the behavior of other families with that knowledge.

2.1.4. *Policy variables*

Flood evacuation system dynamics model is developed to investigate different emergency policy options. Two main sets of policy variables include: flood warnings (media used for dissemination and consistency); and evacuation order (media used for dissemination and timing). For warnings dissemination following media are considered: TV, radio, mail, internet and visit. For dissemination of evacuation orders only two options are in consideration: mail and visit to the household.

2.2. MODEL STRUCTURE

Variables discussed in the previous section are interrelated through the model structure. The basic causal diagram (not including all the variables for simplicity of presentation) is shown in Figure 2. The causal diagram identifies the main feedback forces that determine the behavior of the system captured with our model. The two feedback loops are in the centre of the model connecting three stocks: population under threat; population in process of evacuation; and population that reached safety. The loop on the left side represents the negative feedback and the loop on the right side represents the positive feedback. Reference behavior mode is S-shaped growth (Sterman, 2000) as confirmed with the results to be discussed later (Figures 5–8). Growth of population that reached safety is exponential at first, but then gradually slows with the decrease in the population under threat. The upper boundary value of the system state is also the goal and equals the total population under threat that can be evacuated. An additional negative feedback loop is present in the model structure shown in Figure 2 that links the psychological variables (concern, danger recognition, acceptance and evacuation decision with our main stocks).

2.3. MATHEMATICAL RELATIONSHIPS

The system dynamics approach for modeling human behavior during a flood disaster is applied to the Red River Basin in Canada. In 1997, a major flood in the basin clearly emphasized the need for improvement of the evacuation planning in the basin using state of the art modeling tools (IJC, 2000). The flood event also provided an opportunity to look into the evacuation process as a non-structural measure for the reduction of flood impacts.

2.3.1. *Data collection*

The data set that is used to develop the model presented in this paper is collected through a field survey of families that evacuated during the 1997 flood (Morris-Oswald and Simonovic, 1997). A questionnaire was administered to 52 households involving more than 200 respondents in seven different community types. These seven communities represent a broad range of people affected by the 1997 flood. The interviewees included: (a) an urban community (Kingston Row and Crescent in Winnipeg.); (b) a rural community protected by the ring dike (St. Adolphe); (c) a rural community without the structural protection (Ste. Agathe); (c) suburban community (St. Norbert); (d) an urban fringe community (Grande Pointe); and (e) rural estates/farmers. The survey was conducted less than 1 month after the flood with many families still being in the process of recovery and under considerable stress. Both closed and open-ended questions were used. Detailed discussion of the survey development (independent and dependent variables), pilot testing, sample selection and the analyses of results are available in the report by Morris-Oswald and Simonovic (1997). Verification of the data collected directly by the survey was conducted through the process of public hearings organized by the International Joint Commission two times (at five locations each time), immediately after the flood (Autumn of 1997) and before submission of the final report (Spring of 2000). Total number of participants in these hearings exceeded 2000 people. The final note is that relationships developed and used in the model apply only to the communities in the South Manitoba. It is expected that major value systems captured by the survey will not change with time since the population structure in the flooded regions of the Red River Basin is stable, with its own characteristics and without major change in numbers over time.

2.3.2. *Model relationships*

The data collected through the field survey is processed to establish different relationships among variables in the evacuation model. For example, the relationship in Equation (1) describes the relative importance (weight) of each variable used for representation of the *concern* rate:

$$\begin{aligned}\text{Concern} = {} & (\text{Awareness\_of\_Flood\_Disaster}) * 0.1 \\ & + (\text{Previous\_Flood\_Experience}) * 0.7 \\ & + (\text{Awareness\_of\_Risk}) * 0.2 \end{aligned} \tag{1}$$

Relationship derived for *danger recognition* is

$$\begin{aligned}\text{Danger\_Recognition} = {} & (\text{Age\_factor}) * 0.05 + (\text{Impacts\_of\_warning}) * 0.3 \\ & + (\text{Concern}) * 0.3 + (\text{Rain\_factor}) * 0.1 \\ & + (\text{Inundation\_factor}) * 0.15 \\ & + (\text{Children\_factor}) * 0.05 + (\text{Stay\_Factor}) * 0.05 \end{aligned} \tag{2}$$

Following equation describes different variables involved in the calculation of *acceptance level*:

$$\begin{aligned}\text{Acceptance\_Level} = {} & (\text{Danger\_Recognition}) * 0.2 \\ & + (\text{Behavior\_of\_Others}) * 0.3 \\ & + (\text{Order\_Impacts}) * 0.2 + (\text{Flooding\_Factor}) * 0.3 \end{aligned} \tag{3}$$

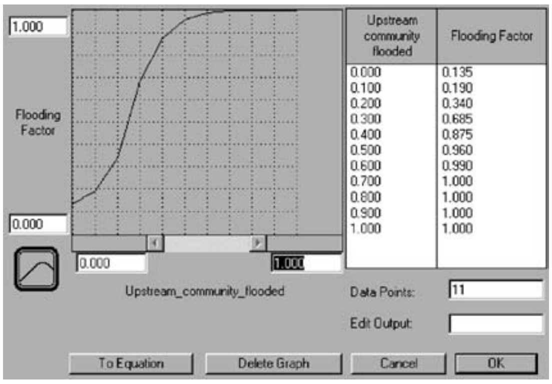
Finally, the *evacuation decision* is expressed as a function of the *acceptance level*, previous experience with evacuation and disaster claims, and support available from the community where family lives:

$$\begin{aligned}\text{Decision} = {} & (\text{Acceptance\_Level}) * 0.7 + (\text{Experience\_factor}) * 0.2 \\ & + (\text{Support\_Factor}) * 0.1 \end{aligned} \tag{4}$$

All variables in Equations (1) through (4) are restricted to values between 0 and 1.

Quantification of weights is done through the model calibration procedure. Data collected from the Manitoba Emergency Management Organization (MEMO) provided details on the evacuation process (length, timing, and number of people) and were compared with the outcome of the model simulations. Weights that generated model output that matched the observed data the best are selected and used in the model.

Other relationships between model variables require graphical description. These relationships are developed from the data collected through the field survey. For example, a graphical relationship for the *flooding_ factor*, which is a function of *upstream_community_ flooded*, is shown in Figure 3. Relative values of the *flooding_ factor* are between 0 and 1. The value of 0 indicates no upstream flooding information. The value of 1 indicates the full knowledge of upstream flooding situation. Relative values of the *upstream_ community_ flooded* are also between 0 and 1. However they are derived from the survey data by calculating the relative ratio of people aware of upstream flooding if it existed. The shape of the graph is reflecting the notion that more knowledge about upstream flooding was available to people, the higher attention is given to this information in their process of making a decision related to personal and family evacuation.



Upstream community flooded	Flooding Factor
0.000	0.135
0.100	0.190
0.200	0.340
0.300	0.685
0.400	0.875
0.500	0.960
0.600	0.990
0.700	1.000
0.800	1.000
0.900	1.000
1.000	1.000

Data Points: 11

Edit Output:

Figure 3. A graphical relationship between *flooding_ factor* and *upstream_community_ flooded.*

Delays and random number generation functions are used for describing different processes in the model. For example, reaching a refuge place after evacuation is conditioned on the individual's knowledge of refuge place location, and inundation of access routes. There are "information" and "material delays" involved in making a decision to evacuate and in reaching a refuge place. An example of information delay is the time difference between the moment when flood warning is issued and the time an individual takes to make an evacuation decision. An example of material delay shown in Equation (5) is the time required by the people in the process of evacuation to reach the final destination. It is captured in the model in the following form:

$$\begin{aligned}\text{Reaching} = \text{DELAY}(&(\text{Evacuation\_In\_Process})\\ &* (\text{Knowledge\_of\_Refuge\_places}) * 0.2 + (\text{Route\_Factor})\\ &* 0.8\ \text{Random}(1, 5, 5))\end{aligned} \tag{5}$$

There are three main stocks in the model. They are: *Population; Evacuation_in_Process;* and *Reached_the_Destination*. The *Population* stock represents the total number of households in the area under threat (52 families with more than 200 individuals in seven different communities in the Red River Basin). The outflow from this stock is the number of families that decide to evacuate. The population stock in mathematical form can be expressed as

$$\text{dPopulation}(t)/\text{d}t = -\text{Evacuating}(t) \tag{6}$$

Second important stock in the model is *Evacuation_in_Process*. This stock represents a difference between the number of families that decided to evacuate and the number of families that reached the refuge:

$$\text{dEvacuation\_in\_Process}(t)/\text{d}t = \text{Evacuating}(t) - \text{Reaching}(t) \tag{7}$$

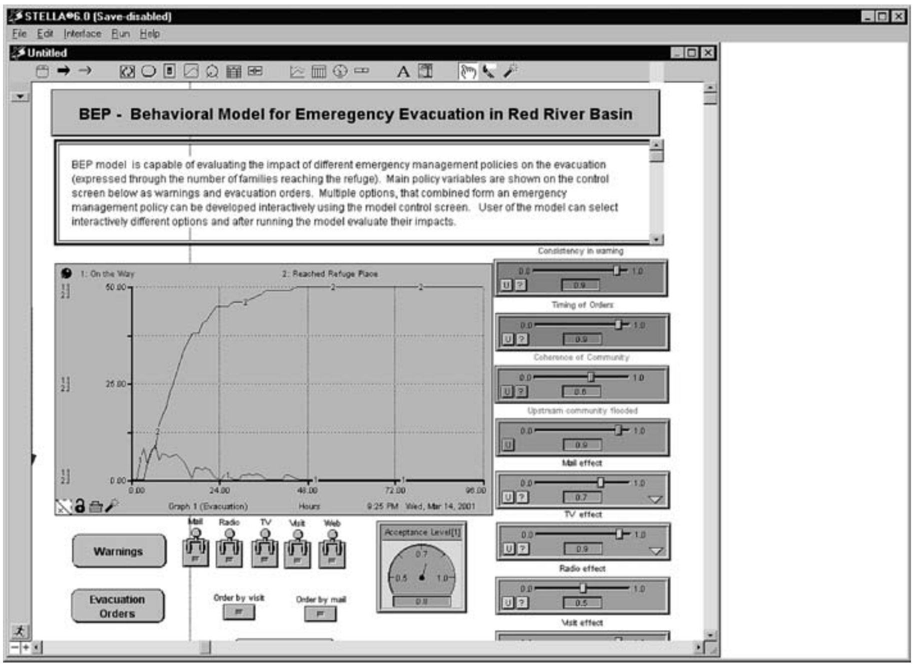
The third stock accumulates the number of families that have reached safety:

$$\text{dReached\_the\_Destination}(t)/\text{d}t = \text{Reaching}(t) \tag{8}$$

2.3.3. *Model architecture*

The flood evacuation system dynamics model is developed in four sectors that are linked together. They are: initial conditions; social factors; psychological factors; and external factors. After mapping each sector and defining connections between different sectors, decision rules are developed and incorporated in the model using logical statements of IF–THEN–ELSE structure. The following rule states that if the threshold value for an evacuation decision is less than or equal to, for example, 0.65 then there will be no evacuation; otherwise there will be evacuation:

$$\text{IF Decision} \leq 0.65 \text{ THEN } 0 \text{ ELSE } 1 \tag{9}$$



BEP - Behavioral Model for Emeregency Evacuation in Red River Basin

BEP model is capable of evaluating the impact of different emergency management policies on the evacuation (expressed through the number of families reaching the refuge). Main policy variables are shown on the control screen below as warnings and evacuation orders. Multiple options, that combined form an emergency management policy can be developed interactively using the model control screen. User of the model can select interactively different options and after running the model evaluate their impacts.

Consistency in warning: 0.0 – 1.0, 0.9
Timing of Orders: 0.0 – 1.0, 0.9
Coherence of Community: 0.0 – 1.0, 0.6
Upstream community flooded: 0.0 – 1.0, 0.9
Mail effect: 0.0 – 1.0, 0.7
TV effect: 0.0 – 1.0, 0.9
Radio effect: 0.0 – 1.0, 0.5
Visit effect

Figure 4. Evacuation model interface.

The evacuation model depends on the input from other models. For example, the information on dynamically varying water levels is provided by a hydrodynamic model; geographic information system provides data on spatial location of each community, its distance from the river, and its relative location to other communities (upstream or downstream). The model is calibrated using the evacuation data for the 1997 flood event.

2.3.4. *Model use*

The model interface shown in Figure 4 is the main control window for the use and navigation of the evacuation model. The main use for this model is to develop different scenarios for assessing the impact of different emergency policy options. An appropriate interface is required to provide the user with an easy process of scenario development and assessment. The upper section of the interface window provides an introduction to the model and may be browsed by scrolling the text within the window. In order to properly use the model, policy selection is required and its description is provided in the next section. Switches and sliders are used to set the value for different variables. All sliders offer the choice of value between 0 and 1. Zero always indicates the lowest level of importance with 1 always indicating the highest level. The model is ready for simulation when all values are selected. A simulation run will start by clicking on the *Run Model* button. The graph window on the interface will show in real time the results of model calculations by redrawing the two lines (time series) shown (1 and 2). Completion of the graph indicates the end of simulation.

2.3.5. *Insights from model simulation*

Basic model results are presented in the form of a graph as shown in Figure 4. A line (numbered 2) shows the number of families (out of 50 stored in the model data base) that have reached a refuge place. The line number 1 shows the number of families on the way. Both variables are shown as functions of time. The total simulation horizon is 96 h, or 4 days. The shape of these two lines is a function of the policy selected and it encompasses the warning distribution, the evacuation orders distribution, characteristics of the community, awareness of incoming flood, and the weights given by community members to different warning and evacuation orders distribution modes.

3. Application of the Evacuation Model to the Analyses of Flood Emergency Procedures in the Red River Basin

The main purpose of the model is to allow for the different policy options available to flood emergency managers to be evaluated before an emergency situation occurs. In this study the different policy choices related to the evacuation warning dissemination in particular are investigated using the model. To demonstrate the utility of the model a set of experiments is designed for testing the efficiency of evacuation procedures (measured in number of hours required for the evacuation of all 50 families) in the Red River Basin. Methodology used for testing the efficiency of flood evacuation procedures in this research is sufficiently general to be applied to other types of disasters.

Following is the description of rigorous procedure used in testing the efficiency of evacuation procedures by running the flood evacuation system dynamics simulation model:

1. Identify policy variables.
2. Test the sensitivity of simulation model results by changing the value of different policy variables.
   (a) Determine the order of testing.
   (b) Identify range for each policy variable.
   (c) Make a record of each simulation.
3. Compare the sensitivity results.
   (a) Order all policy variables according to their impact on the simulation results.

   (b) Measure the impact of each policy variable.
4. Develop analysis scenarios.
   (a) Use the results of sensitivity analysis to develop extreme scenarios.
   (b) Develop a middle scenario.
5. Analyze simulation results for each scenario.
6. Present your results to decision makers.

3.1. SELECTION OF POLICY VARIABLES

Policy variables selected during the development of the model are divided into three different groups. The *first group* includes binary variables that describe two main activities preceding the flood evacuation: (a) warning method; and (b) mode of evacuation order dissemination. Review of the MEMO procedures and a set of public meetings used to evaluate the data needs in the Red River Basin (Science Applications International Corp., 1999) prompted the following choice of policy variables that describe the flood warning method in the Red River Basin: *Mail*, *Radio*, *TV*, *Visit*, and *Web*. Two variables are selected to describe the possible mode of flood evacuation order dissemination: *Order by visit*, and *Order by mail*. All these variables are of a binary nature. They can be used or not. Therefore, a switch representation is used in the model to allow user to select or deselect these variables.

The *second group* of policy variables is selected to describe local triggers of human behavior in the case of flood emergency in the Red River Basin. These variables are: *Warning consistency*, *Timing of the order*, *Coherence of the community*, and *Flooding of upstream community*. These variables may take different values and for all of them a range from 0 to 1 is used. Zero value indicates a low level and a value of one indicates a high level. *Warning consistency* describes how much the flood warning information changes over time. The basic source of this information (time of peak, maximum water level, and duration of peak) is the Water Resources Branch of Manitoba Conservation. The value is determined from the comparison of warnings provided at different time and the content of the warning information. *Timing of order* describes the moment when the evacuation orders are distributed to the public. The source of this information is the MEMO. Timing is measured in number of days before the flood peak and usually affects the individual effort invested in temporary protection of the property. Early orders have negative impact on the local protection effort (people do not have sufficient time to build, for example, temporary dikes) and late orders may result in high risk to the residents under the threat. *Coherence of the community* describes the connections existing between individual members of the community. More coherent communities function more efficiently during the emergency (people helping each other). The final variable, *Flooding of* *upstream community* describes the availability of information on the upstream conditions. It has been shown that this information plays an important role in individual decision making by providing the information to assess the personal level of risk and time available to make an appropriate decision. For the purpose of this study all the data available for the flood of 1997 were collected from the MEMO and the Water Resources Branch of Manitoba Conservation.

The *third group* of policy variables describes the importance of different flood warning modes. Following variables are used: *Mail effect*, *TV effect*, *Radio effect*, *Visit effect*, and *Web effect*. Since these variables are used to indicate the weight given to each of flood warning policy choices a scale from 0 to 1 is used again. Value of 0 indicates the lowest weight and a value of 1 the highest. Most of the data from this group of policy variables were collected for the flood of 1997 during the two public meetings used to evaluate the data needs in the Red River Basin (Science Applications International Corp., 1999).

3.2. SENSITIVITY ANALYSES OF FLOOD EVACUATION STRATEGIES

Six sensitivity experiments are performed to evaluate the impact of four main variables from the second group and two variables from the third group. Sensitivity is not performed on the variables from the first group since they describe real flood evacuation warning and order dissemination options. However, later in this section they are used extensively in developing major scenarios for flood evacuation. Only two variables are selected from the third group after it was detected that the final simulation results are not very sensitive to the change of values in variables from this group.

3.2.1. *Sensitivity to "Warning consistency"*

Results of the survey performed by Morris-Oswald and Simonovic (1997) immediately after the flood of 1997 indicated that consistency in warning has been an issue of concern for most of the residents in the Red River valley affected by the flood. Therefore this variable has been incorporated in the model structure playing an important role in the determination of danger recognition.

A sensitivity test has been done with all of the warning and order dissemination modes used. Five simulation runs are performed simultaneously and a comparative graph of final results is shown in Figure 5a where the values on the vertical axis represent the number of families. Line 1 corresponds to *Warning consistency* of 0 (inconsistent warnings) and line 5 corresponds to *Warning consistency* of 1 (very consistent warnings).

Two main observations are made from this analysis: (a) more consistent warnings increase considerably the efficiency of flood evacuation in the Red

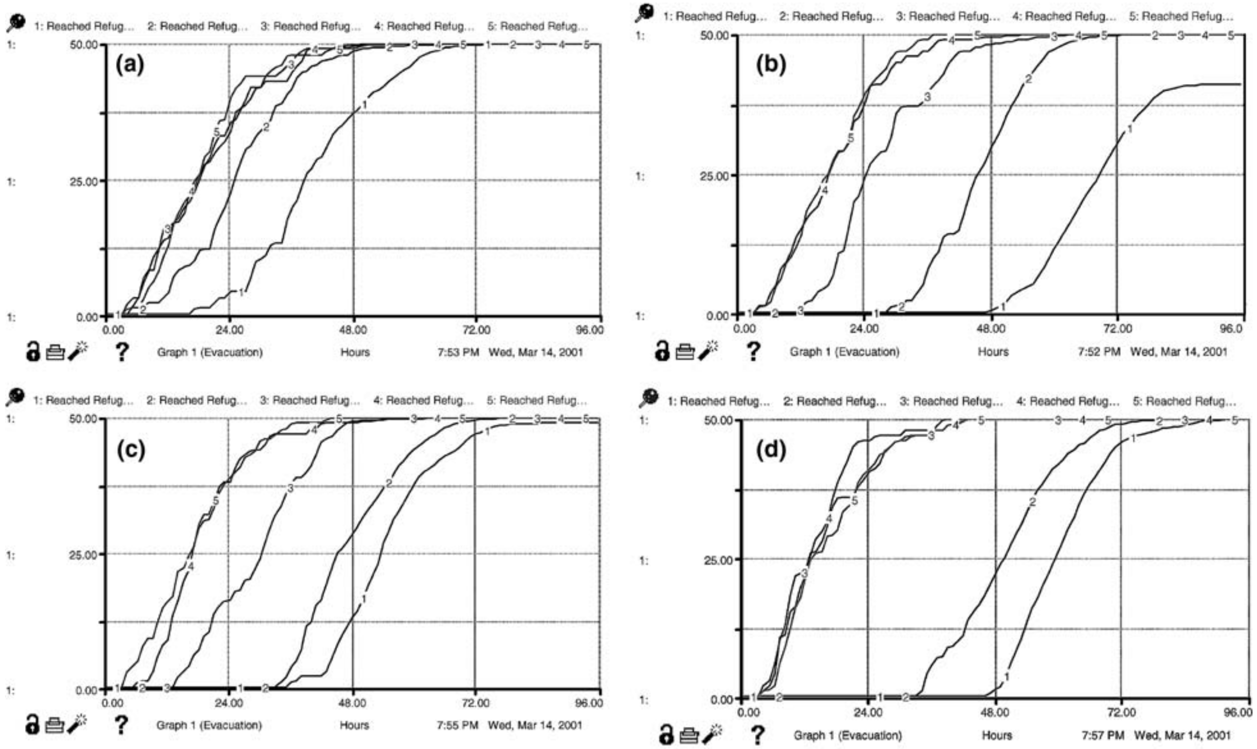


Figure 5. (a) Sensitivity analysis of *"warning consistency"*, (b) sensitivity analysis of "*timing of orders"*, (c) sensitivity analysis of *"coherence of community"*, (d) sensitivity analysis of *"upstream community flooding"*, (e) sensitivity analysis of *"mail effect"*, (f) sensitivity analysis of the *"visit effect"*.

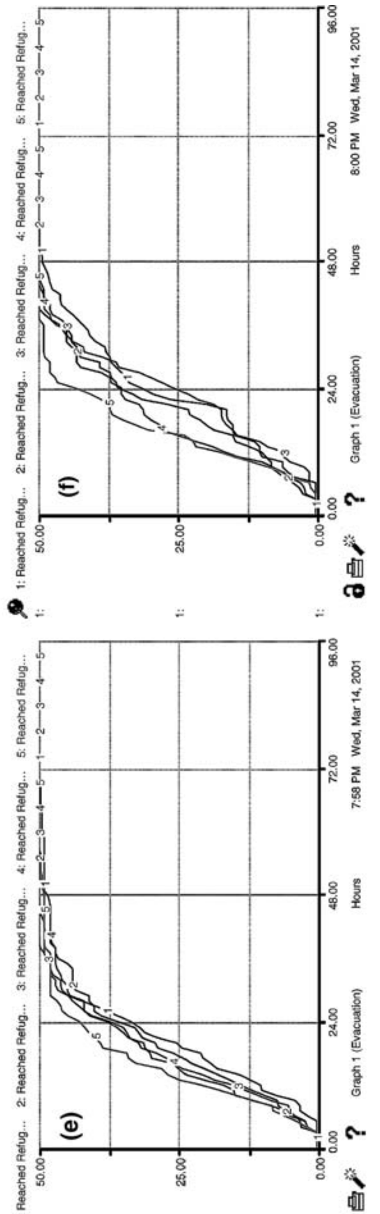


Figure 5. (Continued).

River Basin. Increase in efficiency, measured in the number of days necessary to reach the refuge, reaches 100%. In other words, the time necessary to move the residents to safety can be cut in half with the consistent warning system; and (b) when the warning consistency increases above 0.5 (on the scale from 0 to 1) very minor improvement is observed in the flood evacuation efficiency.

3.2.2. *Sensitivity to "Timing of orders"*

Timing of evacuation orders is established to contribute to the evacuation order acceptance level. Sensitivity to this policy variable has been performed in the same way as for the *Warning consistency*. Five simulation experiments are performed simultaneously changing the values of this variable from 0 to 1. Figure 5b presents the result of sensitivity analysis (line 1 corresponds to late ordering of mandatory evacuation and line 5 corresponds to timely ordering of evacuation).

Following observations can be made from the sensitivity results: (a) *Timing of orders* is a very important policy variable. If the evacuation is not ordered on time some families will not be able to reach the safe place; (b) careful timing of the evacuation order may increase evacuation efficiency up to four times; and (c) when the relative timing is above 0.75 (on the scale from 0 to 1) there is no improvement in evacuation efficiency.

3.2.3. *Sensitivity to "Coherence of community"*

Study by Morris-Oswald and Simonovic (1997) captures an important characteristic of human behavior in emergencies, possibly specific only for the Red River Basin. In more coherent communities people do make decisions together and help each other much more efficiently than in less coherent communities. Example from the Red River Basin is observed with Mennonite communities that were very well organized during the flood emergency of 1997. Therefore, a sensitivity analysis of this variable is performed, having in mind that changing the coherence of the community will not be possible, but can be used into consideration when preparing for the emergency.

Five simultaneous simulation runs are performed as in the previous two cases. A final result is shown in Figure 5c. Simple observations from this analysis are: (a) community coherence affects evacuation efficiency very strongly. Incoherent communities (example for the value of 0 represented with line 1) may not succeed in the evacuation of all families to safety on time; (b) more coherent communities can be evacuated two to three times more efficiently than incoherent communities; and (c) when the coherence of the community reaches 0.75 (on the relative scale from 0 to 1) maximum efficiency of evacuation is already achieved.

3.2.4. *Sensitivity to "Upstream community flooding"*

Awareness of upstream community flooding is identified as one of the factors that determine evacuation order acceptance and a trigger decision to evacuate from the place under threat. In today's world of fast communications it can be expected that information on what is going on upstream will be available and used in making personal evacuation decision.

Impact of this variable is tested through the sensitivity analysis similar to the one above. Five simulations are performed simultaneously and the final result is shown in Figure 5d. Following are the observations that can be made from this analysis: (a) there is obvious grouping of results. If the value of *Upstream community flooding* exceeds 0.25 (on the relative scale between 0 and 1) efficiency of flood evacuation is improved three to four times; and (b) for the values above 0.25 the efficiency of evacuation cannot be increased any more.

3.2.5. *Sensitivity to "Mail effect"*

A third group of policy variables includes weights that can be associated with different modes of flood warning or evacuation order distribution. These relative weights combined with impacts of warning affect danger recognition. During the development of the model it has been identified that all policy variables from the third group play less important role in determining human behavior during emergency.

Sensitivity analysis has been carried out in the similar way as in the previous cases. Five simultaneous simulation runs are performed for the value of *Mail effect* between 0 and 1. Results of the sensitivity analysis are shown in Figure 5e. The main observation inferred from this result is: variation in weight associated with *Mail effect* is not affecting the evacuation process to the great extent. Efficiency of evacuation can be improved by associating higher weight with a particular flood-warning mode. The largest observed increase in the efficiency is in the range of 30%.

3.2.6. *Sensitivity to "Visit effect"*

In a similar way *Visit effect* is participating in the process of determining dynamics of human behavior during an emergency. Testing of the sensitivity of the model performance to this variable is done as above and the results are shown in Figure 5f. Similar observations can be made from this figure: (a) variation in weight associated with *Visit effect* is not affecting the evacuation process to the great extent. The efficiency of evacuation can be improved by associating higher weight with the *Visit effect*; (b) the increase in efficiency is more prominent in the later stages of the evacuation process; and (c) the maximum improvement in efficiency is between 40 and 50%.

3.2.7. *Comparison of sensitivity results*

Sensitivity analyses conducted in this research revealed a number of important issues for emergency managers in the Red River Basin.

(i) Timing of evacuation orders is the most important variable that affects human behavior during the flood emergency in the Red River Basin. Therefore, extreme care should be given to proper forecasting of flood peak and the establishment of time when the evacuation order is issued. The second most important factor is the warning consistency. Evacuation efficiency can be significantly improved by maintaining a high level of warning consistency.
(ii) Emergency managers can benefit from prior knowledge of community coherence. It is shown that more coherent communities are much more efficient in dealing with the emergency.
(iii) Awareness of upstream flooding seems to be a motivating force for making a personal decision about evacuation. Insuring that the residents of the community under threat are informed about upstream emergency situation on time may make evacuation process more efficient and the job of emergency managers much easier.
(iv) Determining the weight that residents are associating with different modes of flood warning can be used in order to make the evacuation process more efficient.

3.3. FLOOD EVACUATION SCENARIOS

Results of sensitivity analyses and survey conducted by Morris-Oswald and Simonovic (1997) together with private communications with MEMO are used to demonstrate the utility of the model by developing four different scenarios and then comparing the results of model simulations. Scenario-based analysis is the main mode of utilization of the model. Therefore, this exercise should be considered more as a demonstration than the real use of the model. It is expected that this model will be used by emergency managers with some knowledge of the emergency type and region under the threat. Their experience and intuition should be used in developing scenarios and interpreting the results of model simulations.

Four scenarios created for model use demonstration are:

(1) *MEMO scenario*. In this scenario a set of policy variables is selected based on the MEMO operation during the 1997 flood. *Mail*, *Radio* and *TV* flood warning modes are used and *Order by visit* mode of dissemination. Assumptions of high *Warning consistency* (0.9) and effective *Timing of the order* (0.9) are made. Realistic values of *Coherence of the community* of 0.6 and *Flooding of upstream community* of 0.5 are used in this scenario. From

the consultation with residents of the Red River Basin a choice of weights is selected as: *Mail effect* of 0.7; *TV effect* of 0.9; and *Radio effect* of 0.5.

(2) *RESIDENTS' scenario*. Flood consultations in the basin revealed that residents of the region had a different prospective of the evacuation process. This scenario is attempting to capture the view of residents. The main difference from the *MEMO scenario* was identified in *Warning consistency* (0.5) and *Timing of the order* (0.4). Rest of the policy variables in this scenario are the same as in the *MEMO scenario*.

(3) *GOOD scenario*. In this scenario an attempt is made to demonstrate the value of using all modes of flood warning (*Mail*, *Radio*, *TV*, *Web*, and *Visit*) and both ways of disseminating evacuation orders (*Order by visit*, and *Order by mail*). High level of *Warning consistency* (0.9) and *Timing of the order* (0.9) are introduced and realistic values of *Coherence of the community* of 0.6 and *Flooding of upstream community* of 0.5 are used. From the consultation with residents of the Red River Basin a choice of weights is selected as: *Mail effect* of 0.7; *TV effect* of 0.9; *Radio effect* of 0.5; *Visit effect* of 0.9; and *Web effect* of 0.9.

(4) *BEST scenario*. In this scenario all the variables are selected at the same level as in the *GOOD scenario* except for the *Flooding of upstream community*. A value of 0.9 is used in this scenario to demonstrate an opportunity in improving efficiency by providing timely information that is, according to the sensitivity analysis, playing an important role in determining the danger recognition rate.

3.3.1. *Analysis of simulation results*

Simulation of four selected scenarios has been performed using the model and final results are shown in Figure 6. The same graph is generated for all four scenarios. It presents a number of families that reached refuge (line 2) and a number of families in the process of evacuation (line 1). Visual comparison of four graphs is showing a considerable difference between scenarios in the evacuation starting time, evacuation efficiency (difference between the starting and ending time), and evacuation speed (slope of the line 2).

BEST scenario is obviously the most effective one and the *RESIDENTS scenario* is the most inefficient. Evacuation starting time is between 28th hour (*RESIDENTS scenario*) and 5th hour (*BEST and GOOD scenarios*). In the case of the least effective scenario all 50 families are in safety after 84 h (*RESIDENTS scenario*) and in the case of the most efficient scenario after 47 h (*BEST scenario*). Conditions created in the *BEST* and *GOOD scenarios* are conductive to the higher acceptance level and danger recognition rate. Therefore, the reaction is fast and the evacuation process is very efficient. Acceptance level calculated by the model for these two scenarios is at 0.8 level (at relative scale between 0 and 1). On the other side *MEMO* and *RESI-*

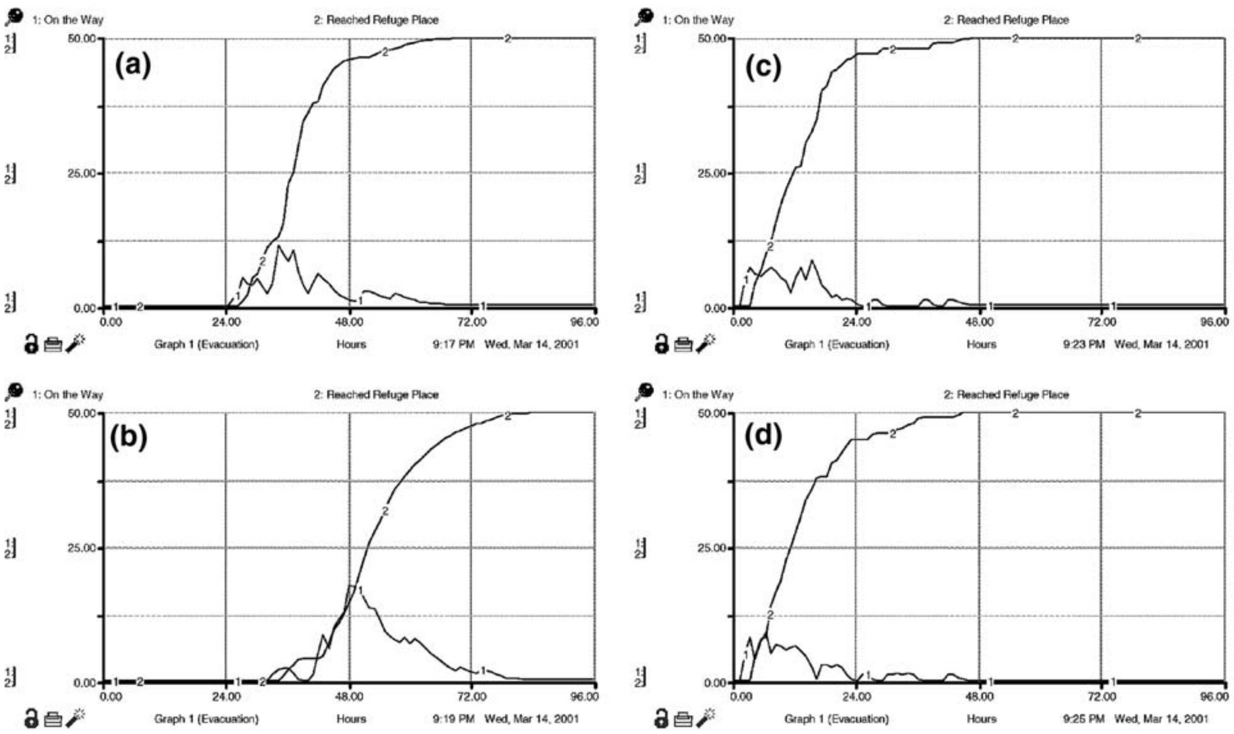


Figure 6. Model simulation results for different scenarios: (a) MEMO scenario, (b) RESIDENTS' scenario, (c) GOOD scenario, (d) BEST scenario.

DENTS scenarios offer a possibility for improvement. It seems that the acceptance level, calculated to be at 0.6 on the relative scale, causes the late reactions of the population. The late start and the slow process did not affect the final outcome. All of the families are evacuated to safety. This evacuation result was expected since the data from Red River Basin were for the mandatory evacuation. However, the insight provided by the model simulation offers assistance to emergency managers. Key policy variables are identified and their impact is evaluated. Future emergency situations can be simulated and their impacts easily evaluated by using the model.

4. Conclusions

In this work a final version of the flood evacuation model has been documented and its utility demonstrated for flood emergency planning in the Red River Basin. The model is shown to be capable of simulating the effect of different flood evacuation policies. The main advantage of using the system dynamics approach for modeling human behavior during emergency situations is that by understanding how a particular structure of feedback loops is capable of generating the observed behavior we get insights into potential solutions. Through the use of the model a number of "what if" questions can be asked and answers to them provided. Sensitivity analyses performed in this research and documented in this paper provide for better understanding of the importance of different factors affecting the evacuation process. We tested numerous alternative management options by developing simulation scenarios. In this way the model can guide emergency managers through most optimistic, most pessimistic, and in-between scenarios.

The flood evacuation model is available for use by emergency managers directly, and it is expected that it can lead to higher quality of decisions and a higher level of emergency preparedness. The ability to capture specific characteristics of the evacuation process during the flood emergency and to answer questions makes this model a powerful planning and analysis tool aimed at preventing the loss of life and the minimization of material damage.

The model can be fine-tuned easily in the light of experience, or with the help of insight provided by an expert. Feedback is invited from emergency managers for follow-up simulations and modifications of the model structure.

The following recommendations are provided for future work:

Recommendation 1 – The model contains a number of exogenous variables. The sensitivity analyses were run to investigate their impact on the model behavior. One of the future research efforts will aim at closing some of the feedback loops on variables that might actually be endogenous. Primary candidates are *Flooding of upstream community* and *Coherence of community*.

Recommendation 2 – The model should be tested with experts from the MEMO in order to evaluate the value of the database incorporated in the model.

Recommendation 3 – An example of a different emergency (well documented and with available data) should be selected to demonstrate the process of transforming the model for use in a different region and for the different type of emergency.

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