Cascading Disaster Models in Postburn Flash Flood

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***Abstract**—A useful method of modeling threats from hazards and documenting their disaster causation sequences is called "cascading threat modeling." This type of modeling enables emergency planners to address hazard and risk assessments systematically. This paper describes a cascading threat modeling and analysis process. Wildfire and an associated postburn flash flood disaster are modeled to serve as examples of the modeling and analysis process. Models are developed for both wildfire and flash flood, and the two models are then linked at a particular threat interface. Additionally, the use of a Federal and State Interagency Technical Team (IAT) for onsite wildfire and postburn flash flood assessment is described. The integration of expert field knowledge held by IAT specialists and agency staff is an essential component in developing credible cascading disaster models. When applied to local hazard mitigation planning, a detailed and systematic picture of local threat, risk, vulnerability, and consequence arises. An example wildfire burn and postburn flash flood is provided as a reference. Additionally, the use of an IAT for onsite wildfire and postburn flash flood assessment is described because this kind of field knowledge is essential in developing credible cascading disaster models.*

Introduction

Scientists commonly think of nature in terms of systems and disaster events occur within natural systems. For some inexplicable reason, disaster practitioners have not typically adopted systems thinking. In current emergency management analysis, disasters are usually studied fragmentally (fragmented), considering one aspect of a disaster at a time. What are considered in disaster assessments are often items arranged in lists or in tables, rather than as component within systems frameworks. Fragmental approaches have public safety shortcomings where extremely dangerous threats hidden within a disaster system may go unnoticed. It is proposed that cascading disaster models be used by emergency practitioners as the basis for conducting hazard and risk analyses and developing those analyses further into plans.

It is proposed herein that methods associated with "systems thinking" about disasters be called disaster systematics. Two kinds of associated information are presented. The first is an explanation of a disaster modeling technique called "cascading disaster modeling" and the second is an explanation of an application of this technique to wildfire and postburn flash flood. Although the concept of cascading disasters is mentioned often in hazard and disaster literature, little has been done in the development of methods for the application of the concept. This author has developed and used a technique for many years both for application in the university classroom (disaster studies) and for application within governmental contexts, including conducting detailed and systematic hazard and risk analyses at the local government level and with State parks.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

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Defining "Analysis" in Hazard Studies

The definition of the word "analysis" requires that the information being studied represent an intellectual or material whole, such that the constituent parts of the intellectual whole can be studied (see American Heritage Dictionary, Fourth Edition, 2000). Therefore, analyzing a hazard or its associated disaster requires understanding disasters in their entirety so that constituent parts can then be studied

The nature of the "whole" is explained in hazard and disaster management literature in terms of cascading disasters where one event in a disaster is connected through a causal sequence to the next event. Hence, we discover that a disaster consists of interconnected cascading causation sequences, from the initiation of the disaster to its culmination. This satisfies the definition of the whole.

Although a disaster exists as an intellectual or material whole, disasters are rarely studied within the framework of a whole. Hazard and disaster analysts most often study disasters through the use of selected isolated point threats, not related to their constituent cascading threat sequences. As such, according to the definition above, it would be impossible to analyze a disaster (break it into its component parts) through that process. Thus, there is some contradiction among emergency planners when the term hazard or disaster analysis is stated when a fragmental process is actually being used.

Cascading Threat Models

Cascading threat models (also known as cascading emergencies or disasters) have long been mentioned by some authors in the hazard and disaster management literature, but generally as only a vague concept. The concept is that disasters begin with a single primary threat and then occur as sequences of events. These sequences of events are most often referred to collectively as "secondary hazards" without the provision of additional definition or development. In this present paper, cascading is referred to in the context of dynamic disaster systems that consist of branching tree structures from a primary threat or event. To make the point that the concept of disaster systems is actively presented in disaster management literature, some quotes are provided in table 1. However, while such references exist, they lack clarification beyond that provided in the quoted text. Also note that an Internet search for the terms "cascading emergencies or disasters" produces something on the order of 1 million "hits."

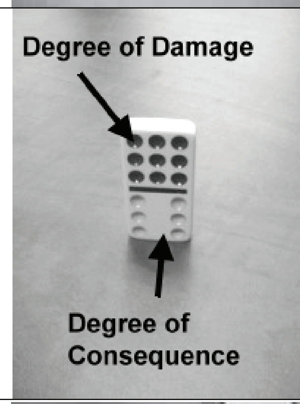
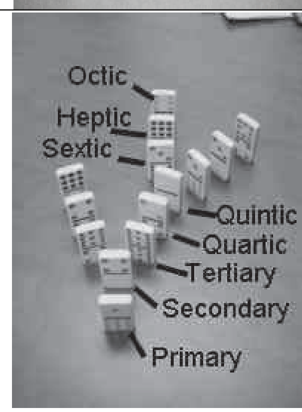
Cascading and Toppling Dominoes Analogy

The concept of cascading disaster events can be illustrated via an analogy involving toppling dominoes. A massive array of dominoes is arranged such that once the initial domino is toppled, striking the next, and so forth, the dominoes then topple in intricate cascading sequences, from beginning to end, often consisting of branching networks. Disasters, as natural systems, operate in much the same fashion. The following examples demonstrate this analogy.

In a disaster, it is not enough to say that there is a primary threat and then all other threats in a sequence are secondary threats. Each threat in a cascading sequence may have its own integral importance, its own degree of damage and degree of consequence. Cascading threat sequences can be identified in Latin as primary, secondary, tertiary, quaternary, quinary, sextenary (or senary), heptenary (or septenary), octenary, nonary, denary, undenary, duodenary, and

Table 1—Examples from disaster management literature.

Reference	Quote
FEMA Independent Study Course, IS 230, Principles of Emergency Management	p. 3.17. Cascading events are events that occur as a direct or indirect result of an initial event. For example, if a flash flood disrupts electricity to an area and, as a result of the electrical failure, a serious traffic accident involving a hazardous materials spill occurs, the traffic accident is a cascading event. If, as a result of the hazardous materials spill, a neighborhood must be evacuated and a local stream is contaminated, these are also cascading events. Taken together, the effect of cascading events can be crippling to a community.
FEMA Independent Study Course, IS 393, Introduction to Mitigation	p. 1-6. Cascading emergencies—situations when one hazard triggers others in a cascading fashion—should be considered. For example, an earthquake that ruptured natural gas pipelines could result in fires and explosions that dramatically escalate the type and magnitude of events.
U.S. Department of Homeland Security National Response Plan, December 2004	p. 4 Additionally, since Incidents of National Significance typically result in impacts far beyond the immediate or initial incident area, the NRP [National Response Plan] provides a framework to enable the management of cascading impacts and multiple incidents as well as the prevention of and preparation for subsequent events.
FEMA for Kids Website, Resources for Parents and Teachers, How Schools Can Become More Disaster Resistant. http://www.fema.gov/kids/schdizr.htm	. . . disasters can have a cascading effect—forest fires can bring mudslides; earthquakes cause fires; tornadoes cause downed power lines.
Resource Materials: Integrating Manmade Hazards into Mitigation Planning Risk Management in a Multi-Hazard World 2003 All-Hazards Mitigation Workshop June 12, 2003 Emergency Management Institute http://www.fema.gov/txt/fima/antiterrorism/resourcematerials.txt	Indirect attacks: infrastructures are really interconnected systems of systems; an attack on one can lead to cascading losses of service (ranging from inconvenient to deadly) and financial consequences for government, society, and economy through public- and private-sector reactions to an attack.
FEMA 428, Asset Value, Threat/Hazard, Vulnerability, And Risk	p. 1-17. Extent of damage is determined by type and quantity of explosive. Effects generally static other than cascading consequences, incremental structural failure, etc.
FEMA 386-7, FEMA State and Local Mitigation Planning How-To Guide, Integrating Man-Made Hazards Into Mitigation Planning. Step. 2, Assessing Risks.	p. 2-11. What is the likelihood of cascading or subsequent consequences should the asset be destroyed or its function lost?
Hazard Analysis and Risk Assessment, 2003 Local Guide, Iowa Homeland Security and Emergency Management Division,	Hazards create direct damages, indirect effects, and secondary hazards to the community. Direct damages are caused immediately by the event itself, such as a bridge washing out during a flood. Indirect effects usually involve interruptions in asset operations and community functions, also called functional use. For example, when a bridge is washed out due to a flood, traffic is delayed or rerouted, which then impacts individuals, businesses, and public services such as fire and police departments that depend on the bridge for transportation. Secondary hazards are caused by the initial hazard event, such as when an earthquake causes a tsunami, landslide, or dam break. While these are disasters in their own right, their consequent damages should be included in the damage calculations of the initial hazard event. Loss estimations will include a determination of the extent of direct damages to property and indirect effects on functional use.
Regional All-Hazards Mitigation Plan, City of St. Louis and counties of St. Louis, Jefferson, Franklin and St. Charles, Missouri, November 2004.	Cascading hazards could include interruption of power supply, water supply, business and transportation.

A single domino, as shown at the right, represents a point threat, as one might expect were a disaster to be a static event. This standing domino could represent a type of electrical transmission line constructed in an urban wildland interface. It is simply a power line at risk from wildfire, although a wildfire has not happened (domino is not yet toppled).	
Here, at the right, we see the same domino but we consider what might happen if the electrical transmission line were to be damaged by a wildfire. Thus, we may consider a degree of damage and an associated degree of consequence. In this case the degree of damage would be 100 percent, or complete, and the degree of consequence is somewhat more than moderate.	
This view, at the right, is of an anticipated dynamic disaster sequence, should the sequence happen. Should the wildfire provide a low level of damage, consequence of even a low level of damage results in a completely negative consequence (see the top number, one dot, on the first domino, which represents the primary threat; see the bottom number on the domino, six dots, which represents the level of consequence). If the primary threat (first domino) happens, then the rest of the cascading sequence may take place, where one threat causes another, and so forth, each with its own relationship between degree of damage and degree of consequence. Numbering is explained in the text.	

so forth. The author proposes using shortened terms to simplify communication: primary, secondary, tertiary, quartic, quintic, sexic, heptic, octic, nonic, decic, undenic, duodenic, and so forth (written communication, Dr. David Larmour, Texas Tech University, 2006). Such nomenclature facilitates communicating about threat sequences. In the illustration above, which shows a branching domino sequence, a disaster analyst could consider how a wildfire would generate a branching set of threat sequences because, for example, the fire spreads because fire support is too far away to provide immediate response. That sequence of events can be analyzed (separated into its constituent parts to be studied). The threat sequence could represent any causation sequence. For example: (1) the delay in response would allow the fire to grow, and (2) the movement of fire support personnel from distant areas could result in traffic accidents, and so forth. Both pathways need to be analyzed.

Multihazard Concept

Cascading threat modeling has its origins in the concept of multihazard events. The term multihazard was introduced by the Federal Emergency Management Agency (FEMA) in 1982-1983 as part of the Utah Multi-Hazard Project. This new concept related multiple hazards to each other through causation sequences. The Utah Multi-Hazard Project included the cities of Provo and Ogden, and Utah and Weber Counties, showing the relationship between earthquake, dam failures, and floods, where a simulated design earthquake would logically cause a dam failure, which would then cause a flood (personal communication, Wes Dewsnup, Utah Multi-Hazard Project, former Program Manager; Utah Division of Comprehensive Emergency Management, July 15, 2006). This concept, though simple, was revolutionary because multihazards lead to multidisciplinary considerations, interactions, and solutions. The concept required diverse groups of specialists from various agencies to work together to solve multihazard problems. Earthquake specialists, dam safety specialists, and flood specialists then needed to work together to solve planning problems that emerged from multiple hazards.

Shortly after the awareness of the multihazard concept, various FEMA publications began to include the term cascading hazards and cascading disasters (see table of references above). It was from this concept of cascading hazards and disasters that this present method of disaster systematics arose in the late 1980s, as both a teaching and planning tool. The initial tool was called a “hazard tree,” and authoritative hazard trees were created by members of the Utah Interagency Technical Team (representatives from several agencies working together) for use in conducting local hazard and risk analyses. This tool was used successfully Statewide for such analyses. Hazard trees and the larger concept of disaster systematics was used as early as 1988 in the classroom at the University of Utah, Center for Natural and Technological Hazards, where students were required to develop hazard trees to understand cascading disaster processes for analysis purposes. The author first published a cascading disaster model in 1991 through the National Research Council’s publication “A Safer Future, Reducing the Impacts of Natural Disasters,” 1991, Chapter 2, Hazard and Risk Assessment.

Modeling Versus Model Analysis

The purpose of creating cascading disaster models is to have credible models available for use in analyses. The models, which often are not complicated, capture the cascading events in disasters. Disasters often consist of many cascading sequences. Computer software can be used to keep track of these sequences, facilitating analysis and even supporting standardized analyses.

Model Development

The human mind cannot recall the amount of sequential information contained within a complex disaster system, but computers can store and display, both in outline and diagram formats, entire disaster systems. Both outline and diagram formats are essential in the development and application of the models. Computers can also store additional text and visual information as background documents within the models through notes and hyperlinked documents of many useful software types (word processing, spread sheets, presentations, Web pages, and so forth). Computers also allow for the creation of aesthetically attractive models suitable for public display and presentation.

Several types of computer software programs are capable of meeting the needs of "cascade modelers," including Inspiration and MindManager. Both of these software programs allow the modeler(s) to work within an outline and or diagram format, and both are powerful and versatile, allowing the modeler(s) to escape the limitations of fragmented hazard and risk thinking–to become disaster systems analysts.

Although completed disaster systems models appear complex and intricate, few of the threat sequences are particularly complex and are often sequences we are familiar with. For example, one sequence from an earthquake model might state that a threat from ground motion causes threat from the shaking of buildings that, in turn, causes threat from falling bricks that, in turn, causes threat from bricks blocking streets that, in turn, causes delaying of emergency vehicles that, in turn, causes threat from the delay of emergency services to people in need of emergency services. But then we notice that falling bricks can cause more than one threat sequence, and that blocking of streets can cause more than one threat sequence. Thus, cascading models branch within themselves, but even the branching sequences are often easy to follow. The team performing an analysis on any of these sequences can perform analyses that range from straightforward to exceptionally complex, and can be multi- and interdisciplinary.

The development of a cascading disaster model must follow a process that provides credibility to the model. Usually, the modeler (generalist), as mentioned, would be an emergency manager or disaster analyst who coordinates a technical team of engineers, geologists, natural resource specialists, fire management specialists, environmental scientists, planners, and others (all specialists) to create a model. Cascading disaster models should be constructed by a team of technical experts who collectively provide best available knowledge into the model. Computer software is used that enables the modeler (generalist) to enter threat sequences directly into the computer during an interview process involving the technical team (specialists). Team members determine model inputs while the modeler enters the information. The software allows the modeler to enter the information (causal sequences) into an outline format/view and display the model as a cascading tree structure in a diagram format/view. The team of specialists collectively determines the threat sequences and the branchings.

Generic and historic models—There are two basic types of cascading disaster models: generic and historic. Generic models are those designed by a modeling team based on their collective experience to document what can happen in a disaster of that type. There is no reference to other disasters in that the model is not intended to reflect any particular disaster event. Generic models have their own threat nomenclature that is written in the present tense. This nomenclature makes the statement throughout the model, from threat to threat, stating that "threat from this causes threat from this that caused threat from this, and so forth." Threat nomenclature is mainly found in the way the verbs are written within the threat symbols (present tense versus past tense). Most example models provided in this paper are representative of generic models. This type of threat nomenclature is either written as "ing" endings or as present tense verbs. See model examples below for these types of endings.

The other basic type of model is the historic model. Historic models are based on research of a particular disaster, and the identified disaster processes (sequences) are captured in that model. The intent is to document what processes happened in that disaster. Because this information documents an event that happened in the past, the threat nomenclature is written in the past tense ("ed" endings or past tense verbs) (fig. 1).

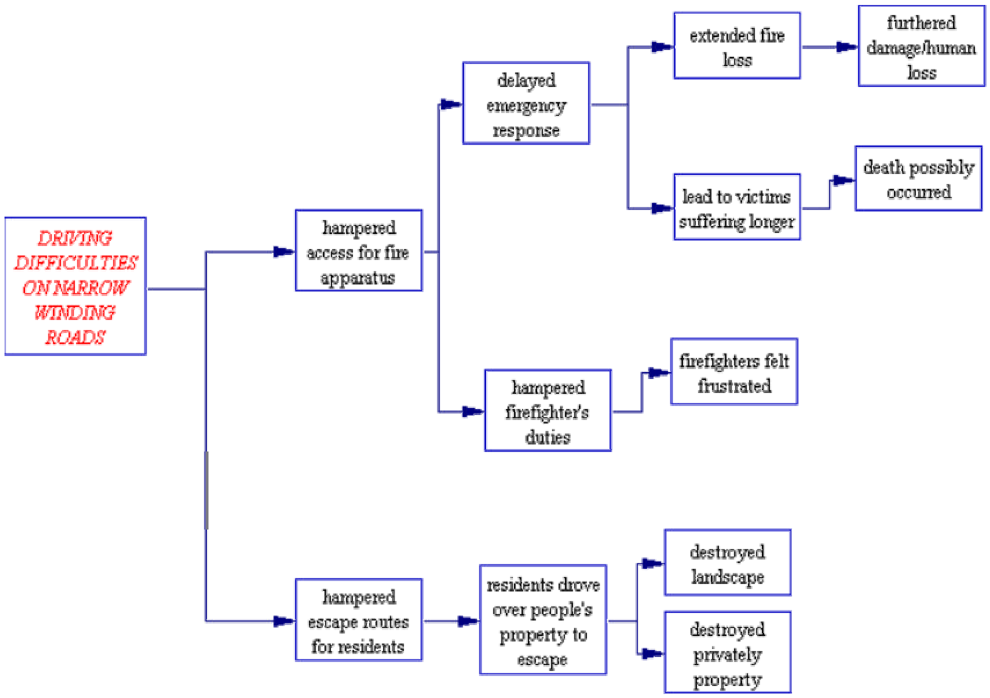


Figure 1—Example of a historic branch of a cascading disaster model of part of the Oakland, CA, wildfire (1991) based on studies of that event.

Threat sequence logic transitions one threat logically to another, depicting the causation sequence. Models must be internally coherent to make sense in their entirety. Thus, one threat must transition logically (causation sequence) and properly (nomenclature) to the next and to the next. This is true if a modeler is developing a generic model (present tense) or a historic model (past tense).

Model geography—Cascading disaster models have **shape, dimension, location, and design**.

The **shape** is that of a branching tree structure, called an index tree. Several graphical examples of a model are provided. Figure 2 is the model for a wildfire. A cascading model for wildfire would begin with a first level index tree, which simply shows our initial sense of what can happen. The fire can then spread uphill, laterally, or downhill, threatening an urban wildland interface community. It can also burn into the community's watershed, introducing the potential for postburn flash flood. The index tree identified the primary and secondary threats that precede the main branches of the model.

The tree can be created and displayed as a top-down tree, a bottom-up tree, a right tree, or a left tree. Experience suggests that either a top-down tree or a right tree functions best. The shape of a tree structure begins with the primary threat, or initial threat that precipitates the cascading sequences of the disaster. Branching sequences follow causing the model to expand. The portion of the tree structure more near the primary threat is termed "proximal," and the portion of the tree structure more distant from the primary threat is termed "distal." At the ultimate proximal end is the primary threat, and at the ultimate distal end are the terminal threats (where the individual model pathways terminate) (fig. 3).

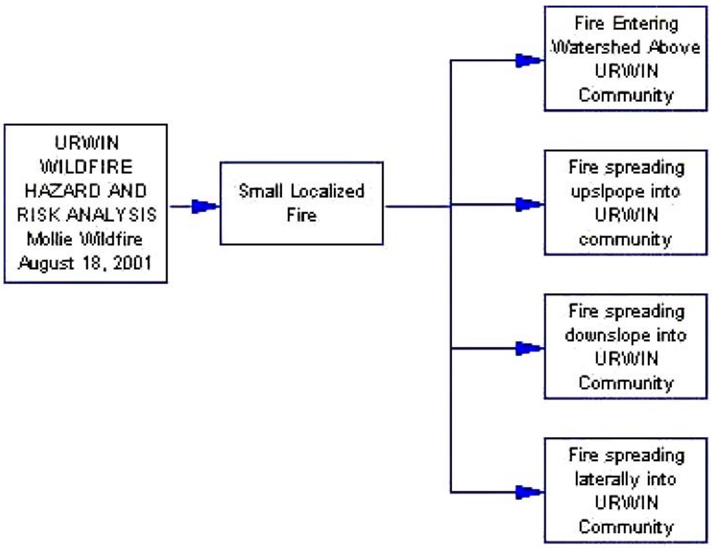


Figure 2—A wildfire begins with the primary threat of a small localized fire. The display of the first few threat layers constitutes an Index Tree, which leads to the rest of an expanded model.

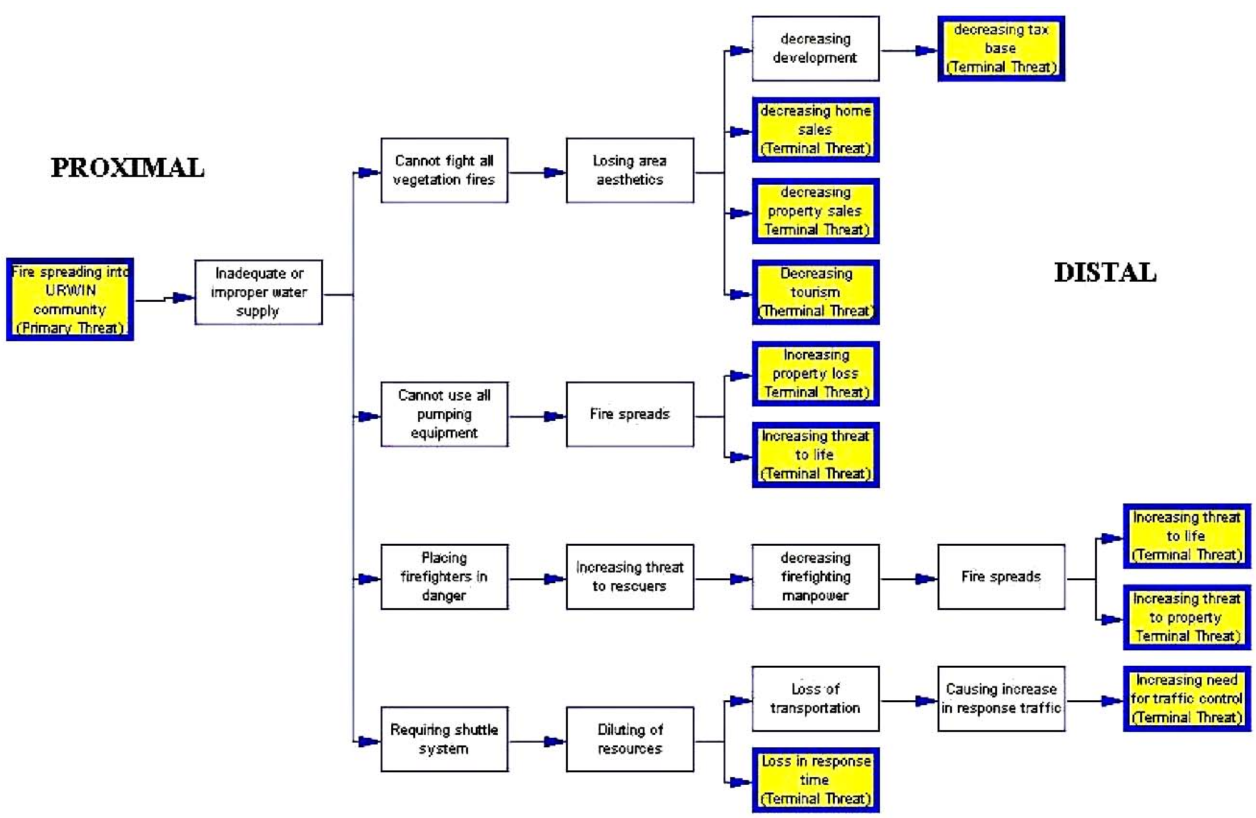


Figure 3—Model branch showing proximal and distal areas and terminal threats.

For **dimension**, the tree has both height and depth determined by the number of branching threat pathways (primary threat to terminal threats). There are as many pathways across the model as there are terminal threats. If the model has 10 terminal threats then the model has a dimension, top to bottom for right trees, of 10 pathways each of which can be analyzed. If the model has 10 pathways, from primary threat to terminal threat, that have, for example, five threats per pathway, then the model is five threats deep, from left to right for a right tree. In this hypothetical example of five threats per pathway, the model would consists of 50 threats, all organized within the 10 pathways. Thus, the model has height (number of pathways - 10) and width (numbers of threats per sequence—a hypothetical number of 10).

There are many threat **locations** within the model. The example in figure 3 depicts 25 threats, each with a unique location within the model that can be identified according to a pathway code. Pathway codes are unique to a particular model, its associated team, and its associated draft date and time. Through the use of pathway codes, team members, or others using the particular model, can communicate about particular threat pathways and understand which pathways they are discussing. Each pathway becomes of interest in a variety of ways: preparedness, response recovery, recovery, training, exercise design, hazard behavior, disaster behavior, and so forth. Given that a pathway consists of a unique threat sequence, then the process of analysis involves studying each threat in its geographic location within the model. It is then important to be able to discuss each threat location with others who may be interested in it. Also note that each individual threat has its own location code.

Figure 4 shows pathway codes for 11 pathways (each terminal threat denotes the end of a pathway) and 24 threats (each box denotes a threat). As shown each threat has a position code number. A threat with two numbers in its code is a secondary threat, and a threat with three numbers is a tertiary threat, and a threat with four numbers is a quaternary threat, and so forth. Numbers are counted from each node between threats and from the top down. The threat position code for a terminal threat is also the pathway code for that pathway (from primary threat at the proximal end of the pathway to the terminal threat at the distal end of the pathway). Thus, in figure 4, one can observe 11 unique pathway codes. As an example of identifying a specific threat, the secondary threat of "inadequate or improper water supply" is located within the box with pathway code "11."

The **design** of the models consists of branches and pathways. Branches are units of a cascading disaster model where two or more pathways originate from a node (that is, the connecting point between two threats). Pathways originating from such a node share design similarities based on the common threat at the proximal end of the branch. Branches that originate from a secondary threat are secondary branches and those that originate from the tertiary threat are tertiary branches, and so forth. Thus, a branch can be discussed by team members as the associated pathways sharing that common characteristic.

Several branches are shown in figure 4. The four pathways of the tertiary branch share the common threat characteristic of "Not Fighting All Vegetation Fires." The two pathways of the quaternary branch share the common threat characteristic of "Fire spreading," which was caused by "Not using all pumping equipment." The two pathways of the sextec branch share the common threat of "Fire spreading."

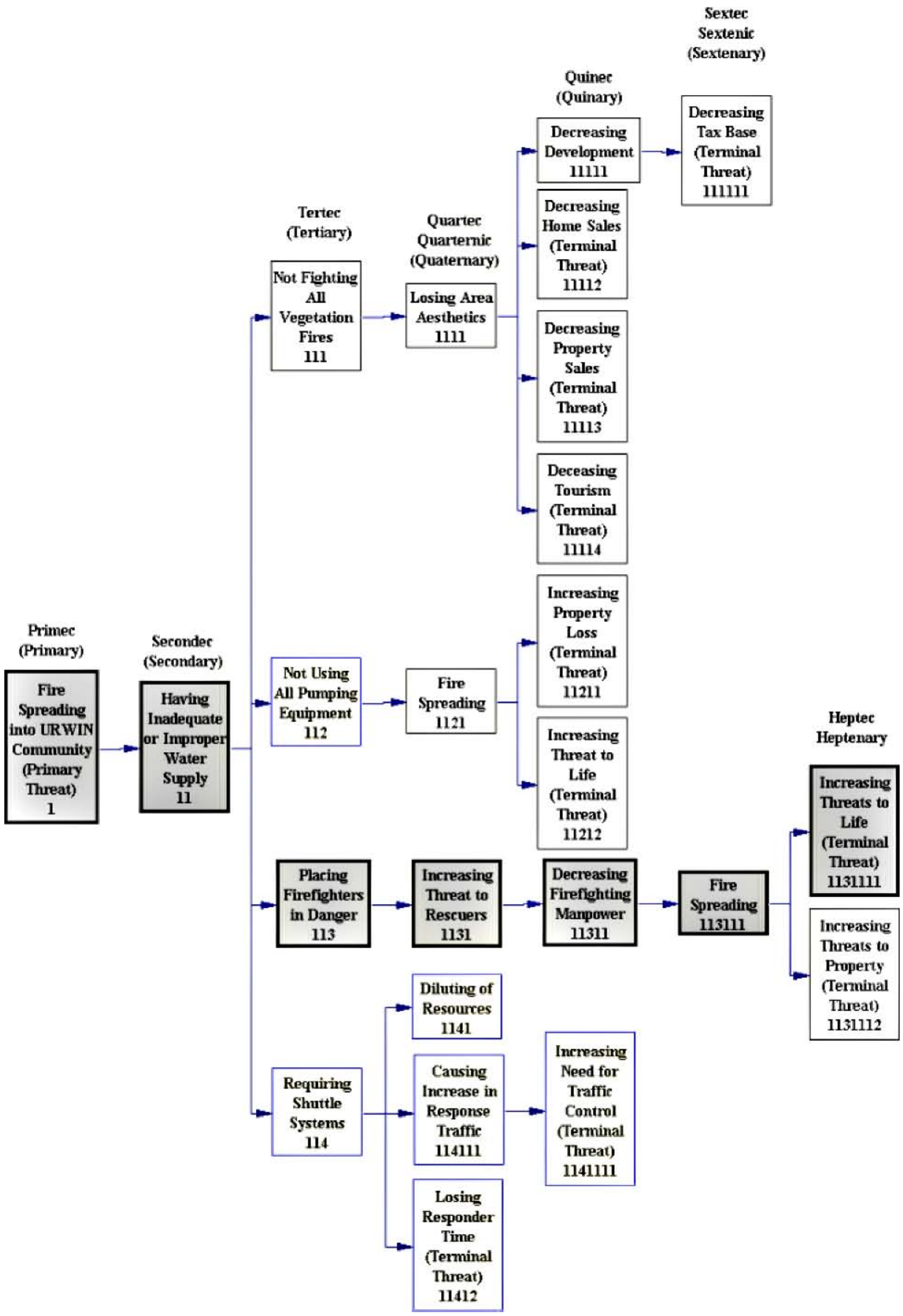


Figure 4—Model branch showing a single pathway highlighted and also showing the unique threat and pathway codes.

Branches can be studied by disaster analysis, but pathways (also referred to as single-file pathways) form the main study unit of a cascading disaster model. Pathways are causation sequences where one threat causes another threat causes another threat causes another threat, and so forth. An example pathway is shown above in figure 4 in the discussion on pathway codes and is separated and shown in figure 5, as well.

Figure 5—Separated single pathway from branch model shown in figure 4.

Single-file causation sequences (pathways) can be studied by a team of hazard and disaster analysts from a variety of perspectives: disaster preparedness, disaster response, disaster recovery, and hazard mitigation. Causation sequences can also be studied from the perspectives of training, exercise design, and so forth. For example, a team of disaster analysts could examine the pathway shown in figure 5 and ask the questions: how might we prepare for, respond to, recover from, or mitigate, such a sequence of events; or how might we train for such a sequence or devise a disaster exercise for such a sequence? In conducting such an analysis, the team might also choose to provide more detail within the model pathway by inserting additional threats.

Antecedent conditions—Cascading disaster models portray disasters and disaster behavior graphically. The same models can also be used to portray hazard behavior by including antecedent conditions—the hazard behaviors that lead to the activation of the primary threat. For example, the presence of propane tanks would also be called a hazard by some disaster analysts. Hazards themselves in these models are simply nouns, or the names of the threats the mind recognizes as hazards to the human built environment and with people themselves.

Figure 6 displays the antecedent conditions that would link a wildfire model to a postburn flash flood model. The antecedent conditions begin with a Damaged Watershed and conclude 11 threats later with a hyperconcentrated flow emerging onto an alluvial fan apex. Antecedent conditions precede the associated disaster, which in this case would be a debris flow disaster associated with the damaged watershed and a significant thunderstorm.

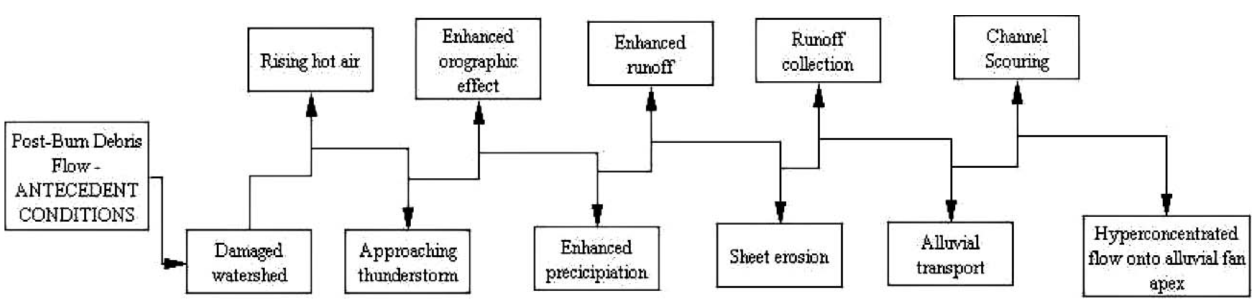


Figure 6—Antecedent conditions that cause the primary threat in disaster genesis.

Model Applications

The value of cascading models has become apparent through several years of application and in a variety of situations.

Cascading models have been used to:

- **Educate community and governmental leaders:** The model as a teaching tool demonstrates to leaders how a particular type of disaster might affect their community, showing generic disaster behaviors as causation sequences, where one threat causes another, causes another, and so forth, or how, through the diagram format, a disaster can "unfold" in their community. The education is meaningful because disasters are commonly thought to happen in random, unpredictable fashion, but in reality leaders learn that disasters happen as systematic processes of causal sequences.
- **Educate IAT members:** Because the human brain is not capable of remembering the details of numerous and complex disaster sequences, the computer-printouts on paper aid team members when they consider what threat pathways are the most dangerous and of highest priority and what strategies might be applied to these pathways to prepare, respond, recover, or to mitigate potential hazard and disaster events.
- **Educate stakeholders and the public:** The process of building community capacity to reduce vulnerability requires public support. The public most often views disaster processes as being too complex to understand and, therefore, tends to avoid gaining an understanding of them. The lay people not versed in hazard and disaster processes and knowledge can understand the logic of cascading disaster model diagrams and, also, the logical threat sequences.
- **Evaluate training:** Models can also be used to identify training needs of the technical team of hazard and disaster managers from the State and Federal agencies, including how to conduct hazard and risk analyses in communities. Team members themselves, in studying a model they created, could identify what knowledge they need in order to understand the sequences in the model.
- **Conduct hazard and risk analyses:** State and local governments are required by Federal law to prepare and submit to the Federal Emergency Management Agency (FEMA, Disaster Mitigation Act of 2000) for approval hazard mitigation plans and emergency operations plans. Such plans are based on hazard and risk analyses. Many agencies of government also conduct these analyses for a variety of needs, or assist local governments in conducting the analyses. Cascading disaster models provide an excellent basis for conducting such analyses that are detailed and systematic. A team of experts can use these models to conduct analyses in a brief period, perhaps 2 hours, considering most any kind of threat that could face a community. Updates to the analyses usually require much less time.
- **Design disaster exercises:** A visual image of disaster as cascading sequences of events provides an excellent basis for designing a disaster exercise. The entire model can be used to develop a comprehensive disaster exercise or it can be used to develop an exercise for selected sequences in a disaster where an exercise would provide the needed training for some aspect of response. The simulated messages (injects) for the exercise could be designed around the threat sequences and relating to the players in the exercise.

- **Conduct planning:** Cascading disaster models can be used for conducting hazard and risk analyses and support the development of response strategies and recommendations. Once a planner comes to the point of adding recommendations, then the hazard and risk analysis becomes more than just an analysis. It begins to look more like a plan. It could become a plan if implementation strategies were also added to the model. Plans, however, are best laid out as text within an outline (table of contents), but the information from the analyses conducted with the model can be transposed into the plan.

Wildfire and Postburn Flash Flood

To relate wildfire to postburn flash flood, refer back to figure 2, which shows a simple view of an index tree including wildfire damaging the watershed. That threat provides the linkage to the cascading threat model for postburn flash flood. City officials too often believe that once a threatening wildfire is contained, the community's vulnerability to disaster is largely over. However, the community then finds itself facing flash flood threat should a significant thunderstorm occur over the damaged watershed (Cornell 1992). In this case, there are now two related cascading disaster models needed, the first for wildfire and the second for postburn flash flood. The two related models would be joined at a terminal threat titled "damaged watershed."

For example, figure 7 displays a wildfire cascading threat model that includes the beginnings of effects of rainfall onto the damaged watershed. Remember that such a model can be as complex as a modeling team wishes to make it. Such threat models, if developed with the assistance of specialized planning teams, gain considerable credibility. This particular model was developed by a combination of wildfire hazard and flood hazard specialists of the Utah Interagency Technical Team in the early 1990s. The process of making a transition from one model (for example, wildfire) to another model (postburn flash flood) introduces the concept of a compound model. (Compound models are caused by a preceding "simple model" and superimpose their own consequences onto the already-existing consequences of the simple, preceding, model. This is a concept too complex to explain in this present paper.) The branching in such a model provides an interesting juncture in the disaster model because it is at this point that the model would actually link to a separate model, representing what happens when the thunderstorm does happen. We then must connect to a debris flow tree modified for the enhanced sediment load. This is a separate model.

Figure 8 presents an index tree for a postburn flash flood cascading threat model. An index tree can be constructed that allows the modeler the option of working with any of the shown pathways, beginning with any of the terminal threats shown. In fact, the entire comprehensive model could be collapsed to the level of the index tree for purposes of illustration.

The Index Tree can be expanded to view a selected branch that would begin with any one of the terminal threats shown in figure 8. This begins the process of analysis. The selected branch provided in figure 9 is an extension from the index tree, diagramming threat sequences arising from the threat of a hyperconcentrated flow impinging onto residential structures. This array of threat sequences shows several aspects of the event that relate to the flow impinging onto residential structures. They all have this one thing in common, which is a characteristic of branches within a cascading disaster model.

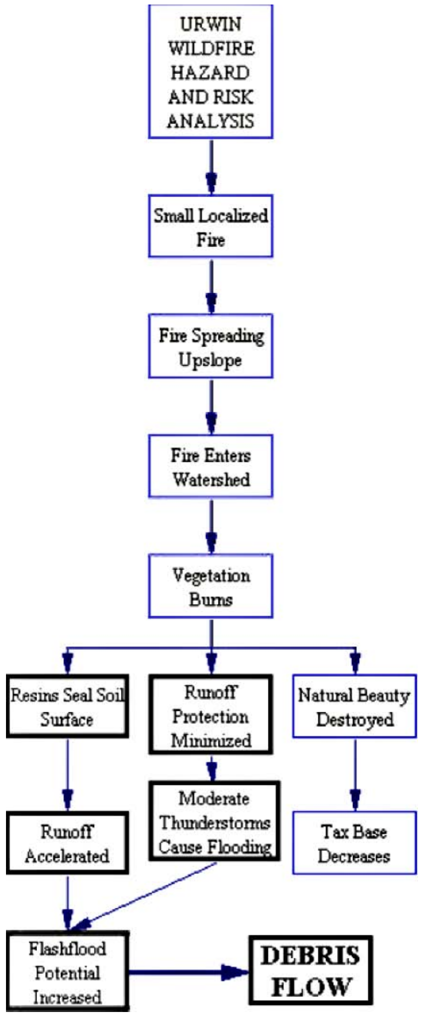


Figure 7—The postburn flash flood (or debris flow/hyperconcentrated flow) model begins at a node within the wildfire model.

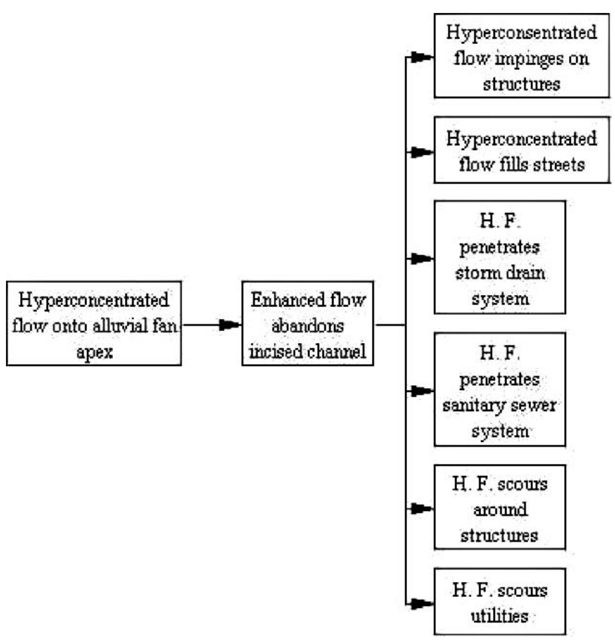


Figure 8—Index tree for postburn flash flood (or debris flow/hyperconcentrated flow).

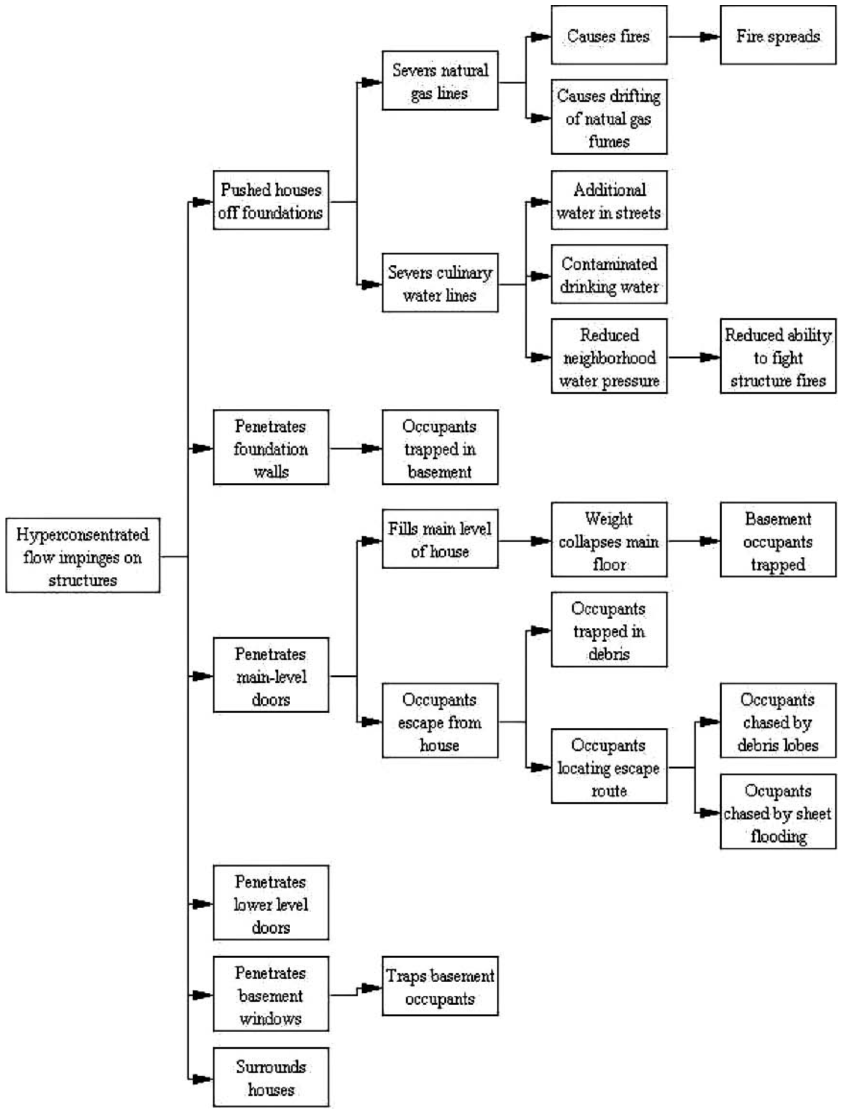


Figure 9—Cascading threat model branch of postburn flash flood stemming from the index tree shown in figure 8.

Branch analysis is useful in determining the variety of sequences that can arise from a single threat node. This could serve as a justification tool for mitigation, which would be an expected objective: to mitigate as many threats as possible with one strategy. Still, the main analytical tools of cascading threat sequences are the single pathways, as the analyst can focus on one particularly interesting or dangerous threat sequence. The single pathway can be displayed, according to the domino explanation provided earlier in this paper, where each threat in a causation sequence has its own degree of damage and degree of consequence. For example, complete damage to a movie theater caused by the flow impinging on the movie theater may have little real consequence for a community, whereas, a small amount of damage to the fire station may have much more consequence. Numerous scenarios of this type (single file pathways) can be identified within the cascading model.

Figure 10—Debris/hyperconcentrated flow causation sequence trapping victims in a basement bedroom.

This single file cascading sequence, shown in figure 10, is a simple three-step pathway regarding water flowing into a basement. As the analyst examines it, however, it becomes apparent that much more study is warranted. Although it is serious enough that adults might be trapped in the basement, one may recognize that children often occupy basement bedrooms and may become victims of the flooding during a night-time postburn flash flood. If the description, in the next section, of the Santaquin, UT, debris flow is correct, that the flow approached silently, then basement rooms would begin filling suddenly with liquefied sediment and other debris without warning. Among debris flow specialists, it is said generally that 6 inches of water flowing over a window well can fill a 10 foot by 10 foot basement room in about 45 seconds, forcing the door closed and making it impossible to open. That being the case, then this single file pathway is worthy of considerable study.

A simple example of an analysis approach for single file pathways is provided in table 2. Notice how the analyst can arrive at a set of mitigation options, addressing each threat in a sequence, and develop an overall mitigation strategy.

Table 2—Example of an analysis approach regarding victims in a basement bedroom.

• Maintain materials for emergency diversion: Prepositioned jersey barriers, straw bales.	• Move children to upstairs bedrooms.	• Use sliding doors for basement rooms.
• Implement home mitigation strategies: deploy sand bags to protect entry points or to divert flows.	• Elevate window wells. • Sandbag window wells. • Board-over window wells. • Fill window wells with bags of gravel to displace water.	• Use delicate door materials that can be easily broken from inside. • Attach basement doors that open in outward direction.
• Build homes at 45 degree angle to uphill slope.	• Construct house without basement windows on uphill side of house.	• Place basement alarms in bedrooms that can be activated by occupants.
• Construct streets in residential area with inverted crowns angled to catch and route flows.	• Use double-pane laminated glass for basement windows.	• Place tools near door so that they are readily available to break door.
• Construct permanent debris basins at apex of flow path.	• Cover window wells with impenetrable plastic shield.	• Remove basement doors until watershed is reestablished.
• Monitor weather, satellite, and Doppler images.	• Tape windows so glass is not easily broken. • Install plastic film to strengthen window panes.	• Place a ladder in occupied rooms.

To conduct such an analysis as shown in table 2, the modeling team of Federal and State hazard and disaster experts meets with a local planning team. The local team being interviewed can view the overall threat model in diagram format (view the tree structure). The analyst leads the local team through the process from branch to branch, even pathway to pathway, determining which branches and pathways have presented problems to the community in the past, or which might present problems in the future. As the local team answers, the analyst types the information into the outline format of the software under each individual threat. The complete interview process, working through an entire model, can take 2 hours, considering that not each threat sequence will apply to the community. Once the analysis is completed with the interview/analysis, then updating the analysis annually will take far less time, based on the local government's interim experience.

To yet advance the analysis into an initial hazard mitigation plan, as the analysis is being conducted, the local team can provide mitigation recommendations as each sequence is discussed. If this is done, then at the end of the analysis, the outline format contains all information provided based on experiences and expectations, and also recommendations for mitigation built within the systematic framework. The overall information can then be transferred to a text document to formulate a hazard mitigation planning document.

Example Scenario: Santaquin, Utah, Postburn Flash Flood

Cascading disaster models are developed based on the real-world experience of interagency technical teams such as the Utah Interagency Technical Team. Since the 1980s, the Utah IAT gained experience working with postburn flash floods of the following locations in Utah: Affleck Park, Emigration Canyon, 1988; Wasatch Mountain State Park, 1991; North Ogden, 1991; Holden, 2000; Orem, 2000; and Farmington, 2003 (State of Utah, Hazard Mitigation Plans). The Mollie Wildfire and postburn flash flood of Santaquin, UT, was an event that was studied in much detail and resulted in much community interaction (fig. 11).

The Santaquin (Utah County) wildfire, named the Mollie Fire, began on August 18, 2001, and produced an 8,000 acre burn directly above the east bench of Santaquin (pop. 4,834). A new development of homes was in proximity to the burn and the wildfire threatened to cause a disaster. Due to the potential for disaster, the fire qualified for a Federal Wildfire Suppression Declaration through the Fire Management Assistance Program of the Federal Emergency Management Agency. By the time the wildfire was contained, it had not burned any homes, due to an excellent fire suppression effort by the State and local fire departments. Some homes had minor damage. At the time of the declaration request, the fire was described as: (1) out of control with conifer vegetation at higher elevations; (2) oak and sage at lower elevations, mixed-in around homes at risk; (3) steep mountain slopes with about 3,000 feet of topographic relief; (4) interspersed rugged canyons; (5) developed areas lie in fire's path within 1 to 3 miles; and (5) threat is to about 900 people and 250 primary residences. In a sense, the entire population on the east side of Interstate 15 was at risk, including 1,315 housing units. These were also at risk from the potential of postburn flash flood. (Mollie Wildfire, BAER Team Report, 2001).

Figure 11—An eastward view across a Santaquin residential area located below a watershed burned by the Mollie Wildfire. The wildfire burned to the ridgeline and the width of the watershed shown here. These residents lived with the daily reminder of a burned watershed and the potential flash flood that could happen with the next thunderstorm or unusual snowmelt.

The composition of an interagency technical team for postburn evaluations for flash flood potential represented several agencies of State and Federal government and enabled the impacted local government to answer most any question and address most any issue. This particular team consisted of the following (Utah Interagency Technical Team ONSITE Report, September, 2001):

- IAT Coordinator, Utah Division of Emergency Services
- Watershed Geologist, USDA. Natural Resources Conservation Service
- Hazards Geologist, Utah Geological Survey
- Engineer/Hydrologist, Division of Water Quality
- Engineer/Hydrologist, Division of Drinking Water
- Engineer/Hydrologist, U.S. Army Corps of Engineers
- Meteorologist, National Weather Service
- Engineer/Hydrologist, USDA Natural Resources Conservation Service, Snow Survey Office

Based on team field assessments, more than 30 field observations were made and those observations resulted in 27 hazard mitigation recommendations relative to wildfire and potential postburn flash flood. This body of knowledge was incorporated into the cascading disaster model for use in future hazard and risk analyses and planning efforts.

In the years following the wildfire, the city of Santaquin experienced two postburn flashfloods. These did not happen immediately after the wildfire, which highlights one of the major challenges of postburn flash flood. Once a watershed is damaged, the threat might remain in effect for up to 6 years while the watershed reestablishes itself. In the meantime, local officials and residents wait for only the possibility of the event.

On the evening of September 12, 2002, just 1 year after the wildfire (August 18, 2001) that damaged 8,000 acres of the watershed above Santaquin, an intense thunderstorm settled onto the watershed. This storm triggered a wildfire related debris flow that damaged houses in the adjacent communities of Spring Lake and Santquin. This debris flow moved and partially buried several automobiles and broke through a wall into a house. It entered other homes through doors of basement windows. Gas meters were torn from their connections, causing leaks and a small fire. Landscaping and property outside of homes were also damaged. The flow also blocked the highline irrigation canal causing additional flooding.

Mayor LaDue Scoville (pers. comm. June 29, 2005) reported that the debris flow that entered the east side of Santaquin entered the neighborhood silently at about dinner time (approximately 6 p.m.). This was unusual in that debris flows have been otherwise described as being noisy, much like the sound of an approaching locomotive. People eating dinner were not aware of the problem until they heard noises of breaking garage doors and the destruction of other doors to their homes. On investigating the sounds, people discovered that mud was flowing in their streets and around their homes. In one case, the mud entered through a main door to the home, breaking it in, and then flowing into the main level. The weight of the mud collapsed the main floor onto the basement, sending a piano through the broken floor. One lady, being forced from her home carrying a baby, was “chased” down the street by the mud flow, but she was able to keep in front of it, escaping. The flowing mix of water and sediment broke through several basement windows filling the basements with the mud. The mayor described the mix as crusty on its surface, but that pressure placed onto it, as with a foot, caused it to turn into a liquid mix and set it to flowing again. The mayor reported that the silent approach of the debris flow made it potentially lethal. Fortunately the debris flow happened early in the evening before people were in bed. The mix filled basement rooms quickly. Had children, or adults, been in basements they likely would have been trapped and killed. This has been a message of emergency managers for at least a decade, that debris flows can fill a basement bedroom in less than a minute, pushing the bedroom door closed and applying such weight as to make it nearly impossible to escape.

No fatalities or injuries occurred, which Mayor Scoville explained as a miracle. The flow surrounded houses and blocked streets, even partially burying automobiles, making it difficult to escape. He explained further that the “liquid mix” remained liquid for days, sealing itself and preventing evaporation of the water. When the city attempted to haul the mix away it liquefied and ran out of the scoops of front end loaders and oozed out the rear gates of dump trucks. This was such a problem that the Utah Department of Transportation would not allow the city to haul the mix on State roads, as it would flow out of the trucks and onto the highway. For several days after the city disposed of the mix in a field, it maintained this fluid consistency.

The city Public Works Director, David Banks, indicated that the debris flow pushed one house off its foundation and separated the natural gas line from the house, causing a leak. The gas company shut off the gas to that neighborhood, but gas remained in the lines. As city workers were digging in the area, underground power lines still had electricity running through them. Excavation by city workers could have severed gas or electrical lines and resulted in electrocution, fire, or explosion; fortunately, such an event did not happen.

Conclusions

Natural disasters are natural systems and happen as cascading causation sequences, and these sequences can be documented using computer software as cascading disaster models. These models can be analyzed according to their branches and single-file pathways. This is a systems approach to analyzing disasters. The opposing method is called the fragmented approach where hazard or disaster concerns to be addressed in assessments are studied from lists and tables. Any technique involving a systems approach should be included in an aspect of disaster science called disaster systematics. It is also proposed that disaster analysts develop and use cascading disaster models when conducting hazard and risk analyses. It is also proposed that fragmented approaches to studying disasters be largely abandoned as they can lead to neglecting dangerous threats that may lie hidden within a disaster system (cascading models).

Although, in this paper, wildfire and postburn flash floods are provided as simplified cascading threat models, the reader's imagination would certainly suggest that complete models can be highly sophisticated/complex based on technical team inputs and model design. The associated analyses would likewise be rather sophisticated if performed by technical teams. Detailed and systematic hazard and risk analyses can be developed with a local government in about 2 hours per hazard (for example: local wildfire hazard and risk assessment), and a mitigation plan with recommendations can also be developed simultaneously.

The example herein makes a strong case for the elimination or greater protection of basement occupancy on alluvial fans below wildfire burn areas, or potential burn areas. The Santaquin, UT, postburn flash flood happened much like other such postburn flash flood events that threaten mountain-front communities. Wildfires are on the increase as development increases in urban wildland interface areas, and postburn flash floods will likely increase as well, similar to the disaster event sequences presented in the Santaquin case. Given the increasing level of vulnerability it would seem necessary from a public safety perspective to examine complete disaster systems rather than fragments of systems (fragmented systems).

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