1. INTRODUCTION

1.1 PURPOSE

The major tools available for responding to the risks and effects of hazards and disasters are land-use controls, insurance, engineered protection works and construction standards, disaster response plans, and emergency warning systems.

Warning systems bear an interesting relationship to other hazard management tools. They are last lines of defense after, for example, engineered solutions are applied to reduce the probability of an event below some acceptable level. Additionally, warning systems for low-probability events often do not make cost-benefit sense. Warning systems are economically rational only when a risk becomes an actual event and when having inadequate or no warning systems is politically and socially unacceptable.

Warning the public of an impending risk is an everyday occurrence in the United States. We have estimated that public emergency warnings are issued, on the average, at least once a day and perhaps even more frequently. The actual number of people who are warned varies across events. For most events, only a few dozen persons need to be warned. However, many events occur that call for warning a population of substantial size. Furthermore, a warning event is often locally unique, although in some communities warnings are more commonplace (e.g., flood warnings along the Mississippi or tornado warnings in Kansas). Warning systems can also be used to communicate information about safety as well as risk; this aspect of warning systems is important because in most warning events more people who can hear the warning are safe than are at risk.

One general purpose of this work is to explore why, from a social science viewpoint, warnings are sometimes effective and sometimes not. Disaster sociologists began to address this issue some three decades ago. Early efforts (Lachman, Tatsuoka, and Bonk 1961; Mack and Baker 1961; Withey 1962; Moore et al. 1963; Drabek 1969) and subsequent studies revealed that discoverable patterns do exist in public warning response. The initial research efforts were followed by several attempts to organize research findings (Withey 1962; Williams 1964; McLuckie 1970, 1973; Mileti 1975). Both original research and attempts to summarize findings have continued (Perry 1985; Drabek 1986); in the last decade, the number of actual studies of public response to disaster warnings has almost doubled. There are now about 200 publications on response to public warnings.

Social science research on emergency warning systems has not been limited to public response studies. Efforts have also been undertaken to understand warning systems from an organizational viewpoint. For example, research has sought to address the structure and processes of organizations involved in detecting the presence of an impending disaster, the evaluation of risk data, and the analysis of variation in the timeliness and content of actual warnings issued to the public. The first systematic attempt to study these organizational aspects of warning systems was conducted by Anderson (1969), and additional studies along this research vein have been conducted in the last two decades (Dynes et al. 1979; Sorensen and Gersmehl 1980; Saarinen and Sells 1985). Several attempts have also been made to systematize these findings (Mileti, Drabek, and Haas 1975; Mileti, Sorensen, and Bogard 1985). However, there are only a few actual analytical case studies on this topic; there are also some three to four dozen anecdotal case histories in print.

Research has also been conducted on warning system technologies, including work on improved technology such as sirens with more audible signals, on increased systems reliability such as more dependable remote activation equipment, and on new technologies such as remote-activated FM radio receivers. A detailed review of such research is beyond the scope of this report, although the report does incorporate current knowledge on technology into the analysis (Tanzos et al. 1983; Towers et al. 1982).

Although several bodies of literature are related to studies of warning and response in emergencies, this study is limited to research on collective stress warning situations involving whole communities or large portions of communities. Considerable attention has already been given to human behavior in building fires (Keating et al. 1983). Human factors research also includes the investigation of response to different type of alarms in a work setting (Hakkinen and Williges 1984); and there is a growing literature in industrial safety about the effectiveness of hazard warnings on placards (Wolgalter 1987). Similarly, in the area of consumer safety, investigations have been conducted on warnings on product labels (Lehto and Miller 1986).

Much is obviously known, from organizational and public response viewpoints, about why warning systems are sometimes successful and sometimes unsuccessful. Despite this knowledge and in spite of prior attempts to pull research findings together in propositional inventories and models, several questions about warning systems remain unanswered.

First, although a rich set of data on human response to disaster warnings exists, a synthesizing theory has never been imposed on these empirical findings. Consequently, we lack a consistent, comprehensive explanation for warning response. In this work, it is our purpose to attempt to achieve this objective—for both public response and organizational aspects of warning systems.

Second, we seek to draw conclusions based on the research record regarding how to build a "good" warning system; that is, how does one design a warning system that takes advantage of existing social science knowledge and current technology to maximize the probability that the system will be effective when implemented.

We also examine existing warnings systems in the United States for over a dozen different hazardous event types. In addition, we evaluate multihazard or overlapping warning systems—that is, the different warning systems needed for each hazard type and the extent of any overlap. Finally, we take stock of current research needs.

1.2 CURRENT WARNING SYSTEMS IN THE UNITED STATES

The nation has constructed warning systems for a wide range of events that can impose a quick-onset threat to the public. Geological events of this sort include earthquakes, volcanic eruptions, tsunamis, and landslides. Climatological hazards that can quickly strike a population include hurricanes, tornadoes, floods, and avalanches. Technology has also imposed emergency situations requiring public warnings. Some of the most obvious are nuclear power plant accidents, hazardous material production accidents at fixed sites, hazardous material transportation accidents, and dam failures. In addition to hazards from the natural and technical worlds, there are two particularly serious social hazards—nuclear attack and terrorist activities. These geological, climatological, technological, and national security events have several important common elements: (1) they represent low-probability risk events that can materialize; (2) they can pose the threat of widespread disaster for a human population when they do occur; (3) their potential impact can be detected; and (4) a public protective response before impact can enhance safety, reduce losses, and save lives. Consequently, public warning systems can be of utility for each of these classes of events, and, in varying degrees, warning systems are currently in place for each of them.

This section reviews the warning systems in place in the nation for each of 14 events. Our emphasis is at the national level for two reasons. First, most detection and forecast efforts are national. Second, local efforts in warning systems are simply too numerous to fit the purpose of this work, although levels below the national one are referenced when a particular warning system being reviewed contains clearly critical subnational detection and forecast elements. As the reader will soon be able to conclude, existing warning systems range from the very elaborate, in the case of nuclear power plant accidents and hurricanes, to those which are relatively underdeveloped.

1.2.1 Earthquakes

The Earthquake Hazards Reduction Act of 1977 established the National Earthquake Hazards Reduction Program (NEHRP). The overall goals of this program are to reduce loss of life and property from earthquakes, and to mitigate the severe socioeconomic disruption that could be induced by a catastrophic earthquake. A range of federal agencies participate in this program, and each works toward the accomplishment of one or a mix of principal NEHRP activities. These include hazard delineation and assessment, seismic design and engineering research, preparedness planning, and earthquake hazard public awareness. Basic research is funded by the National Science Foundation; however, it is the U.S. Geological Survey (USGS) that holds program and operational responsibility to conduct research that could lead to earthquake predictions and warnings.

The scale for ranking general earthquakes hazards information and specific predictions and warnings does not provide a clear distinction as to what constitutes an earthquake warning and what does not. Currently, predictions are classified as long-term, intermediate-term, and short-term. A long-term classification can rest on earthquake potential studies, while a short-term classification would most likely result from actual prediction research. All three classifications provide information about earthquake risk that could suggest appropriate responses to members of the public, ranging from the purchase of earthquake insurance in the case of a long-term prediction to evacuation after a short-term prediction. It is less likely that a scientifically credible short-term prediction would occur in an area not already classified as having long-term earthquake potential: the long-term classification is almost certainly needed to direct the intensified scientific studies requisite for a short-term prediction. Our attention is focused solely on short-term prediction activities that could give rise to a public warning.

Earthquake prediction research within USGS includes the collection of observational data and the development of the instrumentation, methodologies, and understanding necessary to predict damaging earthquakes. Prediction-warnings of this sort would need to be of a time interval that is long enough to allow for public response to the warning and precise enough to avoid unnecessary socioeconomic impacts.

Under the Disaster Relief Act of 1974, USGS has the responsibility to notify appropriate federal, state, and local authorities of earthquake hazards and to provide information as necessary to ensure that timely and effective warning of potential disasters is provided. The director of USGS is charged by the Earthquake Hazards Reduction Act of 1977 (as amended in 1980) with authority to issue an earthquake advisory or prediction as deemed necessary. Such an advisory would be issued after the scientific evidence for a prediction is assembled and presented to the National Earthquake Evaluation Council (NEPEC). Should NEPEC judge that there is scientific merit to a prediction, it would so inform the director of the USGS, who could then issue a prediction to federal, state, and local authorities. Public warnings could then be issued by state offices of emergency services, or by county and city authorities.

The state of California has the most detailed prediction-warning planning. In California, the California Earthquake Prediction Evaluation Council would convene to advise the governor or the governor's Office of Emergency Services (OES) on the scientific merit of prediction. It is also planned that USGS, OES, and the California Division of Mines and Geology could coordinate the issuance of a prediction statement. At present, OES would inform local counties and cities of the prediction, and OES might or might not participate with them in the preparation and dissemination of emergency public warning messages.

1.2.2 Volcanoes

USGS, which conducts basic volcanological research and monitors volcanoes, has the responsibility of assessing the hazards and predicting eruptions of volcanoes. Under the Disaster Relief Act of 1974, USGS is charged with providing technical assistance to state and local government for disaster warnings, including warnings regarding volcanic eruptions.

USGS operates two volcano observation stations for monitoring volcanic activities and conducting research. The Hawaiian volcano observatory has operated since 1922 (and under the direction of USGS since 1956) to study and predict eruptions at Kilauea and Mauna Loa volcanoes. The Cascades Volcano Observatory in Vancouver, Washington, was established in 1981 to study and monitor Cascade volcanoes.

Most warning systems must be tailored to a single volcano or cluster of volcanoes because each volcano is unique. The techniques of volcano monitoring are relatively standard. The basic instruments of hazard monitoring are seismographs, which indicate lava movement; tiltmeters, which indicate inflation and deflation; electronic distance-measuring instruments, which measure lateral displacement; geotimeters, which measure horizontal displacement; surveying equipment, which measures displacement; theodolites, which measure vertical angle changes; and gas sniffers, which analyze gas composition. All provide data useful to short- and long-term predictions and warnings. Volcanoes are also monitored by satellite and air imagery and visual monitoring. The latter is often the only way to detect an actual eruption even in our highly technical age. Radar can be used to track ashfall after an eruption.

The information provided by USGS to state and local officials is usually in a form that is not easily translated into a public warning. While, in some cases, monitoring can provide information on whether an eruption will occur, in others it can predict only probability. Moreover, the precise time, kind, and magnitude of an eruption cannot be easily predicted. USGS can delineate probable impact zones for various hazards on the basis of historical studies, but these are by no means exact boundaries. These predictions are limited by the general problems of extrapolation from historical record; an eruption could exceed the magnitude of previous ones, take a different course, or otherwise vary from recorded behavior.

Different volcanic hazards may require diverse warnings. Volcanic hazards include ash, floods and mud flows (lahars), avalanches, landslides, pyroclastic flows, lateral blast, and lava flows. Secondary hazards include fire and dam failures. Each poses somewhat unique threats to human safety, and some have secondary impacts on environmental systems such as water supply or power systems.

USGS works with media and public officials to provide them with available information on volcanic hazards but does not assume responsibility for disseminating that information to the public. This process varies from site to site and depends on the assumed roles of state and local government and other organizations. At Kilauea, public warning processes are tightly controlled by the county government. At Mount St. Helens, the authority was divided among multiple agencies with no central control. Other potentially hazardous volcanoes, such as Mount Baker or Mono Lake, also have different public information and warning arrangements. One deficiency of volcanic hazard warning systems is the lack of attention given to getting warnings to the public. The failure to warn residents of eastern Washington of ashfall from the massive May 18, 1980, eruption at Mount St. Helens is an example of the effects of an inadequate volcano warning plan.

1.2.3 Tsunamis

Tsunamis are large sea waves generated by seismically induced underseas displacement, avalanches, or volcanic activity. There are two types of tsunamis—distant tsunamis, which travel across the ocean from one coast to another and local tsunamis, which are generated just offshore and travel short distances. The two types pose very different warning problems. Tsunamis occur mainly in the Pacific Ocean; consequently, California, Oregon, Washington, Alaska, and Hawaii are vulnerable to both types of events. Tsunamis are extremely rare events in the Caribbean and on the Atlantic coast. As a result, tsunami warning systems have been developed only in the Pacific.

Distant tsunamis are detected through the Seismic Sea Wave Warning System, developed in 1948 and located in Oahu, Hawaii (Pararas-Carayannis 1986). The May 1960 Chilean tsunami convinced many countries to join the Pacific tsunami warning system. In 1965, the United Nations Educational, Scientific, and Cultural Organization joined the United States to expand the Tsunami Warning Center in Honolulu. Twenty-three nations are now members of the International Tsunami Warning System. The warning system uses a Pacific-wide network of seismograph and tide-monitoring stations. The seismograph stations detect and measure the size and location of undersea earthquakes capable of generating a tsunami. On that basis, the Tsunamis Warning Center in Honolulu issues a tsunami watch, which alerts coastal areas to the possibility of a tsunami and its estimated arrival time, should one have been generated. Next, tide stations nearest the epicenter are contacted to watch for the signs of a tsunami. While such waves cannot be readily seen in open waters, they can be technologically detected as distinctive abnormalities. If these abnormalities are detected, arrival times are calculated for various locations. The observatory then contacts a single warning point in each country in the Pacific region.

The public dissemination of a warning varies with location. In Hawaii, distant-tsunami warnings are issued by state and county civil defense groups, using an elaborate siren system. Maps in telephone directories outline potential run-up zones. A distant tsunami allows police and emergency officials time to get warnings to those who might be affected.

Two local-tsunami warning systems are also in operation in Alaska and Hawaii. In Alaska, the Palmer Observatory collects data from a network of seismographs. When a major earthquake occurs along the coast of Alaska, an immediate warning is issued to civil defense or emergency offices in a 200-mile radius around the epicenter. If wave abnormalities are then detected, the warning is issued for the entire coast of Alaska. The

Hawaiian local tsunami system uses seismographs as well as pressure-sensing instruments on the ocean flood and tide stations to detect earthquakes and tsunamis. When an earthquake of a size and location capable of producing a tsunami is detected, a warning is immediately issued through the Office of Civil Defense. Tide monitoring will confirm whether or not a tsunami has actually occurred, and the warning is quickly adjusted or cancelled.

Local-tsunami warning systems must quickly alert coastal residents to danger. In Hawaii, sirens are the primary mechanism for warning. In more remote locations where fatalities have occurred, signs have been erected instructing people to get above markers showing safe locations when "natural" warnings are experienced. For example, often the sea falls or rises in an unusual manner prior to the major waves. In addition, often the first wave to hit is not the largest, allowing time for people to respond. A major problem with local-tsunami warnings is false alarms. Only a few of the seismic events capable of generating a tsunami will actually do so. Some officials feel that false alarms will undermine the effectiveness of the warning system. Another major problem with all tsunami warnings is that even if a tsunami is confirmed, the coastal run-ups vary markedly with location; thus, area-specific warnings are difficult to make.

1.2.4 Landslides

Ground failures caused by landslides and related failures cause billions of dollars in property losses in the United States each year (U.S. Geological Survey 1982). They exceed the annual combined losses from floods, earthquakes, hurricanes, and tornadoes by many times (Johns 1978). A variety of information is available that can be used to help manage this hazard, for example, through land use controls. In addition, potentially unstable land can be monitored so that populations at risk can be warned of an impending landslide. The most common types of monitoring are field observations, inclinometers, extensometers, and electrical fences or tripwires. There are also methods for monitoring rockfalls. Detection systems that measure increased potential for slope failure are being developed. This system uses a network of rain gauges coupled with empirical and theoretical models depicting the relationship between precipitation and landslide initiation to provide a real-time regional warning system (Keefer et al. 1987).

The Disaster Relief Act of 1974 required USGS to implement a warning system for landslides. USGS currently has three landslide warning categories. These are (1) a degree of risk greater than normal, (2) a hazardous condition that has recently developed or has only recently been recognized, and (3) a threat that warrants consideration of public response to an impending event. The time, place, and magnitude of impending landslides—the elements necessary for a public landslide warning—can be predicted only in areas that have benefited from detailed geological and engineering studies. There have been a few cases where such work that could led to successful public warnings has been completed, as in California.

Landslide warnings currently remain a local responsibility, and no national landslide warning program is funded or is in place. USGS has called for an organized national program (U.S. Geological Survey 1982). Recent assessments do not rank landslide warnings as a high priority (Committee on Ground Failure Hazards 1985).

1.2.5 Hurricanes

Hurricanes occur in both the Atlantic and Pacific Oceans. The Gulf Coast, the Atlantic coast, and the Hawaiian Islands experience the greatest incidence of hurricanes. The National Weather Service (NWS), within the National Oceanic and Atmospheric Administration (NOAA), operates three hurricane centers which take the lead in issuing hurricane forecasts and warnings. These include the National Hurricane Center (NHC) in Miami, the Eastern Pacific Center in San Francisco, and the Central Pacific Hurricane Center in Honolulu. Most warnings are issued for Atlantic hurricanes through NHC. NHC issues bulletins, watches, and warnings regarding location, predicted path, intensity, timing, and probability of landfall. NHC cooperates in its hurricane prediction efforts with the Department of Defense, which assists in collecting data, tracking hurricanes, and issuing forecasts for military bases.

Three primary systems are used for issuing collecting information about hurricanes—weather satellites, reconnaissance aircraft equipped with special instrumentation, and coastal weather radar. A variety of models are used to predict hurricane paths and intensities. These are based on historical records of hurricane movement, short-term meteorological conditions, and dynamics of fluid and air movements, or some combination of techniques. Prediction also depends on the judgments of experienced forecasters. Models and judgments do not lead to precise forecasts of hurricane behavior, however. Considerable uncertainty and error exists in forecasts, and the greater the expected time before impact, the greater the uncertainty. Hurricanes are subject to abrupt, unpredictable changes in course. In addition, they can speed up, stall, or change in intensity, further complicating prediction.

Hurricane watches are issued by NWS about 72 h before expected impact. Watches are issued for very large segments of coastal areas. At about 48 h before landfall, the area to be alerted for a watch or warning can be narrowed to about a 500-mile section of coast. At 24 h, the average forecast error gives a warning zone of from 200 to 250 miles. At each time period, NWS issues a probability that locations along the coast will experience landfall. These probabilities vary from a maximum likelihood of 10% at 72 h to 35–45% at 24 h.

When a hurricane is detected, NHC staff work with coastal offices of NWS in issuing local statements to inform the public about the hurricane. Detailed information is given in hurricane advisories and bulletins disseminated to media and state and local officials via NOAA Weather Wire, a dedicated teletype system, and over NOAA weather radio. Often NHC and local weather service offices are in direct contact with state and local officials.

After hurricane information has been issued by NHC, a variety of channels and methods are used to inform the public of the hurricane forecasts and to recommend protective action. Information comes from state and local officials, the media, or at times directly from NHC. It reaches the public through the media and from door-to-door contact. Often information from one source is inconsistent with another source. Warning content also changes over time as the behavior of the storm changes. Probabilities may increase, then decrease, and then increase again. A storm may veer in another direction, only to loop back in its original direction. Storms may parallel a coast and suddenly move ashore. Thousands or even millions of people may be at risk at some time from a storm. Those involved in hurricane warning systems therefore face many problems in achieving their goal of protecting public health and safety.

Warning systems for hurricanes are connected with hurricane hazard programs, which seek to define areas and populations at risk from storm surge and estimate evacuation times. The studies growing out of these programs help officials know whom to warn and when those at risk need to be prepared to evacuate.

1.2.6 Tornadoes

Tornadoes occur in various parts of the world, but both the greatest number and most severe tornadoes are produced in the United States. Their origins can be traced to severe thunderstorms formed when warm, moisture-laden air sweeping in from the Gulf of Mexico meets cooler, continental air flowing from the west or northwest. Some of these thunderstorms are characterized by the violent updrafts and strong tangential winds that spawn tornadoes, though the details of tornado generation are still not fully understood.

Tornadoes are violently rotating columns of air suspended from cumulonimbus clouds. They begin as funnel-shaped extensions from the clouds and build downward to the ground and darken as they pick up debris. On a local scale, tornadoes are the most destructive of all atmospheric phenomena. Horizontal wind speed near the center of a tornado may exceed 300 mph, and the ground speed, usually 25–40 mph, can range from almost stationary to nearly 70 mph. Paths of tornadoes can range in length from a few miles to several hundred miles and in breadth from a hundred yards to a few miles. In the United States, they generally move in a southwest to northeast direction. They are most prevalent in the spring and occur over much of the eastern two-thirds of the United States, with the highest frequency and greatest devastation experienced in the Middle South and the Midwest. Each year about 500 tornadoes are reported in the United States. They usually form during the middle or late afternoon, and the hours between 3 and 7 p.m. are the most likely period.

Not only are tornadoes only partially understood; they are also difficult to predict, owing to their rapid formation, short lifetime, and relatively small size. When meteorological conditions in a region may allow formation of tornadoes, a tornado watch is issued by NWS; when a tornado has been spotted or has been observed on weather radar, NWS issues a tornado warning.

NWS has statutory responsibility for providing a severe local storms watch and warning service (including tornadoes) for all 50 states. This watch and warning service, available to the general public and to aviation, is provided by NWS through its National Severe Storms Forecast Center (NSSFC) at Kansas City, Weather Service forecast offices (WSFOs), and Weather Service offices (WSOs). In the 48 contiguous states, NSSFC is responsible for issuing and cancelling severe thunderstorm and tornado watches and for alerting local forecast offices (WSFOs) to areas of high potential for severe weather development. Local offices, in turn, issue warnings based on actual sightings of tornadoes or on radar information. WSFOs and WSOs are responsible for informing the general public of potential severe weather and redefining the NSSFC statements for those parts of the states likely to be affected. When warnings are given, they are identified as either a tornado warning or a severe thunderstorm warning.

Weather radar is an essential tool in forecasting the severe weather from which tornadoes can be generated and in spotting actual tornadoes. The U.S. Basic Weather Radar Network (composed of NWS, the U.S. Air Force, and the Navy) operates a number of nonnetwork radars that are used primarily for local forecasting and warning and for providing selected information on severe storms. A planned national system of Doppler radars is now being developed under a joint program of the departments of Commerce, Defense, and Transportation. This program will produce the Next Generation Weather Radar, which is expected to allow more accurate and more highly focused tornado forecasts, owing to its capability of measuring wind velocities within and around tornadoes.

In addition to radar information and satellite data (obtained through NOAA's National Environmental Satellite, Data, and Information Service), basic meteorological data required for NSSFC analyses include those obtained from the surface weather observational network, from rawinsonde (upper air measurement) stations, and from pilot reports of weather hazardous to aviation. NWS also uses observations of severe local weather, especially tornadoes, from citizen spotter networks, state highway patrols and local police departments, local civil defense organizations, cooperative NWS climatological observers, radio and television mobile units, many other employees of local governments, and individual citizens. These reports are received by various means and are not uniform at the various WSOs.

The principal NWS/NOAA systems for collecting and disseminating weather information are the automation and field operations, the radio report, the warning coordination circuit, the NOAA weather wire service (NWWS), and NOAA weather radio. The purpose of NWWS is to transmit consumer-oriented forecasts, watches, warnings, and meteorological data to the mass media for broadcasts to the public. WSFOs and WSOs equipped with NOAA weather radio can transmit weather information continuously to an area about 40 miles in radius. A tonal alert capability is used to activate specially designed NOAA radio receivers during severe weather conditions.

In addition, the National Warning System (NAWAS), which is operated by the Federal Emergency Management Agency (FEMA), can be employed at a time of weather emergency. NAWAS is a hot-line interstate telephone system that connects FEMA warning points with WSFOs, WSOs, and Weather Service Meteorological Observatories within each state and between states. The Emergency Broadcast System (EBS) can also be activated for tornado warnings. Because EBS is operated by individual radio and television stations, arrangements for its use are made before the severe local storm season or may be based on a continuing agreement.

Beside developing and issuing weather reports, NWS provides services involving technical assistance, advice, and consultation. Disaster preparedness assistance is designed to improve the response by community officials and the public to forecasts and warnings. Within available resources, such assistance is carried out by WSOs and warning preparedness meteorologists assigned to some WSFOs, primarily in the eastern, midwestern, and southern states. This NWS effort is coordinated at all levels with FEMA through a formal NOAA-FEMA Memorandum of Understanding.

1.2.7 Floods

NWS has responsibility for much of the nation's flood-warning activities and provides several different services to communities with flood problems, including forecasts and warnings. In addition to NWS, many communities in river basin groups provide local warning systems. These efforts differ between riverine and flash floods.

To predict riverine floods, the NWS has established river forecast centers for major river systems. These centers collect data from WSFOs and use computerized hydrological models to make flood forecasts for several different time frames. The forecasts are sent out to local NWS offices for dissemination to the public. Approximately 2000 communities affected by slow-cresting floods are included in this program.