Chapter 9
Vulnerability Explored and Explained Dynamically

In this chapter we describe system dynamics, reveal how it has been used to refine and extend theory, and discuss an application showing how a system dynamics simulation model contributed to the disaster policy and planning process. Simulation models offer representations of community systems and give emergency managers and other decision makers the opportunity to ask "what if" questions about their policies and the conditions that exist in their communities. System dynamics can be used to explore ideas, describe situations, and to test hypotheses and explain situations. Modeling system causes and describing how the system changes over time provide explanations and offer the potential of identifying leverage points or strategic places to intervene in the system (Senge, 2006, p. 64). System dynamics models have the potential to refine vulnerability theory and contribute in direct, practical ways to the mitigation, preparedness, response, and recovery efforts carried out by emergency managers and human service professionals.

We begin this chapter with an overview of system dynamics, covering the basic concepts of stock and flow variables, information connectors, behavior-over-time, feedback structures, and time delays. These concepts together with the principles of systems characterize system dynamics modeling (Forrester, 1968). Next we describe how resource dependence theory was refined and extended by considering it within a system dynamics framework. Finally, we discuss an application of system dynamics to disaster evacuation. We close with a summary of system dynamics, expressing the value that we believe it could add to vulnerability theory as well as the support for vulnerability theory provided by findings from system dynamics research.

Overview of System Dynamics

System dynamic models examine behavior over time. Human behavior is governed by feedback, so these models are based on feedback structures. Feedback structures that evolve over time include delays that are inherent in any system. Delays are the time it takes for information about behavior to circle back and affect subsequent

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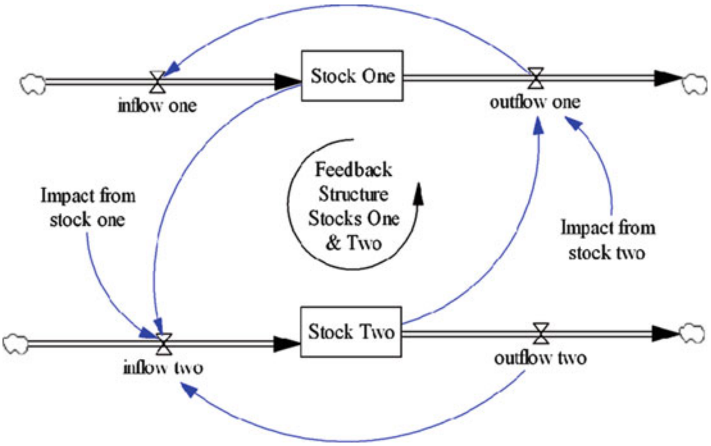

Fig. 9.1 Elements of a system dynamics model illustrated

behavior. Delays are modeled in system dynamics through time-based simulation of stock and flow structures. Stocks are variables that represent things at any point in time. For example, these can be physical things like the number of citizens or disaster workers in the community or the number of families that have reached safety in a flood disaster. Stocks can also be nonphysical things such as concern or danger recognition regarding a hazard. Stocks are barometers of how things are going within a system. Flows are variables that represent actions or activities over time. Stocks are like nouns and flows are like verbs (Richmond, 2004).

Every stock is governed by one or more flows, and the flows are influenced by one or more stocks. This influence is communicated through connectors, which are links that carry information about the level of a stock to a flow. Feedback structures are modeled by linking stocks and flows with connectors. In addition, to facilitate simulation runs, constants or variables called "auxiliaries" or "converters" are included in system dynamic models. These constants or variables enable unit consistency and facilitate the specification of model parameters. Figure 9.1 illustrates the basic elements of a simple system dynamics model, and the following paragraphs discuss briefly each of these concepts.

The model in Fig. 9.1 has two stocks represented by square boxes. Each stock has an inflow and outflow represented by butterfly valves. At the end of each flow there is a cloud symbol. These clouds indicate infinite sources and sinks for the activities of these flows. There are connectors running from the outflows of these stocks to their respective inflows. These two connectors indicate (unrealistically) that whatever goes out of these stocks is immediately replaced. There are also two connectors linking stocks 1 and 2, creating a feedback structure. Stock 1 is connected to the inflow of stock 2 and stock 2 is connected to the outflow of stock 1. There are also two auxiliary variables (impact from stock 1 and impact from stock 2) that specify the magnitude of the effect from stock 1 to the outflow of stock 2, and from stock 2 to the inflow of stock 1.

If there is any impact at all from stock 1 to stock 2, the feedback loop is positive because that impact adds to the amount of the output from stock 2 which as noted above feeds back immediately to its input. If there is no impact (zero) from stock 1 to stock 2, the model remains in equilibrium, and there is no other parameter that can change this trajectory. This is because the impact of stock 2 on stock 1 is simply carried forward to the input of stock 1. In other words, the input to stock 1 is only governed by the output of stock 1. The amount of input to stock 1 is equal to the amount of output from stock 1, so stock 1 remains in equilibrium irrespective of the strength of the impact from stock 2.

Stock and flow diagrams help us understand complex dynamics. They allow researchers to visualize systems in a concrete way. There are a number of software programs for creating stock and flow diagrams and doing system dynamics simulation research. Three widely used programs are Vensim (Ventana Systems—http://www.vensim.com/index.html), ithink or STELLA (isse systems—http://www.iseesystems.com/), and Insight Maker (Insight Maker—http://insightmaker.com/). Insight Maker is free web-based program and there are online tutorials to people get started. Vensim PLE is a free version offered by Ventana Systems and the User Manual is also free.

By plotting behavior over time hazard researchers and policymakers are able to track day-by-day, month-by-month, or year-by-year the levels of key variables. These behavior-over-time (BOT) graphs or reference modes reveal trends that are helpful in the planning process and critical to documenting the success of interventions. Several frequently observed trend patterns include (a) linear increasing or decreasing as reported in previous chapters with much of the research on vulnerability, (b) exponential increasing or decreasing as seen often in the early stage of system change, (c) step increase or decrease as occasionally seen with a radical change in funding (new grant = step increase; loss of grant = step decrease), and (d) cyclical as is typical of most systems. Plotting two or more variables on the same graph reveals relationships and thus facilitates theory construction and testing. Most people, researchers and planners alike, find BOT graphs intuitively appealing, easy to understand, and highly informative.

Feedback is a term from general systems theory, referring to information about a particular behavior returning to affect that behavior at a later point in time. Feedback loops are the most fundamental structural feature of systems (Richardson, 1991). Every decision occurs within a feedback loop. These feedback structures can be graphically summarized as causal loop diagrams (CLDs). CLDs highlight the feedback structure governing the behavior of a system. The visual representation provided through these diagrams helps communicate key aspects of complex systems. CLDs can be helpful at both the beginning and end of a project. They offer a potentially fruitful way to begin thinking about the relationships governing a system, and from these initial sketches researchers can more quickly specify the feedback structure with a stock and flow diagram. CLDs are also a good way to communicate the feedback structures documented through simulations with stock and flow models. Most policy planners and decision makers are not familiar with the stock and flow language of system dynamics, but CLDs are analogous to path models.

There are two types of feedback loops: reinforcing and balancing. Reinforcing feedback loops or positive loops are what drive system growth or decline. The presence of reinforcing loops is commonly referred to as virtuous or vicious cycles, bandwagon effects, or snowball effects. Balancing feedback loops or negative loops involve a system goal. The process represented in balancing loops is closing the gap between the system goal and the current condition. If the current condition rises above the goal, the system responds with a decrease to pull the condition back in line with the goal. If the current condition falls below the goal, the system responds with an increase to push the condition back up in line with the goal. Because of delays in the feedback structure, systems very often rise above and fall below their goals, which results in an oscillating pattern over time.

In community systems the behavior of every variable is driven by some combination of reinforcing and balancing feedback loops. Webs of reinforcing and balancing feedback loops can create counterintuitive behaviors challenging hazard policymakers and emergency service personnel. Models of the structure underlying performance patterns provide policymakers with the ability to discover interrelationships, rather than getting distracted by particular links and linear cause and effect chains (Gillespie, Robards, & Cho, 2004). These models also provide opportunities for vulnerability researchers, policy makers, and emergency managers to focus on recurring patterns, to work on the system, and to be designers of systems rather than merely operators.

As noted above, time delays are a key feature of dynamic systems. Delays may result from lags in the time it takes for one variable to affect another. These lags can be very short such as peoples' reaction to the vibration or shaking of an earthquake or they can be very long such as people changing their behavior in response to a national policy. Delays also occur as a result of variables being embedded in a web of relations, so that the feedback effect transpires through a chain of variables. Reducing delays is an important leverage point for improving performance (Meadows, 2008). It is worth noting that it can take a very long time for hazardous conditions to emerge in the environment. Global warming is an example (Intergovernmental Panel on Climate Change, 2012).

The simulation models of system dynamics are based on initialized stock and flow diagrams. This means that the parameter of each variable in the model is specified for the beginning point of the simulation and equations are written to represent relationships in the model. The model can be set to run in minutes, hours, days, weeks, or any time interval appropriate to the problem under study. The time horizon or period of time to be covered by the model can be set for 60 min, 40 h, 52 weeks, or any time frame needed to fully represent the system behavior. System models are tools for reducing complexity. These models can provide insight into the dynamics that drive conditions such as the vulnerability of a community, and they help identify potential leverage points for intervention. Adding simulation models to the hazards research tool kit has the potential to provide a quantum step forward in understanding and facilitating the vulnerability and resilience of communities (Gillespie et al., 2004).

Adding Dynamics to Refine Resource Dependence Theory

The use of system dynamics to refine existing theories is exemplified by an application of assumptions from system dynamics to resource dependence theory (Pfeffer & Salancik, 2003), creating what Cho and Gillespie (2006) call dynamic resource theory. Resource dependence theory was developed to understand exchanges between organizations. Resources are a driving force in the relationships among organizations, and resource dependence is theorized to shape the nature of relationships among organizations, with both positive and negative effects.

It turns out that the system dynamics focus on feedback loops complements certain weaknesses of resource dependence theory. Dynamic resource theory was created by integrating assumptions of systems dynamics with assumptions of resource dependence theory. Resource dependence theory does not deal with the dynamics of feedback loops. However, these loops are essential for understanding the continuously evolving relationships between organizations. Without reference to the feedback structure, it is impossible to fully capture how the relationship works over time, and thus to solve problems emerging from the relationship. Traditional resource dependence theory postulates statically that if one kind of organization has less power than another, the less powerful organization will experience a decline in the quality of their services. Dynamic resource theory postulates that the level of service quality at any point in time depends on the relative dominance of one or more feedback loops (Cho & Gillespie, 2006).

Resource dependence theory also ignores the goals that actors pursue in the exchange process. Without consideration of goals the relationship tends to be highly abstract or vague. Dynamic resource theory includes the goals sought by each party in the exchange process. These goals are incorporated into system dynamics models as part of the balancing feedback structure through which systems goals are specified.

Two additional features of dynamic resource theory are its accommodation of alliances and understanding of the decision-making environment. Resource dependence theory does not consider alliances among organizations. These alliances can modify the effects of organizations and their provision of resources to other organizations. Dynamic resource theory accommodates sets of actors in explaining the exchange process. Finally, resource dependence theory has not considered the effect of institutional environments on decision-making. Dynamic resource theory can take into account the effects of environmental constraints such as institutional variations or political environments (Cho & Gillespie, 2006).

Vulnerability theory suffers from the same static bias as traditional resource dependence theory. We believe that integrating dynamic assumptions with vulnerability theory will enhance generalizability of the theory. In addition, a focus on feedback loops will strengthen the explanatory power of vulnerability theory. Vulnerability theory has not explicitly incorporated the dynamics of feedback loops. However, as with the exchange of resources, these loops are essential for understanding the continuously evolving relationships between environmental capabilities and liabilities. Lacking an understanding of the feedback structure makes it impossible to know how the variables comprising the capabilities and liabilities got to their current levels, and impossible to know what direction they are heading. Dynamic vulnerability theory can be created in the same way that dynamic resource theory was created, by integrating assumptions of systems dynamics with the assumptions of vulnerability theory. We turn next to a discussion of a study that used system dynamics to facilitate evacuation planning.

System Dynamics Model of Flood Evacuation

One of the few uses of system dynamics modeling in community disaster vulnerability research is a study of the 1997 Red River Basin flood in Manitoba, Canada (Fig. 9.2). Simonovic and Ahmad (2005) used system dynamics to model the household evacuation process during this flood. Knowledge from the evacuation literature was used to conceptualize the model. Data were collected through interviews of households located in the Red River Basin and affected by the flood. The study sample included over 200 evacuees from 52 families. Additional interview and secondary data were obtained from the Manitoba Emergency Management Organization (MEMO) and Manitoba Conservation, both agencies of the Manitoba Government. Fieldwork was carried out to verify the data collected from interviews and MEMO's records of the flood operations. The operations data from MEMO and Manitoba Conservation referred to different points in time during the flood evacuation.

The International Joint Commission organized public hearings at five locations immediately after the flood in autumn 1997, and again before submission of the final report in spring 2000. The purpose of the International Joint Commission, made up of water and stream experts from the USA and Canada, is to resolve problems arising in lakes and rivers shared by the two nations. The total number of participants in these hearings exceeded 2,000 people. Fieldwork in these hearings allowed for verification of the data collected through the survey (Simonovic & Ahmad, 2005).

Concern is defined as the first phase of the process, when a family becomes aware of the risk and has some information about the disaster and its possible impact. In the evacuation model concern further develops into danger recognition, whose values are determined by flood warnings and social factors. Danger recognition is the second phase of the evacuation decision-making process. In this second stage of decision-making, a family becomes aware of the imminent threat and is on alert, closely watching external factors. External factors include information provided by the media, information from authorities, and the inundation levels and rainfall experienced by inhabitants (Simonovic & Ahmad, 2005).

Variables that form one feedback loop governing the decision-making process are concern, danger recognition, acceptance, and evacuation. Psychological factors govern all phases of the evacuation decision-making process. Social factors consist

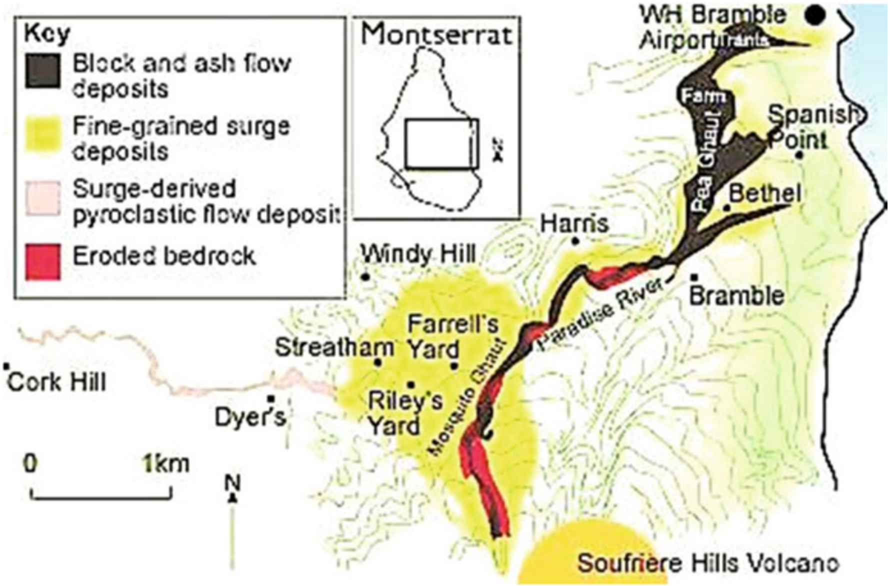

Fig. 9.2 Red River Valley Flood of 1997 in Manitoba, Canada

of variables such as age, years at present address, and number of children in the household. Along with flood warnings, social factors and rain/inundation conditions positively affect the danger recognition variable. Once the danger recognition rate reaches a certain threshold, evacuation orders, knowledge of upstream flooding, and the behaviors of others (a social factor) lead to threat acceptance. The evacuation decision results from the interaction between acceptance and the order to evacuate, evacuation claims experience, and community coherence, which is the level of social support within a community (Simonovic & Ahmad, 2005).

After a family evacuates it is counted as one of those in the process of evacuation. The timeliness of the family's evacuation (measured as the number of hours to reach a safe refuge) will be positively affected by their knowledge of refuge places. For those households without such knowledge, delays in their evacuation are likely. However households eventually gain knowledge of refuge places from other evacuees (Simonovic & Ahmad, 2005).

Simonovic and Ahmad's model of flood evacuation is represented in Fig. 9.3 with a causal loop diagram. The time horizon was set from the beginning of flooding in the Red River Basin until the time when all households had evacuated to a safe refuge. The model consists of three stocks: population under threat, population in the process of evacuation, and population that reached safety. The population under threat stock was the 52 households in the flood area.

In this diagram there are three balancing loops. The loop on the upper left side of the flood evacuation model shows the movement of families from being under threat to evacuating. The negative feedback loop on the lower left side links the psycho-

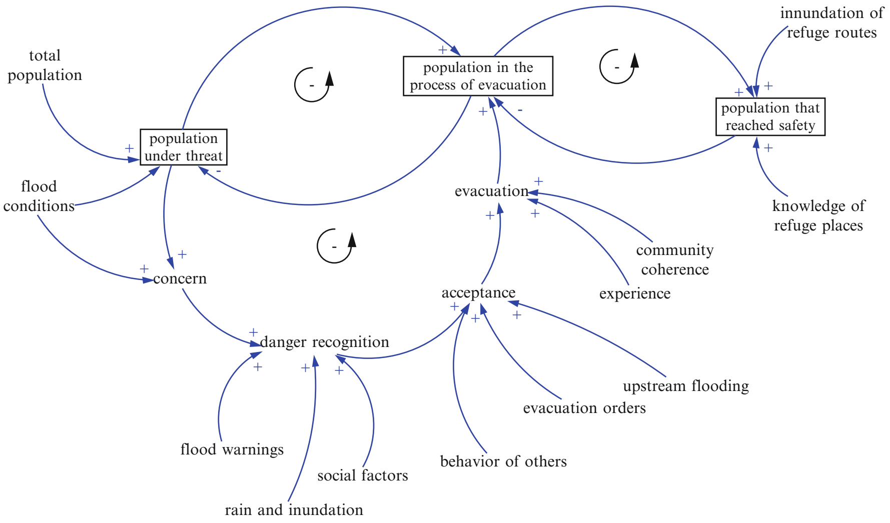

Fig. 9.3 Causal loop diagram of evacuation

logical variables that govern the movement of families from being under threat to being in the process of evacuating. These two stock variables are inversely related to each other; the more households in the process of evacuation, the fewer households which remain under threat.

The loop on the upper right side of the model diagram is a negative feedback loop. This loop shows the movement of people from being in the process of evacuating to having reached safety. This loop is associated with the goal of efficient and effective evacuation. Efficient evacuation refers to the time it takes households to arrive at a safe refuge after they actually begin evacuation. Effectiveness of the evacuation is the percentage of households reaching a safe refuge in a timely fashion, so as to avoid injury, drowning, or being stranded in unsafe conditions.

Delays were written into the model equations and are not represented in the diagram (Simonovic & Ahmad, 2005, p. 37). For example, the families who reached a place of safety are based on knowledge of the refuge location and inundation of refuge routes. Inundated routes create delays and can even prevent people from reaching safety. Information and material delays were also involved in making the decision to evacuate and in reaching a refuge place. An example of information delay is the difference between the point in time when a flood warning is issued, and the time a household takes to make the decision to evacuate. An example of a material delay is the time spent by people in the process of evacuation before arriving at their place of safe refuge.

Nonlinear relationships were programmed with graphic functions (Simonovic & Ahmad, 2005, p. 12). Most of these relationships had initial exponential increases that leveled off over time, resembling S-shaped curves. Some variables were given regression-like weights based on the data collected from MEMO and Manitoba

Conservation. For example, to produce the evacuation decision value, acceptance is weighted by 0.7, experience is weighted by 0.2, and support is weighted by 0.1. In this study, experience is previous experience with evacuation and disaster claims. Support refers to community coherence (social factors), which is the degree to which community members help each other. After being weighted, these three variables are then summed to produce the evacuation decision value. A decision by the household to evacuate is made if the value for the evacuation decision variable is greater than 0.65 (Simonovic & Ahmad, 2005). All variables in the equations are standardized (restricted to values between 0 and 1).

The purpose of the evacuation model was to assess the impact of various disaster policies. There were two groups of policy variables. The first group consisted of variables describing activities preceding the flood situation: the warning method and mode of disseminating the order to evacuate. The flood warning methods included mail, radio, television, the Internet, and a visit to the home. Two variables described the possible modes of disseminating the order to evacuate: visit to the home and order through mail. These variables were measured as dichotomous variables, to indicate whether or not a given method was used. Variables were additionally measured as continuous variables with values ranging from 0 to 1 to indicate the importance of each method used. The values for continuous measurements ranged from 0 (not important) to 1 (highly important).

A second group of policy variables was selected to describe local triggers of human behavior in the case of a flood disaster: warning consistency, timing of orders, coherence of the community, and upstream community flooding. Warning consistency described the variation over time in flood warning information. Timing of orders was the time when evacuation orders were disseminated. The coherence of community was the connections existing between individuals in the community. Upstream community flooding was the availability of information about upstream conditions. All of this information came from the MEMO and the Water Resource branch of Manitoba Conservation.

Sensitivity analysis was used to test outcomes in response to the two policy variable groups. Two outcome variables—evacuation efficiency and evacuation effectiveness—were used for these sensitivity tests. Evacuation efficiency was the number of hours it took for all households to reach a safe refuge. Evacuation effectiveness was the total number of families able to reach safe refuge. Outcome variables that are highly sensitive to policy decisions can improve by 100–400%.

The results of these sensitivity analyses are that timing of orders is the most important variable affecting outcomes during the 1997 Red River Basin flood. The second most important variable is warning consistency, and third is coherence of community. More coherent communities, with many ties among people and households, are much more efficient in dealing with the flood and evacuation. Awareness of upstream community flooding seems to be a motivating force for making a decision to evacuate. Finally, using different kinds of warnings will make the evacuation process more efficient (Simonovic & Ahmad, 2005). These findings support the tenth assumption of vulnerability theory concerning the importance of shared meaning to the progression of disaster vulnerability (Chap. 2, pp. 24 and 25).

Table 9.1 Comparison of three scenarios for flood evacuation efficiency

Variables	Residents'	MEMO	Best
Order dissemination	Visit	Visit	Visit and mail[a]
Community coherence[b]	0.6	0.6	0.6
Warning dissemination			
Mail effects	0.7	0.7	0.7
TV effects	0.9	0.9	0.9
Radio effects	0.5	0.5	0.5
Visit effect	–	–	0.9[a]
Internet effect	–	–	0.9[a]
Upstream flooding[b]	0.5	0.5	0.9[a]
Warning consistency[b]	0.5	0.9[a]	0.9
Timing of order[b]	0.4	0.9[a]	0.9
Acceptance level	0.6	0.6	0.8[a]
Hour evacuation begins	28	24[a]	5[a]
Evacuation time (h)	84	70[a]	47[a]

Note:

[a] Difference between residents' and MEMO scenarios, as well as between MEMO and Best scenarios

[b] Results from sensitivity analyses of most important variables affecting evacuation time

The Simonovic and Ahmad model simulates the effects from different flood evacuation policies. An advantage of systems dynamics for modeling human behavior before, during, and after disasters is that we gain an understanding of how a particular feedback structure generates the observed behavior. This understanding leads to insights regarding potential solutions for problems. Table 9.1 shows the results of three simulation runs testing for evacuation efficiency.

In the worst-performing scenario, named the Residents' scenario, the perspectives of the residents of the flood area were surveyed to assign weights indicating the moderate importance of warning consistency (0.5) and timing of the order variables (0.4). All other weights, and the selection of policy variables, were determined by the operations of the MEMO during the Red River Basin flood. Flooding of upstream community and coherence of the community were also deemed of moderate importance, as indicated by their weights (see Table 9.1). Also, warning was through mail, radio, and television; and evacuation orders were disseminated through a visit to the household. The weights for these means of dissemination were determined by consultation with residents.

The MEMO scenario, with outcomes in between those of the other two scenarios, understandably relied more heavily than the Residents' scenario on the perspective of the MEMO. Like the Residents' scenario, the selection of policy variables was based on the operations of the MEMO during the 1997 flood. The MEMO scenario was different from the Residents' scenario in that warning consistency and timing of orders are more heavily weighted (0.9) and considered more important influences on the evacuation process. Otherwise, the same media for disseminating warnings and evacuation orders were used in the MEMO scenario as in the Residents' scenario. The same weights used in the Residents' scenario for the mail, television, and radio effects were used in the MEMO scenario.

In the best-performing scenario warning took place through the same means as for the other scenarios, except that the Internet and a visit to the home were added. The order to evacuate was through a visit to the home and also through the mail. The weights for mail, television, and radio effects were the same as for the Residents' and MEMO scenarios. Flooding of upstream community, warning consistency, and timing of orders each had a much larger weight (0.9) reflecting the higher importance of these variables for evacuation in the Best scenario.

These three scenarios had large differences in outcomes. The acceptance level for the Residents' and MEMO scenarios is 0.6, while a level of 0.8 was reached for the Best scenario. Acceptance has a direct effect on the evacuation decision as shown in the causal loop diagram (Fig. 9.3). It took all families 84 h to reach a safe refuge in the Residents' scenario, while in the Best scenario all families were at their safe refuge in 47 h. The MEMO scenario produced an evacuation time of 70 h, and intermediate value among the scenarios. Differences in time to safe refuge were accounted for partly by delays in evacuation, particularly for the Residents' scenario. The families in the Residents' scenario began their evacuation on average in the 28th hour, while those in the Best scenario began evacuating in the 5th hour of the simulation, a difference of nearly an entire day.

Simonovic and Ahmad offer three recommendations for future use of their model. First, the model should be tested with emergency management experts to evaluate the value of the database used. Second, the feedback loops should be closed for exogenous variables. Currently, flooding of upstream community, coherence of community and other social factors, flood warnings, evacuation orders, inundation of refuge routes, and knowledge of refuge places are exogenous. Ideally, system dynamic models are completely endogenous (Forrester, 1968). Third, the model should be tested on different disasters to demonstrate the process of transforming the model for use in different regions and different types of disasters.

The Simonovic and Ahmad (2005) study shows how system dynamic models can advance theory and help inform emergency managers and other planners. System dynamics models facilitate concrete specification of theory and produce information that can contribute to higher quality decisions and higher levels of disaster preparedness. For example, the ability of the evacuation model to address policy alternatives makes it a powerful planning and analytic tool. Potentially, it can help reduce community vulnerability, preventing loss of life and minimizing material losses.

Other applications of system dynamics reinforce the potential we have seen in the Simonovic and Ahmad study. Deegan's (2006) model of flood damage shows how property vulnerable to damage is caused by capacity of the local environment to withstand floods, development pressure, property tax needs, perceived risk of development, willingness to mitigate, policy entrepreneurs, and other people pressures. The amount of damage suffered is primarily due to the balance of capabilities and liabilities determined by people pressures. Cooke and Rohleder (2006) build a system dynamics model of safety and incident learning to promote safety in environments prone to technological disasters or so-called "normal accidents." Rudolph and Repenning's (2002) model reveals how an over-accumulation of interruptions can shift an organization from being a resilient, self-regulating system to a fragile, self-escalating system that amplifies the interruptions. The temporal patterns of these results suggest the potential for an early warning system.

Summary

System dynamics assumes that variables are linked in circular processes that form feedback loops. This shift from one-way causality to circular causality and from independent variables to interrelated variables is profound. Instead of viewing mitigation and preparedness as outcomes, they are viewed as ongoing, interdependent, self-sustaining or self-depleting dynamic processes. For systems dynamics the emphasis shifts from local spatial and temporal perspectives of an independent variable affecting a dependent variable, to a web of ongoing interrelated dependencies. System dynamics modeling focuses less on particular variables and more on various patterns of relationships among variables (Gillespie et al., 2004).

Reducing disaster vulnerability and optimizing community safety requires understanding the natural and social systems involved in disasters, communicating clearly with decision-makers about those systems, and identifying effective interventions. The natural hazards and disaster fields are weak in these areas, while system dynamics offers the potential to accomplish all three of these requirements. By drawing the model researchers identify crucial feedback loops that either balance behavior or reinforce a push toward growth or decline. By tracking model parameters over time researchers and policymakers can experiment safely with making changes in complex systems without having to suffer real-life consequences. For example, studying different ways of delivering evacuation orders can be done without actually risking the lives or safety of evacuees in a flood (Simonovic & Ahmad, 2005).

We believe using system dynamics modeling to design safe communities provides the next step forward in understanding the complex situations faced by hazard and disaster researchers. As the field moves beyond static and linear analyses, our ability to understand complex situations will deepen. Using stock and flow models will help promote new insights into the patterns of interconnections that make complex problems so resistant to change. These insights are particularly useful for refining and extending vulnerability theory because of the variety of social, economic, and political processes affecting the disaster vulnerability of communities. Through the use of systems dynamics modeling hazard theorists and researchers will gain understanding and become more effective in confronting the complex problems we face in promoting safe systems (Gillespie et al., 2004).

Simonovic and Ahmad's (2005) findings that evacuation efficiency is improved by the timing of orders to evacuate, the consistency of warnings, and community coherence adds support to the tenth assumption of vulnerability theory regarding the importance of culture, ideology, and shared meaning in reducing vulnerability

(Chap. 2, pp. 24 and 25). Shared meaning is particularly important during evacuation and other response activities because often during that period of time there is confusion, misinformation, and conflicting reports. Cooke and Rohleder's (2006) incident learning model is valuable tool to help reduce confusion, minimize the amount of misinformation, and generate community consensus.

Simonovic and Ahmad's (2005) finding that various policy configurations resulted in different degrees of efficiency in the evacuation process supports the eleventh assumption of vulnerability theory concerning the complex ways that community capabilities, liabilities, and disaster susceptibility are related (Chap. 2, p. 25). While the results from the flood evacuation model were supportive and useful, the full potential of this model is yet to be realized. As Simonovic and Ahmad (pp. 49–50) note, the omitted feedback structure governing the exogenous variables needs to be developed. For example, it is likely that there is a causal link between flood warnings and evacuation orders, and certainly there is a link between flood conditions and flood warnings. Moreover, the specific variables subsumed within the "social factors" construct need to be explicitly incorporated in the model along with the feedback loops that govern their behavior. Vulnerability theorists can refine the evacuation model and use it to further specify and test the assumptions of vulnerability theory.

In this chapter we have drawn on system dynamics to describe support for two of the assumptions underlying vulnerability theory, and to encourage the use of system dynamics in testing, refining, and extending vulnerability theory. In Chap. 10 we summarize the empirical support for vulnerability theory and comment on the strengths and weaknesses of the various perspectives used in developing the theory. We present a master table of the variables used so far in exploring, describing, and testing vulnerability theory. In addition, we offer a high-level map or diagram of vulnerability theory and encourage social work researchers to focus on select segments of the theory. We stress the overlap of social work values and interests with themes in vulnerability theory. We end the chapter and the book with a set of specific recommendations on future research of vulnerability theory.