Integrated Environmental Planning
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CHAPTER 6

Natural Hazard Assessment

Critical to the responsibilities of the planner is the provision of a safe and healthful environment. This particular responsibility directs attention in part to efforts designed to minimize risk and reduce vulnerability to natural hazards. In Chapter 4 we briefly examined a set of natural processes that by virtue of their incidence describe hazards to human populations that share a common geographic location. These processes, while deemed hazards by people, have always existed, and simply define events that shape the earth's surface and identify earth-system responses to the dynamics of climate, geology, and hydrology that explain the realities of a living planet. Therefore, the environment is not hazardous as much as it is a challenge to human populations that seek to use its resources where the presence of certain natural events introduces an element of risk to life and property. From this perspective we can examine the nature and distribution of natural hazards, recognize the risks associated with each, and explore strategies to avoid risk and minimize the threat to human life and property.

The concept of planning with hazard is a somewhat novel approach when compared to the typical mitigation and control strategies that have been employed in the past. Yet, it is an important departure that recognizes the simple fact that rivers flood, hurricanes form in the mid-Atlantic and track toward coastal areas, and some forests do need to burn. This observation also follows the realization that many natural events when subject to human control strategies are made many magnitudes more severe as a consequence of our management efforts. The alternative paradigm of planning with nature rather than attempting to tame it encourages sustainable solutions to hazard management and more realistic programs to reduce vulnerability (Burby, 1998). In this chapter we will examine the nature of hazard and explain the relationship between natural hazards and environmental planning.

Defining hazards and risk

The terms hazard and risk are applied in close association but are often used imprecisely with different implicit meanings. A hazard can be defined as the potential to cause an adverse effect that can lead to harm. Extending this basic definition to include natural events, a natural hazard represents the potential interaction between humans and those natural events that are extreme in nature (Tobin & Montz, 1997). The hazard represents the potential, not the event itself, and this distinction is important because it recognizes the probabilistic nature of hazards and the uncertainty that underlies both the concept and the generating events that introduce it to a population. Therefore, by definition, natural hazards constitute an ever-present threat to society and represent an intrinsic force with which all societies must cope to some degree (Tobin & Montz, 1997).

The hazard exists largely because humans or their activities are constantly exposed to these natural forces, whether on the coastline of North Carolina or along the Hayward Fault on the eastern shore of the San Francisco Bay. Once an event occurs it is referred to as a natural disaster, where the term disaster is defined in relation to the significance of its impact on society. The difference between a hazard and a disaster is therefore made on the basis of causality. We conceive disaster owing to its physical form and geographic consequence, but the potential is ever-present.

Risk may be defined as either the occurrence of an event that results in harm, or as the probability of that occurrence and its consequence. Risk is therefore a presence that can be characterized quantitatively or qualitatively in terms of its likelihood, and can be conceptualized in two fundamental ways (Whyte & Burton, 1980):

1 **Risk as hazard** – a perspective that considers risk as synonymous with hazard: an event or act that holds adverse consequence where the degree of risk is related both to its probability and to the magnitude of its effects.
2 **Risk as probability** – a perspective that explains risk according to probabilistic statements or models: risk defines the probability value of an undesirable event.

Accordingly, reasoning about risk has developed following two contrasting approaches: the normative model of scientific reasoning based on probability theory, and a human-based approach drawing from symbolic logic and symbol manipulation (Lein, 1992). Based on the scientific-reasoning model, risk develops from the probability of a consequence (A) given that event (B) has occurred. This relationship may be expressed as the conditional probability (p) where:

$$p(A/B) = \frac{p(A) \cdot p(B/A)}{p(B)}, \tag{6.1}$$

or in the case of logic stress analysis, a Bayesian probability drawn from a sequence of events of the form:

$$p(A/B) = \frac{p(A) \times p(B/A)}{\Sigma p(B_n) \times p(A/B_n)}. \tag{6.2}$$

In other instances, risk may be expressed using mathematical expectation to predict the likelihood of an event (E) from a set of variables (X), such that

$$E = a_i X_i + a_j X_j + \ldots a_n X_n. \tag{6.3}$$

Human reasoning, by contrast, tends to follow a less rigorous model that is based largely on the use of vague or imprecise concepts that take meaning only within the context of language (Lein, 1992). Risk reasoning in this example becomes a function of individual knowledge, behavior, and prior experience. As demonstrated by Klein and Methlie (1990), the theory of human reasoning suggests that people apply very few formal principles when considering risk or any other type of problem situation. Instead, people rely on heuristics (rules of thumb) tailored to the semantic context of the problem. When one is considering risk, problems often develop when normative models of probability cannot be used to drive meaningful estimates or when such estimates must be interpreted by decision-makers who do not reason in terms of mathematical probabilities. As a consequence, it often becomes necessary to distinguish between empirically based findings of risk and those derived from judgment. This need is becoming increasingly apparent, particularly in situations where risk characterization relies on expert judgment; a situation amply demonstrated by Flemming (1991) and Bonano et al. (1989).

The relationship between hazard and risk is further complicated by the difficulty in separating effects from their actual causes. Hazards have three important components that function in concert to punctuate their significance. These hazard components include a physical perspective, a human dimension, and a spatiotemporal disposition (Tobin & Montz, 1997).

The physical dimension directs attention to the geophysical world and the processes that conspire to define hazards. From this perspective, the physical world is seen as an external force separate from the human world. Although the traditional idea that natural hazards are the exclusive result of geophysical processes has been replaced by a more considered view, knowledge of physical process remains a critical aspect of hazard identification. A moderating influence, that has tempered the conceptualization of hazard and defines process as those external forces that act on human populations, has come from attempts to produce human explanations of natural hazards. This area defines the human dimension component of the hazard and directs focus toward the interaction between physical process and human forces that in combination determine the significance of disasters and produce a more realistic description of risk. For example, Smith (1992) suggests that natural hazards result from a conflict between geophysical processes and people. Hazards, according to this view, develop at the interface between the natural event and the human-use system. In some circumstances the focus of concern eliminates physical processes entirely and concentrates attention on the disruption to society following hazard events. The human dimension considers how events interfere with everyday life, disrupt communities, strain local services and resources, and leave an aftermath that can persist long beyond the initial event. Consideration of a hazard's human dimension must therefore evaluate not just the primary consequence of an event, but the secondary and tertiary effects, and beyond, that continue to shape the human-use system. Recognized in this description are those events that can be triggered by human activities and consequences that can include economic, social, psychological, and technological factors.

While it is accepted that when one is characterizing natural hazards, both physical processes and the human mosaic are important elements of the risk equation, an equally critical factor in defining hazard and risk is the timing of the event and its geographic extent (expression). Time and space have a range of influences on the nature of hazard and the definition of risk. For example, when one is considering a natural hazard, time may be expressed in relation to an event's:

- Frequency
- Duration
- Seasonality
- Timing.

Each of these temporal characteristics must be defined in relative terms, with sensitivity to their conceptual overlap. When placed into the context of a specific process or event they help punctuate where and how in time events manifest. For example, declines in rainfall may have occurred well before drought is identified; similarly, a severe thunderstorm with damaging hail may pass through the planning area in a matter of minutes, only to be followed by another storm complex the next day. Contrasted to this pattern are processes such as earthquakes above a certain magnitude that have reoccurrence intervals of hundreds to thousands of years. Therefore, connected with each hazard is an implicit expression of time. These time traits complicate how society responds to hazard and, more importantly, how risks are perceived and understood.

Because natural hazards form out of natural processes they define a unique geographic expression that places their origin and impact into a definable spatial context. The geographic nature of hazard assumes two critical explanations that must be understood by the planner: (1) location and (2) scale. Some natural processes are spatially ubiquitous in that they operate nearly everywhere on the planet to some degree. Extremes of heat, dryness, and wind velocity may be examples of geophysical processes that are not specific to a fixed geographic location. Conversely, certain natural processes are confined to specific geographic areas or zones, and exhibit a higher frequency of occurrence in particular locales. Thus fault movements are geographically restricted to regions were tectonic processes are active, tornadic activity is more frequent in climatic zones where conditions favor their development, landslides can be anticipated in areas where slope, soil, and geologic conditions are unstable and induce mass wasting. These illustrative examples suggest that hazards display a geographic patterning, and link to geographical processes that share a discernible regionality. Geography also conspires to influence the spatial scale or extent of the hazard. Scale, when considered in relative terms, defines the size of the geographic area where the event and its consequence will form. Some natural events may be highly localized and confined to a limited geographic area. Other events may occur on a scale capable of affecting a much broader geographic area. It is possible to even consider the global effects of some hazards as their influence reaches well beyond where they physically occur. A drought, for example, may influence a large area, perhaps at the continental scale, while the implications of that drought on agriculture may have a global impact. Treating scale as an elastic concept, it can be seen that areas from several square miles to portions of entire continents can be subject to extreme processes that can introduce hazard and place large populations at risk. It is critical for effective planning to understand the meaning of hazard and to place risk into its proper context. A complete understanding, however, is not possible without consideration of those physical processes that induce hazardous events.

A typology of hazard

Natural processes are neutral in their disposition toward human populations; however, when these processes contribute to injury, death, or damage to property they are defined as hazards. But we also recognize that human activities may alter the frequency with which these events occur, increase or decrease their severity, alter the size of the area impacted, influence the rate of exposure of people or property, and influence the vulnerability of hazard-exposed populations (Petak & Atkisson, 1982). For the purposes of rapid identification, natural hazards can be defined in relation to the underlying physical processes responsible for their genesis. These driving natural processes can be placed into three categories: (1) meteorological, (2) hydrological, and (3) geological. Within these general categories hazards can be discussed according to their

- Physical mechanism
- Temporal distribution
- Spatial distribution
- Onset pattern.

Meteorological processes

Extreme meteorological events develop when the factors that define day-to-day weather exceed critical thresholds. The typical elements of weather, such as temperature, wind speed, humidity, radiation, and precipitation, become important when the patterns they form characterize potentially problematic situations. Several of the more common events of weather that achieve hazard status include:

- Tornadoes
- Tropical cyclones
- Severe storms
- Extremes of cold and heat.

Tornadoes A tornado can be described as a violently rotating column of air, a vortex spawned by a thunderstorm, in contact with both the thunder cloud and the ground, often accompanied by a funnel-shaped cloud, progressing over the land in a narrow path (Grazulis, 1993). Recognized as among the most powerful of weather phenomena, a tornado can produce rotating velocities approaching 500 mph and affect a ground area ranging from $^1/_4$ to $^3/_4$ miles wide. The path a tornado follows can be as short as a few tens of yards to over 15 miles long. Extreme events have been known to travel over areas measuring up to one mile wide and 300 miles long (Petak & Atkisson, 1982). Although a tornado can occur anywhere severe thunderstorms develop, certain geographic areas evince climatic regimes that foster more frequent tornado development. In the United States the areas comprising the mid-western and southeastern regions display a higher frequency of tornadoes and tend to be areas of heightened vulnerability. Although tornadoes can occur at any time throughout the year, in North America weather conditions between April and August are the seasonal maximum for these events.

Generally, tornadoes form in association with squall lines with both isolated thunderstorms and thunderstorms accompanying frontal passages. As the storm system develops, one or more tornadoes may form at intervals along the storm track, travel a few miles, lift, and then reform further downfield. With an incidence time lasting minutes to hours, tornadoes reach much higher speeds than a hurricane, but affect a much smaller geographic area. To communicate the power and intensity of these systems several scales of measurement and classification have been devised.

Table 6.1 The Fujita–Pearson tornado scale.

Scale	Wind speed	Effects
F-0	40–72 mph	Chimney damage, tree branches broken
F-1	73–112 mph	Mobile homes pushed off foundation or overturned
F-2	113–157 mph	Considerable damage, trees uprooted
F-3	158–205 mph	Roofs and walls torn down, cars thrown
F-4	207–260 mph	Well-constructed walls leveled
F-5	261–318 mph	Homes lifted off foundation and carried considerable distances, autos thrown near 100 meters

One of the more widely adopted scaling methods is the Fujita classification system (Table 6.1). The Fujita classification system assigns a numeric value to a tornado based on its wind speed in $^1/_4$ mph increments. The Pearson scale is another complementary classification system for categorizing tornado events. This scale applies a logic similar to that used by the Fujita method, but the Pearson scale classifies tornadoes based on path width and length. Using these scales, the magnitude of hazard can be expressed and that information can be used to devise adjustment strategies for tornado events. For example, for a given structure, the expected damage from tornado exposure increases as a function of the Fujita rating of occurrence. With an event given a Fujita rating of 5 (F5), we could anticipate that 65% of all exposed woodframe structures would collapse. This would compare with an F1 event where only 1% of structures would collapse. Perhaps the most vexing problems associated with tornadoes from a planner's perspective are that:

1. While conditions under which they form are understood, the mechanisms that cause them to form remain unclear.
2. They are extremely difficult to measure directly.
3. Mitigating the effects of tornadoes is frustrated by the fact that these events, while localized, are highly random.

Tropical cyclones More commonly known as hurricanes, tropical cyclones involve a mix of devastating winds, flood producing rains, and potentially lethal storm surges. A hurricane is an intense storm of tropical origin with sustained winds exceeding 74 mph. They form over tropical waters where the winds are light, the humidity is high, and the surface water temperature over a wide surface area is warm (79°F/26°C) (Ahrens, 1991). Over the tropical and subtropical north Atlantic and north Pacific oceans these conditions prevail in summer and early fall. This corresponds with the seasonal peak of hurricane frequency during the months between June and November.

In general, several necessary conditions must be present for hurricanes to develop (Pielke, 1990):

1. An ocean area with surface water temperatures above 26°C (79°F).
2. Small wind speed and direction changes between the lower and upper troposphere of less than 15 km/h.
3. The presence of a pre-existing region of lower tropospheric horizontal wind convergence (a tropical wave).
4. A distribution of temperature with height which will overturn when saturated, resulting in cumulonimbus clouds.
5. A location at least 4 to 5 degrees away from the equator.

Hurricanes transition through a series of stages marking their birth to death. Initially a mass of thunderstorms with only a slight wind circulation develops into a tropical disturbance. When sustained winds increase to between 20 and 34 knots and a centralized trough of low pressure appears, the disturbance becomes a tropical depression. As the pressure gradient intensifies and wind speeds increase to between 35 and 64 knots, the tropical depression becomes a tropical storm. Once wind speeds exceed 64 knots (120 km/h) the tropical storm is classified as a hurricane.

Hurricanes that develop over the north Pacific and north Atlantic are directed by an easterly air-

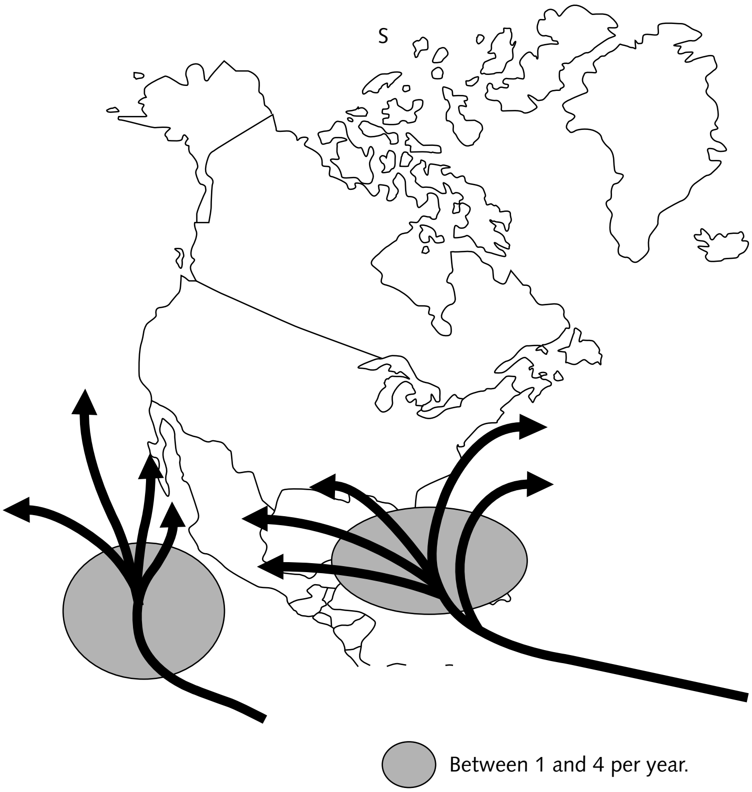

Fig. 6.1 Typical hurricane pathways for North America.

flow. Gradually, these systems swing poleward around the subtropical high, and if they move far enough north, they are captured by the westerly circulation and are steered in a northerly direction. However, the path of a given hurricane can vary considerably. The typical pathways hurricanes follow are illustrated in Fig. 6.1.

While the high winds associated with a hurricane can inflict considerable damage, most of the destruction related to these events is caused by high seas, huge waves, and flooding. Flood risk is due partly to the force of wind pushing water onto the shore and to intense rainfall that can exceed 25 in (63 cm). The combined effect of high water and high winds produces a storm surge that inundates low-lying areas and easily overruns beachfront properties. The Saffir–Simpson scale was developed in an effort to estimate the possible damage a hurricane's sustained winds and storm surge might inflict on a coastal area (Ahrens, 1991). The damage assessment expressed by this scale is based on actual conditions observed during the life-cycle of the storm.

Severe storms Extratropical cyclones can produce a variety of hazards including hailstorms, severe winds, severe snows, and ice storms (Smith, 1992). Some mid-latitude cyclones create special hazards because they develop very quickly. These rapidly deepening depressions are often difficult to forecast since their rate of deepening is often underpredicted. In North America, particularly in the central and Great Lakes regions of the United States, ice and glaze storms are a significant winter hazard. In these geographic areas, the hazard arises when thick accretions of clear ice form on exposed surfaces. Ice accretes on any structure whenever there is liquid precipitation or cloud droplets, and both the air and the object's temperature are below freezing. When these events occur, electric power transmission lines, landscaping trees, and forests are at the greatest risk for damage. Here, the added weight of ice may be sufficient to bend or in some instances bring these objects down.

Temperature extremes Periods of unusually cold or hot weather have been shown to cause a direct threat to human life (Smith, 1992). As suggested in the literature, the average human body is most efficient at a core temperature of 37°C. Given natural variations in temperature, physiological comfort and safety can be maintained within only a narrow thermal range. When the heat balance of the body deviates beyond this range, physiological stress results. Extremes of cold also create hazards in the form of ice and frost, while extremes of heat can be a contributing factor to elevated wildfire risks.

In a review of atmospheric hazards, Smith (1992) identifies several important considerations related to the effects of thermal extremes. First, with reference to physiological hazards, stress to the human body can result from a combination of low temperature and high wind speeds. This wind-chill hazard is common to high latitude and high altitude environments. However, the greatest threat is associated with unexpected outbursts of very cold air into the mid-latitudes in winter. Such a pattern occurs in North America with the development of a high-pressure ridge that forms over the northwestern margins of the continent. The circulation around this ridge allows arctic air to penetrate well into the mid-west and brings cold and frost conditions well into Florida.

Extremes of high temperature can also produce life-threatening situations by imposing severe heat stress on the human body. The problem can be particularly acute when high temperatures are combined with high relative humidity. When these situations arise, heat stress can be common, as the body's ability to cool through evaporative processes becomes less effective and efficient. In prolonged events the physical discomfort can quickly escalate into increased heat-related mortalities (Quayle & Doehring, 1981).

Atmospheric processes can also be modified by the changes in surface composition introduced by urbanization. These modifications have become recognized as the "urban climate," and while they may not represent hazards, they do explain changing conditions that may accentuate hazardous conditions. For example, the altered heat balance of the urban environment contributes to the formation of "hot" sectors in the urban landscape. In these sectors airflow is reduced, emissions concentrate near the ground, and evaporative cooling is substantially reduced by the absence of vegetation. Where building heights increase, more turbulent airflow is common, as is the reduction in direct solar radiation reaching the surface. In these urban canyons, cooler and windier conditions prevail. The general pattern of local climate influenced by urbanization is shown in Fig. 6.2.

Hydrological processes

Hydrologic processes are characterized by the flux parameters that define the hydrologic cycle. These transfer mechanisms influence the distribution of water at the surface and describe the general availability of water to the environmental system. When events transpire that move these parameters above or below their expected condition, a stress relationship can develop that can influence ecosystem functioning and the water resource systems on which human settlement depends. Perhaps two of the more common hydrologic events that evidence deviations sufficient to assume hazard status are floods and drought.

Mechanics of flooding Physically a flood is a high flow of water which overtops either the natural or the artificial banks of a river channel (Smith, 1992). Under natural conditions, the hydrologic processes of the fluvial system have created and maintained stream channels with channel maintenance maximized during bank full discharges. Whenever flow exceeds bank full capacity, and the river spills over onto the adjacent floodplain, the river is at flood stage. All rivers produce this condition at some time, suggesting that flooding is a natural feature of river systems. Consequently, such events cannot be considered a hazard unless the nature of the flood threatens human life and property.

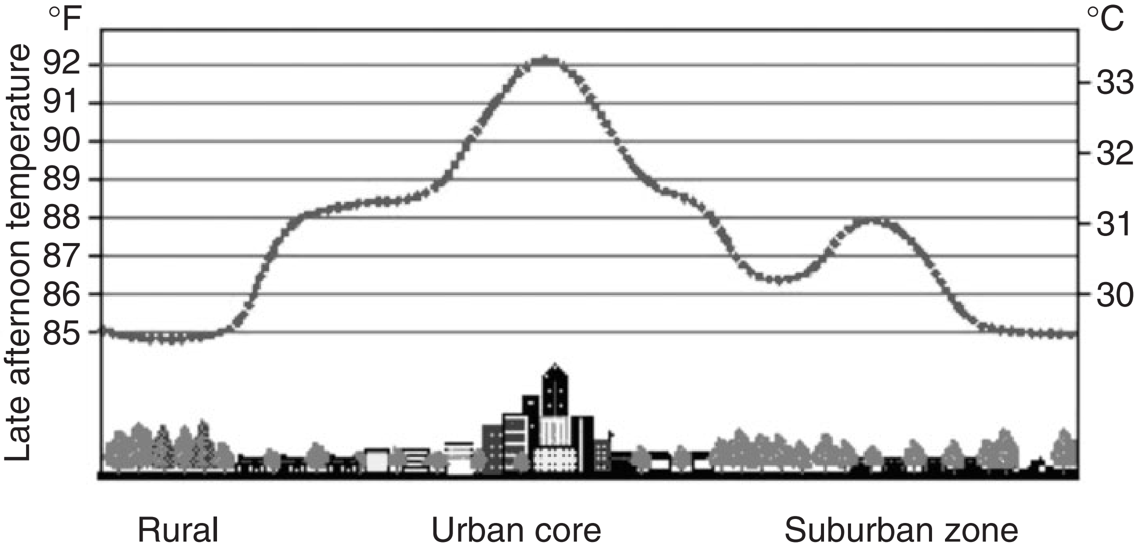

Fig. 6.2 The generalized pattern of urban climate.

When one is defining the concept of a flood, its physical cause can be expressed in two ways. One explanation stresses the hydrologic definition and defines flood magnitude in terms of peak river flow. This definition contrasts with a more hazard-oriented explanation. This alternate expression relates the flood event to the maximum height or stage that water reaches. These two definitions require a careful distinction between the primary causes of floods that result from the driving forces of climate, and those secondary flood-intensifying conditions that occur as a consequence of drainage basin morphology.

Perhaps the most important cause of floods is excessive rainfall. Rainfall events capable of producing floods can vary from seasonal storms that provide precipitation to a large geographic region to nearly random convectional storms that can generate flash-flood conditions over a comparatively localized area. In addition, some flood events can be causally linked to larger atmospheric processes such as the ENSO (el Niño) or its opposing process, la Niña. Within the mid-latitudes prolonged rainfall is frequently related to tropical cyclones or intense atmospheric depressions. Localized convectional systems are also responsible for producing high-intensity rainfall particularly during the summer season. These rainfall events, because they are temporally and geographically concentrated, can generate large volumes of water with a high damage potential. Although rainfall may be the driving force behind flood events, processes such as the seasonal melting of snow and ice can be contributing factors in some areas. The seasonal melt can create widespread flooding, particularly during years of high snow accumulation. Melting during these periods contributes to spring flood events that can be compounded by ice jams that may temporarily dam river channels.

When a flood occurs, the area of the stream's floodplain that will be inundated by water resulting from a stream flow level of a specified flood-frequency is referred to by the name of that frequency interval. This flood frequency interval and the geographic area it will encompass have tremendous importance to hazard assessment and planning. To illustrate this point, consider a flood characterized by a two-year return interval. Such an event will inundate all of the area delineated as the two-year zone of the floodplain. Similarly, a flood stage with a 100-year frequency will inundate the entire 100-year zone of the floodplain. The geographic expression and extent of these zones is depicted in Fig. 6.3.

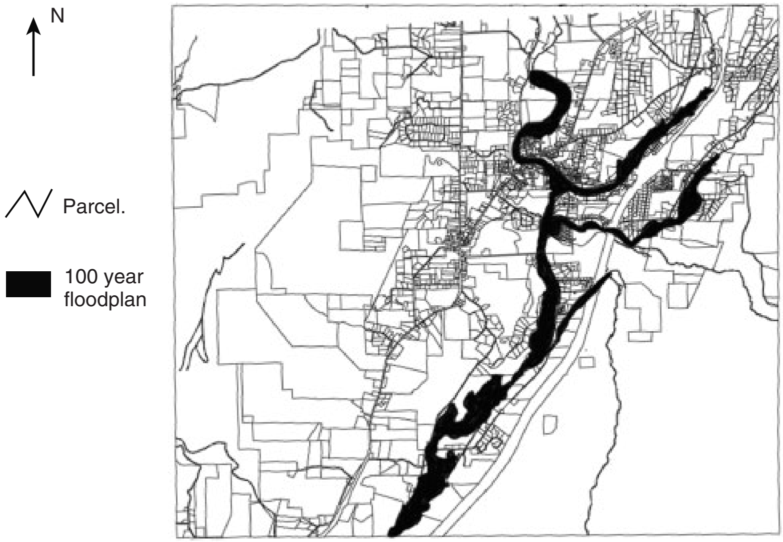

Fig. 6.3 Delineation of flood zones: town of Manchester one hundred year flood hazard zone.

The flood frequency–floodplain relationship illustrated in Fig. 6.3 suggests spatial patterns that can greatly influence the present and future use of flood prone areas. For this reason, floodplains are typically divided into six flood classes or six hazard zones (Petak & Atkisson, 1982). The classification system categorizes the floodplain into zones A through F, where zone A defines the most hazardous area subject to the most frequent flooding, while zone F is the least hazardous. According to the logic of this classification system, the six flood/hazard zones delineate areas that would be inundated by the 2–5, 5–10, 10–25, 25–50, 50–100, and greater that 100-year flood event. Within the drainage basin, however, the geographic shape and extent of these zones will be influenced by local terrain characteristics and river morphology. Thus, the dimensions of a flood zone will differ, and the depth floodwater can reach given a specified magnitude will vary along the course of the river. Within these zones the damage sustained by structures is generally a function of:

1. The type, strength, and elevation of the structure.
2. The depth of the flood waters during the event.
3. The force exerted against the structure by moving floodwaters.
4. The impact of floating debris against the structure.
5. The adverse effects of water intrusion on the structure and its contents.

Frequently overlooked aspects of the flood hazard problem are those factors that contribute to flood-intensifying conditions, particularly those associated with human activities. Floods can be made more intense for a given precipitation level depending on topography, the hydraulic geometry of the drainage basin, soil characteristics, and the density of vegetation cover. In addition to these natural parameters, changes in land cover and land use are also contributing factors. In this regard, two of the more powerful forces that conspire to intensify flood conditions are urbanization and deforestation. Urbanization alters the magnitude and frequency of floods in several ways. Four well-documented impacts of urbanization on flooding are summarized in Table 6.2. Deforestation increases flood run-off with associated increases in surface erosion that decrease channel capacity through sediment deposition. The removal of vegetation causes peak flood flows to increase, and changes the hydrologic regime of the river basin, as evidenced by its unit hydrograph (Fig. 6.4).

Table 6.2 Impacts of urbanization on flooding.

Increased impervious cover
Increased run-off
Increased pollutant and sediment loads
Decreased vegetation cover

Drought Drought is a complex hydroclimatic phenomenon and is perhaps the most persistent environmental hazard experienced in the contiguous United States (Soule, 1992). When compared to other environmental processes, drought is often referred to as a "creeping" hazard because it develops slowly over several months with prolonged effects often spanning a period of years (Smith, 1992). One of the more problematic issues related to drought is the question of definition. Generally drought can be explained in one of three ways (Drought Information Center, 1999), to which a fourth can be added.

1 *Meteorological drought* Meteorological drought is defined usually on the basis of the degree of dryness (in comparison to some "normal" or average amount) and the duration of the dry period. Definitions of meteorological drought must be considered as region specific since the atmospheric conditions that result in deficiencies of precipitation are highly variable from region to region. For example, some definitions of meteorological drought identify periods of drought on the basis of the number of days with precipitation less than some specified threshold. This measure is only appropriate for regions characterized by a year-round precipitation regime such as a tropical rainforest, humid subtropical climate, or humid mid-latitude climate. Locations such as Manaus, Brazil; New Orleans, USA; and London, England, are examples. Other climatic regimes are characterized by a seasonal rainfall pattern, such as the central US, northeast Brazil, west Africa, and northern Australia. Extended periods without rainfall are common in Omaha, Nebraska, Fortaleza, Brazil, and Darwin, Australia; a definition based on the number of days with precipitation less than some specified threshold is unrealistic in these cases. Other definitions may relate actual precipitation departures to average amounts on monthly, seasonal, or annual timescales.

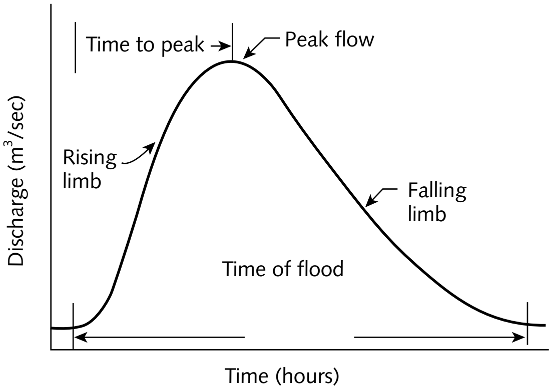

Fig. 6.4 Characteristics of a flood hydrograph.

2 *Agricultural drought* Agricultural drought links various characteristics of meteorological (or hydrological) drought to agricultural impacts, focusing on precipitation shortages, differences between actual and potential evapotranspiration, soil water deficits, reduced groundwater or reservoir levels, and so forth. Plant water demand depends on prevailing weather conditions, biological characteristics of the specific plant, its stage of growth, and the physical and biological properties of the soil. A good definition of agricultural drought should be able to account for the variable susceptibility of crops during different stages of crop development, from emergence to maturity. Deficient topsoil moisture at planting may hinder germination, leading to low plant populations per hectare and a reduction of final yield. However, if topsoil moisture is sufficient for early growth requirements, deficiencies in subsoil moisture at this early stage may not affect final yield if subsoil moisture is replenished as the growing season progresses or if rainfall meets plant water needs.

3 *Hydrological drought* Hydrological drought is associated with the effects of periods of precipitation (including snowfall) shortfall in surface or subsurface water supply (i.e., stream flow, reser-

voir and lake levels, groundwater). The frequency and severity of hydrological drought is often defined on a watershed or river-basin scale. Although all droughts originate with a deficiency of precipitation, hydrologists are more concerned with how this deficiency plays out through the hydrologic system. Hydrological droughts are usually out of phase with or lag the occurrence of meteorological and agricultural droughts. It takes longer for precipitation deficiencies to show up in components of the hydrological system such as soil moisture, stream flow, and groundwater and reservoir levels. As a result, impacts are out of phase with those in other economic sectors because different water use sectors depend on these sources for their water supply. For example, a precipitation deficiency may result in a rapid depletion of soil moisture that is almost immediately discernible to agriculturalists, but the impact of this deficiency on reservoir levels may not affect hydroelectric power production or recreational uses for many months. Also, water in hydrologic storage systems (e.g., reservoirs, rivers) is often used for multiple and competing purposes (e.g., flood control, irrigation, recreation, navigation, hydropower, wildlife habitat), further complicating the sequence and quantification of impacts. Competition for water in these storage systems escalates during drought and conflicts between water users increase significantly.

4 *Socioeconomic drought* Socioeconomic definitions of drought associate the supply and demand of some economic good with elements of meteorological, hydrological, and agricultural drought. It differs from the aforementioned types of drought because its occurrence depends on the time and space processes of supply and demand to identify or classify droughts. The supply of many economic goods, such as water, forage, food grains, fish, and hydroelectric power, depends on weather. Because of the natural variability of climate, water supply is ample in some years but unable to meet human and environmental needs in other years. Socioeconomic drought occurs when the demand for an economic good exceeds supply as a result of a weather-related shortfall in water supply. For example, in Uruguay in 1988–9, drought resulted in significantly reduced hydroelectric power production because powerplants were dependent on stream flow rather than storage for power generation. Reducing hydroelectric power production required the government to convert to more expensive (imported) petroleum and stringent energy conservation measures to meet the nation's power needs.

In most instances, the demand for economic goods is increasing as a result of increasing population and per capita consumption. Supply may also increase because of improved production efficiency, technology, or the construction of reservoirs that increase surface-water storage capacity. If both supply and demand are increasing, the critical factor is the relative rate of change. Is demand increasing more rapidly than supply? If so, vulnerability and the incidence of drought may increase in the future as supply and demand trends converge.

For the purposes of environmental planning, the simplest conceptualization of drought defines it as an unusually dry period that results in a shortage of water (Smith, 1992). From this perspective deficiencies in precipitation may serve as the triggering effect; however, a careful distinction must be made between the shortage of precipitation and the shortage of useful water. Therefore, the concept of drought cannot be separated from the water resource and water allocation issues that surround water at its utilization. A precipitation deficiency associated with drought poses the potential to produce water supply problems, particularly in regions that rely on surface sources as the main origin of supply. Consequently the significance of drought and its relevance to the planning problem relates primarily to three controlling factors:

1 The purposes for which water is required.
2 The ways in which the local hydrologic cycles react to precipitation deficits.
3 The degree of buffering that is available to offset precipitation shortages.

When one is monitoring the duration and intensity of drought, it is convenient to apply an index that encapsulates the spatial pattern of the incidence of drought in terms of a single numerical rating (Katz & Glantz, 1986). A variety of indices

Table 6.3 Procedures followed for calculating PDSI.

Step 1	Estimate potential evapotranspiration, potential soil recharge, potential run-off, and potential loss for an average period of a month for each climatic subdivision.
Step 2	Use the month-by-month water balance accounting to obtain coefficient of evaporation, recharge, run-off, and loss.
Step 3	Compute the amount of precipitation that should have occurred during a given month to sustain potential evapotranspiration, run-off, and moisture storage that would be considered normal and climatically appropriate for existing conditions.
Step 4	Subtract the normal and climatically appropriate value from areally averaged precipitation to obtain a preciptitation excess or deficit.
Step 5	Calculate a moisture anomaly index (Z) and determine the final drought index term from the general relation $Z/3.0$.

have been proposed and several of these have been compared in the drought literature (Oladipo, 1985). Two of the more widely applied drought indices in the United States are the Palmer Drought Severity Index (PDSI) and the Crop Moisture Index (CMI). Although both indices are accepted as representative measures of drought conditions, their focus is primarily directed toward meteorological definitions of drought.

The Palmer index (PDSI) provides an objective method for developing a meteorological characterization of drought. The index expresses drought as a function of precipitation, potential evapotranspiration, antecedent soil moisture, and run-off. Allen (1984) has reviewed the computational procedures followed to derive the index, and full details are given by Palmer (1965). The general procedure is summarized in Table 6.3. The crop moisture index (CMI) was developed primarily to assess and evaluate agricultural drought. The CMI calculates crop moisture conditions by considering the interrelationships between the deviations of precipitation levels from normal, soil-moisture supplies, and evapotranspiration demand.

Placing the derived drought index values into a classification scheme that groups drought stricken areas according to severity or significance facilitates assessment of a drought's geographic pattern. Diaz (1983) has proposed a useful drought classification method. According to this system, a sequence of three or more months with PDSI values less than or equal to –2.0 is considered to represent a drought event, a period of six or more months a major drought event, while a mild drought is defined by PDSI values as less than or equal to –1.0.

Geologic processes

Geological processes relevant to a discussion of natural hazards typically describe events related to tectonic activity or the forces of erosion and mass wasting. When compared to other environmental hazards, the time-scales within which geologic processes behave frequently make them difficult to conceptualize in accurate terms. As a result, the energy released when these events occur is either underestimated or subject to alarmist reactions. Despite these contrasting modes of response, geologic processes introduce significant influences on the utilization of land resources and the density, design, and location of specific land uses. While the list of potentially significant geologic processes to consider is exhaustive, those germane to environmental planning include landslides and mass movements, subsidence and collapse, earthquakes and faulting, coastal processes, and volcanic activity.

Landslides and mass movements Mass downslope movements may occur in a wide variety of geologic materials. Soil, rock, or the combination of the two may fail or migrate downslope under a range of environmental conditions. Some slides may involve a comparatively small amount of material, while others may result from deep failures of large masses of solid rock. Movement can occur on very gradual slopes, on steep terrain, and under diverse climatic conditions. The slides and movements characterized above are part of a more general erosional process referred to as "mass wasting." This fundamental surficial process describes the downslope movement of earth surface

Table 6.4 Principal forms of downslope movement.

Soil or bedrock creep	The slow downslope movement or the gradual plastic deformation of the soil mantle at nearly imperceptible rates.
Rockfalls	The abrupt free-fall or downslope movement of rocks and loosened blocks or boulders of solid rock.
True landscapes	The failure of material at depth and the movement of that material along a rupture or slip surface.
Earth flows	The downslope movement of soil or overburden that become saturated by heavy rains.
Debris or mud flows	The rapid but viscous flow of mud or other surface material.
Snow avalanches	The rapid downslope movement of snow, ice, and associated debris such as rock and vegetation.

materials under the force of gravity. Mass movements can range from soil and rock creep, where rates of movement are measured in centimeters per year, to debris avalanches where velocities may reach 400 km/h. Landslides fall within the middle range of these extremes and can be identified by the presence of a surface rupture.

Various forms of downslope movement carry important hazard potential. Depending on the type of movement and the kind of material involved, mass movements can vary widely with respect to their shape, rate, spatial extent, and impact on the surrounding environment. Consequently, they can pose variable levels of hazard that planners must understand. Brief descriptions of those critical to the planning problem are given in Table 6.4.

To understand the landslide hazard it is important to recognize the factors that make an area susceptible to failure. Once the triggering mechanisms are identified it may be possible to initiate appropriate planning solutions to minimize the hazard and reduce risk. In general, mass downslope movements occur when the component of weight along a surface exceeds the frictional resistance or cohesion of the material (Griggs & Gilchrist, 1977). Therefore, when the strength of the material that comprises the slope is overcome by a downslope stress, the slope fails. Two factors are central to this process: (1) shear strength which defines a slope's maximum resistance to failure, and (2) shear stress which is defined as the component of gravity that lies parallel to a potential or actual surface of slippage. When the equilibrium condition of a slope is disturbed, the shear stress on the material increases. The stress acting on a slope may be affected by several external and internal factors. Any of these may be sufficient to contribute to slope failure. External factors affect the stress acting on a slope and include:

- Changes in slope gradient
- Excess loading
- Changes in vegetative cover
- Shock and vibrations.

Internal factors alter the strength of the material comprising the slope and involve consideration of:

- Changes in water content
- Groundwater flow
- Weathering effects.

Subsidence and collapse Land subsidence is not typically considered a major geologic hazard, yet where it occurs it can pose serious problems to land use and infrastructure. While the process of land subsidence is gradual in most geographic settings, collapse can be sudden with catastrophic consequences. Seven major causes of land-surface subsidence and collapse have been identified. These include:

1. The withdrawal of large volumes of water, petroleum, or natural gas from weakly consolidated sediments.
2. The application of water to moisture-deficient deposits resting above the water table.
3. Tectonic activity.
4. The solution or leaching of soluble subsurface material by groundwater.
5. The removal of subsurface deposits of coal or other mineral resources with inadequate surface support.
6. The melting or disturbance of permafrost.
7. The differential settlement of artificial fill.

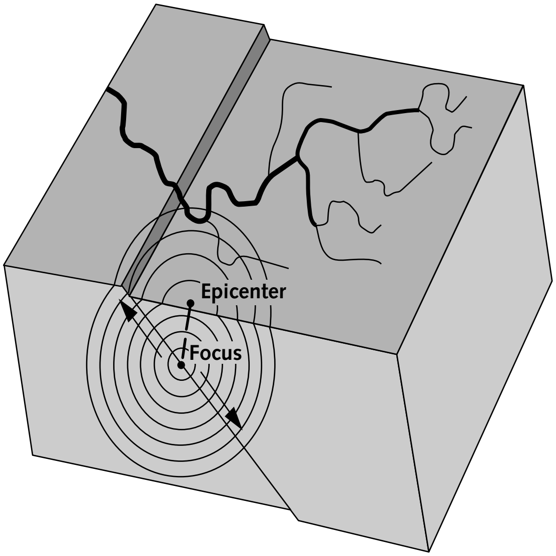

Fig. 6.5 General characteristics of an earthquake.

Earthquake and faulting Earthquakes may be characterized as natural events that involve the moving or shaking of the earth's crust. While the specific triggering mechanisms remain uncertain, it is believed that earthquakes are produced by the release of stresses accumulated as a result of rock rupture along opposing fault planes in the Earth's outer crust (Fig. 6.5). One common source of rupture results from the continuous collisions between plates that comprise the Earth's 10- to 50-mile-thick outer and floating crust. Three different mechanisms are associated with the constantly migrating patterns of these plates:

1 Divergence – describes the situation where tectonic plates spread, move apart, and increase in area.
2 Collision – results when plates converge and reduce in size, forming a subduction zone as one plate overrides another.
3 Transcursion – occurs when two plates slide laterally past each other, producing a series of tears or transcurrent faults.

As shown by Smith (1992), these tectonic processes give rise to a variety of primary and secondary seismic hazards (the secondary earthquake hazards include soil liquefaction, landslides and rockfalls, and tsunami and seiches). Because the tectonic processes described above actively shape and reshape the surface, crustal processes produce distinctive geomorphic features that identify landscapes where faulting is (or was) present. However, it is important to recognize the distinction between active and inactive faults, particularly when assessing seismic hazards. An active fault is one along which movement has occurred in historic or recent geologic time. Active faults suggest that movement is likely to reoccur. Inactive faults are typically older geologic features that provide little evidence to suggest that motion has occurred along their traces in historic or recent geologic time. The lack of recent movement gives reason to assume that a recurrence of movement along the inactive fault is unlikely.

The geomorphic features found along fault zones include:

- Fault Valleys
- Saddles
- Scarps
- Linear ridges
- Offset streams
- Sag ponds
- Landslide scars.

Careful interpretation of these landscape features provides useful insight as to where seismic activity occurs and the extent to which fault processes are active in the region. The next step to forming a complete understanding of the hazard involves consideration of its effects. An earthquake can affect the surface directly or indirectly. Direct effects include ground shaking, surface faulting, and displacement. Indirect effects involve processes characterizing one or more forms of ground failure.

Ground shaking is a term used to describe the vibration of the surface and subsurface during an earthquake. The severity of ground motion at a given location depends upon several factors: (1) the total energy released in the form of seismic waves, (2) the distance from the source of the earthquake (epicenter), and (3) the composition of the surface and subsurface geology. This ground motion is characterized by three types of elastic wave (Table 6.5). Typically, horizontal ground movement produces the greatest structural damage during an earthquake. The magnitude and intensity of ground shaking is measured in either of

Table 6.5 Types of seismic wave.

P wave	Primary, longitudinal, irrotational, push, pressure, dilatational, compressional, or push–pull wave. P waves are the fastest body waves and arrive at stations before the S waves, or secondary waves. The waves carry energy through the Earth as longitudinal waves, moving particles in the same line as the direction of the wave. P waves can travel through all layers of the Earth. P waves are generally felt by humans as a bang or thump.
S wave	Shear, secondary, rotational, tangential, equivoluminal, distortional, transverse, or shake wave. These waves carry energy through the Earth in very complex patterns of transverse (crosswise) waves. These waves move more slowly than P waves, but in an earthquake they are usually bigger. S waves cannot travel through the outer core because these waves cannot exist in fluids, such as air, water, or molten rock.
Lg wave	A surface wave which travels through the continental crust.

two ways. One approach to determine magnitude uses the Richter scale. The Richter scale measures the vibrational energy of the seismic wave. It is based on a logarithmic scale, and each time magnitude is raised one unit, the amplitude of the seismic wave increases tenfold (Smith, 1992). The intensity of ground shaking is explained according to the Modified Mercalli Intensity scale. Because ground shaking displays a close relationship to structural damage, the Mercalli scale provides a subjective method to categorize intensity based on the extent of physical damage observed (Table 6.6).

Another direct effect of an earthquake is surface faulting or displacement. It has been observed that during larger earthquakes, fault slippage may extend to the surface, resulting in abrupt ground displacement. This displacement along the fault plane may be either horizontal or vertical. In addition to sudden surface slippage, more gradual forms of slippage may be noted. This slower, less pronounced displacement is known as fault creep, and in some cases it may be more significant a hazard than surface faulting since it needn't be accompanied by an earthquake. Fault creep describes the overall motion along an

Table 6.6 The Modified Mercalli Intensity scale.

Scale/ level	**Observed effect**
I	Not felt except by a very few under especially favorable conditions.
II	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing cars may rock slightly. Vibration similar to the passing of a truck. Duration estimated.
IV	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensations like heavy truck striking building. Standing cars rocked noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
XI	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.
XII	Damage total. Lines of sight and level are distorted. Objects thrown into the air.

Abridged from *The Severity of an Earthquake*, US Geological Survey General Interest Publication, US Government Printing Office: 1989-288-913.

active fault and is typically characterized by lateral displacement of the surface measured in terms of millimeters per year. Failure to recognize the presence of creep along a fault zone will lead to the gradual deformation of foundations and structures, sidewalks, roads, and underground utility networks.

The indirect effects of earthquakes are most pronounced in geologic settings that are unstable. The strong ground motion generated during an earthquake produces rapid changes in the condition of these unstable materials. The changes produced by ground motion, such as liquefaction and loss of strength in fine-grained materials, contribute to landslides, differential settlement, subsidence, ground cracking, and other alterations at the surface (Griggs & Gilchrist, 1977).

Coastal processes The attractiveness of coastal landscapes has encouraged the widespread development of shoreline and near-shore areas for residential and commercial activities. Coastal environments, however, are extremely dynamic, with active processes continuously changing nearly every facet of the coastal zone. The inherent instability of coastal areas places important emphasis on the processes operating there and how these processes interact with increasing population concentrations within coastal regions. As the coastal landscape is subject to more intensive forms of use, the environmental stress already evidenced in these regions is likely to intensify as well. Therefore, continued use of the coastal environment must account for its dynamic nature and the diverse forces and processes that interact to perpetuate this landscape and maintain its constant state of flux. Two of the more critical active forces in this landscape, particularly when viewed with respect to hazard potential, are beach-forming processes and coastal erosion (Klee, 1999).

Beach processes and beach formation

The shoreline undergoes change as a result of seasonal and storm induced cycles. The beach, therefore, is a buffer zone that shields coastal areas from the direct forces of wave action. The sources and losses of beach sand, the interaction of waves, tidal action, and wind help determine the size, shape, and extent of beach and the changes these features will experience. Three general conditions can be used to describe the prevailing state along the shoreline (Griggs & Gilchrist, 1977):

1. Accretion predominates over erosion as the beach progrades and builds seaward.
2. The shoreline is stable and neither erosion nor accretion dominates.
3. Erosion predominates and losses of beach sand exceed supply.

Several factors are important regulators of the formation of beaches and greatly influence the rate at which sand is supplied to support beach building. These include stream run-off, sea cliff erosion, and drifting sands from inner continental shelves.

Coastal erosion

The greatest concerns to coastal development are the processes that contribute to coastal retreat and the erosion of coastal areas. Marine erosion is similar in many ways to erosion produced by streams. The most pronounced effects are recognized during short periods separated by longer time intervals where only slight erosion may result. There are four natural mechanisms that direct coastal retreat and erosion:

1. Hydraulic impact – describing the action of waves striking against a sea cliff. This process becomes significant where rocks are well bedded, jointed, or fractured.
2. Abrasion – characterizing the grinding force of beach materials as they encounter coastal rocks.
3. Solution – explaining the wetting and drying of rocks within the intertidal zone. In areas dominated by sedimentary rock, prolonged soaking may contribute to dissolution, hydration, ion exchange, or swelling of grains, loosening them and allowing the material to be washed away.
4. Biological activity – describing the direct mechanical boring, scraping, and indirect

chemical solution of pholads, limpets, and sea urchins on rock material. In some instances between 25 and 50% of the surface area of rock can be riddled with boring, which makes it more susceptible to hydraulic and mechanical erosion.

Coastal erosion becomes a major concern in areas where roads, homes, and other structures have been constructed in proximity to beaches or sea cliffs. In these areas oceanic conditions such as exposure to the sea, wave energy, and the presence or absence of a protective beach play a major role in defining the hazard. Of equal importance is the rock material that comprises the sea cliff or shoreline environment. Here, the controlling factors are rock hardness, bedding, and the density and orientation of jointing. Added to these natural forces are the erosional effects induced by human activity. Human action may accelerate or reduce natural rates in a number of ways, several of the more significant including:

- Loading at the edge of a sea cliff beyond the bearing capacity of the formation.
- Alteration of normal drainage.
- Vegetation and landscaping that promotes physical weathering in rock joints.
- Vehicular vibrations transmitted into a sea cliff from roads or parking facilities.

Volcanic activity Recent evidence suggests that there are approximately 500 active volcanoes in the world. However, as Smith (1992) notes, this figure must be used only as an approximation, simply because it is difficult to accurately determine when a volcano no longer poses a threat. Therefore, as a general rule, any volcano that has erupted within the last 25,000 years can be considered active. With respect to their geographical distribution, the location and behavior of volcanoes is strongly controlled by plate tectonics, with 80% of the world's active volcanoes found in subduction zones where one plate is actively being consumed by another. Along these subduction zones the most prevalent form of subduction volcano is the stratocone volcano. This geomorphic feature produces explosive conditions and reflects the "classic" conceptual image of volcanic activity. There are, however, many different forms of volcano, each with distinctive eruption patterns (Ritter, 1986).

In considering the nature of volcanic eruptions, magnitude is often measured in terms of explosive capacity, where the release of energy is equated with "*x*" tons of TNT. One method that attempts to quantify this relationship is the Volcanic Eruption Index (VEI). The VEI defines 8 classes of eruption on a scale from 1 to 8. The scale in based on measures of ejecta, height of the cloud column, and related criteria (Nuhfer et al., 1993). In many cases the composition of lava provides a reasonable indication of the explosive potential of a volcano. For example, basaltic magma, because it is low in silica content, high in iron and magnesium and fluid, tends to have a low explosive potential. Rhyolitic magma, however, because of its relatively high levels of silica, acidic nature, and viscosity, has a high explosive potential. Temperature is another factor to consider, particularly with respect to lava flow. When lava reaches the surface at a temperature between 800 and 1,200°C, it will move rapidly, slowing as it cools.

Eruptions, lava flow, and related seismic activity can produce a series of events that pose a hazard. The primary effects of volcanic activity include:

- Pyroclastic Flow
- Air fall Tephra
- Lava Flow.

While secondary effects describe events such as:

- Lahars
- Landslide
- Volcanic gases
- Tsunami.

Hazard, risk, and uncertainty

The natural events discussed in the previous section concern us when they result in negative consequences that harm people or property. Yet the nature of hazardous events, their spatial and temporal distribution, and the exact nature of their consequences and impact are shrouded in an envelope of uncertainty. Put simply, we know that San Francisco is located on the San Andreas fault, but we are not absolutely certain when the next major earthquake will occur, where on the fault it will be located, what its magnitude will be, or what its consequences will be with respect to loss of life or property. To a large degree those answers are subject to the laws of probability and underscore the uncertainty inherent to hazard assessment and planning. For this reason, planning with hazards should operate on the premise that hazardous events are a given; and the planner must work toward a better understanding of risk and develop strategies to narrow uncertainty down to a level that can be more effectively managed.

As Tobin and Montz (1997) note, there is a tendency to erroneously equate risk with hazard. While the concept of risk is an integral part of hazard, the terms are not synonymous. We can define hazard simply as an event that can produce harm, while risk explains the probability that an event will occur. Therefore, risk can be considered as the product of the probability of occurrence and anticipated loss given the hazard. This relationship may be expressed simply as:

$$\text{Risk} = \text{probability of occurrence} \times \text{vulnerability}.$$

Although this is a useful representation, the formula does not take into account geographic differences in population size or other factors that affect and refine the description of risk. From a planner's perspective, risk is a multiplicative function of hazard, exposure, vulnerability, and response that can be expressed more appropriately as:

$$\text{Risk} = f(\text{Hazard} \times \text{Exposure} \times \text{Vulnerability} \times \text{Response}),$$

where:

Hazard = the occurrence of an adverse event.
Exposure = the size and characteristics of the affected population.
Vulnerability = the potential for loss.
Response = the extent to which mitigation measures are available.

In actuality, risk is more complex than even this functional relationship and extends well beyond the bounded rationality of probability theory. Because the nature of risk associated with a natural hazard can shape both individual and societal perceptions and actions, it is critical to not only understand risk in technical terms, but also to describe how risk is perceived and managed. This more detailed conceptualization places emphasis on the process of risk characterization and its role in hazard decision-making and planning.

Risk characterization

The process of risk characterization has been discussed in detail by Stern and Fineberg (1996). Typically, risk characterization is defined as the process of estimating the consequence of human exposure to a hazard. As a process, risk characterization has traditionally followed as the final step in procedures aimed at assessing risk. Recently, it has been suggested that viewing characterization as a summary stage in assessment carries serious deficiencies (Stern & Fineberg, 1996). This has led to a reformulation of the concept, which now places risk characterization at the very beginning of an assessment process that must:

1. Be decision driven.
2. Recognize all significant concerns.
3. Reflect both analysis and deliberation.
4. Be appropriate to the decision.

In this context, the purpose of risk characterization is to enhance practical understanding and to illuminate choices as they apply to hazards. The ultimate goal of this process is to describe a potentially hazardous situation in as accurate, complete, and decision-relevant a manner as possible, addressing the significant concerns of the interested and affected parties and making this information understandable and accessible to all concerned (Stern & Fineberg, 1996).

Risk characterization begins with the formulation of a problem (the likelihood of harm) and ends with a decision. Overall, characterization entails a five-phase sequence:

1. A judgment sequence – that begins with problem formulation, the selection of options and outcomes, and moves through information-gathering and synthesis.
2. A deliberation sequence – where the limitations and challenges surrounding the hazard

are explored and a set of standards and goals is established.

3 An analysis sequence – where data are assembled and examined to form an understanding of the probabilities associated with the hazard.
4 An integration sequence – that links goals and standards to the characterization of the hazard and its associated risk.
5 An implementation sequence – where policy recommendations and actions are put into motion to reduce vulnerability.

Although a systematic characterization of risk is critical for effective planning, the results of a risk characterization can be misleading if the uncertainty surrounding the process is not interpreted correctly. A common problem when attempting to explain risk relates to the observation that risk characterization often gives the impression of greater scientific certainty or unanimity than truly exists. In these instances, risk characterization may suggest that uncertainty is exclusively a matter of measurement, when in fact its presence may be a matter of disagreement about whether a particular theory applies, or reflect differences in judgment regarding how to infer something that is unknown from something that is known, or simply the impression that certain risks do not exist when in actuality they have not been analyzed (Stern & Fineberg, 1996). The simple truth, however, is that uncertainty pervades all consideration, evaluation, and analysis of risk. Thus, while we strive to eliminate it from the assessment problem, the best we can achieve is a narrowing down of uncertainty until it can be managed.

As an active element of risk assessment, uncertainty derives from the probabilistic nature of occurrences and outcomes and the efficacy of various choices (Tobin & Montz, 1997). Because it is an active element of assessment, it requires special consideration in hazard planning for several reasons:

- It is found in all elements of risk.
- The level of uncertainty is not the same for each element or all hazards.
- Individuals differ in their interpretation and tolerance of uncertainty.
- Reducing uncertainty is not a simple matter.
- Uncertainty may be increased by combined risk.

It is not surprising that the manner by which risk is defined, estimated, and communicated relates to uncertainty. For the planner, understanding this fundamental concept is critical to the formulation of an effective response to hazard.

Uncertainty defines a characteristic presence that surrounds the likelihood, magnitude, distribution, and implications of risk. As a feature of process, uncertainty may arise from a range of factors and conditions. Several of the more obvious sources include:

1 Random variations and chance outcomes of the physical world.
2 Lack of knowledge about the world.
3 An incomplete understanding of process.
4 Lack of an appropriate model of a risk-generating process.
5 Simple ignorance.

A useful taxonomy of uncertainty was presented by Suter et al. (1987). Their taxonomy greatly illuminates the sources and issues surrounding the subject and frames the topic of uncertainty in a manner that can be easily understood. Although it was written with reference to the problem of environmental impact analysis, its concepts are germane to our discussion and can be easily applied to the question of hazard planning and assessment. According to their characterization, uncertainty may be divided into two main classes: defined and undefined uncertainty (Fig. 6.6). Defined uncertainty explains uncertainty intrinsic to the event in question, such as a river flood of a given stage. Undefined uncertainty describes the inherently unknowable and remains largely beyond our consideration. While there is little that can be done to reduce undefined uncertainty, defined uncertainty can be reduced further into two main subclasses, referred to a identity and analytical uncertainty (Suter et al., 1987).

With reference to environmental risk, identity uncertainty defines that uncertainty surrounding the identity of features or individuals affected by an event at some future point in time. Analytical uncertainty explains the uncertainty that develops from the various attempts and methods used to quantify risk and predict events and their

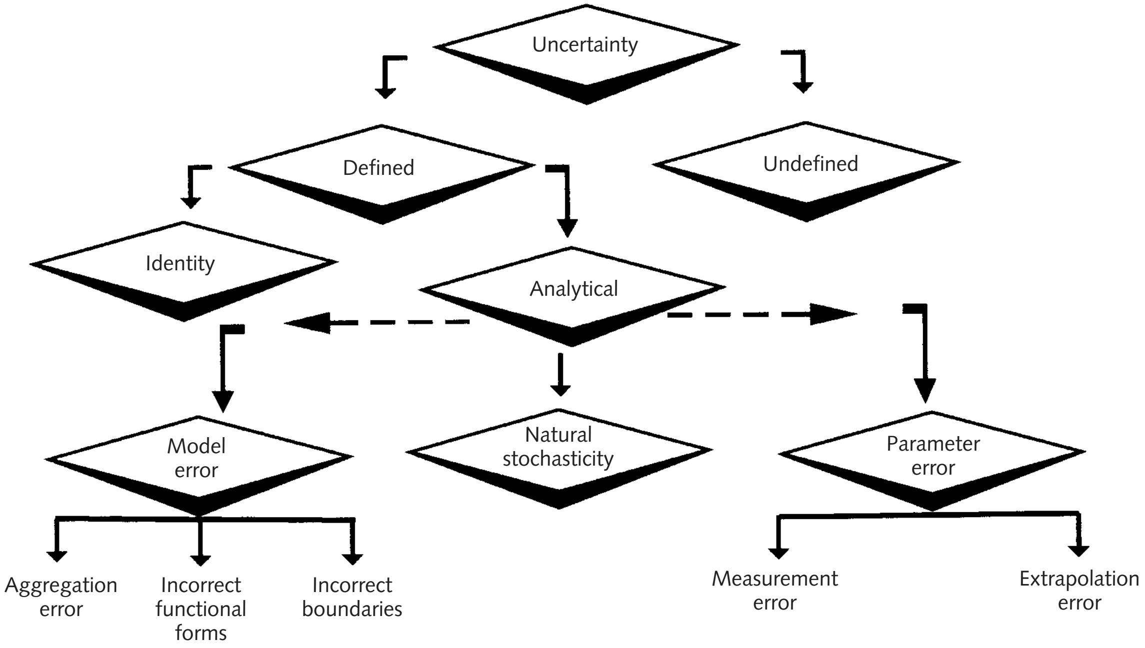

Fig. 6.6 A typology of uncertainty.

consequences. Three important sources of uncertainty can be noted in this context:

1 Uncertainty resulting from the approach used to conceptualize events and their causal mechanisms.
2 Uncertainty that manifests from the natural stochasticity intrinsic to natural processes.
3 Uncertainty associated with measurement error and problems related to the quantification of risk.

To a large degree, risk is an outgrowth of uncertainty. Its presence underscores the need to understand where risk is prevalent and assess risk in relation to the trifold influence of process, consequence, and uncertainty. This is not a simple task given the observation that society all too often overreacts to some risks while virtually ignoring others (Zechhaser & Viscuss, 1990). As a consequence, this pattern suggests that when considering natural hazards, too much importance may be placed on risks of low probability but high salience, risks of commission rather than omission, and risks whose magnitudes are difficult to estimate (Zechhaser & Viscuss, 1990). Therefore, when one is defining risk in relation to natural processes several important considerations must be incorporated into the risk characterization processes (Whyte & Burton, 1980):

- Risks involve a complex series of cause-and-effect relationships that tend to be connected from source to effect by pathways that may include environmental, technological, and social variables that need to be modeled and understood in context.
- Risks are connected to each other, suggesting that several risks occur simultaneously within the same geographical area.
- Risks are connected to social benefits such that a reduction in one risk usually means a decline in the social benefits to be derived from accepting the risk.
- Risks are not always easy to identify, suggesting that identification frequently occurs long after serious adverse consequences have been experienced.

- Risks can never be measured precisely owing to their probabilistic nature; therefore quantification is always a question of estimation to some degree.
- Risks are evaluated differently over space and time and between various social settings; thus a risk considered serious in one location may be considered unimportant elsewhere.

These factors help to frame risk characterization and direct the methodologies used to conduct an analysis of hazard.

Hazard analysis and assessment

The problem of hazard analysis and risk assessment can be approached in a number of ways. Because the physical hazard and the land use near the hazard may change significantly over time, it is generally necessary to evaluate both existing and future socioeconomic and geophysical conditions within the hazard area. With this information, a clearer determination of the types and magnitudes of damage that may be anticipated from an event now and in the near future can be described.

Practical limitations aside, an appropriate evaluation of a hazard requires a determination of the probability of occurrence of a natural event that poses a threat together with its various intensity levels (Petak & Atkisson, 1982). Here, intensity relates to parameters such as wind velocities, water depth, ground shaking, and slope movement. Because natural events are always active, only those intensity levels capable of producing significant damage are of concern. In this context, hazard intensity is related to the integrity of exposed structures where vulnerability to a given intensity level becomes a function of the design, material composition, occupancy, and construction and maintenance practices of structures in the region.

To effectively assess the levels of risk associated with exposure to a natural hazard, analysis must be conducted in such a manner to provide information on 6 critical elements of risk (Petak & Atkisson, 1982):

1 Identification and description of the characteristics, geographic distribution, potential effects of hazardous events common to the planning area.
2 Assessment of the vulnerability of several classes of building and their occupants to each hazard identified.
3 Identification and measurement of the major primary, secondary, and high-order effects associated with exposure by geographic location of buildings and their occupants to each hazard event.
4 Identification and explication of the major candidate public problems associated with the effects identified.
5 Explanation of the costs and characteristics of the strategies available for mitigating effects induced by exposure.
6 Description of the public policy instruments that may facilitate hazard mitigation.

A comprehensive procedure for conducting a hazard assessment consists of a sequence of analytic stages that expand on the 6 elements listed above (Fig. 6.7). The major steps suggested by this sequence include:

- Hazard analysis
- Vulnerability analysis
- Loss analysis
- Risk analysis.

Although risk assessment may be approached following a clearly defined systematic methodology, a complicating factor throughout analysis stems from the contrasting meanings attached to the concept of risk. These differing interpretations greatly influence what it is that is being measured and how. Therefore, risk may be expressed in an assessment in one of four ways (Tobin & Montz, 1997):

1 Real
2 Statistical
3 Predicted
4 Perceived.

Regardless of definition, the goal of analysis is to define management strategies to minimize, distribute, or share the potentially adverse consequences of a hazard, and suggest options to manage risk in the future. Here, the integration of hazard assessment and mitigation with the local

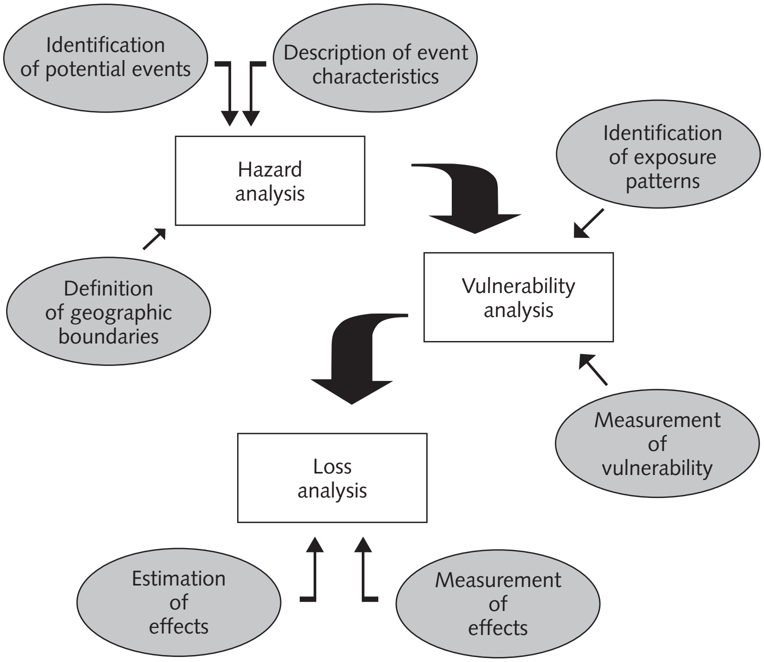

Fig. 6.7 The comprehensive risk assessment process.

land-use and environmental planning becomes critical.

Planning with hazards and risk

Hazard mitigation and environmental planning share several themes in common (Godschalk et al., 1998): both are future oriented, both are concerned with anticipating tomorrow's needs, both are proactive, both attempt to gear immediate activities to longer-term goals and objectives. Traditionally, hazard mitigation, however, has been achieved by either: (1) adopting a locational approach to land use that reduces future losses by limiting development in hazardous areas, or (2) adopting a design approach which focuses on promoting safe construction practices in hazardous areas. The logic behind these mitigation strategies is relatively straightforward. By managing the location of land use, local governments work to shift existing development away from zones of known hazard and direct new land uses toward areas that are hazard free. Through design management, communities can employ a mix of regulatory measures such as building codes or special-purpose ordinances to reduce damage or draw on nonregulatory programs to inform and instruct developers on the use of damage-reducing design techniques. With most hazard mitigation measures, land-use management has had to contend with a range of problems that have limited its use and reduced its effectiveness (Burby, 1998). These include:

- Problems in maintaining commitment.
- Shortfalls in management capacity.
- Lack of private-sector compliance.
- Failure to act at a regional scale.

As a consequence, these barriers suggest that land-use management alone may not be sufficient to adequately address natural hazard mitigation. Instead, focus has shifted toward a local planning approach that strives to create the appropriate combination of control measures with an emphasis on their effectiveness, efficiency, equality, and feasibility (Burby, 1998). This planning for mitigation approach reflects a significant departure from the practice of hazard management in several important ways. Chief among these is the recognition that appropriate mitigation will vary depending on local circumstance. Therefore, prescription from federal or state agencies down to the local level may overlook critical factors and not reduce vulnerability as intended. According to Burby (1998), taking a local planning approach is one means to ensure that:

- Information on the nature of possible future hazard events is available to the public.
- Land subject to natural hazards is identified and managed in a manner compatible with the type, assessed frequency, and damage potential of the hazard.
- Land subject to hazards is managed with due regard for the social, economic, aesthetic, and ecological costs and benefits to all stakeholders.
- All reasonable measures are taken to avoid hazards and potential damage to existing properties at risk.
- All reasonable measures are taken to alleviate the hazard and damage potential resulting from development in hazardous areas.

Mitigation planning, therefore, combines technical analysis and community participation to enable communities to choose between alternative strategies for managing change. In this context the planning program is intended to produce a plan for avoiding or mitigating harm from natural events and for recovering from their consequences (Godschalk et al., 1998). The general design of this approach can be summarized as a series of choices that direct attention toward:

1. The approach taken to encourage stakeholder participation. This initial step in hazard mitigation planning involves enlisting community support and assistance in formulating the plan. Because some mitigation measures may be controversial, building public involvement promotes awareness. Awareness can include media campaigns, public-school information kits, or homeowner/developer seminars aimed at informing and motivating the community to address natural hazards. As awareness of the hazards improves, more collaborative involvement of the community can be realized. This helps establish meaningful mitigation goals and objectives by combining technical planning, public participation activities, and political action together with a focus on implementation.

2. The emphasis given within each component of the plan. An effective hazard mitigation plan will consist of four essential elements: (1) an intelligence component that will define the problem and provide justification for the policies and actions recommended in the plan, (2) a goals component that consists of a statement of community values as a basis for the policies and actions recommended in the plan, (3) an actions component that provides the details of the policies or programs of action designed to achieve the desired mitigation goal, and (4) an evaluation component that explains how hazard assessment and implementation of the recommended mitigation strategies will be monitored and evaluated.

3. The type of plan. Because plans vary in styles, formats, and emphases, not all types of plans are equally suitable for hazard mitigation. The choice of plan involves selecting an approach to fit the preferences of the community. There are two alternatives to select from: (1) developing the mitigation plan as a separate, stand-alone document focusing on hazards, or (2) incorporating hazard mitigation into the comprehensive community plan. If integration into the comprehensive plan is selected, then the next choice to be made determines whether the plan will be structured as a land classification plan, a future land-use design, a verbal policy plan, a land-use management plan, or a hybrid of the above types.

4. The mitigation strategy. The final area of choice in developing the hazard plan involves selection of the mitigation strategy that will be applied by the community. This aspect of hazard planning is far more substantive in nature and directs attention toward the selection of a particular strategy to achieve mitigation of the hazard(s).

Choice involves consideration of the pragmatic (Godschalk et al., 1998):

- Taking a coercive approach versus a cooperative approach to influence private-sector behavior.
- Employing one local governmental power over another.
- Shaping future development versus addressing existing developments at risk.
- Controlling the hazard versus controlling human behavior.
- Taking action before a disaster occurs versus taking action afterward during recovery.
- Going it alone versus taking an intergovernmental and regional approach.

Although mitigation is often considered synonymous with increasing structural integrity, it is far more useful to view mitigation as a management strategy that balances current actions and expenditures with potential losses from future hazard occurrences. Thus mitigation activities identify those approaches that either (1) eliminate or reduce the probability of occurrence of a hazardous event, or (2) reduce the impact of the hazard occurrence. Two broad categories of mitigation can be described:

- Preparedness activities – define the role of government, organizations, and individuals take in developing, testing, and maintaining programs to save lives and minimize disaster damage.
- Response activities – explain programs designed to provide emergency assistance following a disaster and reduce the probability of secondary damage.

A useful taxonomy of mitigation measures was offered by Petak and Atkisson (1982). According to this schema, mitigation can be divided into seven categories:

1 Approaches that involve measures to minimize the probability of hazard occurrence and/or to protect areas and building sites from the hazard.
2 Approaches that focus on strengthening buildings exposed to the hazard or on the design of site-level systems for protecting buildings from hazards.
3 Approaches that give attention to site development schemes for protecting structures from hazards.
4 Approaches that involve the identification of hazard-prone sites and the application of measures to prevent or restrict their development and use.
5 Loss recovery, relief, and community rehabilitation approaches.
6 Hazard warning and population evacuation systems.
7 Approaches that provide policy-makers with the information and decision assistance tools that facilitate rational and effective hazard management decision-making.

With a focus on mitigation, coordinated planning with hazard suggests a departure from simple hazard management to a more comprehensive view of the problem that encourages a change in the accepted norms of a society (Tobin & Montz, 1997). This new management model, illustrated in Fig. 6.8, suggests that through the combined influence of planning, changes in perception, and the sociological and economic realities faced by communities, new concepts of risk and vulnerability will emerge. For the planner, hazard management is more than ameliorating geophysical events, but also requires modifying the human use system. To this end Blaike et al. (1994) offer 12 principles that can be used to guide hazard planning efforts:

1 Vigorously manage mitigation.
2 Integrate elements of mitigation into development planning.
3 Capitalize on a disaster to initiate or develop mitigation.
4 Monitor and modify to suit new conditions.
5 Focus attention on protection of the most vulnerable.
6 Focus on the protection of loves and livelihoods of the vulnerable.
7 Focus on active rather than passive approaches.
8 Focus on protecting priority sectors.
9 Emphasize measures that are sustainable over time.
10 Assimilate mitigation into normal practices.

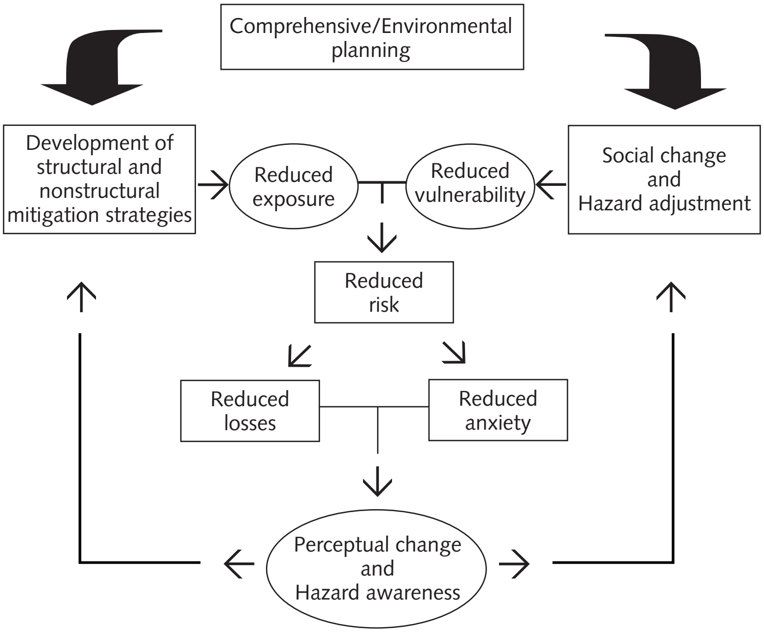

Fig. 6.8 The planning with hazards model.

11 Incorporate mitigation into specific development projects.
12 Maintain political commitment.

Summary

Natural processes often present risks and hazards to humans and should influence the form and location of development. As important responsibility of the environmental planner involves identifying the type and incidence of natural hazards common to the planning area and communicating the risks associated with each to decision-makers. A selection of natural hazards were reviewed in this chapter with a focus on their origins and consequences. From this discussion the concept of risk was introduced and the uncertainties inherent to risk assessment methods were examined. The chapter concluded with a treatment of the planning approaches available to better manage risk and reduce the adverse effects of hazardous events.

Focusing questions

How is risk different from a hazard?

Events that represent hazards have important characteristics. What general characteristics do hazards share?

Which hazards presented in this chapter are common to your planning area and what methods have been used to communicate the risk associated with each?

What does it mean to plan with hazards and how does this depart from traditional planning approaches?

Discuss the role of uncertainty in risk and hazard management: what effect does it have on policy-making?