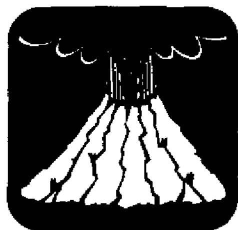

Volcanoes

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Background and Nature of Volcanoes

The eruption of Mount St. Helens in 1980 was the first volcanic disaster to occur in the United States in recent times. Apart from volcanoes in Hawaii, to be mentioned later, the most recent previous eruptions were a minor one at Mount Lassen, California, in 1914 and the massive eruption of Mount Katmai in 1912, a then-remote Alaskan peak. Since 1980, explosive eruptions have occurred around the world in populated areas such as at Pagan, Mariana Islands; El Chichon, Mexico; Galunggung, Indonesia; Mayon, Philippines; and, catastrophically, at Ruiz, Colombia, where in 1985 over 23,000 people died in a vast mud flow.

Although the Mount St. Helens eruptions in 1980 led to the relatively small number of 67 deaths, the scale of the May 18th event and the widespread ashfalls reawakened interest in volcanic hazards and provided the impetus for numerous scientific investigations, particularly in the area of public health. It is scarcely an exaggeration to say that before 1980 medical information on health hazards associated with volcanic activity was largely restricted to a few anecdotal or sparse accounts.

Distribution and Types of Volcanoes

About 500 volcanoes worldwide were active in historic times, and 100 or more of these have been notorious for the frequency or severity of their eruptions in populated areas (1,2). Some notable eruptions are listed in Table 1 (3). Most volcanoes, including those in the United States, are in a belt bordering the Pacific Ocean and referred to as the "Ring of Fire." A second belt stretches from southeastern Europe through the Mediterranean and southern Asia into Indonesia, where historically most deaths from volcanic eruptions have occurred In addition, isolated volcanoes are found in the Pacific, Atlantic, and Indian Oceans. Most volcanoes lie within 300 kilometers (186 miles) of the sea in earthquake zones.

About 400 of the 500 known active volcanoes in the world lie where tectonic plates undergo compression (subduction zones), e.g., the Pacific "Ring of Fire," and these tend to be explosive. Explosive volcanoes can erupt violently and release large quantities of ash. Volcanoes in Hawaii and Iceland, on the other hand, are characterized by large lava flows and copious gas emissions but little ash. Volcanoes with both explosive and effusive characteristics are classified as "mixed."

Geologists now believe that there are at least 35 volcanoes with explosive potential located in the eastern United States and Alaska, the most dangerous being the Cascade Range and the Mono-Inya Craters of California (4). The Hawaiian volcanoes of Mauna Loa and Kilauea have major lava eruptions every few years; they have been intensively studied by geologists but pose little risk to human life compared with their explosive cousins on the U.S. mainland.

Temporal Patterns of Eruption

Volcanologists predict the general behavior of a volcano from available evidence on its geologic characteristics and past activity For most volcanoes, statistical information on the timing of previous eruptive events for use in predicting future eruptions is sparse. For the few about which data exist, random eruption patterns (e.g., Mauna Loa, Hawaii), clustering (e.g., Kilauea, Hawaii), and the increasing probability of a violent eruption as time passes since the last eruption (e.g., Hekla, Iceland) have all been identified (1-3).

If the timing, size, and nature of a volcanic eruption could be accurately foretold, loss of life could be prevented by timely evacuation measures. In practice, this goal is remote. Warning of a reawakening of volcanic activity may be given by premonitory events such as small earthquakes or minor emissions of gas and ash over weeks or months. Specific monitoring techniques—including seismography and measurements of ground deformation, gaseous emissions, and thermal activity—may all be used Cost consideration makes it impossible for all the world's active and dormant volcanoes to be regularly monitored by scientists. Alarmingly, severe eruptions have occurred at sites not even suspected of being volcanoes, e.g., Mount Lamington, Papua, where 2,942 people were killed in 1951 (3).

Ideally, hazard evaluation and emergency planning should be undertaken in all volcanic areas. A hazard evaluation made by U.S. Geological Survey scientists in 1978 (5) successfully predicted the impact of an eruption from Mount St. Helens, but the eruption that occurred on May 18, 1980, could be foretold only as a likely occurrence "possibly within

TABLE 1. Volcanic eruptions since A.D. 1600 that have caused over 8,000 deaths

Volcano	Date of eruption	Number killed	Lethal agent
Laki, Iceland	1783	9,350	Ashfalls destroyed crops and animals, causing starvation
Unzen, Japan	1792	14,300	70% killed by cone collapse; 30% by tsunami
Tambora, Indonesia	1815	92,000	Most deaths from starvation
Krakatoa, Indonesia	1883	36,417	90% killed by tsunami
Mt. Pelee, Martinique	1902	29,025	Pyroclastic flows
Ruiz, Colombia	1985	23,000	Mud flow

Source Reference 3.

this century." For subsequent minor eruptions, however, geologists using monitoring techniques were able to improve their predictions to a day or less beforehand, providing important information for emergency-service personnel and for persons who continued to work in the volcano's vicinity.

Although advances in prediction and surveillance methods are likely, for the foreseeable future catastrophes such as that which occurred at Ruiz seem inevitable Volcanic activity is unlikely to have lessened over the last thousands of years, whereas population expansion into volcanic areas has undoubtedly increased. History can still repeat itself in the form of events such as the destruction of Pompeii by Vesuvius in A.D. 79 when 16,000 people died. It is therefore increasingly important that effort in disaster mitigation is directed toward planning public health and other emergency measures while such predictive uncertainties remain.

Eruptive Hazards and Factors Influencing Morbidity and Mortality

The most common major lethal hazards in volcanic eruptions are pyroclastic flows and lahars, or mud flows (3). Unlike other hazards associated with eruptions, these provide little chance of survival to populations exposed, though the risk will depend on the size and nature of an eruption and local topographic factors, as well as on the proximity of populations. Asphyxiant gases will also be most dangerous near craters or fissures on or close to the volcano's flanks. Because gravity is crucial in determining the flows of solids and dense gases, low-lying areas and valleys near the volcano are generally at greatest risk. The public health consequences to be discussed first are those in the vicinity of the volcano.

Primary Factors

BLAST AND PROJECTILES

Blast is explosive force and is most destructive when accompanied by pyroclastic flow. Blast alone will shatter windows, leading to lacerations, and produce noise audible over long distances. Lethal rock fragments of varying sizes can be explosively ejected at any time. Large projectiles may damage houses and, if hot, start fires.

PYROCLASTIC FLOWS AND SURGES

These are mixtures of hot gases, ash, fine pumice, and rocks. Whether propelled by gravity or by explosive force over a crater rim, they travel at speeds of 50-150 km/hour, (31-91 mph) which—together with their content of solids—creates a powerful destructive momentum. Their temperatures are in the range of 600-900 C, though in some parts of the flow the temperature peak may be short-lived, so that survival under certain conditions is just barely feasible (6). The major lethal effects of pyroclastic flows lie in the density and temperature of the ash and rock fragments, which may cause asphyxia and inhalational injuries as well as body-surface burns. The thickness of deposited ash is less important, though persons closest to the volcano may be killed by blast or buried in ash and rock debris. The concentrations of toxic gases are probably relatively unimportant. In general, the chances of survival are small; for example, only two out of 22,000 people in the town of St. Pierre survived the pyroclastic flow at Mount Pelee in 1902 (Table 1).

The best opportunity to investigate the causes of death from pyroclastic flows was in the aftermath of the lateral-directed blast and pyroclastic flows from the May 18, 1980, eruption of Mount St. Helens. Despite official warnings and the establishment of restricted zones by local officials, over 100 people were within close range at the time of the eruption, including loggers going about their work. The lines of downed trees marked an abrupt cutoff of the maximal blast forces in an area of destruction extending as far as 27 km (17 miles) from the crater; 83% of people died in this zone (7). Examination of the bodies retrieved showed that 17 deaths had been caused by asphyxia and five by thermal injuries (two of the five decedents also had injuries to airways). Only three persons had been killed in trauma to the head from trees (two) or rocks (one). Three loggers located at a spot 19 km from the crater survived the direct blast with second- and third-degree burns affecting 33%-47% of body surface. Two died in the hospital from adult respiratory-distress syndrome induced by inhalation of hot, fine ash particles (8,9).

MUD FLOWS AND FLOODS

Mud flows (lahars) are frequent and deadly concomitants of eruptions. The heat from pyroclastic flows, lava, and steam blasts may melt glaciers and snow, whereas heavy rain may accompany ash eruptions. The water from these or other sources, e.g., crater lakes, will mix with ash and rock debris to form huge volumes of material with the consistency of concrete that is capable of engulfing everything in its path and destroying roads and bridges. After the May 18, 1980, eruption of Mount St. Helens, mud flows traveled down the Cowlitz and Toutle Rivers as far as 21 km (13 miles). The average speed of these flows along the valleys was only about 32 km/hour (20 mph), so that people living in their path downriver had time to be warned to escape, but those nearer the volcano were less fortunate An estimated 85% died in the blast and mud-flow areas. No warning preceded the vast mud flow from the Ruiz, Colombia, volcano in 1985, which overwhelmed the town of Armero located 48 km (30 miles) away. The water in mud flows is sometimes scalding hot and can cause burns. Because river valleys are natural courses for mud flows, flooding may be a direct consequence of the filling of rivers and lakes. In addition, the deposited mud will alter the levels and courses of existing rivers, thereby posing a serious risk of future floods in the event of heavy rains. Floods may also be caused by avalanches into lakes or by melting ice and snow.

LAVA FLOWS

Lava flows from effusive volcanoes are very destructive of property, but their slow speed usually permits the inhabitants to escape in good time. Exceptionally, in 1977 a very fluid lake of lava at Nyiragongo, Zaire, drained suddenly, killing 300 people. In large effusive eruptions, diversion barriers and other methods of influencing the direction of a lava flow may be attempted.

EARTHQUAKES

Local earthquakes that frequently accompany eruptions may damage property and endanger life (see chapter on earthquakes). For example, the limited lava eruption of Mount Etna, Sicily, on December 25, 1985, was accompanied by several earth tremors, one of which destroyed a hotel in the vicinity and killed one person.

TSUNAMIS

These giant sea waves produced by subterranean shocks and explosions have caused heavy loss of life. Their occurrence is unpredictable, but they can devastate coastlines. The greatest loss of life from an eruption in recent times was caused by tsunamis after the eruption of Krakatoa in 1883 when over 36,000 people were drowned on the coasts of nearby Java and Sumatra

GASES

Deaths caused by gases are uncommon compared with other volcano-associated fatalities, though it must be admitted that many such deaths may have gone unrecorded because accurate assessments of cause of death in volcanic eruptions are the exception rather than the rule. Tall volcanoes fortunately exert a "stack" effect, which—together with the heat and force of an eruption—usually results in dispersal of gases into the atmosphere. There are occasions, however, when gases may concentrate or be released at ground level.

The chief volatile emissions are water vapor, carbon dioxide, hydrogen sulfide, and sulfur dioxide, followed by hydrogen chloride, hydrogen fluoride, carbon monoxide, hydrogen, helium, and radon. Inorganic volatile material such as mercury may also be important in certain volcanoes, e.g., Kilauea. Organic volatile materials (polynuclear aromatic and halogenated hydrocarbons) may also be detected in eruptive plumes, particularly if the heat of the eruption has incinerated trees and other vegetation. Plumes from Mount St. Helens' eruptions were also found to contain appreciable quantities of carbonyl sulfide, carbon disulfide, and nitrogen dioxide (10).

Direct health effects. From the health viewpoint, volcanic gases can be classified as asphyxiants or respiratory irritants. Buildup of asphyxiant gases to lethal concentrations is likely only in the vicinity of a volcanic crater or fissure, whereas irritant gases may exert their effects in much lower concentrations for many kilometers downwind.

Animals grazing on many slopes of volcanoes in enclosed or low-lying regions have been asphyxiated, probably by carbon dioxide (CO_2) because it is denser than air. Hydrogen sulfide has also been reported to kill birds and cause sheep to be blinded. Children, geologists, and others roaming volcanic mountain areas are also at risk (11). On the Dieng Plateau, Java, in 1979, 142 people died while attempting to flee from a mild eruption, apparently overwhelmed by a powerful emission of CO_2, the source of which was less than 2 km away (11). In 1984 a cloud of CO_2 emitted from Lake Monoun situated in a volcanic field in Camaroon is believed to have killed 37 people (12). One hypothesis for this event is that it was caused by an overturning of the stratified waters of the lake in which CO_2 had slowly accumulated from a volcanic source (13). In 1986 a remarkable gas release occurred at Lake Nyos only 95 km (59 miles) to the northwest of Lake Monoun when about 1,700 people died. A huge amount of gas flowed at night into a mountainous, remote area north of the lake for as far as 20 km (12 miles) away; in a densely populated region the death toll would probably have been enormous. Hydro-geological tests of the water indicated that CO_2 was the sole—or at least major—gas released (14). Whether the gas was emitted by a volcanic eruption or by a mechanism hypothesized for Lake Monoun is unclear, though further investigations of the lake may provide an answer. The findings will have important implications for preventive measures at this as well as other lakes in volcanic areas.

widely studied in humans since it is a common air pollutant in industrialized countries for which recommended occupational and community exposure limits exist. Acute irritation to the lungs by sulfur dioxide may lead to effects ranging from subclinical constriction of the small airways in healthy adults (at concentrations in inspired air as low as 1 ppm for a few minutes) to frank asthma in susceptible persons. Exposure to low concentrations over long periods may result in an increase in respiratory illnesses in the general population. Regular exposure of the general population to volcanic plumes containing hazardous levels of sulfur dioxide and its aerosols has occurred at the Masaya Volcano, Nicaragua, during periods of very active degassing (13). With some volcanoes, e.g , San Cristobal in Nicaragua, the plumes of gas can travel down the slope to populated areas

on some days, depending on the weather conditions (13). During the eruptions of Kilauea, Hawaii, in 1983, gas sampling was undertaken to exclude a threat of sulfur dioxide to local populations (15). In the days after the eruption of La Soufriere in St. Vincent in 1979, Leus and his colleagues observed an increase in hospital admissions for children with a diagnosis of asthmatic bronchitis, but whether this was caused by inhalation of gases or ash (or both) is unclear (16).

Indirect health effects (e.g., acid rain). Rain falling through a volcanic plume will dissolve sulfur dioxide and other gases, becoming acidic in the process. At Masaya, Nicaragua, the rain water has been as acidic as pH 2.5-3.5, and people have complained that it has caused eye and skin irritation (13). In developing countries rain water is often collected from metal roofs and used for drinking. Health problems may arise if the acid rain dissolves metals or has a high fluoride content; the latter can occur if the plume contains a high concentration of hydrogen fluoride. Gases and acid rain will corrode machinery and cause damage to local crops.

ASHFALLS

The column of an explosive eruption will form a large plume that can travel in some instances for hundreds of kilometers downwind and cover a huge area with a layer of ash of various depths. An ashfall leaving a deposit 0.3 meters deep at a distance of 80 km (50 miles) from Mount St. Helens has occurred and could happen again. In such an event an unfavorable wind could cause ashfalls in some large cities west of the volcano. The eruptions in 1980 were on a much smaller scale: the maximum depth of ash was just over 4 cm in places (Figure 1) when the May 18 plume was blown eastward to the less populated areas.

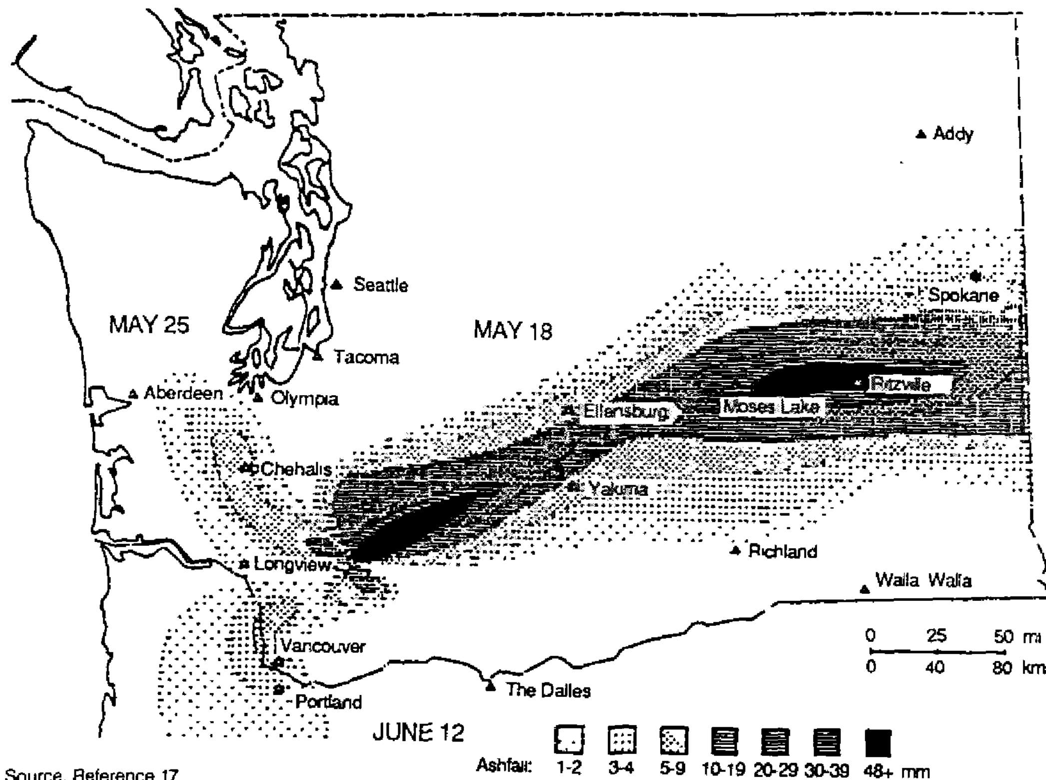
In the eruption plume, gases and other volatile material adheres to ash particles as they fall and, being readily soluble, will be washed off by rain into watercourses and onto crops. Icelandic eruptions, for example, are notorious for the high fluoride content of their ash. Freshly emitted ash may impart a sulfurous or pungent smell to the air, and the adherent volatile material probably adds to the irritant effects fine ash has on the lungs.

Volcanic ash can be produced from the explosion of old rock as well as from the release of pressure on the magma (fresh liquid rock) inside the volcano. The size of ash particles and their mineral composition vary among volcanoes and different eruptions (even of the same volcano). In general the finer particles in a volcanic plume fall farthest away. The particles may be small enough to be readily inhaled deep into the lungs; coarser particles will lodge in the nose or eyes and can also irritate the skin. In the ashfall from the Mount St. Helens' eruption on May 18, over 90% of the particles were within the respirable range in size, and ash continued to be resuspended in the air for a week afterwards until it rained. The elevated concentrations of fine ash in the air led to widespread anxiety about possible health effects (17).

DIRECT HEALTH CONSEQUENCES

Respiratory and ocular effects. Epidemiologic surveillance of trends in emergency room visits and hospital admissions

FIGURE 1. Ashfall after first three major eruptions of Mount St. Helens in 1980 (May 18, May 25, and June 12) and locations of Washington and Oregon hospitals in the Centers for Disease Control Epidemiological Surveillance System



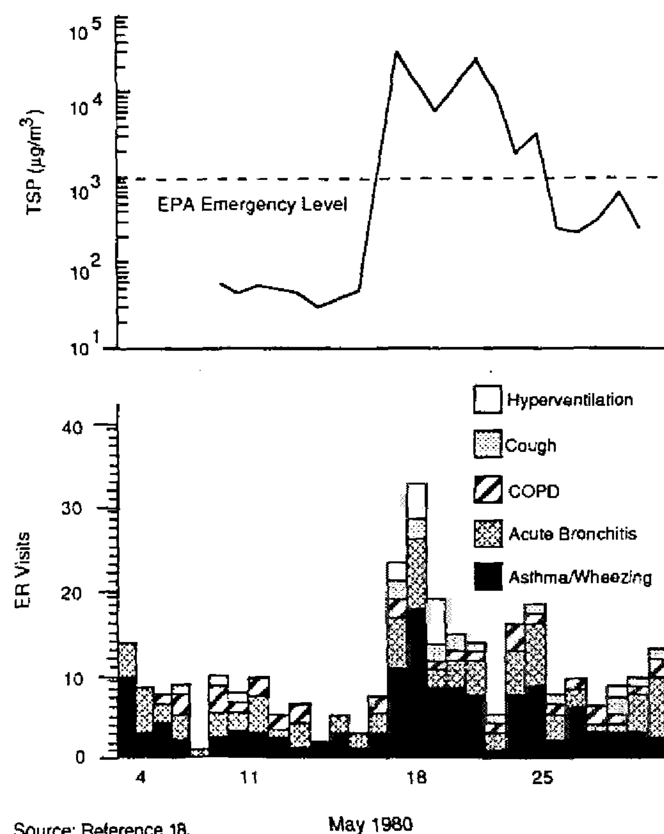
Source. Reference 17

after each of the three main 1980 eruptions of Mount St. Helens revealed increases in the number of patients admitted for asthma and bronchitis (Figure 2) (17). In addition a household survey in Yakima showed that about a third of the patients with chronic lung disease who did not go to a hospital reported an exacerbation of their respiratory symptoms that was associated with the high levels of respirable ash in the ambient air (18). These patients would undoubtedly have been more severely affected if they had not heeded advice and their own common sense by staying indoors through the worst conditions. No deaths were attributed to the respiratory effects of the ash. Despite the absence of any good data, there is little doubt that the impact of similar eruptions in less-privileged countries would be greater.

Geologists do not routinely analyze ash for the presence of crystalline silica; therefore, the finding by health scientists that the Mount St. Helens' ash contained 3%-7% of this mineral by weight was first disputed and later confirmed (19). Outdoor occupational exposures for groups such as loggers and farm workers were potentially high enough to cause permanent lung damage (silicosis), but only if high exposure continued as a result of the volcano's erupting ash periodically over many years.

Eye irritation and minor corneal abrasions can result if ash particles enter the eye. These effects are not serious, but persons who wear contact lenses and persons heavily exposed to ash should wear protective eye gear.

FIGURE 2. Total suspended particulate (TSP) levels in ambient air before and after the May 18, 1980, eruption of Mount St. Helens and number of emergency room (ER) visits for asthma and bronchitis at the two major hospitals of Yakima, Washington, May 1980



Source: Reference 18.

Toxic effects. The Mount St. Helens' ash was repeatedly tested for evidence of leachable elements, such as fluoride, but nothing abnormal was found. This result contrasts with findings in some Icelandic eruptions in which even a fine deposit of ash is sufficient to kill grazing animals. Elevated fluoride levels (as high as 9 ppm) were measured in streams after the Hekla eruptions of 1947 and 1970; water containing concentrations in excess of 1 ppm can cause bone disease (osteofluorosis) in humans if consumed over long periods (20). Water quality can also be adversely affected by acidic ash.

Mental health. The threat of an eruption or of having to cope with the aftermath of a major eruption may adversely affect mental health, according to investigators after the Mount St. Helens' eruptions (21).

INDIRECT HEALTH CONSEQUENCES

Since heavy ashfalls can cause widespread disruption, they can have serious public health implications.

Collapse of buildings. In North America, ordinary building codes and regulations do not usually take into account abnormally heavy roof loads. The flat roofs in modern public buildings and houses are particularly at risk of collapsing if the depth of accumulated ash exceeds a few inches, especially if rain falls on them (the rain greatly increases the weight). Old people and the infirm may be at special risk because they are advised to stay in their homes during an ashfall and therefore are unable to keep a susceptible roof clear of ash. Even the fittest individuals, however, are at risk of injury from falling off roofs. Flimsy dwellings in developing countries are especially prone to collapse under the weight of ash.

Lightning. Heavy lightning can frequently accompany an ash plume for kilometers from the volcano. Ground strikes can cause fatalities and fires.

Transportation and information dissemination. Virtually all transport can come to a halt in a heavy ashfall because of the impenetrable darkness and the damaging effect of ash on automobile, train, and plane engines. Cities could come to a virtual standstill for several days in the event of a massive ashfall, with implications for ambulance, fire, and police services. Automobile breakdowns and accidents due to slippery roads or poor visibility may pose serious problems. Telephone systems can become rapidly overloaded with anxious callers, and telephone switchgear may be damaged by the infiltrating ash. Radio and television transmission may suffer serious interference while the ash is falling.

Public utilities. Moist ash can be a good conductor of electricity and can cause short-circuiting of outdoor power equipment such as insulators, resulting in power outages. Engineers may be hampered in their repair tasks by transport problems. Many of the consequences of power outages are obvious; a less obvious consequence is that water supplies dependent on electrical pumping would be jeopardized.

Water supplies could also be restricted from fallen ash in reservoirs and rivers, which could clog filtration plants. Water quality could be impaired through turbidity and changes in pH. Sewage disposal machinery is rapidly overloaded and put out of action by abrasive ash.

Infectious hazards. The flooding and disruption of rivers and lakes could provide suitable conditions for the spread of leptospirosis and, in endemic areas, malaria.

General Risk Factors

General factors that contribute to the severity of the impact of the volcanic hazards listed include the following:

LACK OF PUBLIC AWARENESS

With population growth, human settlements have arisen in volcanic areas because of the economic benefits provided, e.g., from agricultural and logging activities and tourism. The obvious economic benefits have been perceived as outweighing the less tangible risks of volcanic activity, the latter tending to be ignored by local populations in developed and developing countries alike. Local officials responsible for community and industrial planning may also perceive risks associated with volcanic activity as insignificant until a major eruption occurs.

INADEQUATE MONITORING

Hazard evaluation by volcanologists has been undertaken for few of the world's volcanoes so far. Resources for the regular monitoring of volcanoes are limited, particularly in developing countries. Even when regular monitoring is being undertaken, dangerous eruptions can occur without adequate warning, e.g., Mount Mayon in 1984.

FALLIBILITY OF WARNINGS

Warnings given by volcanologists may not be acted on by government officials and local populations because of the fallibility inherent in predicting eruptions. Prolonged evacuation of populations can lead to severe socioeconomic disruption and much antagonism if an eruption fails to materialize.

VULNERABILITY OF POPULATIONS

The politicosocial development of a country may seriously limit the options available for adopting preventive measures. Residents of impoverished communities may feel that they have little choice but to remain where they are even when threatened by imminent volcanic activity. Disruption of communication links in such communities may also greatly add to loss of life after an eruption.

Preventive Measures

Some of the numerous public health consequences of major volcanic eruptions are common to other types of natural disasters, e.g., trauma from collapsing buildings, drownings, and deaths from exposure and starvation—still realities in developing countries despite modern international relief measures. Preventive measures outlined here are specific to volcanic eruptions (20,22). Guidance on general problems of the management of volcanic emergencies is also available (23).

Pre-Eruption Measures

As noted previously, the deadly eruptive phenomena responsible for the greatest loss of life are pyroclastic flows, pyroclastic surges, and lateral blasts (all health-related phenomena), mud flows, and tsunamis.

The only adequate preventive measures against these volcanic consequences are evacuation and the demarcation of restricted zones when an area is threatened by an eruption. In most instances the number of injured survivors in relation to the number of persons killed will be small; therefore, the role of medical treatment facilities in reducing the human scale of disaster must be limited, regardless of the influx of victims. Premonitory signs of renewed eruptive activity of an explosive volcano will therefore signal a public health emergency and the need for immediate planning measures involving public and occupational health officials at the earliest stage.

The measures in the vicinity of the volcano include:

- Evacuation and demarcation of at-risk areas, key preventive measures that essentially are decisions to be taken by government officials after consultation with volcanologists. Information from health officials also needs to be taken into account—e.g., on the feasibility of evacuating the sick, aged, and very young upon short notice. The health and welfare of persons evacuated temporarily or for long periods is also a public health matter. The safety of specific groups of workers who may be permitted into dangerous areas needs careful, unbiased assessment and dissemination of information on risks and benefits.
- Search and rescue plans for the dead and any marooned survivors after the eruption, including the sites for emergency field casualty stations and morgues and designation of their staff.
- Rehearsal of local hospital emergency plans for a sudden influx of victims with a) body-surface burns and lung damage from inhalation of hot ash and b) all kinds of trauma.
- Provision of emergency air-monitoring equipment for toxic gases.

In addition, planning for heavy ashfalls over a wide area, if applicable, should include arrangements for:

- Providing laboratory facilities for the collecting and analyzing of ash for leachable toxic elements and for monitoring drinking water quality. Specialist laboratories should be made available for measuring particle size and crystalline silica content of the ash, and for checking the bioavailability of toxic elements, e.g., in milk.
- Providing equipment for monitoring exposures to airborne ash in the community and in outdoor occupational groups.
- Stockpiling lightweight, disposable, high-efficiency masks, if indicated, for distribution to the public after an ashfall. Goggles and more robust respiratory protection may be needed for emergency workers and other outdoor workers.
- Preparing for possible temporary breakdowns of water supplies and sewage treatment plants, including ensuring adequate chlorination or the issuing of "boil water advisories."
- Maintaining emergency health services and hospitals.
- Providing emergency shelter and food relief.

Post-Eruption Measures

An emergency health team with medical, epidemiologic, and community health skills should be formed immediately after an eruption, and its membership should be planned before the emergency. One important function is collaborating with other agencies in an official disaster-coordinating

center and giving advice and information relating to all health aspects arising from the disaster. Field surveys may need to be conducted a) to collate epidemiologic information on the dead and survivors (e.g., cause of death and injury) and to collaborate with rescue teams and b) to make rapid assessments of health problems arising in the areas of heavy ashfall as soon as travel conditions permit.

Epidemiologic surveillance through a network incorporating hospitals and emergency rooms in affected areas will provide valuable information on the health impact of the disaster. Through such an information system the respiratory effects of the Mount St. Helens' ashfalls were first detected. The emergency and rescue services will perform many reactive tasks; further details can be found elsewhere (20,22). If a heavy ashfall has occurred, a key preventive measure is to maintain road blocks and adequate traffic controls in affected areas.

DISSEMINATION OF INFORMATION

At least 10-15 explosive eruptions occur throughout the world every year, but—with the exception of certain volcanoes, e.g., Merapi, Indonesia, which can erupt devastatingly every 15 years or so—they are uncommon or rare events in many parts of the world. Local communities may therefore be bewildered when told about a threatening eruption, and it will be essential to supply detailed information on what steps they should take before and after the eruption occurs.

Advice and equipment, including emergency warning systems, should be provided for people who are permitted to live or work in restricted or high-risk areas near a volcano. The mode of evacuation and the location of evacuation centers need to be specified. Similar provision should be made for those areas that might suffer heavy ashfall. Examples of brochures posted or given to households and workers for Mount St. Helens are given elsewhere (22). As in other types of disaster, radio and television will be essential for transmitting warnings and providing pre- and post-eruption advice.

Surveillance Measures

The shortcomings of facilities for monitoring volcanoes have already been noted. Accordingly, a good case can be made for an international team of experienced field volcanologists capable of traveling by invitation whenever an eruption threatens to rapidly set up monitoring systems and provide advice to local scientists and officials. Such collaboration will almost certainly be welcomed by scientists in developing countries and would go a long way toward mitigating volcanic disasters.

Critical Knowledge Gaps and Research Recommendations

There is hardly any aspect of volcanism in populated areas about which current knowledge cannot be increased (22). Unfortunately, international efforts to coordinate the management of volcanic disasters remain fragmentary, and there is little evidence that any international advances in preventive health and safety measures have been made since the Mount St. Helens' eruptions in 1980. A recently published monograph summarizing many of the health research activities in the wake of the Mount St. Helens' eruptions should serve as a valuable reference for future investigators dealing with other volcanoes (24). We especially need more information on health sequelae in developing countries in which the populations are most vulnerable and scientific studies are often difficult to perform. Considerable uncertainty is inherent in extrapolating from the experience of Mount St. Helens in the United States to countries in which the people may be underfed, may have inadequate housing and sanitation, and may be subject to a high incidence of fatal childhood respiratory infection.

An example is provided by the eruption of Ruiz, Colombia, in 1985. From the sparse reports in the literature, it would appear that few survive a massive mud flow, since virtually all people in the area are instantly engulfed. Nevertheless, numerous survivors were found for many days after the Ruiz eruption, as recorded by the world's media. We need to know more about how to reduce the vulnerability of populations to these predictable events, the best ways of rescuing survivors from mud flows, and the types of medical treatment that may be required before and after survivors arrive at the hospital. Such information has obvious implications for rescue services and saving lives and illustrates the importance of close collaboration between health and other emergency workers if advances in mitigating volcanic disasters are to be made.

Summary

Many major volcanic eruptions are preceded by premonitory events. Even so, geologists cannot usually predict with certainty the timing and size of an eruption. The first warning of reawakening of activity may therefore signal a public health emergency requiring from the outset the collaboration of health officials with other key groups in emergency planning.

The demarcation of restricted areas in the vicinity of the volcano is an essential first step in preventing loss of life from mud flows and pyroclastic flows; shorelines may also be at risk from tsunamis.

Pollution of air by respirable ash particles may exacerbate respiratory symptoms among patients with asthma and other chronic respiratory diseases. The greatest risk from asphyxiant gases is in topographic depressions lying within a few kilometers of a volcanic crater or fissure, but irritant gases such as sulfur dioxide may exacerbate respiratory disease and cause ecological effects from acid rain for kilometers downwind. Carbon dioxide is odorless, and the "rotten eggs" smell of hydrogen sulfide rapidly disappears if it is present in dangerous levels. Hydrogen sulfide also has irritant properties. Instruments for measuring concentrations of these gases should therefore be available in volcanic and geothermal areas where the potential for human exposure exists.

The best protection against the respiratory effects of fine ash is afforded by weather-proofed housing and lightweight, disposable, high-efficiency, industrial face masks to be worn when outdoors. Outdoor occupational groups may require heavy-duty industrial respirators and goggles. The public should avoid or evacuate areas at risk from gases. Appara-

tus for monitoring ambient and personal air levels for ash particles and gases may be essential for advising residents and workers.

The breakdown of public utilities, information systems, and transport; the needs of evacuees; and the damage caused by mud flows, floods, heavy ashfalls, earthquakes, and lightning can pose numerous direct and indirect health problems that remain poorly documented. An epidemiologic surveillance system linking emergency medical centers proved to be a valuable information resource after the Mount St. Helens' eruptions in 1980. Some of the health hazards are common to other natural disasters, but laboratory studies of ash to determine the presence of leachable toxic elements are essential so that advice can be given on contamination of water and food supplies for both humans and livestock. These studies should be performed immediately after an ashfall. Specialized laboratories should be available to measure particle characteristics, crystalline silica content, and other properties of the ash so that its short- and possibly long-term respiratory effects can be determined.

Advice on combating the numerous health consequences of eruptions should be encapsulated in handouts for the population and workers, and these handouts should be distributed before an eruption occurs. After an eruption, an emergency coordinating center is invaluable for the rapid and accurate dissemination of advice to officials and the public. Because the health and safety needs of populations in active volcanic areas are potentially so numerous, multidisciplinary approaches to planning and emergency response are essential.

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Hurricanes

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Background and Nature of Hurricanes

Factors That Contribute to Hurricanes

A hurricane is defined as a rotating wind system that whirls counterclockwise in the northern hemisphere, forms over tropical water, and has sustained wind speeds of at least 74 miles/hour (45.9 km/hour). This whirling mass of energy is formed when circumstances involving heat and pressure nourish and nudge the winds over a large area of ocean to wrap themselves around an atmospheric low. **Tropical cyclone** is the term for all wind circulations rotating around an atmospheric low over tropical waters. A **tropical storm** is defined as a cyclone with winds from 39 to 73 mph, and a **tropical depression** is a cyclone with winds less than 39 mph.

It is presently thought that many tropical cyclones originate over Africa in the region just south of the Sahara. They start as an instability in a narrow east-to-west jet stream that forms in that area between June and September as a result of the great temperature contrast between the hot desert and the cooler, more humid region to the south. Studies show that the disturbances generated over Africa have long lifetimes, and many of them cross the Atlantic. In the 20th century an average of 10 tropical cyclones each year whirl out across the Atlantic; six of these become hurricanes (1). The hurricane season is set as being June 1 through November 30. An "early" hurricane occurs in the 3 months before the season, and a "late" hurricane takes place in the 3 months after the season (2)

Hurricanes are well-organized. The 10-mile-thick inner spinning ring of towering clouds and rapid upper motion is defined as the hurricane's eyewall; it is here that condensation and rainfall are intense and winds are most violent Harbored within the eyewall is the calm eye of the hurricane—usually 10-20 miles across—protected from the inflowing winds and often free of clouds. Here, surface pressure drops to a minimum, and winds subside to less than 15 mph. Out beyond the eyewall, the hurricane forms into characteristic spiral rain bands, which are alternate bands of rain-filled clouds. In the typical hurricane, the entire spiral storm system is at least 1,000 miles across, with hurricane-force winds of 100 miles in diameter and gale-force winds of 400 miles in diameter. A typical hurricane liberates about 100 billion kilowatts of heat from the condensation of moisture, but only about 3% of the thermal energy is transferred into mechanical energy in the form of wind. Sustained wind speeds up to 200 mph have been measured, but winds of about 130 mph are more typical. It is estimated that an average hurricane produces 200 billion tons of water a day as rain (1)

Most of the flooding associated with hurricanes does not come from the intense rain but from what is known as the "storm surge" The winds and low pressure around the hurricane eye tend to raise the level of the ocean 1-2 feet. When this dome of water, perhaps 50 miles across, moves into shallow coastal water, the decreasing water depth transforms it into a storm surge that can rise high above normal sea level, bringing the seas well inland. Depending on the strength of the storm and local bottom conditions where the storm comes ashore, the storm surge may cause the sea to rise as much as 20 feet higher than normal. The storm surge is superimposed on normal, astronomically based tides. In turn, wind waves are superimposed on the storm surge. The worst circumstance is to have the storm surge strike the coast at the time of high tide During hurricane Camille in August 1969, one of the strongest U.S. hurricanes of this century, the storm surge was estimated to be 30 feet high (1).

The destructive power of a hurricane is determined by the way storm surge, wind, and other factors are combined. Hurricane forecasters have developed a five-category disaster potential scale to make comparisons easier and to make the predicted hazards of approaching hurricanes clearer. Category 1 is a minimum hurricane, category 5 a maximum hurricane (Table 1)(2).

Hurricanes generally move along their path at speeds of less than 20 mph, especially in the formative stages, but on rare occasions one will race along up to 60 mph. Hurricanes have an initial westward-moving flow. If they drift far enough northward, they can be caught by the prevailing westerly wind of the mid-latitudes and redirected to the east or northeast. Their direction is also influenced by other large-scale weather conditions. A southeastward-advancing cold front, for example, can stall a northwestward-moving hurricane off the U.S. coast and perhaps nudge it back out to

TABLE 1. Saffir/Simpson hurricane scale ranges

Scale number (category)	Central pressure millibars	Central pressure inches	Winds (mph)	Surge (in feet)	Damage
1	≥980	≥28.94	74-95	4-5	Minimal
2	965-979	28.50-28.91	96-110	6-8	Moderate
3	945-964	27.91-28.47	111-130	9-12	Extensive
4	920-944	27.17-27.88	131-155	13-18	Extreme
5	<920	<27.17	>155	>18	Catastrophic

Source: Reference 2.

TABLE 2. Number of hurricanes (direct hits) affecting the United States, by individual states, 1900-1982, according to Saffir/Simpson hurricane scale

Area	Catagory number 1	2	3	4	5	All	Major hurricanes (>category 3)
U.S. (Texas to Maine)	48	33	40	13	2	136	55
Texas	9	9	8	6	0	32	14
(North)	4	3	2	4	0	1	6
(Central)	2	2	1	1	0	6	2
(South)	3	4	5	1	0	13	6
Louisiana	5	5	7	3	1	21	11
Mississippi	1	1	4	0	1	7	5
Alabama	4	1	4	0	0	9	4
Florida	16	14	15	5	1	51	21
(Northwest)	9	6	5	0	0	20	5
(Northeast)	1	7	0	0	0	8	0
(Southwest)	5	3	5	2	1	16	8
(Southeast)	4	10	7	3	0	24	10
Georgia	1	4	0	0	0	5	0
South Carolina	5	4	2	1*	0	12	3
North Carolina	9	3	6	1*	0	19	7
Virginia	1	1	1*	0	0	3	1*
Maryland	0	1*	0	0	0	1*	0
Delaware	0	0	0	0	0	0	0
New Jersey	1*	0	0	0	0	1*	0
New York	3	0	4*	0	0	7	4*
Connecticut	2	1*	3*	0	0	6	3*
Rhode Island	0	1*	3*	0	0	4*	3*
Massachusetts	2	1*	2*	0	0	5	2*
New Hampshire	1*	0	0	0	0	1*	0
Maine	4	0	0	0	0	4	0

*Indicates all hurricanes in this category were moving at >30 mph.

Note State totals do not equal U S totals, and Texas and Florida sectional totals do not equal state totals.

Source Reference 3

sea. However, hurricanes may follow very erratic paths, and it is unsound to generalize about what direction they will take.

Once a hurricane moves over the mainland, its supply of evaporated water from the ocean surface is cut off and its power eventually diminishes, but not before it dumps enormous quantities of rain on the land below (1).

Trends over Time

In the period 1900-1982, 136 hurricanes struck the United States directly, 55 of these were of at least category-3 intensity (Table 2). Florida felt the effects of both the highest number (51) and the most intense of these storms, with Texas, Louisiana, and North Carolina following in descending

TABLE 3. Number of hurricanes of various categories to strike the United States each decade of the 20th century

	Category					All	Major
Decade	**1**	**2**	**3**	**4**	**5**	**(Categories 1-5)**	**(Categories 3-5)**
1900-1909	4	4	4	2		14	6
1910-1919	8	3	5	3		19	8
1920-1929	7	2	3	2		14	5
1930-1939	4	5	6	1	1	17	8
1940-1949	7	8	7	1		23	8
1950-1959	8	1	7	2		18	9
1960-1969	4	5	3	2	1	15	6
1970-1978	5	1	3			9	3
TOTAL	**47**	**29**	**38**	**13**	**2**	**129**	**53**

Note Only the highest category to affect the United States has been used
Source Updated from Hebert and Taylor 1975

order (3) The number of hurricanes of various categories to strike the United States in each decade from 1900 through 1978 is shown in Table 3. Based on 100 years of record keeping on hurricanes, the National Weather Service has observed that on the average, a category 4 or higher hurricane strikes the United States once every 5 years (2). However, in the period 1950-1978, both the number and intensity of land-falling hurricanes decreased sharply. The expected number of hurricanes in the period 1958-1977 was 34, but only 14 were observed. A study by Hebert and Taylor in 1975 showed that as of 1970 almost 80% of coastal residents from Texas to Maine had never experienced a direct hit by a major hurricane. Many of these 28 million residents had moved to coastal sections during the preceding 20 years. This below-average trend continued through 1984 (4). During that time, rapid growth of the coastal population continued.

In 1985 the number of hurricanes striking the U.S. mainland was more in keeping with the average pattern. In that year six hurricanes struck the U.S. mainland; two were of category 3 or higher. Hurricane Gloria was measured as a category 5 over the Atlantic Ocean; it struck Cape Hatteras, North Carolina, as a category 4, and went on to strike Long Island as a category 3. Hurricane Elena struck Florida, Alabama, and Mississippi as a category 3. Many people considered 1985 an abnormally devastating year for hurricanes because they had been lulled into thinking that major hurricanes seldom struck the U.S. mainland because of their experience during a below-average period. However, a specialist at the National Weather Service is quick to point out that 1985 more closely approximated the average (H. Gerrish, personal communication).

Factors Influencing Morbidity and Mortality

Although hurricane winds do much damage, the wind is not the biggest killer in a hurricane. Most victims die by drowning. The flooding that accompanies a hurricane, for the most part, does not come from the intense rain but from the storm surges. The National Weather Service estimates that storm surges cause nine of every 10 hurricane-associated fatalities (1).

Table 4 lists the deadliest hurricanes to strike the United States in this century (1900-1982). The 12 deadliest hurri-

TABLE 4. The deadliest (25 or more deaths) U.S. hurricanes, 1900-1982, in descending order of severity

	Hurricane	Year	Category	Deaths
1.	Texas (Galveston)	1900	4	6,000
2	Florida (Lake Okeechobee)	1928	4	1,836
3.	Florida (Keys/S. Texas)	1919	4	600-900†
4.	New England	1938	3*	600
5.	Florida (Keys)	1935	5	408
6	AUDREY (Louisiana/Texas)	1957	4	390
7	Northeast U.S.	1944	3*	390§
8.	Louisiana (Grand Isle)	1909	4	350
9.	Louisiana (New Orleans)	1915	4	275
10	Texas (Galveston)	1915	4	275
11	CAMILLE (Miss./La)	1969	5	256
12.	Florida (Miami)	1926	4	243
13.	DIANE (Northeast U S.)	1955	1	184
14.	Southeast Florida	1906	2	164
15.	Mississippi/Alabama/Pensacola	1906	3	134
16.	AGNES (Northeast U.S.)	1972	1	122
17	HAZEL (S C /N C.)	1954	4*	95
18.	BETSY (Fla/La)	1965	3	75
19.	CAROL (Northeast U.S.)	1954	3*	60
20.	Southeast Florida/La.-Miss.	1947	4	51
21.	DONNA (Fla./Eastern U S.)	1960	4	50
22.	Georgia/Carolinas	1940	2	50
23.	CARLA (Texas)	1961	4	46
24.	Texas (Velasco)	1909	3	41
25	Texas (Freeport)	1932	4	40
26.	South Texas	1933	3	40
27	HILDA (Louisiana)	1964	3	38
28.	Southwest Louisiana	1918	3	34
29.	Southwest Florida	1910	3	30
30.	CONNIE (North Carolina)	1955	3	25
31	Central Louisiana	1926	3	25

* Moving >30 mph
† Over 500 of these lost on ships at sea
§ 344 of these lost on ships at sea.

Note. Information for earlier years

Year	Location	Deaths
1881	Georgia/South Carolina	700
1893	Louisiana	2,000
1893	South Carolina	1,000-2,000

Source Reference 5.

canes were all classified as the equivalent of category 4 or higher. All but two of the 31 deadliest hurricanes were major hurricanes. The exceptions were the inland flood-producing hurricanes Agnes and Diane. In association with the other 29 hurricanes, the death tolls are primarily a result of the 15- to 20-foot rise of the ocean (storm surge) associated with these hurricanes (5). During hurricane Camille, the storm surge was estimated to be 30 feet high; 256 persons died in that hurricane. Among them were 23 of 24 persons at Pass Christian, Mississippi, who refused to evacuate and held a "hurricane party" instead. The three-story apartment they were in was obliterated by the storm surge, leaving nothing but the foundation. The one survivor was buffeted about in the debris-strewn waters before eventually being swept into a tree top, where she was found and rescued the next morning. A storm surge in the Louisiana bayou country in October 1893 killed 2,000 people. A storm surge on Lake Okeechobee, Florida, in September 1928 broke the dikes and claimed 1,836 victims. A storm surge struck the Florida Keys in 1935, leading to a loss of 408 lives; one that struck Louisiana in 1935 left a death toll of 390 (1).

The decreased death tolls in the past 20 years may reflect the below-average number of major hurricanes striking the most vulnerable areas. However, as the incidence and intensity of land-falling hurricanes reverts to the average pattern, the death tolls may again rise because of increased coastal growth. If warnings are heeded and preparedness plans developed, the death toll can be reduced, but large property losses are inevitable.

The six hurricanes that struck the U.S. mainland in 1985 are shown in Table 5 by category and number of associated deaths (5). It is interesting to note that Juan, only a category 2 hurricane, had the highest death toll. Most of these were drowning deaths associated with the flash flooding that resulted from the heavy rainfall that accompanied the hurricane

More detailed information on risk factors contributing to morbidity and mortality from coastal and flash flooding is included in the chapter on floods.

TABLE 5. Hurricanes striking U.S. mainland in 1985, by category and number of associated deaths

1985 Hurricanes (Areas affected)	Category	Number of deaths
Gloria (North Carolina to Maine)	4 - Cape Hatteras 3 - Long Island	8
Elena (Florida, Louisiana, Alabama, Mississippi)	3	4
Juan (Louisiana, Mississippi, Florida Panhandle)	2	12
Kate (Florida Panhandle, Georgia)	2	5
Danny (Louisiana)	1	1
Bob (Alabama)	1	0

Source Reference 5

Public Health Implications

Prevention and Control Measures

The principal steps to follow for preventing death and injury associated with hurricanes are:

1. To identify meteorologic precursors of hurricanes and track their course and potential development into hurricanes.

   The National Hurricane Center of the National Oceanic and Atmospheric Administration in Coral Gables, Florida, has developed a highly sophisticated system for identifying and tracking tropical cyclones. A tropical cyclone may first be identified by satellite and then tracked by radar. In addition, computer portrayals of the behavior of hurricanes are valuable to atmospheric scientists in studying the inner workings of these tropical storms. Information gained during flights by highly instrumented aircraft into hurricanes helps to form a more complete picture of storm conditions.

2. To issue early hurricane warnings to provide for timely evacuation when indicated.

   The highly sophisticated tracking system of the National Hurricane Center probably provides a better early-warning system for hurricanes than is available for any other type of weather-related disaster. Although hurricanes sometimes follow an erratic course, the predictions of when and where they may strike are certainly more reliable than those for flash floods and tornadoes. The hurricane warnings are communicated through the National Weather Service Communication Network, and the information is readily available to the media. Radio and television usually give high visibility to such events and can be very effective in alerting the public to the potential danger of a hurricane.

3. To enforce stringent land-use management practices and building codes in high-risk areas.

   Unfortunately, indiscriminate development permitted along the Atlantic and Gulf coasts in the past 20 years has lead to densely populated high-risk areas. However, more stringent building codes have been introduced in many areas, and most building codes require a building to sustain winds of 130 mph. Florida recently changed its building code to require structures to withstand winds of 140 mph rather than 130 mph.

4. To develop emergency contingency plans in high hurricane-risk areas to provide for an orderly evacuation and adequate shelter capacity for evacuees.

   Evacuation from coastal areas is a critical preventive measure for hurricanes because of the great danger from storm surges. Most coastal communities have contingency plans, and Texas and Florida have very well-developed plans. There has been some concern that the people may not respond to evacuation recommendations because they have been lulled into a false

sense of security because of the below-average number of dangerous hurricanes that have struck the United States in the past 20 years. However, most people chose to evacuate during the 1985 hurricanes, and some people had to evacuate twice during hurricane Gloria because of the erratic path of that hurricane.

Because of heavy development and increased population density on some of the offshore islands along the Atlantic and Gulf Coast, special attention must be given to the time necessary to provide an orderly and successful evacuation across the causeways connecting the islands to the mainland.

For other preventive and control measures relating to flooding and high winds, the reader is directed to the chapters on floodings and tornadoes.

Surveillance

The National Hurricane Center not only has a very effective tracking system for hurricanes but also collects and analyzes data on hurricanes from all over the world. It routinely prepares and disseminates written reports based on these data.

For surveillance activities related to morbidity and mortality from hurricane associated floods, the reader is referred to the chapter on floods.

Research Recommendations

1. Because the meteorologic factors contributing to hurricanes have been studied in some detail, a good deal of information is available on this phenomenon. However, more information is needed on factors influencing the variable pattern of incidence and intensity of hurricanes striking the United States over time.
2. Emergency contingency plans for various coastal communities are tested and should be evaluated when hurricanes strike a particular community. The plans should be revised on the basis of these findings.
3. Does protection from wind speed also protect buildings from storm surges? Can those buildings designed to withstand winds of 130 mph also withstand sea surges of 25-30 feet? Research is needed to address these questions.

Other research recommendations related to hurricane associated flooding are addressed in the chapter on floods.

Summary

In the period 1900-1982, 136 hurricanes directly hit the U.S. mainland. Fifty-five of these storms were category 3 or higher. Florida experienced both the highest number of hurricanes and those of greatest intensity. The hurricane season is defined as June 1 through November 30. In the period 1950-1978, both the number and intensity of land-falling hurricanes in the United States decreased sharply. These circumstances created a false sense of security with regard to dangers involved in living near coastal areas and led to massive development and increased population density in potentially high-risk areas. In 1985 six hurricanes struck the United States, two of these were category 3 or higher. The National Weather Service considers the 1985 incidence more in keeping with the average pattern than that seen in the previous several years.

Although hurricane winds do much damage, the wind is not the biggest killer in a hurricane. Most victims die by drowning. The flooding that accompanies a hurricane, for the most part, comes not from the intense rain but from storm surges. The National Weather Service estimates that storm surges cause nine of every 10 hurricane-associated fatalities.

Critical prevention measures are in place for limiting morbidity and mortality associated with storm surges from hurricanes if people will follow warnings and orders to evacuate. These preventive measures involve early detection and tracking of hurricanes so that timely warnings can be issued and orderly evacuation from threatened coastal areas carried out. The National Hurricane Center in Coral Gables, Florida, has developed a very sophisticated system for identifying and tracking hurricanes, and the warnings issued by the Center are timely and have a high success rate for accurately predicting the time and place a hurricane may strike the United States. Most coastal communities have developed emergency contingency plans that provide for evacuating and sheltering people. The mortality associated with the flash flooding that often accompanies a hurricane is more difficult to control because technology for accurately predicting the exact time and place a flash flood might occur is still limited.

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