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Warning Triggers in Environmental Hazards: Who Should Be Warned to Do What and When?

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Determining the most effective public warnings to issue during a hazardous environmental event is a complex problem. Three primary questions need to be answered: Who should take protective action? What is the best action? and When should this action be initiated? Warning triggers provide a proactive means for emergency managers to simultaneously answer these questions by recommending that a target group take a specified protective action if a pre-set environmental trigger condition occurs (e.g., warn a community to evacuate if a wildfire crosses a proximal ridgeline). Triggers are used to warn the public across a wide variety of environmental hazards, and an improved understanding of their nature and role promises to: (1) advance protective action theory by unifying the natural, built, and social themes in hazards research into one framework, (2) reveal important information about emergency managers' risk perception, situational awareness, and threat assessment regarding threat behavior and public response, and (3) advance spatiotemporal models for representing the geography and timing of disaster warning and response (i.e., a coupled natural-built-social system). We provide an overview and research agenda designed to advance our understanding and modeling of warning triggers.

KEY WORDS: Hazards; protective actions; warning systems

1. INTRODUCTION

When the forecast of hazard impact reaches a level that warrants issuing warnings, determining the best protective action recommendations (PARs) for a threatened population can be a complex problem.[(1–5)] Three key questions arise: (1) What target groups should take protective action? (2) What is the most appropriate PAR for each target group? and (3) When should these PARs be initiated?[(6–12)] The first question involves careful identification of population segments that are likely to be adversely affected.[(13,14)] The second question involves selecting the best available PARs for different target groups, and the third question requires assessing the amount of time that target groups will need to complete their protective actions before hazard impact.[(15,16)] These questions can be complicated by uncertainty in the interacting components of a highly dynamic system and compounded by time pressure, which can lead to decision errors.[(17–20)] Accordingly, emergency managers must consider the likelihood and cost of "false positive" decisions to issue warnings when hazard impact fails to occur and "false negative" decisions to continue normal activities when hazard impact occurs.

Given the wide range of environmental hazards faced by an expanding global population, an

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increasing number of procedures are being developed to simplify the warning process, generally with the goals of avoiding casualties and improving transparency in the decision-making process. One early example is the system of measurable emergency action levels, emergency classes, and automatic protective actions required at commercial nuclear power plants.[21] In general terms, a warning trigger is a decision rule that links an *environmental condition* to a *PAR* for a specified *target group* that answers the question: "Who should take what action and when?" Triggers are proactive as they tie anticipated adverse environmental conditions to PARs ahead of the need to warn relevant target groups. This allows emergency managers to "stay ahead of the curve," as triggers define the point in time to change from "wait and see" to "take immediate action." They can be formulated for a variety of threats and should pass four tests to be effective: (1) the trigger condition can be readily detected; (2) the target group is well-defined, can receive warnings, and is receptive to taking action; (3) there is a feasible PAR that is effective in providing protection; and (4) suitable warnings can be disseminated in time for protective actions to be completed by most, if not all, of the target group.

Despite the critical role and wide use of triggers, there has been little study of how they are set by emergency managers, as well their efficacy in conjunction with integrated early warning systems.[22,23] In one of the few empirical studies, experiment participants searched for information about approaching hurricanes, assessed the threat to their assigned jurisdiction, and issued PARs for different target groups.[24,25] More often, behavioral hazards research focuses on public response to warnings,[5,26,27] and transportation research focuses on traffic modeling and routing in evacuation networks.[28–30] Although these two areas have merged with new methods for incorporating behavioral research findings into evacuation modeling,[31–33] protective action research could benefit from a framework that ties these disparate research themes to existing research on modeling hazard behavior (e.g., toxic plume dispersal, fire spread, hurricane movement), as well as the cognitive aspects of protective action decision making. Warning triggers may provide a means to unify these related research areas, as formulating one requires simultaneously considering dynamic interactions between natural, built, and social systems (Fig. 1). Our goal is to provide an overview of warning triggers and outline a preliminary research agenda for their study.

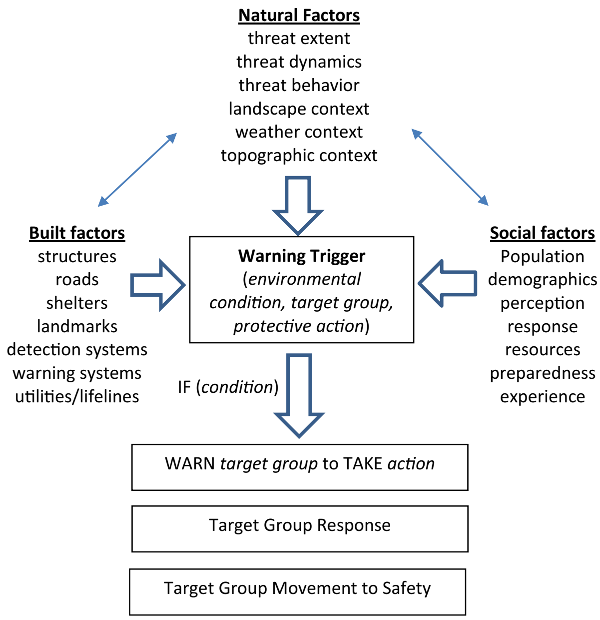

Fig. 1. Common natural, built, and social input factors used in defining a warning trigger.

2. DEFINING WARNING TRIGGER ELEMENTS

2.1. Environmental Trigger Conditions

An unambiguous trigger *condition* is a critical component in effectively timing a warning, and this can be defined using direct observations of environmental cues (perceiving an extreme event or a change in its behavior) or measurements from sensors to detect cues beyond the capability of human perception. The former might be a spotter observing a tornado funnel cloud or wildfire flame front, whereas the latter includes tsunami detection buoys,[34] chemical release monitors,[35] flash flood stream gauges,[36] tornado weather radars,[37] lake pressure transducers,[38] wildfire detection systems,[39] and seismographs for earthquakes[40,41] or volcanic eruptions.[42] Table I provides examples of trigger conditions, target groups, and PARs across a range of hazards.

Trigger conditions generally fall into four categories: (1) early changes in environmental conditions signaling the likelihood of an extreme environmental event with potentially adverse outcomes (e.g., extreme temperature, precipitation rate, wind speed, shoreline recession, flame lengths), (2) the actual occurrence of a hazardous event, (3) changes in event

Table I. Example Warning Triggers for Environmental Hazards (Condition, Target Group, PAR)

Hazard	Condition (When?)	Target Group (Who?)	PAR (What?)
Dust storm	Visibility < 0.5 miles	County	Avoid driving in low-visibility conditions
Earthquake	P-wave arrival (sensor)	Metropolitan area	Exit unsafe buildings
Flash flood	Rainfall > 1.00" per hour in upper canyons	County	Avoid canyons
Flood	Flood height >5 feet	County residents	Evacuate riverine areas; do not ford flooded roads; keep children away from flooded areas
Glacial lake outburst flood	Outburst flood detected	Downstream towns	Evacuate
HAZMAT release	Immediately following release	Two-mile radius around spill location	Shelter-in-place
High winds	Sustained winds >30 mph for one hour; gusts >60 mph	County residents; high-profile vehicles	Wind warning
Hurricane	3:00 pm (predicted arrival of tropical storm force wind)	Households in CAT 3 inundation zone	Evacuate inland
Landslide	Rainfall >1" per hour on steep slopes for more than three hours	Households on steep slopes	Evacuate steep slopes
Malaria outbreak	Intense rainfall well above average	Region	Vector control with appropriate drugs
Poor air quality	PM 2.5 > 100 ppm	County residents	Cease wood burning; reduce driving; minimize industrial emissions
Postfire debris flow	Rainfall >0.75" per hour on burn scar	Households in run-out zone	Flash flood warning
Road icing	Temperature <32°	Drivers on major roads	Avoid travel
Sea-level rise	Storm surges intolerable	Island nation	Migration
Terrorism	Increased DHS security level (e.g., yellow to orange)	TSA employees	See DHS actions for each level
Tornado	Hook echo present in Doppler image near populated areas	Locations within the tornado warning polygon	Take cover; seek safety in basement, underground shelter, or sturdy structure
Thunderstorm	Doppler radar image	County residents	Postpone outdoor activities
Volcanic lahars	Geosensors	Downslope communities	Evacuate lahar paths
Wildfire	Fire crossing ridgeline toward communities	Named or delimited communities	Evacuate
Winter storm	Snowfall >6" in 12 hours	County residents	Avoid long-distance travel

magnitude (measured at the hazard source) or intensity (measured at some other point such as the target group), or (4) a threat crossing a geographic threshold. They can be quantitative or qualitative, but even the latter can vary in specificity and complexity. For example, fire occurrence is a common qualitative trigger condition, but a more specific indicator would be a flame front crossing a prominent ridgeline, river, or road toward a community. Example technological triggers include an explosion near a town or a chemical spill into a river. Threat attributes can also be used to formulate a trigger condition by defining a threshold value that, once exceeded, results in a warning.[43] However, even if trigger conditions are objectively measured, they might be subjectively related to the level of threat and can vary widely in value, even across agencies in the same county (e.g., rainfall rate and duration thresholds for landslides).[44]

2.2. Target Groups

A second critical question is determining the population to warn. If potential impact locations can be identified in advance, an emergency planning zone can be delimited *a priori*.[45] In other cases, the definition of the target group must be improvised, usually with the goal of limiting ambiguity, so as to maximize compliance by those deemed at risk while avoiding unnecessary protective action decisions by those not at risk (e.g., shadow evacuees that create unnecessary traffic delays). Approaches to this problem vary in efficacy depending on the scenario, and there are many examples where the means for specifying the target group impeded effective communication and PAR compliance.[46]

Salient built environmental features are one means for delimiting zone boundaries including prominent roadways, but physiographic features can also be used, as in "everyone on Manhattan Island (physical feature) south of Central Park (built feature)" or "households west of Horsetooth Reservoir and north of West Colorado Road 38E." Administrative boundaries can also be used if target group members have good mental maps of the boundary, as in "Montgomery County," "the City of Norman," or specific postal codes. Point, linear, or areal buffers are also used, as in "anyone within two miles of the spill site (point)" or "households within a half-mile from the American River (line)" or "residents within two miles of Graniteville (area)." However, this method of defining triggers can be problematic because people tend to make inaccurate distance judgments,[47] and even the provision of risk area maps can produce limited success because some people are still unable to identify their respective risk area.[48,49]

The technology for defining and communicating with at-risk groups is continually improving, and geotargeted warnings can now be transmitted to cell phones within a defined polygon of any size and shape.[50–52] When warnings are staged (i.e., a series of target subgroups is warned to take protective action at successive times), the problem is complicated by the need to define multiple target zones and protective action initiation times.[14,53,54] Physical, social, or built environmental attributes are also used to delimit target zones, as in "households on steep, nonvegetated slopes," or "children and the elderly," or "residents residing in a mobile-home." People who rely on a common resource can also be targeted for a warning, as in "water users in Las Vegas,"[55] or people conducting a stated activity (e.g., drivers, nonresidents, or back-country skiers).

2.3. Protective Actions

Protective actions are taken to preserve public health and safety from an environmental threat, and a key challenge is determining the most effective action to recommend.[4,56] While evacuation is the most common PAR, alternatives include shelter-in-place (remaining in one's structure or location) and shelter-in-refuge (a short trip to a safer place in the threat area). The latter two options have been recommended in chemical emergencies,[57] tornadoes,[58] hurricanes,[59] wildfires,[60,61] tsunamis,[62] and threats where a nearby structure or safer area provides sufficient protection in less time than evacuating. This option has the benefit of reducing traffic delays for those who lack access to adequate shelter and must evacuate. Other PARs include preparatory actions (e.g., packing bags and securing the home), avoidance behaviors (e.g., avoiding actions such as traveling, starting fires, or drinking tap water), or preparedness actions (e.g., maintaining water supplies or knowing how to turn off utilities).

3. CONCEPTUAL FRAMEWORKS FOR SETTING TRIGGERS

3.1. Estimated Hazard Impact and Evacuation Times

A significant need in trigger research is integrating hazard impact forecasts and evacuation time estimates (ETEs)[28,29,31] to improve protective action decisions. Most ETE studies begin at warning initiation because the incident detection and PAR decision time components are implicitly assumed to have negligible effects on the results of the analysis. Instead, ETE studies generally assume a *loading function* to model the rate at which vehicles travel through the evacuation route system. The resulting function is typically an *S*-curve that represents the mathematical product of warning receipt, evacuation preparation, and evacuation travel times that reaches an asymptote below 100% because not everyone is willing or able to leave (i.e., the x-axis represents time and the y-axis indicates the cumulative percentage of the target group that has evacuated). Fig. 2 highlights the importance of the oft-neglected positioning of the ETE *S*-curve in a broader time frame, where the deadline imposed by hazard impact is shown as a dotted vertical line. Note that the percentage of the risk area population who have completed evacuation before hazard impact depends significantly on the time at which the warning process begins.

If emergency managers make an evacuation decision at t_3, a portion of the risk area population is still evacuating when hazard impact occurs, whereas

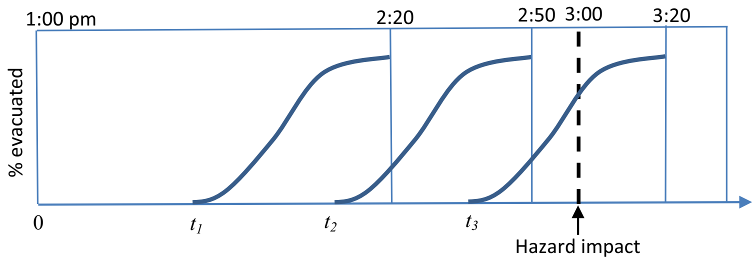

Fig. 2. The importance of a well-timed trigger in evacuation planning and modeling where t_1, t_2, and t_3 represent three different trigger conditions being met.

if the decision is made at t_2, the entire risk area population has reached safety with about 10 minutes to spare. Moreover, if the decision is made at t_1, the *safety margin* is increased to 40 minutes. However, uncertainty increases the further ahead the hazard impact is forecasted (and also exists in the evacuation response curves), which means emergency managers must make intuitive judgments regarding these estimates and, thus, the appropriate safety margin.(63–66) Given this perspective, "zero" on the traditional evacuation planning and modeling x-axis (e.g., t_{1-3}) can be viewed as a variable for emergency managers to set (or resolve) using a trigger condition, whether it is an explicit rule or an intuitive decision based on many factors (see Fig. 1). As critical as warning timing can be in PAR efficacy, few decision support models have been developed to combine factors from all three environmental spheres to resolve this question.(67–70)

3.2. Geographic Triggers

An alternative to the ETE S-curve is a *decision arc*(71,72) or *evacuation trigger point*(73–75) that is computed by multiplying the forward movement speed of the hazard (a rate) by the time required for the target population to complete its protective action. Fig. 3 depicts a generic threat approaching a target group located in a defined risk area. The threat is initiated at 1:00 pm and detected at 1:05 pm, with a trigger set to provide one hour for the target group to complete an evacuation, assuming the threat continues to advance at an average of 1 mph after crossing the trigger buffer (i.e., it is 1 mile from the target group). The threat crosses the trigger point at 2:00 pm, whereby the target group is warned to evacuate. The first households start preparing at 2:10 pm, and the first few households begin evacuating at 2:15 pm. At 2:45 pm, emergency managers verify the percent of the target group that has evacuated (PAR compliance). The threat reaches the risk area at 3:00 pm, so the trigger successfully provides one hour of warning, preparation, and response. While this example is intentionally simplified, this can be a very complex, dynamic, and uncertain process in practice, and many triggers may need to be formulated, altered, or canceled in one event.

3.3. Triggers and Slack Time

If a potentially threatening environmental event is detected early enough, emergency managers have *slack time* before they need to issue a warning. This slack allows them to monitor hazard onset and thus reduce the likelihood of false positive or negative decision errors. Fig. 4(a) shows the time phases for a scenario in which there is slack time embedded within decision time (i.e., zero represents the time at which the event occurs). The left-hand side of decision time (black) is the interval during which the trigger is formulated, and the right-hand side (light gray) is the interval during which environmental conditions are monitored until detection of the trigger condition initiates a warning. If the environmental hazard has a rapid onset, or the time required to formulate a warning trigger is prolonged (or both), there may be no slack time. In extreme cases, hazard impact might occur before target groups can take protective actions. Fig. 4(b) represents the case where the trigger is formulated before an event occurs, so the slack time (gray line) takes place between trigger formulation (black line) and trigger condition detection. In this case, the postdetection decision time is negligible, and emergency managers can proceed directly to warning initiation.

4. RESEARCH AGENDA

The objectives of the research agenda are to: (1) extend current theory on protective actions to include warning triggers; (2) promote descriptive empirical studies on how emergency managers

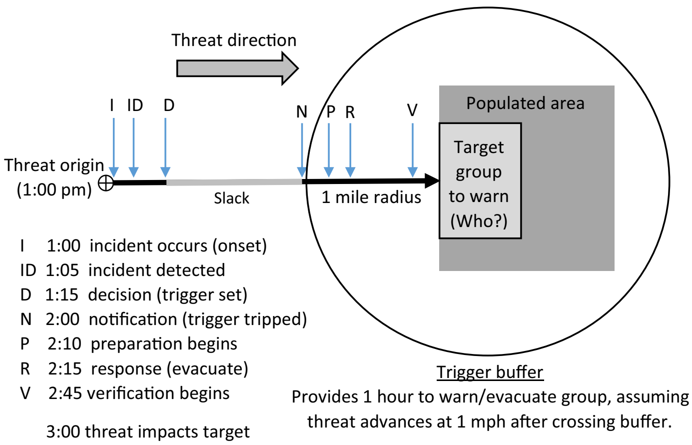

Fig. 3. Protective action time phases in geographic space as a threat approaches a target group.

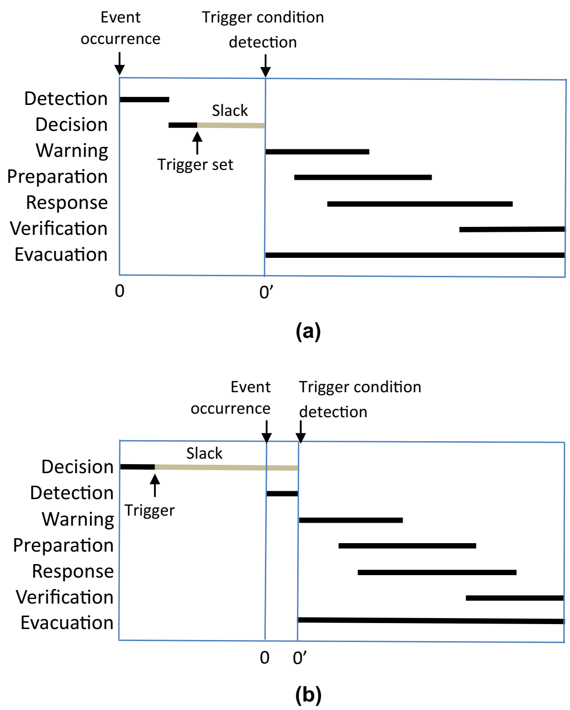

Fig. 4. Protective action time phases with trigger duration (slack) shown in gray for a postevent (a) and preevent (b) trigger. An event (threat) occurs at time 0, and 0' is the time at which the trigger condition is detected.

identify and select triggers; (3) develop and test cognitive and physical models of how triggers are identified, set, and implemented; and (4) advance the modeling of triggers as a coupled natural-built-social system. The practical aim is to improve emergency manager training, community resilience, and public safety.

4.1. Conceptual Frameworks

Current research focuses on better representing and integrating the natural (e.g., hazard initiation, progression, and impact), built (e.g., evacuation route system), and social (e.g., milling, compliance, family member accounting) dimensions of the warning and evacuation process.[76,77] A key opportunity lies in developing new conceptual frameworks to advance our understanding of the nature and role of triggers in the geography and timing of PARs used in public warnings. Example research questions include: (1) How can triggers be placed in the context of existing theoretical frameworks for warning and protective action? (2) What new theoretical frameworks are needed to improve our understanding of triggers? and (3) How can trigger constructs be placed in the context of existing theories on situational awareness and threat assessment?

4.2. Empirical Studies

Triggers are used across many hazards, particularly when early warning systems allow for monitoring hazard attribute thresholds.[78] In some cases, the thresholds are not explicitly articulated, which can make them difficult to share.[79,80] There are few standards for defining triggers, and the geography of their definition and use is an important area of study. Questions in this research area include: (1) What triggers were used for different environmental hazards and what are their key elements? (2) What factors entered into setting a trigger in a given event and what is their relative importance? and (3) What methods were used to define the environmental trigger condition, target group, and PAR in a given event (Table II)?

Table II. Example Empirical Triggers in Past Disasters

Event	Environmental Condition		Target Group		PAR
	Type	Detection	Definition	Type	
2003 Old Fire, San Bernardino County, California	Threat geography: fire approaching from south	Perceived	Named places	Mountain communities	Evacuate
2005 Graniteville Chlorine Release	Threat event: train crash	Perceived	Boundary	Buffer (1 mile from crash)	Evacuate buffer area
2011 Tohuku Tsunami, Japan	Threat events: quake, tsunami	Measured	Boundary	Buffer: coastal inundation zone	Evacuate to higher ground
2012 Waldo Canyon Fire, Colorado Springs	Threat geography: fire crossing ridge	Perceived	Boundary	Named places, salient features: roads	Evacuate to east of I-25
2015 Tulsa–Sand Springs Tornado	Threat event: tornado signature on radar	Perceived, measured	Boundary	Polygon drawn around southeastern Osage County along I-244 near downtown Tulsa	Shelter in storm shelter, basement, or interior room of home
2015 San Marcos, TX Flood	Threat geography: flood data and flood history	Measured, perceived	Named places	Neighborhoods and streets	Evacuate to higher ground or temporary shelter
2015 Calbuco Volcano, Chile	Threat event: ash release from volcano	Perceived	Boundary	Buffer: 20-km radius surrounding the volcano	Evacuate to outside 20-km buffer area

4.3. Trigger Cognition

Triggers are cognitive constructs that emergency managers craft to determine PAR selection and target group response. Thus, *n* different experts might formulate *n* different triggers for the same event. There is a need to improve our understanding of experts' mental models,[81,82] cognitive processes,[83] and cognitive styles[84] in formulating triggers and subsequently testing this understanding against existing protective action decision theory and models. Research questions in this area include: (1) What cognitive theories might be used to improve our understanding of the processes by which emergency managers define triggers? (2) How are the myriad static and dynamic natural, built, and social factors selected, weighed, and combined to set triggers? (3) What domain-specific and broader knowledge defines expertise in identifying, setting, and detecting triggers? and (4) To what extent do risk thresholds, especially the balancing of false positive and false negative decision errors, influence the timing and selection of PARs?

4.4. Assessing Trigger Efficacy

There is a need to improve our understanding of factors that affect trigger efficacy. For example, an effective trigger condition may be one that is tied to environmental cues that target groups can perceive and understand (e.g., levee overtopping), as well as grounded in current science (e.g., health implications of poor air quality). This is an important issue because trigger conditions defined by unfamiliar measurement scales can result in overresponses such as a shadow evacuation. For example, during the Three Mile Island nuclear power plant emergency, the state governor issued a warning based on a radiation-exposure-level trigger of 5 millirem and a target group of pregnant women and preschool children within five miles of the Three Mile Island nuclear power plant. This unambiguously defined target group only encompassed about 10,000 people at most, but stimulated an evacuation by nearly 150,000.[85] Questions in this theme include: (1) What attributes comprise an effective trigger, and what might constitute a poorly defined one? and (2) What triggers worked well in real events, which ones didn't, and what are the differences in these two types of situations?

4.5. Modeling Triggers in Natural-Built-Social Systems

Trigger modeling should span the event timeline from hazard initiation through hazard impact, as well as the response timeline from incident detection through PAR verification. This is a very interdisciplinary modeling arena, as it involves hazard dynamics through time and space, emergency manager decision making, the hazard exposure and hazard vulnerability of the built environment, target group response, and evacuation traffic analysis and management. Modelers should treat all aspects of the hazard scenario as unknowns rather than assumed givens (e.g., environmental trigger condition, target groups, PARs). Questions in this area include: (1) What new modeling frameworks and approaches need to be developed to pursue the question of "who should take what action and when should they respond" in a dynamic natural-built-social context? and (2) What real-time emergency decision support systems need to be developed?

4.6. Assessing Error and Uncertainty in a Dynamic Context

The factors in Fig. 1 that influence trigger definition vary in uncertainty, which affects the spatiotemporal aspects of the target group's PARs. Specifically, uncertainties about hazard impact location, intensity, and arrival time raise issues about the probabilities and costs of false positive and false negative decision errors. In particular, concern about false negative errors can lead to defining a target group more broadly and warning it sooner. Addressing uncertainty in all aspects of an event that may affect who needs to take what action and when remains a relatively underresearched topic. While initial work on the effects of uncertainty on PAR decision making has begun,[24,25] much more is needed. Research questions in this theme include: (1) What role does uncertainty play in setting and detecting triggers? (2) How can uncertainty in trigger input factors be communicated to emergency managers? and (3) What common errors occur in setting triggers and how can we minimize their negative impact?[86]

4.7. Visualization for Decision Support

Communicating triggers is a challenge, but there are opportunities to use methods in scientific visualization to convey them and associated uncertainty to both emergency managers and target groups.[87–89] Research questions in this area include: (1) How can triggers be depicted graphically to help communicate and detect the triggering condition? (2) How can uncertainty about the elements in both chains of events (hazard progression and target group response) be conveyed to emergency managers? and (3) How can analysts model and visualize the dynamics of the coupled natural-built-social system within which triggers are set?

4.8. Training and Policy

One natural outcome of warning trigger research is improved training and policy for emergency managers. Questions in this area include: (1) How can we better train emergency managers to set effective triggers? (2) Is there a way to reduce the likelihood of selecting incorrect triggers by training emergency managers more effectively? (3) What are the key steps that are taken in formulating triggers (e.g., environmental trigger condition, target group, and PAR)? and (4) When should a decision point (i.e., postponing target group and action specification) be used over a trigger condition? Trigger policy is also in need of study, and many jurisdictions provide information about their approaches (e.g., fire crews retreat when flame lengths exceed 3 m in Australia). Questions in this area include: (1) What trigger policies have agencies set for different environmental hazards? (2) What methods can be used to compare the effectiveness and resource requirements of different trigger policies? and (3) How can trigger research be developed to best inform policy?

5. CONCLUSION

While warning triggers have not been a significant research topic in environmental hazard and disaster research, their study may lead to advances in protective action theory, modeling, and practice. The research agenda described provides an initial direction for progress in this critical area. Warning triggers are a very interdisciplinary topic, so there is a need for a wide range of perspectives on their role in protective action decision making, modeling, and decision support.

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