

CHAPTER 5

PRINCIPAL HAZARDS IN THE UNITED STATES

This chapter describes the principal environmental hazards that are of greatest concern to emergency managers in communities throughout the United States. Each of these hazards will be described in terms of the physical processes that generate them, the geographical areas that are most commonly at risk, the types of impacts and typical magnitude of hazard events, and hazard-specific issues of emergency response.

Introduction

Most of the hazards that concern emergency managers are environmental hazards, which are commonly classified as natural or technological. Natural hazards are extreme events that originate in the natural environment, whereas the technological hazards of concern to emergency managers originate in human controlled processes (e.g., factories, warehouses) but are transmitted through the air and water. The natural hazards are commonly categorized as meteorological, hydrological, or geophysical. The most important technological hazards are toxic chemicals, radiological and nuclear materials, flammable materials, and explosives.

The list of natural and technological hazards that could occur in the United States is much larger than can be addressed here. Accordingly, this chapter focuses on the hazard agents that most commonly confront local emergency managers. The first section addresses four meteorological hazards—severe storms (including blizzards), severe summer weather, tornadoes, and hurricanes. It also includes wildfires because these are significantly influenced by lack of rainfall. The second section describes three hydrological hazards—floods, storm surges, and tsunamis. The third section addresses geophysical hazards—volcanic eruptions, earthquakes, and landslides. The material in these three sections is drawn primarily from Alexander (1993), Bryant (1997), Ebert (1988), Federal Emergency Management Agency (1997), Hyndman and Hyndman (2005), Meyer (1977), Noji (1997), Scientific Assessment and Strategy Team (1994), and Smith (2001). The fourth section covers technological hazards, primarily toxic, flammable, explosive, and radiological materials. The material in these three sections is drawn primarily from Edwards (1994), FEMA (no date, a), Goetsch (1996), Kramer and Porch (1990), and Meyer (1977). The last section summarizes information on biological hazards. The material in this section is drawn primarily from World Health Organization (2004), World Health Organization/Pan American Health Organization (2004), and Chin (2000).

The chapter does not address emergencies caused by large, unexpected resource shortages, energy shortages being a prime example. Nor does it address slow onset disasters such as ozone depletion, greenhouse gas accumulation, deforestation, desertification, drought, loss of biodiversity, and chronic environmental pollution. For information on these long term hazards, see sources such as Konratyev, Grigoryev and Varotsos (2002).

Meteorological Hazards

The principal meteorological hazards of concern to emergency managers are severe storms (including blizzards), severe summer weather, tornadoes, hurricanes, and wildfires.

Severe Storms

The National Weather Service (NWS) defines a severe storm as one whose wind speed exceeds 58 mph, that produces a tornado, or that releases hail with a 3/4 inch diameter or greater. The principal threats from these storms are lightning strikes, downbursts and microbursts, hail, and flash floods.

Lightning strikes can cause casualties, but these tend to be few in number and widely dispersed so they are easily handled by local emergency medical services units. However, lightning strikes also can initiate wildfires that threaten entire communities—especially during droughts (see the discussion of wildfires below). Downbursts (up to 125 mph) and microbursts (up to 150 mph) are threats to aircraft as they take off or land. This creates a potential for mass casualty incidents. Large hail generally causes few casualties and the associated damage rarely causes significant social or economic disruption. The areas with the greatest thunderstorm hazard are in the desert southwest (northwest Arizona), the plains states (centered on Kansas) and the southeast (Florida), but only the latter two areas have high population densities.

Severe winter storms pose a greater threat than those at other times of year because freezing temperatures produce substantial amounts of snow—whose volume exceeds that of an equivalent amount of rain by a factor of 7-10. A severe winter storm is classified as a blizzard if its wind speed exceeds 38 mph and its temperature is less than 21°F (degrees Fahrenheit). These conditions can produce significant wind chill effects on the human body. Table 5-1 shows increasing wind speed significantly accelerates the rate at which a low temperature causes frostbite. It is important to recognize that a temperature of 40°F and wind speed of 20 mph will not freeze water, even though the wind chill is 30°F.

These storms can immobilize travel, isolate residents of remote areas, and deposit enormous loads of snow on buildings—collapsing the long-span roofs of gymnasiums, theaters, and arenas. In addition, the weight of ice deposits can bring down telephone and electric power lines. The hazard of winter storms is most pronounced in the northern tier of states from Minnesota to northern New England, but also can be extremely disruptive farther south where cities have less snow removal equipment.

Table 5-1. Wind Chill Index.

		Temperature (°F)																	
		40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
Wind speed (mph)	5	36	31	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57	-63
	10	34	27	21	15	9	3	-4	-10	-16	-22	-28	-35	-41	-47	-53	-59	-66	-72
	15	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77
	20	30	24	17	11	4	-2	-9	-15	-22	-29	-35	-42	-48	-55	-61	-68	-74	-81
	25	29	23	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78	-84
	30	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87
	35	28	21	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82	-89
	40	27	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-84	-91
	45	26	19	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86	-93
	50	26	19	12	4	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81	-88	-95
	55	25	18	11	4	-3	-11	-18	-25	-32	-39	-46	-54	-61	-68	-75	-82	-89	-97
60	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98	

Source: National Weather Service <<http://www.noaa.nws.gov>>

Note: Wind Chill Temperature is defined only for temperatures less than or equal to 50°F and wind speeds greater than 3 mph. Bright sunshine may increase the wind chill temperature by 10-18°F.

Frostbite times	 30 minutes	 10 minutes	 5 minutes
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Extreme Summer Weather

Emergency managers should be concerned about extreme heat because this can be a silent killer within the community. The body responds to high heat by using evaporating sweat to cool itself.

However, high humidity decreases the efficiency with which perspiration can discharge heat, so the body's core (internal) temperature rises. When the heat gain exceeds the amount the body can remove, extreme core temperatures can cause a series of heat-related disorders. The least serious condition is *heat cramp*, which is characterized by mild fluid and electrolyte imbalances. Next in severity is *heat syncope*, which causes sudden loss of consciousness that disappears when the victim lies down. *Heat exhaustion* produces symptoms of weakness or dizziness and *heat stroke* is a condition in which the victim might be delirious or comatose. Unless treated effectively by rapid cooling, heat stroke can produce neurological damage and fatalities in about 15% of those affected.

Temperature and humidity are combined into a heat index of *apparent temperature* the National Weather Service uses for weather advisories (see Table 5-2). Apparent temperatures of 80-90°F warrant *caution* because prolonged exposure and physical activity can cause fatigue. *Extreme caution* should be taken when apparent temperatures reach 90-105°F because prolonged exposure and physical activity can cause heat cramp and heat exhaustion. *Danger* exists when apparent temperatures reach 105-130°F because prolonged exposure and physical activity can cause heat stroke. *Extreme danger* exists when apparent temperatures exceed 130°F because heat stroke is imminent.

Hazard maps show the most severely exposed areas are in the desert Southwest, Mississippi Valley, and Southeastern states. Demographic groups at greatest risk are outdoor laborers, the very old (particularly those over 75), the very young, and those who have chronic diseases. The problem can be especially severe in the inner cities where city buildings re-radiate sunlight (increasing the ambient temperature) and block the wind (decreasing evaporative cooling). Those who live in residences lacking air conditioning have the greatest exposure when they live in high crime areas where they might even be afraid to open the windows for fans.

Table 5-2. Heat Index.

		Temperature (° F)						
		80	85	90	95	100	105	110
Relative humidity (%)	40%	79	84	90	98	109	121	135
	50%	80	86	94	105	118	133	
	60%	81	90	99	113	129	148	
	70%	82	92	105	122	142		
	80%	84	96	113	133			
	90%	85	101	121				

Source: National Weather Service < www.noaa.nws.gov>

Note: This chart is based upon shady, light wind conditions. Exposure to direct sunlight can increase the Heat Index as much as 15°F.)

Heat Index	Possible Heat Disorder
80°F - 90°F	Caution: Fatigue possible with prolonged exposure and physical activity.
90°F - 105°F	Extreme caution: Sunstroke, heat cramps and heat exhaustion possible.
105°F - 130°F	Danger: Sunstroke, heat cramps, heat exhaustion likely; heat stroke possible.
Greater than 130°F	Extreme danger: Heat stroke highly likely with continued exposure.

Tornadoes

Tornadoes form when cold air from the north overrides a warmer air mass and the cold air descends because of its greater weight. The descending cold air is replaced by rising warm air, a process

that initiates rotational flow inside the air mass. As the tornado forms, pressure drops inside the vortex and the wind speed increases. The resulting high wind speed can destroy buildings, vehicles, and large trees. The resulting debris becomes entrained in the wind field, which adds to the tornado's destructive power.

There are approximately 900 tornadoes each year in the United States, most of which strike Texas, Oklahoma, Arkansas, Missouri, and Kansas. However, there is also significant vulnerability in the North Central states and the Southeast from Louisiana to Florida. Tornadoes are most common during the spring, with the months of April-June accounting for 50% of all tornadoes. There also is predictable diurnal variation, with the hours from 4:00-8:00 pm being the most frequent time of impact. Tornadoes have distinct directional tendencies as well, most frequently traveling toward the northeast (54%), east (22%), and southeast (11%). Only 8% travel north, 2% travel northwest, and 1% travel west, southwest, or south, respectively. There also is a tendency for tornadoes to follow low terrain (e.g., river valleys and to move in a steady path, although they sometimes times skip about—missing some structures and striking others. A tornado's forward movement speed (i.e., the speed at which the funnel moves forward over the ground) can range 0-60 mph but usually is about 30 mph. Tornadoes can vary substantially in physical intensity and this attribute is characterized by the *Fujita scale*, which has a low end of F0 (maximum wind speed of 40 mph) and a high end of F5 (maximum wind speed of 315 mph). The Fujita scale has been criticized for neglecting the effects of construction quality, thus overestimating windspeeds for tornadoes that are F3 and higher. Discussion is underway to replace the existing Fujita scale with an Enhanced Fujita scale (for further information, see meted.ucar.edu/resource/wcm/html/230.htm for a powerpoint presentation. For discussion of this change, see www.wind.ttu.edu/F_Scale/default.htm).

Only about one third of all tornadoes exceed F2 (111 mph). The impact area of a typical tornado is 4 miles (mi) in length but has been as much as 150 mi. The typical width is 300-400 yards (yd) but has been as much as 1 mi. It is important to recognize that 90% of the impact area is affected by a wind speed of less than 112 mph, so many structures in a stricken community will receive only moderate or minor damage. Only about 3% of tornadoes cause deaths and 50% of those deaths are residents of mobile homes—structures that are built substantially less sturdily than site-built homes.

There has been an increased number of tornadoes reported during recent years, but this is due in part to improved radar and spotter networks. However, tornadoes have been observed in locations where they have not previously been seen, suggesting some long-term changes in climate are also involved. Detection is usually achieved by trained meteorologists observing characteristic clues on Doppler radar. Over the years, warning speed has been improved by NOAA Weather Radio, which provides timely and specific warnings. Those who do not receive a warning can assess their danger from a tornado's distinct physical cues; dark, heavy cumulonimbus (thunderstorm squall line) clouds with intense lightning, hail and downpour of rain immediately to the left of the tornado path, and noise like a train or jet engine. The most appropriate protective action is to shelter in-place, which is universally recommended to be a specially constructed safe room (Federal Emergency Management Agency, no date, b). If a safe room is not available, building occupants should shelter in an interior room on the lowest floor. Mobile home residents should evacuate to community shelter and those who are outside should seek refuge in a low spot (e.g., a small ditch or depression) if in-place shelter is unavailable.

Hurricanes

A hurricane is the most severe type of tropical storm. The earliest stages of hurricane development are marked by thunderstorms that intensify through a series of stages (tropical wave, tropical

disturbance, tropical depression, and tropical storm) that result in a sustained surface wind speed exceeding 74 mph. At this point, the storm becomes a hurricane that can intensify to any one of the five Saffir-Simpson categories (see Table 5-3).

The nature of atmospheric processes is such that few of the minor storms escalate to a major hurricane. In the average year there are 100 tropical disturbances, 10 tropical storms, 6 hurricanes, and only 2 of these hurricanes strike the US coast. Hurricanes in Categories 3–5 account for 20% of landfalls, but over 80% of damage. Category 5 hurricanes are rare in the Atlantic (three during the 20th Century), but are more common in the Pacific. Tropical storms draw their energy from warm sea water, so they form only when there is an increase in sea surface temperature that exceeds 80°F. For most Atlantic hurricanes, this takes place in tropical water off the West African coast. These storms are generated when the surface water absorbs heat and evaporates, and the resulting water vapor rises to higher altitudes. When it condenses there, it releases rain and latent heat of evaporation. An easterly steering wind (which is named for its direction of origin, so an easterly wind blows from east to west) pushes these storms westward across the Atlantic. The hurricane season begins the first of June, reaches its peak during the month September, and then decreases through the end of November.

Table 5-3. Saffir-Simpson Hurricane Categories.

Saffir/ Simpson Category	Wind Speed (mph)	Velocity Pressure (psf)	Wind Effects
1	74 -95	19.0	<ul style="list-style-type: none"> • Vegetation: some damage to foliage. • Street signs: minimal damage. • Mobile homes: some damage to unanchored structures. • Other buildings: little or no damage.
2	96 -110	30.6	<ul style="list-style-type: none"> • Vegetation: much damage to foliage; some trees blown down. • Street signs: extensive damage to poorly constructed signs. • Mobile homes: major damage to unanchored structures. • Other buildings: some damage to roof materials, doors, and windows.
3	111 -130	41.0	<ul style="list-style-type: none"> • Vegetation: major damage to foliage; large trees blown down. • Street signs: almost all poorly constructed signs blown away. • Mobile homes: destroyed. • Other buildings: some structural damage to small buildings.
4	131 -155	57.2	<ul style="list-style-type: none"> • Street signs: all down. • Other buildings: extensive damage to roof materials, doors, and windows; many residential roof failures.
5	>155	81.3	<ul style="list-style-type: none"> • Other buildings: some complete building failures.

Source: Adapted from National Hurricane Center < www.nhc.noaa.gov/aboutsshs.shtml >

Hurricanes have a definite structure that is very important to understanding their effects. The hurricane *eye* is an area of calm 10-20 miles in radius that is surrounded by bands of high wind and rain that spiral inward to a ring around the eye, called the *eyewall*. The entire hurricane, which can be as much as 600 miles in diameter, rotates counterclockwise in the Northern Hemisphere. This produces a storm surge that is located in the *right front quadrant* relative to the storm track. Hurricanes have a forward movement speed that averages about 12 mph, but any given hurricane can be faster or slower than this. Indeed, each hurricane's speed can vary over time and the storm can even stall at a given point for an extended period of time. Atlantic hurricanes tend to track toward the west and north, but can loop and change direction. Storm intensity weakens as it reaches the North Atlantic (because it derives less energy

from the cooler water at high latitudes) or makes landfall (which cuts the storm off from its source of energy and adds the friction of interaction with the rough land surface).

Hurricanes produce four specific threats—high wind, tornadoes, inland flooding (from intense rainfall), and storm surge. The strength of the wind can be seen in the third column of Table 5-3, which shows that the pressure of the wind on vegetation and structures is proportional to the square of the wind speed. That is, as the wind speed *doubles* from 80 mph in a Category 1 hurricane to 160 mph in a Category 5 hurricane, the velocity pressure *quadruples* from less than 20 pounds per square foot (psf) to over 80 psf. Damage from high wind (and the debris that is entrained in the wind field) is a function of a structure's exposure. Wind exposure is highest in areas directly downwind from open water or fields. Upwind hills, woodlands, and tall buildings decrease exposure to the direct force of the wind but increase exposure to flying debris such as tree branches and building materials that have been torn from their sources.

Storm clouds in the outer bands of a hurricane can sometimes produce tornadoes that are mostly small and short-lived. Hurricanes can also produce torrential rain at rates up to four inches/hour for short periods of time and one US hurricane produced 23 inches over 24 hours. Such downpours cause severe local ponding (water that fell and did not move) and inland flooding (water that fell elsewhere and flowed in). Both inland flooding and storm surge are discussed below under hydrological hazards.

Hurricane disasters resulted in relatively few casualties in the US during the 20th Century. The worst hurricane disaster occurred in Galveston, Texas, in 1900 when over 6000 lives were lost in a community of about 18,000. However, coastal counties have experienced explosive population growth in recent decades, which creates the potential for another catastrophic loss of life—Hurricane Katrina being a notable example. Moreover, economic losses are increasing substantially over time. Inflation makes only a small contribution to the increase; most of the increase is due to increased population in vulnerable areas and increased wealth (per person) in those areas (Pielke & Landsea, 1998). There is extreme variation in losses by decade due to variability in the number of storms. For example, the two decades from 1950-1969 experienced 33 hurricanes whereas the equivalent period from 1970-1988 experienced only six hurricanes.

Hurricanes are rapidly detected by satellite and continually monitored by specially equipped aircraft. Storm forecast models have been developed that have provided increasing accuracy in the prediction of the storm track. Nonetheless, there are forecast uncertainties about the eventual location of landfall, as well as the storm's size, intensity, forward movement speed, and rainfall. One of the biggest problems is that the long time required to evacuate some urbanized areas (30 hours or more, see Lindell, Prater, Perry & Wu, 2002) requires warnings to be issued at a time when storm behavior remains uncertain. The strike probability data in Table 5-4 indicate many coastal jurisdictions must be warned to evacuate even though the storm will eventually miss them. Moreover, there is significant uncertainty about the wind speed and, thus, the inland distance that must be evacuated.

Appropriate protective actions for hurricanes are well understood; within the storm surge/high wind field risk areas, shelter in-place is recommended only for elevated portions (i.e., above the wave crests) of reinforced concrete buildings having foundations anchored well below the scour line (the depth to which wave action erodes the soil on which the building rests). Authorities generally recommend that evacuation be completed before evacuation routes are flooded or high wind can overturn motor homes and other high profile vehicles. Outside storm surge risk areas, shelter in-place is suitable for most permanent buildings with solid construction, but debris sources should be controlled and permanent

shutters should be installed on windows (or temporary shutters stored for quick installation). Evacuation is advisable for residents of mobile homes in high wind zones.

Table 5-4. Uncertainties about Hurricane Conditions as a Function of Time before Landfall.

Forecast period (hours)	Absolute landfall error (nautical miles)	Maximum probability	Miss/Hit Ratio	Average wind speed error (mph)
72	>200	10%	9 to 1	23
48	150	13-18%	7 to 1	18
36	100	20-25%	4 to 1	15
24	75	35-50%	2 to 1	12
12	50	60-80%	2/3 to 1	9

Source: Adapted from Emergency Management Institute/National Hurricane Center (no date)

Wildfires

All fires require the three elements of the fire triangle: *fuel*, which is any substance that will burn; *oxygen* that will combine with the fuel; and enough *heat* to ignite fuel (and sustain combustion if an external source is absent). The resulting combustion yields heat (sustaining the reaction) and combustion products such as toxic gases and unburned particles of fuel that are visible as smoke. Wildfires are distinguished mostly by their fuel. *Wildland* fires burn areas with nothing but natural vegetation for fuel, whereas *interface* fires burn into areas containing a mixture of natural vegetation and built structures. *Firestorms* are distinguished from other wildfires because they burn so intensely that they warrant a special category—in this case, they create their own local weather and are virtually impossible to extinguish. Wildfires can occur almost anywhere in the United States but are most common in the arid West where there are extensive stands of conifer trees and brush that serve as ready fuels. Once a fire starts, the three principal variables determining its severity are fuel, weather, and topography. Fuels differ in a number of characteristics that collectively define fuel type. These include the fuel’s ignition temperature (low is more dangerous), amount of moisture (dry is more dangerous), and the amount of energy (resinous wood is more dangerous). A given geographical area can be defined by its fuel loading, which is the quantity of vegetation in tons per acre, and fuel continuity, which refers to the proximity of individual elements of fuel. Horizontal proximity can be defined, for example, in terms of the distance between trees. Vertical proximity can be defined in terms of the distance between different levels of vegetation (e.g., grasses, brush, and tree branches). Weather affects fire behavior by wind speed and direction as well as temperature and humidity. Wind speed and direction have the most obvious effects on fire behavior, with strong wind pushing the fire front forward and carrying burning embers far in advance of the main front. High temperature and low humidity promote fires by decreasing fuel moisture, but these can vary during the day (cooling and humidifying at sunset) as well as over longer periods of time. Topography affects fire behavior by directing prevailing wind currents and the hot air produced by the fire. Canyons can accelerate the wind by funneling it through narrow openings. Steep slopes (greater than 10°) take advantage of a fuel’s location in the fire’s heated updraft, which allows the advancing fire front to dry nearby fuels through radiant heating and also provide a ready path for igniting these fuels. A fire’s forward movement speed doubles on a 10° slope and quadruples on a 20° slope.

Wildland fires are a major problem in the US because an average of about 73,000 such fires per year burn over three million acres. Approximately 13% of these wildfires are caused by lightning, but people cause 24% of them accidentally and 26% of them deliberately. The greatest loss of life from a US wildfire occurred in the 1871 Peshtigo, Wisconsin wildfire that killed 2200 people (Gess & Lutz, 2002).

More recently, the 1991 Oakland Hills California wildfire killed 25 people, injured 150, and damaged or destroyed over 3,000 homes. Major contributors to the severity of this wildland urban interface fire were the housing construction materials (predominantly wood siding and wood shingle roofs), vegetation planted immediately adjacent to the houses, and narrow winding roads that impeded access by fire fighting equipment.

The US Forest Service maintains a Fire Danger Rating System that monitors changing weather and fuel conditions (e.g., fuel moisture content) throughout the summer fire season. Some of the fuel data are derived from satellite observations and the weather data come from hundreds of weather stations. Appropriate protective actions include evacuation out of the risk area, evacuating to a safe location (e.g., an open space such as a park or baseball field having well-watered grass that will not burn), and sheltering in-place within a fire-resistant structure (e.g., a concrete building with no nearby vegetation).

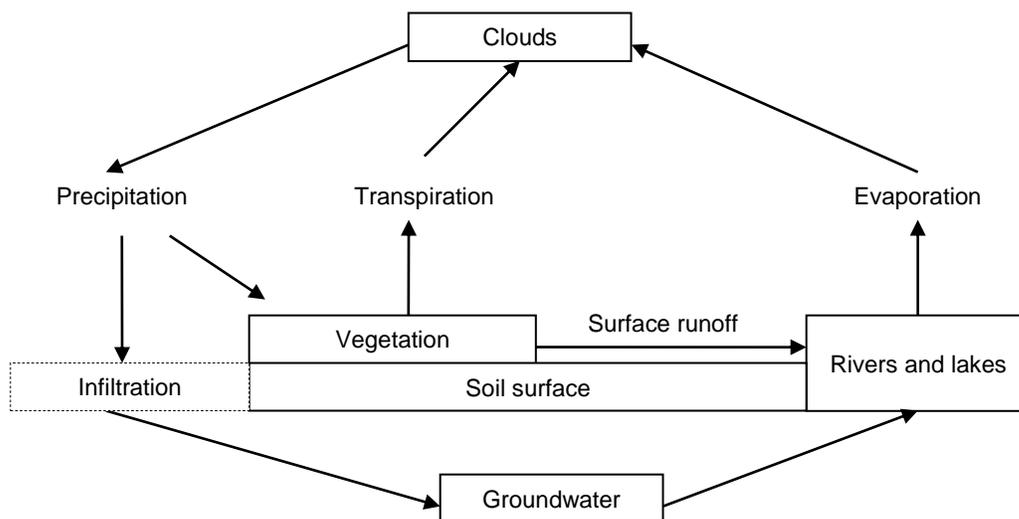
Hydrological Hazards

The principal hydrological hazards of concern to environmental hazard managers are floods, storm surges, and tsunamis.

Floods

Flooding is a widespread problem in the United States that accounts for three-quarters of all Presidential Disaster Declarations. A flood is an event in which an abnormally large amount of water accumulates in areas where it is usually not found. Flooding is determined by a hydrological cycle in which precipitation falls from clouds in the form of rain and snow (see Figure 5-1). When it reaches the ground, the precipitation either infiltrates the soil or travels downhill in the form of surface runoff. Some of the water that infiltrates the soil is taken up by plant roots and transported to the leaves where it is transpired into the atmosphere. Another portion of the ground water gradually moves down to the water table and flows underground until reaching water bodies such as wetlands, rivers, lakes, or oceans. Surface runoff moves directly to surface storage in these water bodies. At that point, water evaporates from surface storage, returning to clouds in the atmosphere.

Figure 5-1. The Hydrological Cycle.

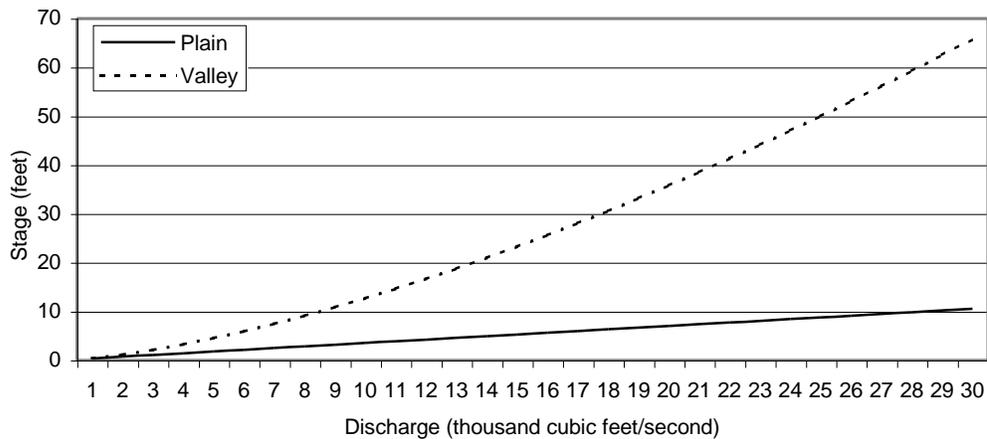


There are seven different types of flooding that are widely recognized. *Riverine (main stem)*

flooding occurs when surface runoff gradually rises to flood stage and overflows its banks. *Flash flooding* is defined by runoff reaching its peak in less than six hours. This usually occurs in hilly areas with steep slopes and sparse vegetation, but also occurs in urbanized areas with rapid runoff from impermeable surfaces such as streets, parking lots, and building roofs. *Alluvial fan flooding* occurs in deposits of soil and rock found at the foot of steep valley walls in arid Western regions. *Ice/debris dam failures* result when an accumulation of downstream material raises the water surface above the stream bank. *Surface ponding/local drainage* occurs when water accumulates in areas so flat that runoff cannot carry away the precipitation fast enough. *Fluctuating lake levels* can occur over short-term, seasonal, or multiyear periods, especially in lakes that have limited outlets or are entirely landlocked. *Control structure (dam or levee) failure* has many characteristics in common with flash flooding.

Floods are measured either by discharge or stage. Discharge, which is defined as the volume of water per unit of time, is the unit used by hydrologists. Stage, which is the height of water above a defined level, is the unit needed by emergency managers because flood stage determines the level of casualties and damage. Discharge is converted to stage by means of a rating curve (see Figure 5-2). The horizontal axis shows discharge in cubic feet per second and the vertical axis shows stage in feet above flood stage. Note that high rates of discharge produce much higher stages in a valley than on a plain because the valley walls confine the water.

Figure 5-2. Stage Rating Curve.

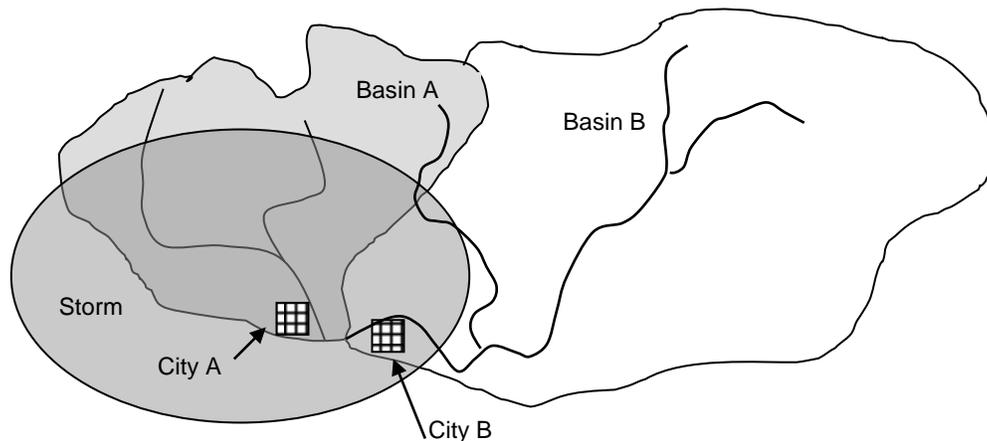


Flooding is affected by a number of factors. The first of these, precipitation, must be considered at a given point and also across the entire watershed (basin). The total precipitation at a point is equal to the duration of precipitation times its intensity (frequently measured in inches per hour). Total precipitation over a basin is equal to precipitation summed over all points in the surface area of the basin. The precipitation's contribution to flooding is a function of temperature because rain (a liquid) is immediately available whereas snow (a solid) must first be melted by warm air or rain. Moreover, as indicated by Figure 5-3, the precipitation from a single storm might be deposited over two or more basins and the amount of rainfall in one basin might be quite different from that in the other basin. Consequently, there might be severe flooding in a town on one river (City A) and none at all in a town on another river (City B) even if the two towns received the same amount of rainfall from a storm.

As the hydrological cycle makes clear, flooding is also affected by surface runoff, which is

determined by terrain and soil cover. One important aspect of terrain is its slope, with runoff increasing as slope increases. In addition to slope steepness, slope length and orientation to prevailing wind (and, thus, the accumulation of rainfall and snowfall) and sun (and, thus, the accumulation of snow) are also important determinants of flooding.

Figure 5-3. Map of the Distribution of Precipitation from a Storm.



Slope geometry is also an important consideration. Divergent slopes (e.g., hills and ridges) provide rapid runoff dispersion. By contrast, convergent slopes (e.g., valleys) provide runoff storage in puddles, potholes, and ponds. Mixed slopes have combinations of these, so slope mean (the average slope angle) and variance (the variability of slope angles) determine the amount of storage. A slope with a zero mean and high variance (a plain with many potholes) will provide a larger amount of storage than a slope with a zero mean and low variance (a featureless plain). Similarly, a slope with a positive mean and high variance (a slope with many potholes) will provide a larger amount of storage than a slope with a positive mean and low variance.

Soil cover also affects flooding because dense low plant growth slows runoff and promotes infiltration. In areas with limited vegetation, surface permeability is a major determinant of flooding. Surface permeability increases with the proportion of organic matter content because this material absorbs water like a sponge. Permeability also is affected by surface texture (particle size and shape). Clay, stone, and concrete are very impermeable because particles are small and smooth, whereas gravel and sand are very permeable—especially when the particles are large and have irregular shapes that prevent them from compacting. Finally, surface permeability is affected by soil saturation because even permeable surfaces resist infiltration when soil pores (the spaces between soil particles that ordinarily are filled with air) become filled with water. Groundwater flows via local transport to streams at the foot of hill slopes and via remote transport through aquifers. Rapid in- and outflow through valley fill increases peak flows whereas very slow in- and outflow through upland areas maintains flows between rains.

Evapotranspiration takes place via two mechanisms. First, there is direct evaporation to atmosphere from surface storage in rivers and lakes. Second, there is uptake from soil and subsequent transpiration by plants. Transpiration draws moisture from the soil into plants' roots, up through the stem, and out through the leaves' pores (similar to people sweating). The latter mechanism is generally much higher in summer than in winter due to increased heat and plant growth, but transpiration is negligible during periods of high precipitation.

Stream channel flow is affected by channel wetting which infiltrates the stream banks (horizontally) until they are saturated as the water rises. In addition, there is seepage because porous channel bottoms allow water to infiltrate (vertically) into groundwater. Channel geometry also influences flow because a greater channel cross-section distributes the water over a greater area, as does the length of a *reach* (distinct section of river) because longer reaches provide greater water storage. High levels of discharge to downstream reaches can also affect flooding on upstream reaches because flooded downstream reaches slow flood transit by decreasing the river's elevation drop.

Flooding increases when upstream areas experience deforestation and overgrazing, which increase surface runoff to a moderate degree on shallow slopes and to a major degree on steep slopes as the soil erodes. The sediment is washed downstream where it can silt the channel and raise the elevation of the river bottom. These problems of agricultural development are aggravated by flood plain urbanization. Like other cities throughout the world, US cities have been located in flood plains because water was the most efficient means of transportation until the mid-1800s. Consequently, many cities were located at the head of navigation or at transshipment points between rivers. In addition, cities have been located in flood plains because level alluvial soil is very easy to excavate for building foundations. Finally, urban development takes place in flood plains because of the aesthetic attraction of water. People enjoy seeing lakes and rivers, and pay a premium for real estate that is located there.

One consequence of urban development for flooding is that cities involve the replacement of vegetation with *hardscape*—impermeable surfaces such as building roofs, streets, and parking lots. This hardscape decreases soil infiltration, thus increasing the speed at which flood crests rise and fall. Another factor increasing flooding is intrusion into the flood plain by developers who fill intermittently flooded areas with soil to raise the elevation of the land. This decreases the channel cross-section, forcing the river to rise in other areas to compensate for the lost space.

Flood risk areas in the US are generally defined by the 100-year flood—an event that is expected to have a 100-year recurrence interval and, thus, a 1% chance of occurrence in any given year. It is important to understand that these extreme events are essentially independent, so it is possible for a community to experience two 100-year floods in the same century. Indeed, it is *possible* to have them in the same year even though that would be a very *improbable* event. This statistical principle is misunderstood by many people who believe there can be only one 100-year flood per century. The belief that a 100-year flood occurring this year cannot be repeated for another 100 years (or at least nearly 100 years) is a very dangerous fallacy. Moreover, a 100-year flood is an arbitrary standard of safety that reflects a compromise between the goals of providing long-term safety and developing economically valuable land. A 50-, 200-, or even a 500-year standard could be used instead. Community adoption of a 50-year flood standard would provide more area for residential, commercial, and industrial development. However, the resulting encroachment into the flood plain would lead to more frequent damaging floods than would a 100-year flood standard. Alternatively, a community might use different standards for different types of structures. For example, it might restrict the 100-year floodplain to low intensity uses (e.g., parks), allow residential housing to be constructed within the 500-year floodplain, and restrict nursing homes, hospitals, and schools to areas outside the 500-year floodplain.

Emergency response to floods is supported by prompt detection, which is local or regional in scope. This includes automated devices such as radar for assessing rainfall amounts at variable points in a watershed, rain gages for detecting rainfall amounts at predetermined points in a watershed, and stream gages for detecting water depth at predetermined points along a river. Detection also can be achieved by

manual devices such as spotters for assessing rainfall amounts, water depth, or levee integrity at specific locations (planned before a flood or improvised during one). Once data on the quantity and distribution of precipitation have been collected, they are used to estimate discharge volumes over time from the runoff characteristics of a given watershed (e.g., soil permeability and surface steepness) at a given time (e.g., current soil saturation). Once discharge volume is estimated, it can be used together with downstream topography (e.g., mountain valley vs. plain) to predict downstream flood heights.

Timely and specific warnings of floods are provided by commercial news media as well as NOAA Weather Radio. The most appropriate protective action for persons is to evacuate in a direction perpendicular to the river channel. Because flash floods in mountain canyons can travel faster than a motor vehicle, it is safest to climb the canyon wall rather than try to drive out. It also is important to avoid crossing running water. Just two feet of fast moving water can float a car and push it downstream with 1000 pounds of force.

Storm Surge

Storm surge is an elevated water level that exceeds the height of normal astronomical tides. It is most commonly associated with hurricanes, but also can be caused by extratropical cyclones (nor'easters). The height of a storm surge increases as atmospheric pressure decreases and a storm's maximum wind speed increases. Storm surge is especially significant where coastal topography and bathymetry (submarine topography) have shallow slopes and the coast has a narrowing shoreline that funnels the rising water. These factors are magnified when the storm remains stationary through several tide cycles and the affected coast is defined by low-lying barrier islands whose beaches and dunes have been eroded either by human development or by recent storms. Storm surge—together with astronomical high tide, rainfall, river flow, and storm surf—floods and batters structures and scours areas beneath foundations as much as 4-6 feet below the normal grade level. At one time, storm surge was the primary source of casualties in all countries, but inland flooding is now the primary cause of hurricanes deaths in the US. However, surge is still is the primary source of casualties in developing countries such as Bangladesh. In these countries, population pressure pushes the poor to farm highly vulnerable areas and poverty limits the development of dikes and seawalls, warning systems, evacuation transportation systems, and vertical shelters (wind resistant structures that are elevated above flood level).

Tsunamis

Tsunamis are commonly referred to as "tidal" waves but they are, in fact, sea waves that are usually generated by earthquakes. In addition, tsunamis can be caused by volcanic eruptions or landslides that usually, but not always, occur undersea. Tsunamis are rare events because 15,000 earthquakes over the course of a century have generated only 124 tsunamis, a rate of less than 1% of all earthquakes and only 0.7 tsunamis per year. This low rate of tsunami generation is attributable to earthquake intensity; two-thirds of all Pacific tsunamis are generated by shallow earthquakes exceeding 7.5 in magnitude.

Tsunamis can travel across thousands of miles of open ocean (e.g., from the Aleutians to Hawaii or from Chile to Japan) at speeds up to 400 mph in the open ocean, but they slow to 25 mph as they begin to break in shallow water and run up onto the land. Tsunamis are largely invisible in the open ocean because they are only 1-2 feet high. However, they have wave lengths up to 60 miles and periods as great as one hour. This contrasts significantly with ordinary ocean waves having wave heights up to 30 feet, wave lengths of about 500 feet, and periods of about 10 seconds. Tsunamis can have devastating effects in some of the places where they make landfall because the waves encounter bottom friction when the water depth is less than 1/20 of their wavelength. At this point, the bottom of the wave front slows and is

overtaken by the rest of the wave, which must rise over it. For example, when a wave reaches a depth of 330 feet, its speed is reduced from 400 mph to 60 mph. Later, reaching a depth of 154 feet reduces its speed to 44 mph. This causes the next 650 feet of the wave to overtake the wave front in a single second. As the wave continues shoreward, each succeeding segment of the wave must rise above the previous segment because it can't go down (water is not compressible) or back (the rest of the wave is pressing it forward). Because the wavelength is so long and wave speed is so fast, a large volume of water can pile up to a very great height—especially where the continental shelf is very narrow. It is important to note that the initial cue to tsunami arrival might be that the water level drops, rather than rises. Indeed, this was the case in the 2004 Indian Ocean tsunami. People's failure to understand the significance of the receding water contributed to a death toll exceeding 200,000. An initial *wave* is created only if the seafloor rises suddenly, whereas an initial *trough* is created if the seafloor drops. In either case, the initial phase will be followed by the alternate phase (i.e., a wave is followed by a trough or vice-versa).

Tsunamis threaten shorelines worldwide and have no known temporal (i.e., diurnal or seasonal) variation. If a tsunami is initiated locally (i.e., within a hundred miles), the potential for a tsunami can be detected by severe earthquake shaking. However, coastal residents' only physical cue to a remotely initiated tsunami is wave arrival at coast, although the arrival of a trough (making it appear that the tide went out unexpectedly) should be recognized as a danger sign. International tsunami warning systems base their detection of remote tsunamis on seismic monitoring to detect major earthquakes and tidal gauges located throughout the Pacific basin to verify tsunami generation. Once tsunami generation has been confirmed, alerts can be transmitted throughout the Pacific basin. The need for prompt action can be inferred from tsunami's forward movement speed; a tsunami generated 100 miles away from a coast can arrive in about 15 minutes.

The physical magnitude of a tsunami is extremely impressive. Wave crests can arrive at 10-45 minute intervals for up to six hours and the highest wave, as much as 100 ft at the shoreline, can be anywhere in the wave train. The area flooded by a tsunami is known as the inundation zone, which equivalent to a 100-year floodplain or hurricane storm surge risk area. Because of the complexities in accounting for wave behavior and the characteristics of the offshore bathymetry and onshore topography, tsunami inundation zones must be calculated by competent analysts using sophisticated computer programs. The physical impacts include casualties caused by deaths from drowning and traumatic injuries from wave impact. Property damage is caused by the same mechanisms.

Regarding protective measures, sheltering in-place in elevated structures can protect against surge. However, steel reinforced concrete structures on deep pilings are required to withstand wave battering and foundation scour. Consequently, evacuation to higher ground is the most effective method of population protection. Evacuation to a safe distance out of the runup zone is obviously difficult on low-lying coasts, but it also can be difficult where there are nearby hills if the primary evacuation route runs parallel to the coastline.

Geophysical Hazards

To properly understand geophysical hazards, it is important to recognize the earth's three distinct geological components. The *core* consists of molten rock at the center of the earth, the *crust* is solid rock and other materials at the earth's surface that vary in depth from four miles under the oceans to 40 miles in the Himalayas, and the *mantle* is an 1800 mile thick layer between the core and the crust. According to tectonic theory, the earth's crust is defined by large plates that float on the mantle and move gradually in

different directions over time.

Tectonic plates can diverge, converge, or move laterally past each other. When they diverge, new material is generated from below the earth's mantle, usually at mid-ocean ridges, that flows very slowly (at a rate of a few inches per year) away from the source. This process produces a gradual expansion of the plate toward an adjoining plate. Thus, one plate converges with another plate and the heavier material (a seafloor) is *subducted* under lighter material (a continent). In the US, this process is taking place in the Cascadian Zone along the Pacific coast of Washington, Oregon, and Northern California. Tectonic activity produces intermittent movement, which causes earthquakes and sometimes tsunamis. In addition, the subducted material travels to great depth within the earth where it is liquefied under intense heat and pressure. The resulting magma causes volcanic activity.

Crustal plates also move laterally past each other as, for example, the North American plate is moving northward past the Pacific Plate along the San Andreas fault. Friction can lock the fault and increases strain until it is released suddenly in an earthquake; the longer the fault is locked, the more energy is stored until it is released. Finally, there is some intraplate activity such as the mid-ocean "hot spots" that have formed the Hawaiian Islands and mid-continental fault zones. One US example is the New Madrid Seismic Zone affecting Missouri, Illinois, Indiana, Kentucky, Tennessee, Mississippi, and Arkansas.

These tectonic processes give rise to the most important geophysical hazards in the US—volcanic eruptions and earthquakes. However, landslides are another geophysical hazard that will also be addressed in this section.

Volcanic Eruptions

Volcanoes are formed when a column of magma (molten rock) rises from the earth's mantle into a magma chamber and later erupts at the surface, where it is called lava. Successive eruptions, deposited in layers of lava or ash, build a mountain. Major eruptions create craters that are gradually replaced in dome-building eruptions. Cataclysmic eruptions create calderas that leave only a depression where the mountain once stood. US volcanoes (recently erupted) are located principally in Alaska (92) and Hawaii (21), as well as along the west coast of the 48 contiguous states (73): Oregon has 22, California has 20, and Washington has 8. Vulcanologists distinguish among 20 different types of volcanoes that vary in the type of ejected material, size, shape, and other characteristics, but the two most important types of volcanoes are shield volcanoes and stratovolcanoes. Shield volcanoes produce relatively gentle *effusive* eruptions of low-viscosity lava, resulting in shallow slopes and broad bases (e.g., Kilauea, Hawaii). Stratovolcanoes produce *explosive* eruptions of highly acidic lava, gas, and ash, resulting in steep slopes and narrow bases. One well known stratovolcano is Mt. St. Helens, Washington, which erupted spectacularly in 1980 (see Perry & Greene, 1983; Perry & Lindell, 1990).

The principal threats from volcanoes include gases and tephra that are blasted into the air, pyroclastic flows that blast laterally from volcano flanks, and the heavier lava and lahars that generally travel downslope. Many gases are dangerous because they are heavier than air, so they accumulate in low-lying areas. Other than harmless water vapor (H₂O), some gases are simple asphyxiants that are dangerous because they displace atmospheric oxygen (carbon dioxide, CO₂; methane, CH₄). There are also chemical asphyxiants (carbon monoxide, CO) that are dangerous because they prevent the oxygen that is breathed in from reaching the body's tissues. In addition, there are corrosives (sulfur dioxide, SO₂; hydrogen sulfide, H₂S; hydrogen chloride, HCl; hydrogen fluoride, HF; and sulfuric acid, H₂SO₄) and radioactive gases (such as radon, Ra). Tephra consists of solid particles of rock ranging in size from

talcum powder (“ash”) to boulders (“bombs”). Pyroclastic flows are hot gas and ash mixtures (up to 1600°F) discharged from the crater vent. Lahars are mudflows and floods, usually from glacier snowmelt, with varying concentrations of ash. The impacts of volcanic eruption tend to be strongly directional because ashfall and gases disperse downwind; pyroclastic flows follow blast direction and lava and lahars travel downslope through drainage basins. The forward movement speed of the hazard varies. Gas and tephra movements are determined by wind speed, usually less than 25 mph. Pyroclastic flows can move at over 100 mph. Lava typically moves at walking speed (5 mph) but can travel faster (35 mph) on steep slopes. Lahars move at the speed of water flow, usually less than 25 mph, but can exceed 50 mph in some instances.

The physical magnitude of the hazard also differs for each specific threat. Inundation depths for ashfall and lahars can range up to tens of meters in depth. Lava flows and pyroclastic flows are so hot that any impact is considered to be unsurvivable. Similarly, the impact area also varies by threat. Tephra deposition depends on eruption magnitude, wind speed, and particle size, with traces of ash circling the globe. Lava flows, lahars, and pyroclastic flows follow localized drainage patterns, so safe locations can be found only a short distance from areas that are totally devastated. These considerations indicate volcano risk areas can be defined as listed in Table 5-5.

Table 5-5. Volcano Risk Areas.

Category	Name	Distance*	Threats
1	Extreme	0-100 m	High risk of heat, ash, lava, gases, rock falls, and projectiles
2	High	100-300 m	High risk of projectiles
3	Medium	300-3000 m	Medium risk of projectiles
4	Low	3 km – 10 km	Low risk of projectiles
5	Safe	> 10 km	Minimal risk of projectiles

* (In meters and kilometers; these distances do not include mudflows and floods that can travel up to 100 km or tsunamis that can travel thousands of km.)

Source: Adapted from < www.volcanodiscovery.com >

The physical impacts of a volcanic eruption vary with the type of threat. Gases can cause deaths and injuries from inhalation, but pyroclastic flows are more dangerous because they can cause deaths and injuries from blast, thermal exposure, and inhalation of gas and ash. In addition, they also can cause property damage from blast, heat, and coverage by ash (even after it has cooled). Tephra causes property damage from excess roof loading, shorting of electric circuits, clogged air filters in vehicles, and abrasion of machinery. Deaths and injuries can be caused by bomb impact trauma, and health effects can result from ash inhalation (including fluoride poisoning of grazing animals). Lava causes property damage from excess heat and coverage by rock (when cooled). Deaths and injuries from thermal exposure to lava can occur, but are rare because it moves so slowly. Lahars can cause property damage from flooding and coverage by ash (when water drains off) and deaths from drowning. Tsunamis cause property damage from wave impact and water saturation, as well as deaths from drowning and traumatic injuries. In addition, volcanic eruptions can cause tsunamis and wildfires as secondary hazards.

The threat of volcanic eruption can be detected by physical cues indicating rising magma. These include earthquake swarms, outgassing, ash and steam eruptions, and topological deformation (changes in slope, flank swelling). Appropriate protective measures include sweeping ash from building roofs and evacuating an area at least six miles in radius for a crater eruption and 12-18 miles in the direction of a flank/lateral eruption. People also should be evacuated from floodplains threatened by lahars. The

principal problem in implementing evacuations is that there are substantial uncertainties in the timing (onset and duration) of eruptions, so people have sometimes been forced to stay away from their homes and businesses for months at a time. In some cases, the expected eruption never did materialize, causing severe conflict among physical scientists, local civil officials, and disrupted residents.

Earthquakes

When an earthquake occurs, energy is released at the *hypocenter*, which is a point deep within the earth. However, the location of an earthquake is usually identified by a point on the earth's surface directly above the hypocenter known as the *epicenter*. Earthquake energy is carried by three different types of waves, P-waves, S-waves, and surface waves. P-waves, typically called primary waves but are more properly known as pressure waves, travel rapidly. By contrast, S-waves, typically called secondary waves but technically known as shear waves, travel more slowly but cause more damage. The third type, surface waves, includes Love waves and Rayleigh waves. These have very low frequency and are especially damaging to tall buildings.

The physical magnitude of an earthquake is different from its intensity. *Magnitude* is measured on a logarithmic scale where a one-unit increase represents a 10-fold increase in seismic wave amplitude and a 30-fold increase in energy release from the source. Thus, a M8.0 earthquake releases 900 (30 x 30) times as much energy as a M6.0 earthquake. By contrast, *intensity* measures the impact at a given location and can be assessed either by behavioral effects or physical measurements. The behavioral effects of earthquakes are classified by the Modified Mercalli Intensity Scale, which defines each category (see Table 5-6, column 1) in terms of its behavioral effects of earthquake motion on people, buildings, and objects in the physical environment (column 3). Physical measurements can be assessed in terms of average peak acceleration (column 4), which describe seismic forces in horizontal and vertical directions. This acceleration is measured either as the number of millimeters per second squared (mm/sec²) or as a multiple of the force of gravity ($g = 9.8$ meters/sec²)

The impact of an earthquake at a given point is determined by a number of factors. First, intensity decreases with distance from the epicenter, with slow attenuation along the fault line and more rapid attenuation perpendicular to the fault line. In addition, soft soil transmits energy waves much more readily than bedrock, and basins (loose fill surrounded by rock) focus energy waves. Thus, isoseismal contours (lines of constant seismic energy) can be extremely irregular, depending on fault direction and soil characteristics. The complex interplay of these factors can be seen in Figure 5-4, which displays the isoseismal contours (lines of equal seismic intensity) for the 1994 Northridge earthquake.

Within the impact area, the primary earthquake threats (mostly associated with plate boundaries) are ground shaking, surface faulting, and ground failure. Ground shaking creates lateral and upward motion in structures designed only for (downward) gravity loads. In addition, unreinforced structures respond poorly to tensile (upward stretching) and shear (lateral) forces, as do “soft-story” (e.g., buildings with pillars rather than walls on the ground floor) and asymmetric (e.g., L-shaped) structures. Moreover, high-rise buildings can demonstrate resonance, which is a tendency to sway in synchrony with the seismic waves, thus amplifying their effects.

Surface faulting—cracks in the earth's surface—is a widespread fear about earthquakes that actually is far less of a problem than popularly imagined. The vulnerability of buildings to surface faulting is easily avoided by zoning regulations that prevent building construction within 50 feet of a fault line. Unfortunately, zoning restrictions are infeasible for utility networks (water, wastewater, and fuel pipelines, electric power and communications lines, roads and railroads) that must cross the fault lines.

Table 5-6. Modified Mercalli Intensity (MMI) Scale for Earthquakes.

Category	Intensity	Type of Damage	Max. acceleration (mm/sec ²)
I	Instrumental	Detected only on seismographs	< 10
II	Feeble	Some people feel it	< 25
III	Slight	Felt by people resting; like a large truck rumbling by	< 50
IV	Moderate	Felt by people walking; loose objects rattle on shelves	< 100
V	Slightly strong	Sleepers awake; church bells ring	< 250
VI	Strong	Trees sway; suspended objects swing; objects fall off shelves	< 500
VII	Very strong	Mild alarm; walls crack; plaster falls	< 1000
VIII	Destructive	Moving cars uncontrollable; chimneys fall and masonry fractures; poorly constructed buildings damaged	< 2500
IX	Ruinous	Some houses collapse; ground cracks; pipes break open	< 5000
X	Disastrous	Ground cracks profusely; many buildings destroyed; liquefaction and landslides widespread	< 7500
XI	Very Disastrous	Most buildings and bridges collapse; roads, railways, pipes and cables destroyed; general triggering of other hazards	< 9800
XII	Catastrophic	Total destruction; trees driven from ground; ground rises and falls in waves	> 9800

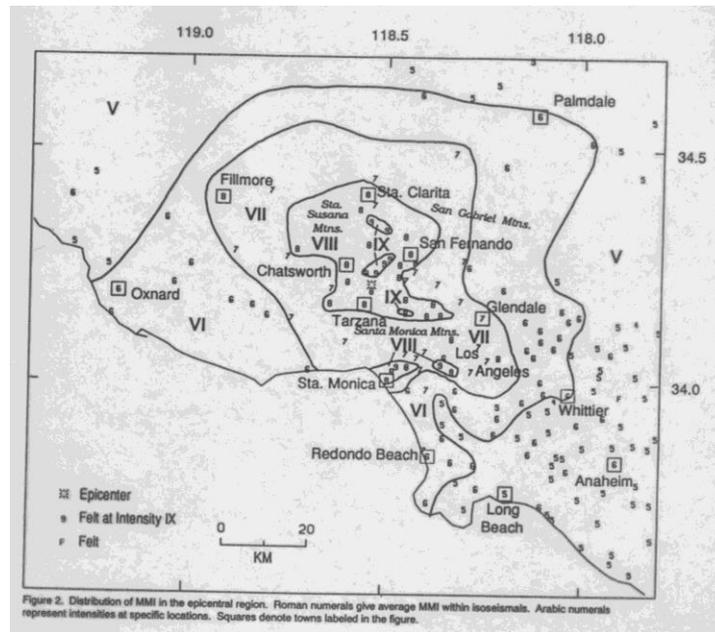
Source: Adapted from Bryant (1991).

Ground failure is defined by a loss of soil bearing strength and takes three different forms. Landsliding occurs when a marginally stable soil assumes a more natural angle of repose (a more detailed discussion is presented in the next section). Fissuring or differential settlement occurs when loose fill, which is very prone to compaction and consolidation, is located next to other soils that are less prone to this behavior. Finally, soil liquefaction is caused by loss of grain-to-grain support in saturated soils (e.g., where there is a high water table). Ground failure is a threat because building foundations need stable soil to support the rest of the structure. Even partial failure of the soil under the foundation can destroy a building by causing it to tilt at a dangerous angle.

Earthquakes also can cause major secondary threats such as tsunamis, dam failures, hazardous materials releases, and building fires. Tsunamis were addressed earlier, but dam failures can occur if ground shaking causes earth or rock dams to rupture or the valley walls abutting the dam to fail. Hazardous materials releases can occur if ground shaking causes containment tanks or pipes to break. Fires are caused by broken fuel and electric power lines that provide the necessary fuel and ignition sources. In addition, fire spread is promoted when broken water lines prevent fire departments from extinguishing the initial blazes.

As yet, there is no definitive evidence of physical cues that provide reliable forewarning of an imminent earthquake. Unusual animal behavior has been observed, but this has not proved to be a reliable indicator of an imminent earthquake. The Chinese successfully predicted an earthquake at Haicheng in 1975 and saved thousands of lives by evacuating the city. However, there was no forewarning of the 1976 earthquake at Tangchan. Currently, earth scientists are examining many potential predictors such as increased radon gas in wells, increased electrical conductivity and magnetic anomalies in soil, and topographic perturbations such as changes in ground elevation, slope, and location (“creep”). There were great expectations for short-term earthquake predictions 30 years ago, but seismologists currently give only probabilities of occurrence within long periods (5, 10, or 20 years).

Figure 5-4. Isoseismal Contours for the Northridge Earthquake.



Source: Adapted from Dewey, et al. (1994).

Very short term forewarning of earthquakes can sometimes be initiated by detection of the relatively harmless P-waves that arrive from distant earthquakes a few seconds before the arrival of the damaging S-waves and surface waves. Currently, however, there is no method of advance detection and warning for local earthquakes because these are so close to the impact area that P-waves and S-waves arrive almost simultaneously. Protective measures can be best understood by the common observation that “earthquakes don’t kill people, falling buildings (especially unreinforced masonry buildings) kill people”. Thus, building occupants are advised to shelter in-place under sturdy furniture while the ground is shaking. Those who survive the collapse of their buildings typically attempt to rescue those survivors who remain trapped, but the success of this improvised response depends upon the type of building. Unreinforced masonry buildings are much more likely to collapse, but search and rescue from these structures can be relatively easy. By contrast, steel-reinforced concrete buildings are much less likely to collapse, but search and rescue is extremely difficult unless sophisticated equipment is available to well-trained urban search and rescue teams. Unfortunately, almost all victims will die by the time remote urban search and rescue (USAR) teams arrive because crush injuries usually kill within 24 hours. However, USAR teams take longer than this to mobilize and travel to the incident site. Another problem with earthquakes is that destruction of infrastructure (electric power, fuel, water, wastewater, and telecommunications) impairs emergency response. Consequently, households, businesses, and local governments must be self-sufficient for at least 72 hours until outside assistance can arrive.

Landslides

The term *landslide* is often used to refer generically to a number of different physical phenomena involving the downward displacement of rock or soil that moves because of gravitational forces. *Slides* occur because a failure surface is created by two distinct soil strata and the upper stratum is displaced downslope. Some slides are triggered by earthquakes or volcanic eruptions. However, many are caused by heavy rainfall that saturates soil, increasing the weight of the upper surface and lubricating the failure

surface. *Debris flows* have such a high water content distributed throughout the soil mass that they act like a viscous (thick) fluid. *Lateral spreads* involve the outward movement of material on the sides and downward movement of material on the top of a soil mass. *Topples* and *falls* involve rock masses that detach from steep slopes and either tilt or fall free to a lower surface.

Slopes remain stable when shear stress is less than shear strength. Shear stress increases with the steepness of the slope and the weight placed on that slope. Shear strength depends upon the internal cohesion (interlocking or sticking) of soil particles and the internal friction of particles within a soil mass, which is reduced by soil saturation. Thus, landslides are most common in areas having steep slopes composed of susceptible soils types (i.e., ones with low internal cohesion) that are stratified (creating failure surfaces) and saturated with water. Slide probability is commonly increased by four different conditions. The first occurs when slopes have been cleared of vegetation, whereas the second occurs when excavations for houses and roads use the “cut and fill” method on unstable steep slopes. (This technique is used to create a level surface on a slope by cutting soil out of a section of hillside and using it to fill the area below this cut.) The third condition creating landslides occurs when the construction of many buildings and roads significantly increases the weight placed on the slope and the fourth condition occurs when construction of access roads removes support from the foot of the slope.

Landslide risk areas can be mapped by conducting geological surveys to identify areas having slopes with distinct soil strata that are likely to separate when saturated or shaken. Visible cues of imminent slides can also be seen at the head and toe of a potential slide area, which can be monitored to determine whether to take protective actions. These include installing slope drainage systems or retaining walls, and temporarily evacuating or permanently relocating the population at risk.

Technological Hazards

Hazardous materials (also known as *hazmat*) are regulated by a number of federal agencies including the US Department of Transportation, US Environmental Protection Agency, US Nuclear Regulatory Commission, and the Occupational Safety and Health Administration of the US Department of Labor. In addition, the US Coast Guard and Federal Emergency Management Agency of the US Department of Homeland Security have responsibilities for emergency response to hazmat incidents. Because these agencies have different responsibilities, they have correspondingly different definitions of hazmat. According to the Department of Transportation, hazmat is defined as substances that are “capable of posing unreasonable risk to health, safety, and property” (49CFR 171.8).

Until the late 1980s, the location, identity, and quantity of hazmat throughout the United States was generally undocumented. However, Title III of the Superfund Amendments and Reauthorization Act—SARA Title III (also known as the Emergency Planning and Community Right to Know Act—EPCRA) of 1986 required those who produce, handle, or store amounts exceeding statutory threshold planning quantities of approximately 400 Extremely Hazardous Substances (EHSs) to notify local agencies, their State Emergency Response Commission (SERC), and the US EPA. Nonetheless, the Chemical Abstract Service (CAS) lists 1.5 million chemical formulations with 63,000 of them hazardous. There are over 600,000 shipments of hazmat per day (100,000 of which are shipments of petroleum products). Fortunately, only a small proportion of these chemicals account for most of the number of shipments and the volume of materials shipped (see Table 5-7, adapted from Lindell & Perry, 1997a). These hazmat shipments result in an average of 280 liquid spills or gaseous releases per year, the vast majority of which occur in transport. Of these spills and releases, 81% take place on the highway and

15% are in rail transportation. These incidents cause approximately 11 deaths and 311 injuries per year.

Table 5-7. Volume of production for top 12 EHSs, 1970–1994.

Rank in top 50	Chemical name	Year				% increase 1970-1994
		1970	1980	1990	1994	
1	Sulfuric acid	29,525	44,157	44,337	44,599	51
8	Ammonia	13,824	19,653	17,003	17,965	30
10	Chlorine	9,764	11,421	11,809	12,098	24
13	Nitric acid	7,603	9,232	7,931	8,824	16
23	Formaldehyde	2,214	2,778	3,360	4,277	93
25	Ethylene oxide	1,933	2,810	2,678	3,391	75
31	Phenol	854	1,284	1,769	2,026	137
33	Butadiene	1,551	1,400	1,544	1,713	10
34	Propylene oxide	590	884	1,483	1,888	220
36	Acrylonitrile	520	915	1,338	1,543	197
37	Vinyl acetate	402	961	1,330	1,509	275
47	Aniline	199	330	495	632	218

Source: Adapted from Lindell and Perry (1997a).

Emergency managers typically expect to find hazmat produced, stored, or used at fixed-site facilities such as petrochemical and manufacturing plants. However, such materials are also found in facilities as diverse as warehouses (e.g., agricultural fertilizers and pesticides), water treatment plants (chlorine is used to purify the water), and breweries (ammonia is used as a refrigerant). Hazmat is transported by a variety of modes—ship, barge, pipeline, rail, truck, and air. In general, the quantities of hazmat on ships, barges, and pipelines can be as large as those at many fixed site facilities, but quantities usually are smaller when transported by rail, smaller still when transported by truck, and smallest when transported by air. Small to moderate size releases of less hazardous materials at fixed site facilities are occupational hazards but often pose little risk to public health and safety because the risk area lies within the facility boundary lines. However, releases of this size during hazmat transportation are frequently a public hazard because passers-by can easily enter the risk area and become exposed. The amount that is actually released is often much smaller than the total quantity that is available in the container but prudence dictates that the planning process assume the plausible worst case of complete release within a short period of time (e.g., 10 minutes in the case of toxic gases, see US Environmental Protection Agency, 1987). In addition to the quantity of the hazmat released, the size of the risk area depends upon its chemical and physical properties.

The US DOT groups hazmat into nine different classes—explosives, gases, flammable liquids, flammable solids, oxidizers and organic peroxides, toxic (poisonous) materials and infectious substances, radioactive materials, corrosive materials, and miscellaneous dangerous goods. Each of these hazmat classes is described in the remainder of this section. It is important to be aware that classification of a substance into one of these categories does not mean it cannot be a member of another class. For example, hydrogen sulfide is transported as a compressed gas that is both toxic and flammable.

Explosives are chemical compounds or mixtures that undergo a very rapid chemical transformation (faster than the speed of sound) generating a release of large quantities of heat and gas. For example, one volume of nitroglycerin expands to 10,000 volumes when it explodes; it is this rapid increase in volume that creates the surge in pressure characteristic of a blast wave. Explosives vary in their sensitivity to heat and impact. Class A consists of high explosives that *detonate* (up to 4 mi/sec),

producing overpressure, fire, and missile hazards. Class B consists of low explosives that *deflagrate* (approximately .17 mi/sec—about 4% as fast as a detonation) and cause fires and flying debris (usually referred to as missile hazards). Class C consists of low explosives that are fire hazards only. Explosives can cause casualties and property damage due to overpressure from atmospheric blast waves or missile hazards. Destructive effects from the quantities of explosives found in transportation can be felt as much as a mile or more away from the incident site.

Compressed gases are divided into flammable and nonflammable gases. Nonflammable gases—such as carbon dioxide, helium, and nitrogen—are usually transported in small quantities. These are a significant hazard only if the cylinder valve is broken, causing the contents to escape rapidly through the opening and the container to become a missile hazard. Flammable gases (acetylene, hydrogen, methane) are missile and fire hazards. Rupture of gas containers can launch missiles up to a mile, so evacuation out to this distance is advised if there is a fire. Large quantities of flammable gases, such as railcars of liquefied petroleum gas (LPG), are of significant concern because the released gas will travel downwind after release until it reaches an ignition source such as the pilot light in a water heater or the ignition system in a car. At distances of one-half mile or more, the gas cloud can erupt in a fireball that flashes back toward the release point. Emergency managers need to understand the community-wide hazards associated with fires arising from flammable gases. Consequently, this topic is discussed in greater detail later in this chapter.

Flammable liquids, which evolve flammable vapors at 80°F or less, pose a threat similar to flammable gases. A volatile liquid such as gasoline rapidly produces large quantities of vapor that can travel toward an ignition source and erupt in flame when it is reached. When a flammable liquid is spilled on land, there should be a downwind evacuation of at least 300 yards. A flammable liquid that floats downstream on water could be dangerous at even greater distances and one that is toxic requires special consideration (see the section on toxic chemicals, below). A fire involving a flammable liquid should stimulate consideration of an evacuation of 800 yards in all directions.

Flammable solids self-ignite through friction, absorption of moisture, or spontaneous chemical changes such as residual heat from manufacturing. Flammable solids are somewhat less dangerous than flammable gases or liquids, because they do not disperse over wide areas as gases and liquids do. A large spill requires a downwind evacuation of 100 yards, but a fire should stimulate consideration of an evacuation of 800 yards in all directions.

Oxidizers and organic peroxides include halogens (e.g., chlorine and fluorine), peroxides (e.g., hydrogen peroxide and benzoyl peroxide), and hypochlorites. These chemicals destroy metals and organic substances and also enhance the ignition of combustibles (a spill of liquid oxygen can cause the ignition of asphalt roads on a hot summer day). Oxidizers and organic peroxides do not burn, but are hazardous because they promote combustion and some are shock sensitive. A large spill should prompt a downwind evacuation of 500 yards and a fire should initiate an evacuation of 800 yards in all directions.

Toxic chemicals, which can have large impact areas, are classified in a number of ways. DOT Class 2 consists of nonflammable gases and Class 6 is defined as poisons. Class A includes gases and vapors, a small amount of which is an inhalation hazard, whereas Class B consists of liquids or solids that are ingestion or absorption hazards. Many of these chemicals are defined by SARA Title III/EPCRA as EHSs. Toxic materials are a major hazard because of the effects they can produce when inhaled into the lungs, ingested into the stomach by means of contaminated water or food, or absorbed through the skin by direct contact. Of these exposure pathways, inhalation hazard is typically the greatest concern because

high concentrations achieved during acute exposure can kill in a matter of seconds. Nonetheless, prolonged ingestion can cause cancers in those who are exposed and also can cause genetic defects in their offspring. Moreover, chemical contamination of victims poses problems for volunteers and professionals providing first aid and transporting victims to hospitals. These chemicals vary substantially in their volatility and toxicity, so evacuation distances following a spill or fire must be determined from the Table of Protective Action Distances in the *Emergency Response Guidebook* (US Department of Transportation, 2000, see www.dot.gov). Emergency managers need to understand the community-wide hazards that could result from a toxic chemical release. Consequently, this topic is discussed in greater detail later in this chapter.

Infectious substances have rarely been a significant threat to date because there are relatively few shipments of these substances, they usually are transported in small quantities, and they have restrictive requirements for packaging and marking. However, infectious substances have the potential to be used in terrorist attacks, so emergency managers should be knowledgeable about them. This topic is discussed in greater detail in the section on biological hazards.

Radioactive materials are substances that undergo spontaneous decay, emitting ionizing radiation in the process. The types and quantities of materials transported in the US generally have very small impact areas. With the exception of nuclear power plants, for which planning is supported by state and federal agencies and electric utilities, releases of radioactive materials are likely to involve small quantities. Nonetheless, even a few grams of a lost radiographic source for industrial or medical X-rays can generate a high level of public concern. Here also, the recently recognized threat of terrorist attack from a “dirty bomb” that uses a conventional explosive to scatter radioactive material over a wide area deserves emergency managers’ attention because of the potential for long-term contamination of central business districts. A large spill should prompt a downwind evacuation of 100 yards and a fire should initiate an evacuation of 300 yards in all directions. Emergency managers need to understand the community-wide hazards that could arise from a release of radioactive materials. Consequently, this topic is discussed in greater detail later in this chapter.

Corrosives, which are substances that destroy living tissue at the point of contact, can be either acidic or alkaline. Examples of acids include hydrochloric acid (HCl) and sulfuric acid (H₂SO₄), whereas examples of alkaline substances (caustics) include sodium hydroxide (NaOH), potassium hydroxide (KOH), and ammonia (NH₃). In addition to producing chemical burns of human and animal tissues, corrosives also degrade metals and plastics. The most frequently used and transported substances in this class are not highly volatile, so the geographical area affected by a spill is likely to be no greater than 100 yards unless the container is involved in a fire or the hazmat enters a waterway (e.g., via storm sewers). These chemicals vary substantially in volatility and toxicity, so evacuation distances following a spill or fire must be determined from the Table of Protective Action Distances in the *Emergency Response Guidebook*.

Miscellaneous dangerous goods, as the name of this category suggests, this class comprises a diverse set of materials such as air bags, certain vegetable oils, polychlorinated biphenyls (PCBs), and white asbestos. Materials in this category are low to moderate fire or health hazards to people within 10-25 yards.

Fires

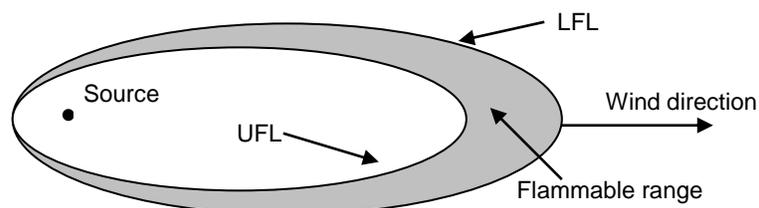
Flammable materials support rapid oxidization that produces heat and affects biological systems by thermal radiation (burns). As noted earlier in the section on wildfires, combustion requires the three

elements of the fire triangle: *fuel*, which is any substance that will burn; *oxygen* that will combine with the fuel; and enough *heat* to ignite the fuel. Combustion usually yields enough heat to sustain the combustion reaction, but it also produces combustion products that might be more dangerous than the heat. Combustion of simple hydrocarbons or alcohols as fuels generally yields carbon dioxide, carbon monoxide, water vapor, and unburned vapors of the fuel as combustion products. More complex and heavier substances such as pesticides also yield carbon dioxide, carbon monoxide, water vapor, and unburned vapors of the fuel. However, they also produce highly toxic chemicals. It can be very difficult to predict what will be the combustion products from a building fire (e.g., an agricultural warehouse) because the temperature of the fire is variable over time and from one location to another in the fire, and the chemicals reacting with each other often are variable over time and from one location to another in the fire.

In understanding combustion, it is important to recognize an important distinction between gases and liquids. A gas is a substance that, at normal temperatures and pressures, will expand to fill the available volume in a space. By contrast, a liquid is a substance that, at normal temperatures and pressures, will spread to cover the available area on a surface. Any liquid contains some molecules that are in a gaseous state; this is called vapor. All liquids generate increasing amounts of vapor as the temperature increases and the pressure decreases. Conversely, at a given temperature and pressure, the amount of vapor in a liquid varies from one substance to another. There are three temperatures of each flammable liquid that are important because they determine the production of vapor. In turn, vapor generation is important because *it is the vapor that burns, not the liquid*. The three important temperatures of a liquid substance are its boiling point, flash point, and ignition temperature. The boiling point is the temperature of a liquid at which its vapor pressure is equal to atmospheric pressure. Vapor production is negligible when a fuel is below its boiling point but increases significantly once it exceeds this temperature. The flash point of a liquid is the temperature at which it gives off enough vapor to flash momentarily when ignited by a spark or flame. A liquid is defined as combustible if it has a flash point above 100°F. (e.g., kerosene) and flammable if it has a flash point below 100° F. (e.g., gasoline). The final temperature to understand is the ignition temperature, which is the minimum temperature at which a substance becomes so hot that its vapor will ignite even in the absence of an external spark or flame.

Gases and vapors have flammable limits that are defined by the concentration (percent by volume in air) at which ignition can occur in open air or an explosion can occur in a confined space. The lower flammable/explosive limit (LFL/LEL) is the minimum concentration at which ignition will occur. Below that limit the fuel/air mixture is “too lean” to burn. The upper flammable/explosive limit (UFL/UEL) is the maximum concentration at which ignition will occur. Above that limit the fuel/air mixture is “too rich” to burn. When released from a source, a flammable gas or vapor disperses in an approximately circular pattern if there is no wind but in an approximately elliptical pattern in the normal situation in which the wind is blowing (see Figure 5-5).

Figure 5-5. Flammable Plume.



The most dangerous flammable substances have a low ignition temperature, low LEL, and wide flammable range. Indeed, gasoline is widely used precisely because of these characteristics. It has a low flash point (−45 to −36°F), a low LFL (1.4-1.5%), and a reasonably wide range (6%). By contrast, peanut oil is useful in cooking because it has the opposite characteristics—a high flash point (540°F) and an undefined LFL because it does not vaporize.

An important hazard of flammable liquids is a *Boiling Liquid Expanding Vapor Explosion* (BLEVE), which occurs when a container fails at the same time as the temperature of the contained liquid exceeds its boiling point at normal atmospheric pressure. BLEVEs involve flammable or combustible compressed gases that are not classified as “explosive substances”, but can produce fireballs as large as 1000 feet in diameter and launch shrapnel to distances up to one half mile from the source.

Toxic Industrial Chemical Releases

Toxic industrial chemical releases are of special concern to emergency managers because the airborne dispersion of these chemicals can produce lethal inhalation exposures at distances as great as 10 miles and sometimes even more. The spread of a toxic chemical release can be defined by a dispersion model that includes the hazmat’s chemical and physical characteristics, its release characteristics, the topographic conditions in the release area, and the meteorological conditions at the time of the release. The chemical and physical characteristics of the hazmat include its quantity (measured by the total weight of the hazmat released), volatility (as noted earlier, higher volatility means more chemical becomes airborne per unit of time), buoyancy (whether it tends to flow into low spots because it is heavier than air), and toxicity (the biological effect due to cumulative dose or peak concentration). It also includes the chemical’s physical state—whether it is a solid, liquid (remember, a substance above its boiling point is a vapor), or a gas at ambient temperature and pressure. In general, vapors and gases are major hazards because they are readily inhaled and this is the most rapid path into the body.

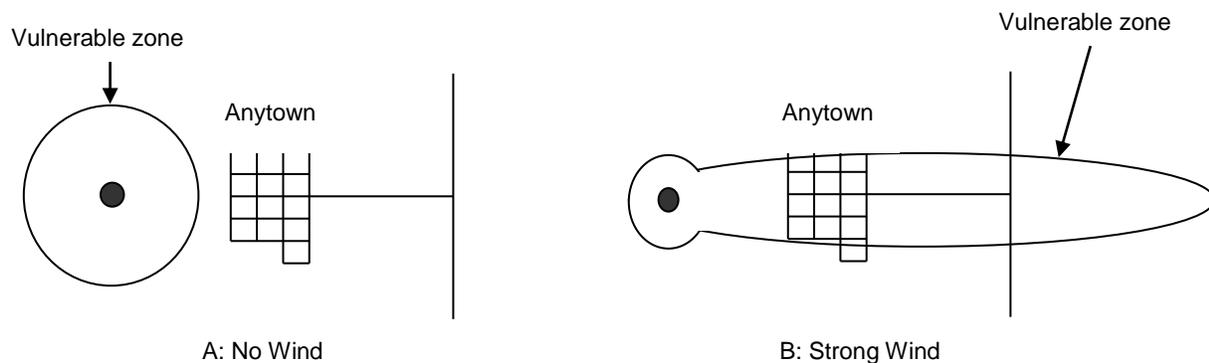
Release characteristics are defined by the chemical’s temperature and pressure in relation to ambient conditions, its release rate (in pounds per minute), and the size (surface area) of the spilled pool if the substance is a liquid. Temperature and pressure are important because the rate at which the chemical disperses in the atmosphere increases when these parameters exceed ambient conditions. The release rate is important because it determines the concentration of the chemical in the atmosphere. Specifically, a higher release rate puts a larger volume of chemical into a given volume of air, thus increasing its concentration (where the latter is defined as the volume of chemical divided by the volume of air in which it is located).

Topographical conditions relevant to liquid spills include the slope of the ground and the presence of depressions. As is the case with flooding, steep slopes allow a liquid to rapidly move away from the location of the spill. Both flat slopes and depressions decrease the size of a liquid pool which, in turn, affects the size of the pool’s surface area and reduces the rate at which vapor is generated from it. Thus, dikes are erected around chemical tanks to confine spills in case the tanks leak and hazmat responders build temporary dikes around spills for the same reason. Topographical characteristics also affect the dispersion of a chemical release in the atmosphere. Hills and valleys are land features that channel the wind direction and can increase wind speed at constriction points—for example, where a valley narrows and causes wind speed to increase due to a “funnel” effect. Forests and buildings are rough surfaces that increase turbulence in the wind field, causing greater vertical mixing. By contrast, large water bodies have very smooth surfaces that do not constrain wind direction and, because they provide no wind turbulence, allow a chemical release to maintain a high concentration at ground level where it is most dangerous to

people nearby.

The immediate meteorological conditions of concern during a hazmat release are wind speed, wind direction, and atmospheric stability class. The effect of wind speed on atmospheric dispersion can be seen in Figure 5-6, which shows a release dispersing uniformly in all directions when there is no wind (Panel A). Thus, the plume isopleth (contour of constant chemical concentration) corresponding to the Level of Concern (LOC) for this chemical is a circle. The nearby town lies outside the vulnerable zone so its inhabitants would not need to take protective action. However, Panel B describes the situation in which there is a strong wind, so the plume isopleth corresponding to the LOC for this chemical takes the shape of an ellipse. In this case, the nearby town lies inside the vulnerable zone and would need to take protective action.

Figure 5-6. Effects of Wind Speed on Plume Dispersion.



As Table 5-8 indicates, the atmospheric stability class can vary from Class A through Class F. Class A, the most unstable condition, occurs during strong sunlight (e.g., midday) and light wind. This dilutes the released chemical by mixing it into a larger volume of air. Class F identifies the most stable atmospheric conditions, which take place during clear nighttime hours when there is a light wind. These conditions have very little vertical mixing, so the released chemical remains highly concentrated at ground level.

Table 5-8. Atmospheric Stability Classes.

Surface Wind Speed (mph)	Strength of sunlight			Nighttime conditions	
	Strong	Moderate	Slight	Overcast \geq 50%	Overcast < 50%
< 4.5	A	A-B	B	-	-
4.5-6.7	A-B	B	C	E	F
6.7-11.2	B	B-C	C	D	E
11.2-13.4	C	C-D	D	D	D
>13.4	C	D	D	D	D

A: Extremely Unstable Conditions
 B: Moderately Unstable Conditions
 C: Slightly Unstable Conditions

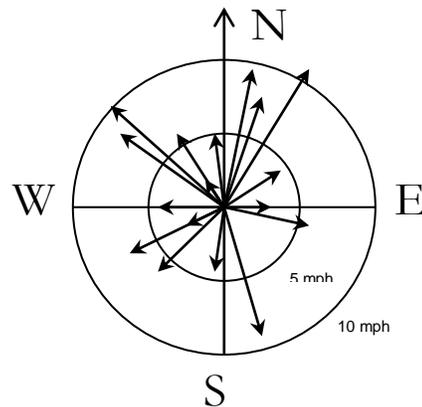
D: Neutral Conditions (heavy overcast day or night)
 E: Slightly Stable Conditions
 F: Moderately Stable Conditions

Source: Adapted from FEMA, DOT, EPA (no date, a).

It is important to recognize that meteorological characteristics can sometimes remain stable for days at a time, but at other times can change from one hour to the next. Figure 5-7, adapted from

McKenna (2000), displays the wind direction at each hour during the day of the accident at the Three Mile Island (TMI) nuclear power plant in terms of the orientation of an arrow. Wind speed is indicated by the length of the arrow. The figure shows wind speed and direction changed repeatedly during the course of the accident, so any recommendation to evacuate the area downwind from the plant would have referred to different geographic areas at different times during the day. This would have made evacuation recommendations extremely problematic because the time required to evacuate these areas would have taken many hours. Consequently, the evacuation of one area would have still been in progress when the order to initiate an evacuation in a very different direction was initiated.

Figure 5-7. Wind Rose from 3:00 a.m. to 6:00 p.m. on the First Day of the TMI Accident.



Source: Adapted from McKenna (2000).

The ultimate concern in emergency management is the protection of the population at risk. The risk to this target population varies inversely with distance from the source of the release. Specifically, the concentration (C) of a hazardous material decreases with distance (d) according to the inverse square law (i.e., $C = 1/d^2$). However, distance is not the only factor that should be of concern. In addition, the density of the population should be considered because a greater number of persons per unit area increases risk area population. Moreover, there might be differences in susceptibility within the risk area population because individuals differ in their dose-response relationships as a function of age (the youngest and oldest tend to be the most susceptible) and physical condition (those with compromised immune systems are the most susceptible).

Toxic chemicals differ in their exposure pathways—inhalation, ingestion, and absorption. Inhalation is the means by which entry into the lungs is achieved. This is generally a major concern because toxic materials can pass rapidly through lungs to bloodstream and on to specific organs within minutes of the time that exposure begins. Ingestion is of less immediate concern because entry through the mouth into the digestive system (stomach and intestines) is a slower route into the bloodstream and on to specific organs. Depending on the chemical's concentration and toxicity, ingestion exposures might be able to be tolerated for days or months. Authorities might choose to prevent ingestion exposures by withholding contaminated food from the market or recommending that those in the risk area drink boiled or bottled water. Absorption involves entry directly through the pores of the skin (or through the eyes), so it is more likely to be a concern for first responders than for local residents. Nonetheless, some chemicals can affect local populations in this way, as was the case with the release of methyl isocyanate during the accident in Bhopal, India, in 1984.

The harmful effects of toxic chemicals are caused by alteration of cellular functions (cell damage or death), which can be either acute or chronic in nature. Acute effects occur during the time period from 0–48 hours. Irritants cause chemical burns (dehydration and exothermic reactions with cell tissue). Asphyxiants are of two types; simple asphyxiants such as carbon dioxide (CO₂) displace oxygen (O₂) within a confined space or are heavier than oxygen so they displace it in low-lying areas such as ditches. By contrast, chemical asphyxiants prevent the body from using the oxygen even if it is available in the atmosphere. For example, carbon monoxide (CO) combines with the hemoglobin in red blood cells more readily than does O₂ so the CO prevents the body from obtaining the available O₂ in the air. Anesthetics/narcotics depress the central nervous system and, in extreme cases, suppress autonomic responses such as breathing and heart function.

Chronic, or long-term, effects can be general cell toxins, known as cytotoxins, or have organ specific toxic effects. In the latter case, the word *toxin* is preceded by a prefix referring to the specific system affected. Consequently, toxins affecting the circulatory system are called hemotoxins, those affecting the liver are hepatotoxins, those affecting the kidneys are nephrotoxins, and those affecting the nervous system referred to as neurotoxins. Other chronic effects of toxic chemicals are to cause cancers, so these chemicals are referred to as carcinogens. Mutagens cause mutations in those directly exposed, whereas teratogens cause mutations to the genetic material of those directly exposed and, thus, mutations in their offspring. The severity of any toxic effect is generally due to a chemical's rate and extent of absorption into the bloodstream, its rate and extent of transformation into breakdown products, and its rate and extent of excretion of the chemical and its breakdown products from the body (i.e., the substances into which the chemical decomposes).

Research on toxic chemicals has led to the development of dose limits. Some important concepts in defining dose limits are the LD-50, which is the dose (usually of a liquid or solid) that is lethal to half of those exposed, and the LC-50, which is the concentration (usually of a gas) that is lethal to half of those exposed. Based upon these dose levels, authoritative sources have devised dose limits that are administrative quantities that should not be exceeded. LOCs are values provided by EPA indicating the *Level of Concern* or “concentration of an EHS [Extremely Hazardous Substance] above which there may be serious irreversible health effects or death as a result of a single exposure for a relatively short period of time” (US Environmental Protection Agency, 1987, p. XX). IDLHs are values provided by NIOSH/OSHA indicating the concentration of a gas that is *Immediately Dangerous to Life or Health* for those exposed more than 30 minutes. TLVs are *Threshold Limit Values*, which are the amounts that the American Conference of Government Industrial Hygienists has determined that a healthy person can be exposed to 8–10 hours/day, 5 days/week throughout the work life without adverse effects.

Weaponized Toxic Chemicals

Although it seems plausible that a deliberate attack might use explosives to cause release toxic chemicals from a domestic source such as a chemical plant, rail car, or tank truck, it also is possible that a weaponized toxic agent might be used. Such agents were originally used by the military in battles dating back to World War I. Over the years, attention turned to increasingly toxic chemicals that, by their very nature, require smaller doses to achieve a significant effect (e.g., disability or death). One consequence of the more advanced toxic agents is that they can affect victims through absorption in secondary *contamination*. That is, chemical residues on a victim's skin or clothing can affect those who handle that individual. Indeed, any object on which the chemical is deposited becomes an avenue of secondary contamination (World Health Organization, 2004). A list of the most likely weaponized toxic agents is

presented in Table 5-9. Some of these agents are produced by biological processes (botulism, anthrax, and encephalitis) that affect victims through the production of toxins and, thus, are more properly considered to be chemical weapons (World Health Organization, 2004).

Table 5-9. Weaponized Toxic Agents.

Agent	Example
Tear gases/other sensory irritants	Oleoresin capsicum (“pepper spray”)
Choking agents (lung irritants)	Phosgene
Blood gases	Hydrogen cyanide
Vesicants (blister gases)	Mustard gas
Nerve gases	O-Isopropyl Methylphosphonofluoridate (Sarin gas)
Toxins	Clostridium botulinum (“botulism”)
Bacteria and rickettsiae	Bacillus anthracis (“anthrax”)
Viruses	Equine encephalitis

Source: Adapted from World Health Organization (2004)

A terrorist attack involving a toxic chemical agent might be detected initially by fire, police, or emergency medical services personnel responding to a report of a mass casualty incident. Likely symptoms include headache, nausea, breathing difficulty, convulsions, or sudden death—especially when these symptoms are displayed by a large number of people in the same place at the same time. In this case, the appropriate response will be the same as in any other hazardous materials incident. Specifically, there will be a need to control access to the incident site, decontaminate the victims as needed, and transport them for definitive medical care. In addition to the normal coordination with emergency medical services and hospital personnel, it is appropriate for emergency managers to be aware of the assistance that is available from local poison control centers. Other than that, the capabilities needed to respond effectively to an attack using toxic chemicals will be much the same as those needed for an industrial accident involving these materials (World Health Organization, 2004). Unfortunately, few communities—even those with a significant number of chemical facilities—have hospitals with the capability to handle mass casualties from toxic chemical exposure caused by either an industrial accident or a terrorist attack.

In the event of a terrorist attack, emergency managers will need to deal with a consideration that is not encountered in most other incidents to which they respond. Specifically, the incident site will be considered a crime scene by law enforcement authorities. Consequently, emergency managers must learn about the basic procedures these personnel will follow, including collecting evidence, maintaining a chain of custody over that evidence, and controlling access to the incident scene. This latter issue should be carefully coordinated to avoid a conflict between emergency management procedures for victim rescue and law enforcement procedures for crime scene security.

Radiological Material Releases

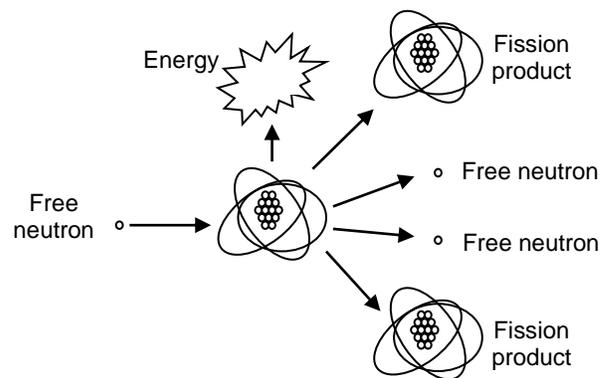
There are 123 nuclear power plants in the US, most of which are located in Northeast, Southeast, and Midwest. To understand the radiological hazards of these plants, it is necessary to understand the *atomic fission reaction*. The atoms of chemical elements consist of positively charged protons and neutrally charged neutrons in the atom’s nucleus, together with negatively charged electrons orbiting around the nucleus. Some unstable chemical elements undergo a process of spontaneous decay in which a single atom divides into two less massive atoms (known as fission products) while emitting energy in the form of heat and ionizing radiation. The ionizing radiation can take the form of alpha, beta, or gamma radiation. Alpha radiation can travel only a very short distance and is easily blocked by a sheet of paper

but is dangerous when inhaled (e.g., Pu-plutonium). Beta radiation can travel a moderate distance but be blocked by a sheet of aluminum foil. Gamma radiation can travel a long distance and can be blocked only by very dense substances such as stone, concrete, and lead.

Radioactive materials are used for a variety of purposes. Small quantities of some materials are used as sources of radiation for medical and industrial diagnostic purposes (e.g., imaging fractured bones and faulty welds). Large quantities of other radiological materials are used as sources of heat to produce the steam needed to drive electric generators at power plants. In these nuclear power plants, enriched uranium fuel fissions when struck by a free neutron (see Figure 5-8). The thermal energy released is used to heat water and, thus, produce steam. The free neutrons are used to continue a sustained chain reaction and the fission products are waste products that must eventually be disposed in a permanent repository.

The fuel temperature is controlled by cooling water and the reaction rate is controlled by neutron absorbing rods. The amount of fission products increases with age, so the reactor is refueled by moving the fuel in stages toward the center of the reactor vessel. Spent fuel, which contains a significant amount of radioactive fission products and some uranium, is stored onsite until transfer to a repository. The nuclear fuel is located in the plant's reactor coolant system (RCS), where it is contained in fuel pins that are welded shut and inserted into long rods that are integrated into assemblies. Cooling water is pumped into the reactor vessel where it circulates, picks up heat (and small amounts of radioactive fission products) from the fuel, and flows out of the reactor vessel.

Figure 5-8. The Atomic Fission Reaction.



There are two types of RCSs, Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs). In PWRs, the core coolant water is pressurized (the pressurizer is a device used to control the pressure in the reactor vessel) to prevent it from boiling. The hot water passes through a heat exchanger (called the steam generator), gives up its heat, and returns to the reactor vessel, completing the primary coolant system. The water in the secondary coolant system is allowed to boil, producing steam in the steam generator. In BWRs, the core coolant water is allowed to boil, generating steam directly. The steam is delivered to the turbine, spinning it to make electricity. The RCS is located in a containment building (the turbine is in an adjacent building), which is constructed with thick walls of steel-reinforced concrete to withstand high internal pressures or external missile impact. However, it has many penetrations for water pipes, steam pipes and instrumentation and control cables. These penetrations are sealed during normal operations, but the seals could be damaged during an accident that allows radioactive material to escape from the containment building into the environment.

During a severe accident involving irreversible loss of coolant, the fuel will first melt through the steel cladding, then melt through the RCS, and finally escape the containment building (probably through a basemat melt-through or steam explosion). This process could produce a release as soon as 45-90 minutes after core uncover. If the core melts, the danger to offsite locations depends upon containment integrity. Early health effects are likely if there is early total containment failure and are possible if there is early major containment leakage. Otherwise, early health effects are unlikely. The problem is that containment failure might not be predictable (McKenna, 2001).

A radioactive release would involve a mix of radionuclides (i.e., a variety of radioactive substances that vary in their atomic weight) and this mix is called the *source term*. The source term is defined by three classes of radionuclides—particulates, radioiodine, and noble gases. Particulates include uranium (U) and strontium (Sr), the latter of which is dangerous because it is chemically similar to calcium (Ca) and therefore tends to be deposited in bone marrow. Radioiodine (I-131) is dangerous because it substitutes for nonradioactive iodine in the thyroid and, thus, can cause thyroid cancer. Noble gases such as krypton (Kr) do not react chemically with anything, but are easily inhaled to produce radiation exposures while they remain in the lungs.

The source term is also characterized by its volatility. As noted in connection with toxic chemicals, volatility is an important characteristic of a substance because higher volatility means more of the radionuclide becomes airborne per unit of time and stays airborne. The quantity of radioactivity released can be measured in terms of the number of pounds or kilograms, but this is not a very useful measure because two different source terms with the same mass might emit very different levels of radiation. Consequently, the amount of radioactivity (ionizing radiation) released is measured by the number of disintegrations per unit time (Curies). In fact, these disintegrations are what a Geiger counter measures. The amount of radioactivity is usually measured in curies of an individual radionuclide or class of radionuclides.

Exposure pathways for radiological materials are similar to those of toxic chemicals. Breathing air that is contaminated with radioactive materials can cause inhalation exposure and eating food (e.g., unwashed local produce) or drinking liquids (e.g., water or milk) that is contaminated can cause ingestion exposure. Contamination also can enter the body through an open wound such as a compound fracture, laceration, or abrasion, but radiological materials do not cause absorption exposures because they do not pass through the skin. However, because radiological materials release energy, they can produce exposures via direct radiation (also known as “shine”) from a plume that is passing overhead. If the plume has a significant component of particulates, these might be deposited on the ground, vegetation, vehicles, or buildings and the direct radiation from the deposited particulates would produce a continuing exposure. In some cases, the small particles of deposited material could become resuspended and inhaled or ingested. In this connection, it is important to recognize the distinction between irradiation and contamination. Irradiation involves the transmission of energy to a target that absorbs it, whereas contamination occurs when radioactive particles are deposited in a location within the body where they provide continuing irradiation.

Measuring radiation dose is somewhat more complicated than measuring doses of toxic chemicals. As noted earlier, a Curie is a measure of the activity of a radioactive source in atomic disintegrations/second, whereas a Roentgen is a measure of exposure to ionizing radiation. A rad is a measure of absorbed dose, and a rem (“Roentgen equivalent man”) is a measure of committed dose equivalent. The term *committed* refers to the fact that contamination by radioactive material on the skin or

absorbed into the body will continue to administer a dose until it decays or is removed. The term *equivalent* refers to the fact that there are differences in the biological effects of alpha, beta, and gamma radiation. Weighting factors are used to make adjustments for the biological effects of the different types of radiation. However, for offsite emergency planning purposes, one rem is approximately equal to one rad.

The health effects of exposure to ionizing radiation are defined as early fatalities, prodromal effects, and delayed effects. Early fatalities occur within a period of days or weeks and are readily interpreted as effects of radiation exposure. Early fatalities begin to appear at whole body absorbed doses of 140 rad (which is equal to 1.4 Gray, the new international scientific unit) but less than 5% of the population would be expected to die from such exposures. Approximately 50% of an exposed population would be expected to die from a whole body dose of 300 rad and 95% would be expected to die from a dose of 460 rad.

Prodromal effects are early symptoms of more serious health effects (e.g., abnormal skin redness, loss of appetite, nausea, diarrhea, nonmalignant skin damage), whereas delayed effects are cancers that might take decades to manifest themselves and might only be associated with a particular exposure on a statistical basis. Genetic disorders do not reveal their effects until the next generation is born. Prodromal effects would be expected to manifest themselves in less than 2% of the population at a dose of 50 rad, whereas 50% would be expected to exhibit prodromal symptoms at 150 rad and 98% would be expected to show these symptoms at 250 rad.

The delayed effects of radiation exposure can be seen in Table 5-10, which lists the number of fatal cancers, nonfatal cancers, and genetic disorders that can be expected as a function of the number of person-rem (that is, the number of persons exposed times the number of rems of exposure per person). The small numbers involved are indicated by the fact that the coefficients are presented in scientific notation (i.e., $2.8 \text{ E-}4 = .00028$). That is, 2.8 fatal cancers, 2.4 nonfatal cancers, and 1 genetic effect are expected if 10,000 people are each exposed to 1 rem of radiation to the whole body.

Table 5-10. Average Risk of Delayed Effects (Per Person-Rem)

Effect	Whole body	Thyroid	Skin
Fatal cancers	2.8 E-4	3.6 E-5	3.0 E-6
Nonfatal cancers	2.4 E-4	3.2 E-4	3.0 E-4
Genetic disorders	1.0 E-4		

Source: Adapted from McKenna (2000).

It is important to be aware of the differential biological affinity of radionuclides for specific organs. Whole body radiation refers to the response of the “typical” cell to irradiation, reflecting the common components and structures all cells share. By contrast, the thyroid is sensitive to I-131 and bone marrow is sensitive to Sr-90. Organ differences in dose-response arise because rapidly dividing cells, found in the gut (damage causes diarrhea and vomiting) and hair follicles (damage causes hair loss), are especially susceptible. There also are individual differences in dose-response. For example, fetuses are extremely susceptible because all of their cells are dividing rapidly, and the same is generally true of preschool children. Unfortunately, recommendations for protective action by pregnant women are easily misinterpreted. The concern is for the health of the highly susceptible fetus, not that of the much less susceptible adult woman. Other population segments include those at risk of any environmental insult: the very old, the very young, and those with compromised immune systems.

Population protective actions for radiological emergencies are based upon three fundamental attenuation factors—*time*, *distance*, and *shielding*. Evacuation reduces the amount of time exposed and increases distance from the source, whereas sheltering in-place can provide shielding if this is done within dense materials that absorb energy and are airtight. To determine when protective action should be initiated, the EPA has developed Early Phase Protective Action Guides (PAGs), which are specific criteria for initiating population protective action in radiological emergencies (Conklin & Edwards, 2001). Note that the whole body dose listed in Table 5-11 for initiating evacuation (1 rem) is only a small fraction of the exposure level that would be expected to produce prodromal effects in the most susceptible 2% of the general population.

Table 5-11. EPA Protective Action Guides

Organ	EPA PAGs ^a (rem/Sv)	Protective Action ^b
Whole body	1-5 (.01-.05)	Evacuation
Thyroid	25 (.25)	Stable Iodine (KI)

^a Dose inhalation from and external exposure from plume and ground deposition.

^b Actions should be taken to avert PAG dose.

* Evacuation is considered to be the most effective protective action for nuclear power plant accidents at American sites.

Biological Hazards

According to the World Health Organization (2004, p. 5), biological weapons are “those that achieve their intended target effects through the infectivity of disease-causing micro-organisms and other such entities including viruses, infectious nucleic acids, and prions”. Some biological agents produce toxins and, thus, are actually chemical weapons whose “chemical action on life processes [is] capable of causing death, temporary incapacitation or permanent harm” (World Health Organization, 2004, p. 6).

Emergency managers should recognize that most biological agents likely to be used in deliberate attacks on their communities also exist as natural hazards. They also could be released accidentally from fixed-site facilities (e.g., commercial or academic laboratories) or in transportation among those facilities. These biological agents exist at low levels of prevalence in human populations or, alternatively, in animal populations from which they can spread to human populations. Indeed, one quarter of the world’s deaths in 1998 were caused by infectious diseases. The major consequence of most biological agents is the *magnification* of their effects by infection, unlike chemical agents that generally experience *dissipation* over time and distance. Biological agents magnify their effects by multiplying within the target organisms, but chemical agents cannot do this.

Biological agents can be dispersed by contaminating food or water to achieve exposure through ingestion. For example, a terrorist attack might attempt to introduce a plant or animal infection that would affect people through the food distribution system. However, this system is routinely monitored by the US Department of Agriculture and state departments of agriculture. In some cases, these agencies already receive support from state emergency management agencies when natural outbreaks occur. For example, collaborative relationships have been demonstrated in recent cases of Bovine Spongiform Encephalopathy (BSE—“mad cow” disease) and naturally occurring outbreaks of livestock anthrax.

Alternatively, a biological agent can be used to create an aerosol cloud of liquid droplets or solid particles to achieve an inhalation hazard. The aerosol can be dispersed either in the open environment or through a building’s heating, ventilation, and air conditioning (HVAC) system, but the latter is likely to produce more casualties because the concentration of the biological agent will be greater. The

effectiveness of the dispersion will depend on the hazard agent's physical (particle size and weight) characteristics. Micrometeorological variation can produce corresponding variation in the dispersion of the hazard agent and, under certain conditions, extreme dilution or loss of its viability. Nonetheless, epidemic spread could compensate for poor initial dispersion.

As is the case with some toxic chemical agents, biological agents can be very difficult to detect when symptoms do not appear until long after exposure occurs. The incubation period for biological agents is free of symptoms, so tourists or business travelers might travel a long way from the attack site before they become symptomatic. Consequently, infection with a contagious agent could cause secondary outbreaks that are caused by victims of the initial exposure transmitting the agent to people with whom they come into contact during their travels. Thus, infection can spread widely before local authorities are aware that an attack has even occurred.

The dispersal of the victims at the time the symptoms are manifested and the similarity of these symptoms to those of routinely encountered diseases such as influenza could impede prompt recognition of an attack. The major problem here is that the symptoms of biological agents are frequently indistinguishable from common maladies such as colds and influenza. Consequently, the occurrence of a covert biological agent release is most likely to be identified by noting a significant increase in the incidence of such symptoms. This would either be achieved by health care providers in emergency rooms and clinics supplemented by the health surveillance system operated by the public health department.

There is an emerging sensor technology for detecting many biological agents. These sensors can identify the presence of agents at a very early stage rather than awaiting the development of symptoms in human populations. However, they can only detect these agents at specific locations and, because of their expense, cannot currently be widely distributed. For the foreseeable future, their deployment is likely to be limited to the most critical facilities. Consequently, it is important for emergency managers to establish a working relationship with their local health departments. In turn, these will have established contacts with regional laboratories and state and federal public health agencies to provide assistance in identifying the agent, treating the victims, and decontaminating the incident site.

Countermeasures for biological agents include isolation and quarantine. *Isolation* is the action taken to prevent those who are known to be ill with a contagious disease from infecting others. It typically is associated with special treatment to remedy the disease. By contrast, *quarantine* is used to prevent those who might have been exposed to a biological agent but do not currently exhibit symptoms. Thus, they might not become ill and, indeed, they might not even have the disease. However, it is critical to prevent them from infecting others. Thus, quarantine is somewhat similar to sheltering in-place from toxic chemical hazards. The difference is that people being quarantined are asked (or legally required) to remain indoors in order to protect others from themselves (because *they* are the hazard) rather than to protect themselves from an external hazard. Although there is extensive research on household compliance with evacuation warnings, the same cannot be said for isolation and quarantine. Nonetheless, it seems safe to say the level of compliance will be less than perfect, so emergency managers should try to assess local residents' perceptions of these protective actions if the need to implement them arises.

In addition, biological agents can be combated by vaccines that provide protection against specific agents and other therapeutic agents that seek to block the body's reaction to the agent. Emergency managers will be particularly interested in the latter type of therapy because a generic therapeutic mechanism would be effective against a wide variety of biological agents, just as a wide-spectrum antibiotic is effective against a range of bacteria.