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Geology in Environmental Management

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Chapter 1: Geology in Environmental Management

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Abstract

From the geological perspective, the two overriding environmental management concerns are the destructive impact of hazardous natural events on human health and property and the deleterious impact of human activity on the natural environment. The knowledge derived from the geological sciences serves as the basis for a more enlightened approach to the reduction of unnecessary risk involved in the siting and construction of buildings and transportation networks, as well as the extraction of natural resources and waste management. Armed with such knowledge along with political sensitivity, environmental managers will have opportunities for positive social impact in negotiating the challenges as they weigh costs, risks, and benefits. When considering natural resource and energy issues, environmental managers should foster science-based solutions to maximize resource utilization while minimizing harmful impacts, bearing in mind externalities and long-term consequences.

The chapter provides an overview of key geological aspects of environmental management, illustrating fundamental principles via representative examples. The main geological subjects addressed include volcanic eruptions, earthquakes, coastal processes, fresh water resources, waste management, and fossil fuel resources. They are discussed in tandem with their associated environmental problems and risks.

Key words
volcanic hazards, lahar, earthquake hazards, tsunami, seismic safety, liquefaction, slope instability, coastal hazards, barrier island, flooding hazards, eutrophication, saline lake, groundwater overdraft, sinkhole, solid waste disposal, nuclear waste disposal, coal mining, acid mine drainage, petroleum system, *Deepwater Horizon* oil spill, hydraulic fracturing ("fracking")

1.1 Introduction

From the geological perspective, there are two overriding environmental management concerns: 1) the destructive impact of hazardous natural events on human health and property and 2) the deleterious impact of human activity on the natural environment. This two-way flow of undesirable influence creates a complex web in which the ambitions of groups of people from differing economic and social circumstances come into conflict. The dynamism of Earth's near-surface processes has often caught people unaware, leading to sudden loss of life and livelihood. The knowledge derived from the geological sciences serves as the basis for a more enlightened approach to the reduction of unnecessary risk involved in the siting and construction of buildings and transportation networks, as well as the extraction of natural resources and waste management.

When facing the possibility of a natural disaster - volcanic eruption, earthquake, landslide, flood - the avoidance of hazardous areas is perhaps the simplest and surest protective measure. However, in many cases homes, infrastructure, and even entire cities are built in the line of fire. The aesthetic appeal of a seaside house, favorable farming conditions, and ingrained traditions all motivate residents to remain in potentially hazardous areas. Engineers are able to devise complex and effective defenses, but these are expensive. Since these measures may provide protection for disasters that have not occurred within historic memory, decision makers may be reluctant to mandate them. The tensions between the scientific/technical and the political sides of environmental issues play out in *cost-benefit* and especially, *risk-benefit* analyses (Petroski, 2013), by which the possible rewards to be derived from an activity or policy are weighed against the expense or hazard entailed. One management question that must be considered is: Who pays for damages to private property caused by natural disasters?

This chapter provides an overview of the geological underpinnings of several key environmental concerns. It is neither comprehensive nor encyclopedic, but rather employs illustrative examples to highlight the major environmental management issues presented. It takes the point of view that environmental management should 1) protect populations from undue exposure to natural hazards and 2) protect natural systems from undue *anthropogenic* pressure.

Several of the examples presented are illustrated with aerial or satellite imagery. If the reader is not acquainted with the benefits of and insights derived from the "bird's eye view", observation of familiar places with web-based utilities such as Google Earth is recommended. As an invitation to further exploration, the appendix to this chapter provides the coordinates of all places discussed herein, so that they may be virtually visited at the reader's leisure. Recognizing that this book will be read by specialists from different disciplines, the geological, ecological, and engineering technical terms are flagged with italic type upon first use. The appended reference list to this chapter includes many publications that merit further reading, including several peer-reviewed general review articles along with contributions from journalists succinctly summarizing the political and social implications of the technical issues raised.

1.2 Volcanic Hazards

We will examine two of the principal types of volcanic hazards afflicting urbanized areas. One is the direct, often violent, eruption of *pyroclastic* materials. Unlike liquid lava, pyroclastic debris solidifies at the same time that the volcano ejects it, so that it may coat the ground as a blanket of fine volcanic ash or roar down the volcano's slope as a hot flow impossible to outrun. In an explosive eruption, ash is typically propelled high into the atmosphere and may be transported long distances by prevailing winds. The other hazard type is a *lahar*, in which erupted material such as ash mixes with water, usually during a volcanic disturbance, and destructively flows down river valleys like a fast-moving wall of wet concrete.

1.2.1 Mt. Vesuvius - Ancient Pompeii and Modern Naples

The disastrous eruption of Mt. Vesuvius in ancient Roman times (AD 79) began to capture public imagination during the 18th century, when serious excavations started there. The fascination continued in modern times and the ruined Roman cites of Pompeii and Herculaneum remain popular tourist destinations, having details remarkably preserved by the eruption's massive volcanic deposits (Fig. 1-1). The environmental management aspect of the tragedy leads one to consider why people

Figure 1. Plaster casts of victims of the disastrous AD 79 eruption of Vesuvius. (Photo: Lancevortex; Wikipedia, 2014a)

would build cities near a volcano and how they may best prepare themselves for a possible future eruption, in other words, to contemplate a classic risk-benefit dilemma.

Central western Italy, a fertile region with a pleasant climate and good harbors, would certainly have been an attractive place to settle, then as now. Peoples of the ancient world did not have the benefits of our scientific knowledge base nor the instrumentation that we use to study active volcanoes. Nonetheless, contemporary historical accounts indicate that the AD 79 eruption was preceded by strong earthquakes and it could be presumed that inhabitants in cities near Vesuvius did feel some concern for their safety from time to time. While archeologists estimate that the death toll within Pompeii proper may have been as high as 2000, it is more difficult to estimate how many survived (or at least managed to flee beyond the city limits), perhaps between 6 and 20 thousand. The eruption occurred in two phases. During the initial phase, the city was blanketed with ash fallout (*pumice lapilli*) propelled by a pressurized steam (*phreatic*) explosion. This was followed by several waves of flow deposits (*pyroclastic density currents*) possibly as hot as 400 °C. Many of the victims during the initial phase were sheltering indoors and killed as roofs collapsed under the weight of the accumulating ash, particularly flat or low-angle roofs. The hot pyroclastic currents of the second phase were more thoroughly destructive, killing those who had managed to hide safely during the ash fall. Walls facing the oncoming flow collapsed, while those standing parallel to the flow direction tended to endure. The force of the flow diminished as it progressively demolished wall after wall in its path. Since the "milder" initial phase of the eruption was nonetheless deadly, we may conclude that structures built near volcanoes prone to ash eruptions should, at a minimum, have steeply-sloping roofs (Luongo et al., 2003a; 2003b).

It is instructive to view Mt. Vesuvius and the surrounding urban areas in their spatial context. A map prepared from a satellite image (Fig. 1-2) shows that Pompeii is only about 8 km southeast of the volcanic vent. During the AD 79 eruption, prevailing winds blew the initial ash cloud towards the south, burying Pompeii and hindering evacuation prior to the arrival of the more destructive pyroclastic flows. Although Herculaneum is even closer to the summit, it lies to the west and was spared the brunt of the ash fall, giving most of its inhabitants time to flee in advance of the flows which ultimately engulfed both cities (Luongo et al., 2003a).

To acquire the image used in Figure 1-2, the satellite's sensors recorded *visible light* as well as *infrared radiation*. The colors were added later during image processing and were chosen to give a "natural" look, with vegetation appearing green and urban areas tan to mauve. Water appears black and the few clouds present are white wisps. Close examination of Figure 1-2 allows us to appreciate how near the present-day Naples metropolitan area lies to a still-active volcano and to imagine what might happen if Vesuvius erupts again, this time with a much larger population in the danger zone. While the volcano is intensively monitored for eruption precursors such as earthquakes and ground swelling, prompt and effective evacuation would obviously present a daunting logistical challenge. Mobilization due to a false alarm would lead to widespread consternation, thus decision makers would be under intense pressure while attempting to make the correct call. An excess of caution may also have consequences, as an Italian court sentenced seven scientists to prison for manslaughter for failing to

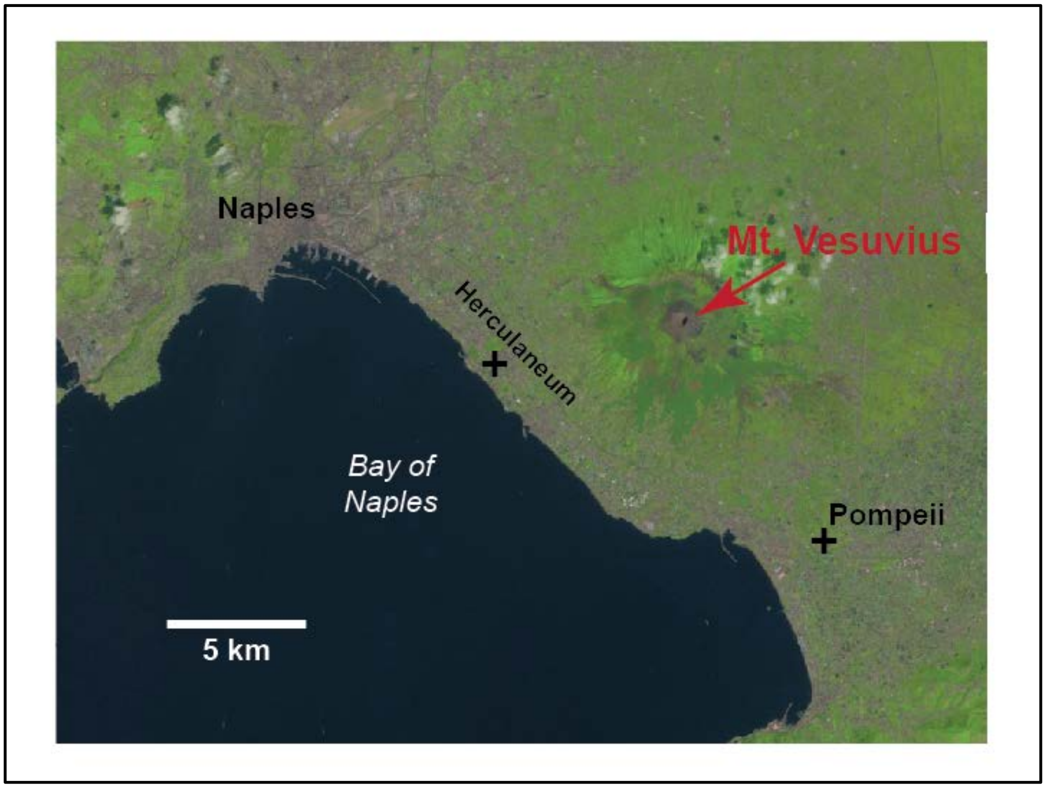

Figure 2. Map showing the proximity of the Mt. Vesuvius volcanic crater to the ruins of Pompeii and Herculaneum, as well as the present Naples metropolitan area. Base: natural color Landsat image from 1999, U.S. Geological Survey. North is at the top of all maps in this chapter unless otherwise indicated.

issue a safety warning in advance of the deadly 2009 earthquake in L'Aquila, Italy (Povoledo and Fountain, 2012).

1.2.2 Volcanic Eruptions and Aviation

While the authorities in Naples are prudent to prepare for a nearby eruption, those in tectonically quiet northern European capitals such as London, Paris, and Berlin do not normally worry about such matters. That changed in April, 2010, during the eruption of Eyjafjallajökull in a remote part of Iceland more than 2000 km to the northwest (Fig. 1-3). While this eruption was considered to be of moderate intensity, prevailing air currents swept a large mass of fine pyroclastic ash over most of Europe, paralyzing commercial air traffic for several weeks. The concern was that the tiny ash particles (< 63 μm in diameter) could cause jet engines to stall in flight, if they are present in sufficient concentration in the atmosphere (> 2 mg m^{-3}). The 2010 eruption began with a phreatic phase, as melting glaciers on the summit of Eyjafjallajökull provided water for the pressurized steam. The resulting explosion propelled pyroclastic debris as high as 11 km into the air, which is roughly the cruising altitude of commercial airliners. Eruptions continued for the next 40 days, with some pulses of ejecta reaching nearly that altitude again. Aside from the immediate concern for passenger and aircraft safety, the environmental management issues in this case are primarily financial, as this eruption caused thousands of flight cancellations and over a billion dollars in direct losses to airlines, with attendant costs rippling through the world economy. Health issues are another factor, as the finer ash particles provoke respiratory ailments at sufficiently high concentrations in air. Nine Volcanic Ash Advisory Centers (VAACs) have been established to provide timely alerts should an eruption anywhere in the world pose a hazard to aviation or human health, based on numerical modeling of eruptive and atmospheric conditions (Langmann et al., 2012).

1.2.3 Lahar Hazards: Northwestern Washington State

Major active *stratovolcanoes*, including Mt. Rainier near the Seattle-Tacoma (Washington) metropolitan area, are formed by alternating eruptions of liquid lava and solid pyroclastics such as ash. Mt. Rainier's last major eruption was about 1000 years ago, but *radiometric* dating methods exploiting the known *half-lives* of radioactive *isotopes* naturally present in its rocks have recognized numerous eruptive episodes which occurred at the present volcanic edifice over the past one million years. While a lava or pyroclastic eruption of Mt. Rainier would be sufficient to trigger governmental disaster response efforts by itself, the flanks of this volcano are also prone to hazardous mudflows (Fig. 1-4). These lahars form as hot erupting material mixes with snow and ice in the mountaintop glaciers, creating a dense, but fast-moving and deadly slurry. Some of the material on the peak of Mt. Rainier has been *hydrothermally* altered during past eruptions in the presence of hot, chemically-reactive fluids. The alteration has weakened these rocks, making them prone to catastrophic collapse during an eruptive disturbance, thus forming another source of lahar material (John et al., 2008).

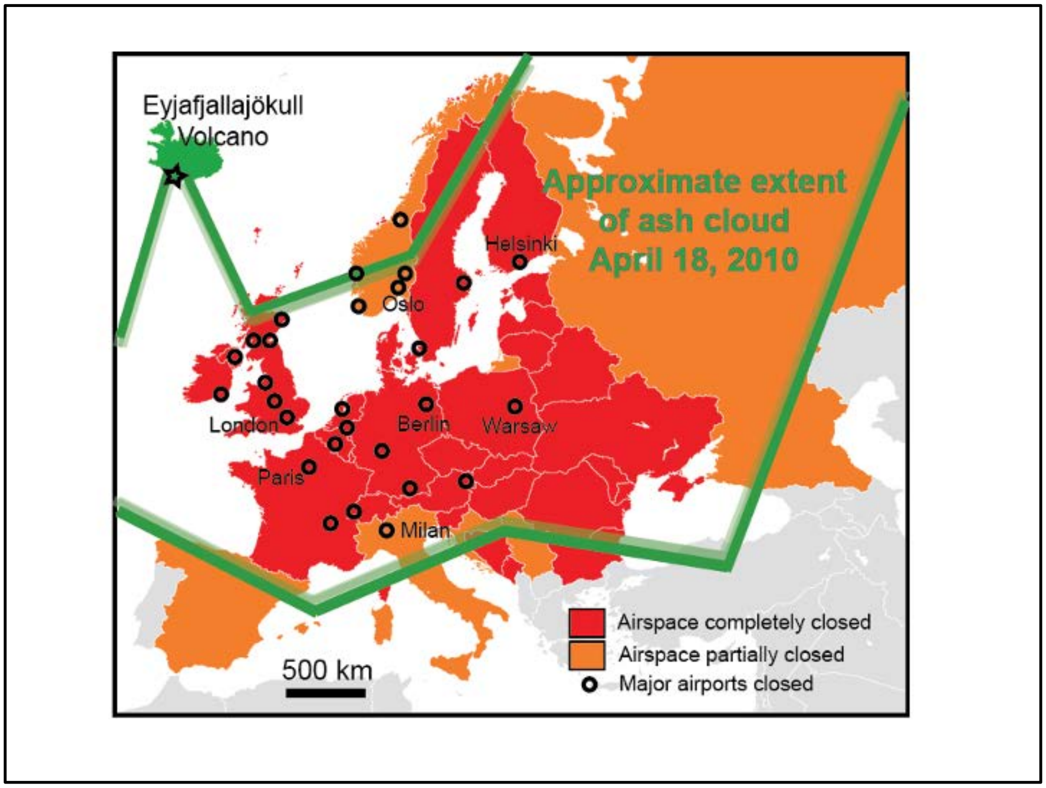

Figure 3. Map showing disruption to European air travel during the 2010 eruption of Eyjafjallajökul on Iceland. Green lines enclose area impacted by the ash cloud on April 18, 2010 (Met Office, 2014). On that day, airspace was completely closed in countries colored red and partially closed in those in orange (Wikipedia, 2014b). Black circles mark major airports closed on the previous day (The New York Times, 2010).

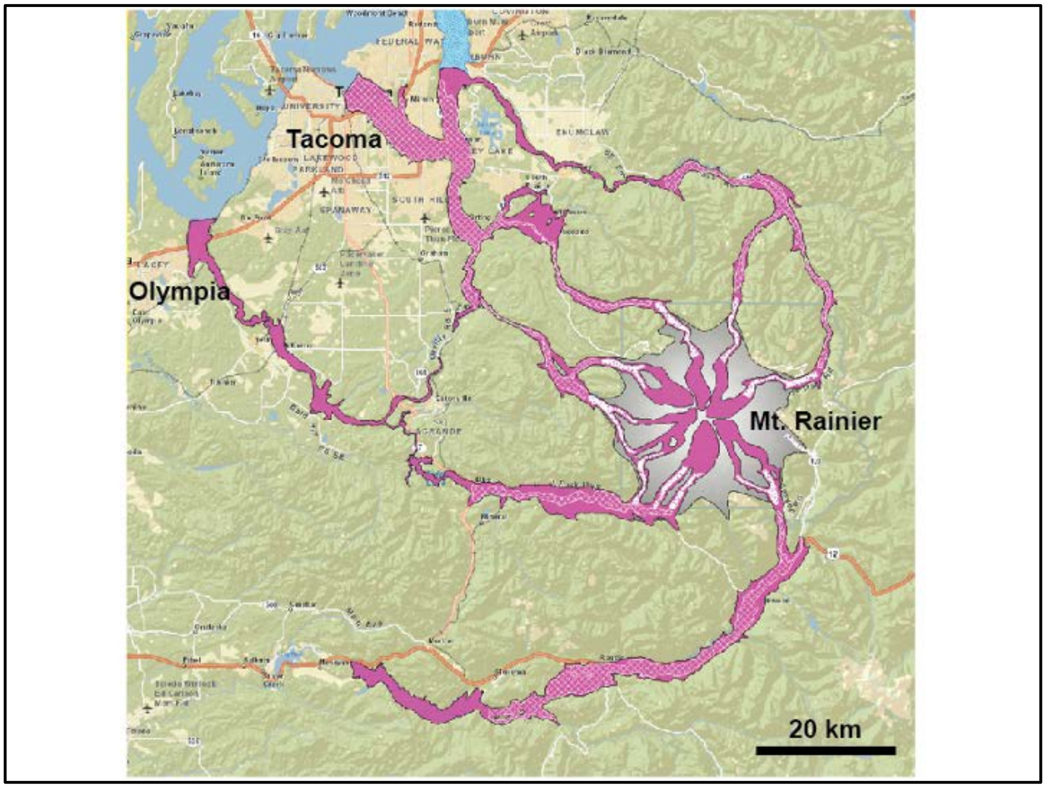

Figure 4. Map showing the lahar hazards in the region south of Seattle, Washington in the event of a volcanic eruption at Mt. Rainier. Solid pink: large lahars with a 500-1000 year recurrence interval. Cross-hatched pink: moderate lahars with a 100-500 year interval. Speckled blue: old lahars buried by younger sediment. Gray: lava or pyroclastic flows. Source: Washington State Geology and Earth Resources Division. (Washington State Department of Natural Resources, 2013).

We can see on Figure 1-4 that past lahars follow existing stream valleys as they descend the mountain, initially radially in all directions, but then turning westward and northwestward towards the coast, unfortunately the most densely populated part of the region. The map distinguishes between major lahar events with a 500 to 1000 year *recurrence* interval and flows that are smaller, but likely to occur more frequently (every 100 to 500 years). Both the magnitude and recurrence intervals are important in assessing risk factors when planning for lahars (or any other type of natural disaster). The destructive power inherent in lahars was evident on Mt. Ruapehu, New Zealand in 2007, during an event that was triggered by a landslide of previously erupted pyroclastic material (Fig. 1-5).

Lahars on Mt. Rainier may be "hot", spawned by active eruptions or "cold", rarer events triggered by landslides. In either case, the downstream communities would be at risk, necessitating early warning systems and evacuation plans. Precursor earthquake activity would herald an eruption and thus also provide a timely warning of an impending lahar. On the other hand, sensors placed along the stream valleys would likely be the only signal of an approaching lahar resulting from a cold landslide, leaving little time for evacuation. In the Seattle-Tacoma region, educating the public about the dangers of lahars and effective emergency procedures forms an integral part of disaster preparedness plans. In addition to residents in their homes, planners must account for workers at their job sites, tourists, and patients in hospitals, as well as commuters and travelers in transit at the time of an event (Wood and Soulard, 2009). Such complexities pose a serious challenge to environmental managers and public safety officials.

1.3 Earthquake-related Hazards

The *tectonic* forces jostling Earth's *lithospheric plates* are the drivers of explosive eruptions at volcanoes such as Vesuvius, Eyjafjallajökull, and Rainier. They are also responsible for earthquakes, which principally occur at the boundaries between tectonic plates. In some regions plates collide, crumpling and twisting into non-volcanic mountain ranges such as the Himalayas and the Alps. In other areas, the results of a collision will entail one plate *subducting*, diving down beneath its overriding opponent. In still other parts of the globe, plates are observed to pull away from each other, forming an ever-widening *rift* in the intervening gap. In a fourth tectonic style, opposing plates slip past one another in a *strike-slip* or lateral motion. We will review several representative examples of earthquake-related hazards provoked by subduction (Japan) and lateral motion (California), along with attendant environmental management considerations.

1.3.1 The Great East Japan Earthquake and Tsunami

Northern Japan sits perilously close to the plate boundary at which the Pacific plate is subducting beneath the far western extension of the North American plate at an average rate of about 9 cm yr^{-1}. In 2011, the powerful Great East Japan earthquake registered a slip of more than 20 m at the plate boundary in a matter of seconds, at its *focus* under the Pacific Ocean about 130 km off the coast of the city of Sendai. Having an extraordinarily high *moment magnitude* (M_W) of 9.0, it was one of the

Figure 5. The 2007 Ruapehu lahar in New Zealand. For scale, note the green picnic table in the lower left corner. (Photo: G. Mackley) (Ra)

strongest earthquakes in recorded history, killing about 17,500 people, as well as destroying coastal municipalities and infrastructure, notably the Fukushima nuclear power station (Lin et al., 2012; Wang et al., 2012). The statistics reflect the extreme misfortune. In addition to the deaths, about a half million residents were rendered homeless, millions lost electrical service, transportation systems were paralyzed, wide areas were contaminated by radioactive materials from the Fukushima plant, and damage costs were expected to exceed $200 billion (Davis et al., 2012).

The sudden, strong vertical motion on the seafloor triggered a powerful *tsunami* with *run-up* heights from 3 to 35 m, depending on the location along the Japanese coast. Roughly 92% of the fatalities due to this earthquake are directly attributable to the tsunami (Lin et al., 2012). Figure 1-6 dramatically illustrates the awesome destructive force involved, which overwhelmed the protective measures that had been in place. Regional planning accounted for strong earthquakes of only up to M_W 7.7. While it is not possible to forecast earthquakes days or hours in advance (as can be done with major storms), long term predictions did foresee an event stronger than M_W 8.0, which perhaps should have motivated planners to further strengthen engineering standards and coastal defenses (Davis et al., 2012). (Note that the magnitude scale is *logarithmic*, such that an M_W 8.0 event releases nearly triple the energy of an M_W 7.7 earthquake and an M_W 9.0 is almost ninety times stronger.)

Disaster management, as a critical component of environmental management, requires long-term planning in advance of a disaster, alertness prior to an event (to the extent that warnings are possible), emergency relief in the immediate aftermath, and continuing recovery efforts. The long-term processes before and after a disaster particularly benefit from environmental awareness, as they involve defensive engineering that should do more good than harm, land-use planning to ideally keep the most vulnerable zones free of buildings and infrastructure, and the establishment of the safest possible evacuation routes (Nakanishi et al., 2013).

1.3.2 California Seismic Safety Standards and Preparedness

The Pacific plate slips northward relative to the North American plate along coastal California from the Mexican border to Mendocino County north of San Francisco. The *right-lateral* strike-slip San Andreas fault delineates this unusual plate boundary and passes through or near to the state's two major urban clusters, each with millions of inhabitants. Major destructive earthquakes have occurred here in historic times, notably the M_W 7.8 San Francisco earthquake of 1906. Since the motion on a strike-slip fault is primarily horizontal rather than vertical, a major co-occurring tsunami is unlikely. Nonetheless, prudent residents remain alert to the possibility of a tsunami originating in other parts of the tectonically-active Pacific rim (Fig. 1-7).

The California Geological Survey (CGS) has been charged by the state legislature with the implementation of its Seismic Hazards Mapping Act. As part of the risk assessment, probabilistic projections constitute a major portion of this effort. Since the future cannot be precisely predicted, modeling the likelihood of a particular event becomes the sensible means for planning in the face of uncertainty. This is a general principle applicable to risk-benefit studies involving all types of natural threats. For example, seismic hazard maps should "show ground shaking levels which have a 10%

Figure 6. The powerful tsunami following the 2011 Tohoku earthquake stranded a ferry boat atop a building in Otsuchi, Japan. (Photo: Yomiuri Shimbun, via Associated Press and The New York Times)

Figure 7. A street sign near the Pacific Ocean beach in San Francisco, California indicating the tsunami evacuation route heading inland towards higher ground. (Photo: M.A. Kruge)

probability of being exceeded in 50 years" (CGS, 2003). In addition to specifying probable occurrence, the regulations stipulate the consideration of seismic source type, earthquake frequency (based on the *paleoseismic* record or geological evidence of past earthquakes), range of earthquake magnitudes, seismic wave *attenuation* or loss of strength over distance at a site, and the extent to which a particular building site will amplify ground motion. All of this is done in the context of the Uniform Building Code and land use policy (CGS, 2004).

1.3.3 Liquefaction Hazards in San Francisco

An additional factor specified in the California seismic regulations (CGS, 2004) is *liquefaction* or the temporary loss of cohesion in water-saturated soils during an earthquake (Holzer et al., 2010). The potential for dangerous liquefaction is evaluated by geologic mapping, examination of groundwater data, drilling of geotechnical boreholes to sample subsurface soils and sediments, and seismic data collection (CGS, 2004). Areas of greatest concern tend to be low-lying and underlain by recently-deposited sediments and particularly by artificial fill often used in the past to convert wetlands into building sites. The results of such studies are summarized on maps, such as the one prepared for San Francisco (Fig. 1-8), on which the zones colored green are at risk for liquefaction. One of these vulnerable areas is the Marina District, where buildings did indeed collapse during the 1989 M_W 6.9 Loma Prieta earthquake (Fig. 1-9). Buildings of a particular size and construction were the most severely affected, apparently as they were by chance most closely attuned to the frequency of the seismic waves and because they were constructed before the advent of modern seismic standards (Sivathasan et al., 2000). Such a map is useful in determining which properties are candidates for seismic retrofitting, how stringent the engineering requirements should be for new structures, and which properties might be too risky to purchase.

1.3.4 Earthquake-Induced Slope Failures in the San Francisco Bay Area

The last criterion specified in the state regulations concerns landslides caused by earthquakes. The objective in this case is to consider slope stability and to compute the *factor of safety* for a given location based upon soil properties (*shear strength*), slope angle, and likely nature of seismically-induced ground motion. Mapping of old landslides is essential, made more effective with the advent of *aerial photography* and other forms of *remote sensing* such as those involving radar. Recent landslides with historical records are the most useful for these purposes. The results of the investigations can then be summarized in map form, such as the blue-shaded zones marking landslide prone areas in San Francisco on Figure 1-8. As might be expected, the likelihood of seismically-induced landslides increases with increasing earthquake magnitude, proximity to *epicenter*, and local shaking intensity (as measured on the *Mercali* s*cale*). Rock fall and slides, as well as soil slides, slumps, and avalanches are among the most common types of earthquake-related landslides (Keefer, 2002).

Housing developments in Daly City, California (just to the south of San Francisco on the Pacific coast) are vulnerable to earthquake-induced slope failures as they were built within or near the San

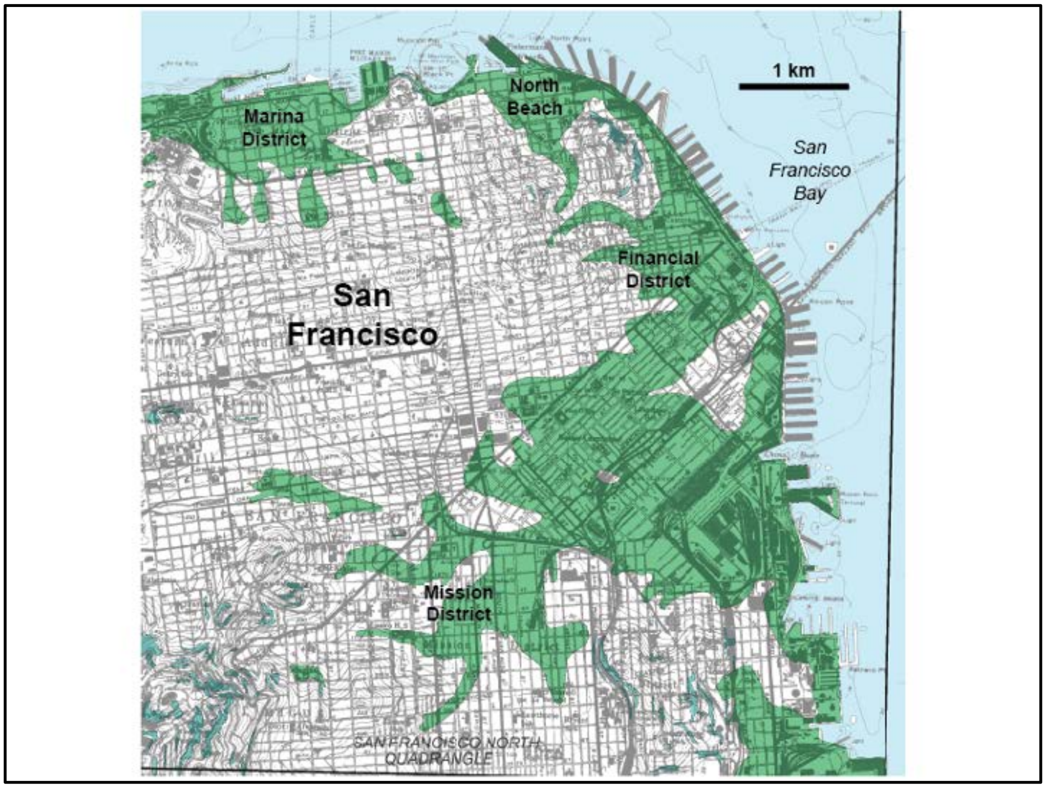

Figure 8. Map showing the zones (in green) within the city of San Francisco that are prone to liquefaction during an earthquake. Blue zones are prone to landslides. (Modified from Calif. Div. of Mines and Geology, 2000)

Figure 9. Aid workers carrying supplies past a collapsed building in San Francisco's Marina District in the aftermath of the 1989 Loma Prieta earthquake. Soils in the Marina District are prone to liquefaction (Fig. 8). (Photo: California Conservation Corps)

Andreas fault zone (SAFZ). A sequence of three aerial images acquired years apart depict the hazards involved (Fig. 1-10). The first image, taken in 1956 prior to the real estate development, provides the context (Fig. 1-10A). The SAFZ trace, shown in orange, trends northwest-southeast across the image. Since this is a right-lateral strike-slip fault, the western block is moving northward relative to the eastern block, expressing a major tectonic feature - the boundary between the Pacific and North American plates at this location. The epicenter of the M_W 7.8 San Francisco quake in 1906 was in the SAFZ only about 5 km north of this location (Chourasia et al., 2008). In 1956, California Highway 1 still ran close to the sea, but was obviously at risk, as a large landslide zone is clearly visible around it. The blue line in Figure 1-10A traces the position of the *scarp* at the head of the landslide as it appeared in 2011. The large light gray patch in the upper center of the image is land that was being prepared for housing construction, which was already underway to the immediate north. The red lines trace the position of the future street grid, perilously close to the scarp in the SAFZ at the bottom of the photo.

Housing construction continued into the 1960's, filling what had been open land with hundreds of closely-spaced homes, evident in the 1968 image (Fig. 1-10B). By this time, the coastal stretch of Highway 1 had been long abandoned due to slope instability and rerouted to the east. In the view from 2011, the three zones marked in yellow indicate places where homes were lost due to slope instability (Fig. 1-10C). An entire half block at zone 1 has been abandoned and demolished, along with the street (traced in yellow), and gaps in the house sequences at zones 2 and 3 are apparent. Looking more closely at site 1 in 2011, the missing section of street (in yellow) and the eerie absence of houses in the fault zone are evident (Fig. 1-11A). A similarly close view of zone 3 shows the gap, wide enough for five houses, their lots consumed by the advancing scarp (Fig. 1-11B). The house marked with the red X at the edge of the gap (Fig. 1-11B) is also marked in Figure 1-12, which shows the details on the ground at zone 3. Close examination of the aerial image from 1968 (Fig. 1-10B) reveals that eight homes planned for the northwestern corner of zone 1 were prudently never constructed, while 24 houses that were built there had to be demolished over the years.

Plagued by cracked walls, collapsed roadways, the potential for ruptured gas and water lines, and worse, the municipality was ultimately obliged to condemn properties at these sites. Conditions worsened after heavy winter rains (particularly intense during episodic *El Niño-Southern Oscillation or ENSO* years) saturated the soil, reducing its load-bearing abilities. Stabilization measures would have proven to be too costly and ultimately likely ineffective. The environmental management process involved a search for funds to buy out long-time property owners as well as working with the residents on a one-to-one basis (Pence, 2000). It should have been clear in the 1950's just from the aerial photograph (Fig. 1-10A) that landslide-prone sites near a major active fault zone were unsuitable construction sites. This raises the environmental management concerns regarding land-use, building codes, and financial responsibility for damages due to natural hazards.

In a relevant European case, owners of a Spanish hotel and adjacent homes destroyed in a 1994 landslide sued local and regional governments for damages. While the buildings had been constructed in a known slide-prone area, the structures had nonetheless been granted building permits that did not require prior geotechnical investigations. The suit against the governmental bodies might have been successful, except that the landslide was triggered by an intense, record-breaking rainstorm which the

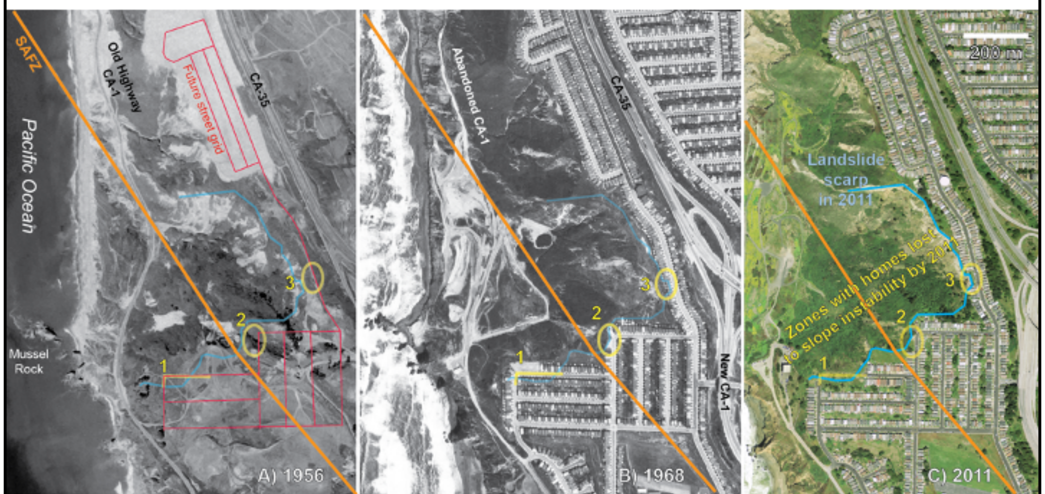

Figure 10. A series of three aerial images showing the landslide-prone coastal district of Daly City, California where the San Andreas Fault Zone (SAFZ, traced approximately in orange) intersects the Pacific coast. A) Taken in 1956, prior to the construction of the housing developments. Calif. Highway 1 runs close to the coast following a former railroad right-of-way. The bright patch of land in the upper middle of the image has been cleared and prepared for housing construction, already underway just to the north. Red lines show the traces of the future street grid. The major landslide along the SAFZ southeast of the fault's intersection with the ocean appears dark gray and is outlined in blue based on the future position of the scarp (Fig. 10C). Zones 1-3 mark the sites of future problems seen in Figures 10B and 10C. B) The view taken in 1993 shows the densely clustered single-family homes completed by the 1960's. The coastal segment (in green) of Calif. Highway 1 seen in Figure 1A has been abandoned due to slope instability and has been relocated to the west side of the image. Close examination of sites 1and 2 reveals missing houses at the edge of the SAFZ landslide while the houses at site 3 are still present. C) At site 1 more houses have been lost along with a portion of the street, as the landslide scarp (in blue) encroached upon the development. The scarp afflicting site 2 is clearly visible, while houses at site 3 are now missing. (Base images: U.S. Geolgical Survey. SAFZ location: Bonilla et al., 1998)

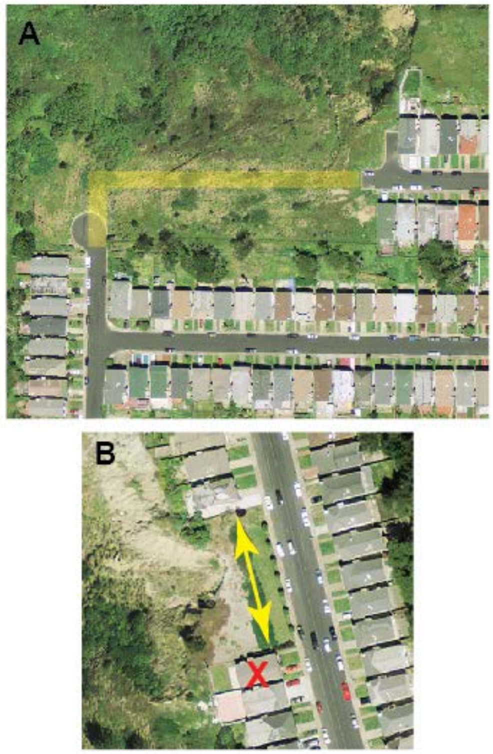

Figure 11. Enlargements of the 2011 aerial image (Fig. 10C) showing details of the Daly City, California landslide area in the San Andreas Fault Zone. Smaller houses are ca. 8 X 14 m. A) Site 1 showing missing houses and street (traced in yellow) at the head of the scarp. B) Site 3 showing a gap (yellow arrow) wide enough for five houses and the encroaching scarp. House X is one marked in Figure 11. (Base image: U.S. Geological Survey)

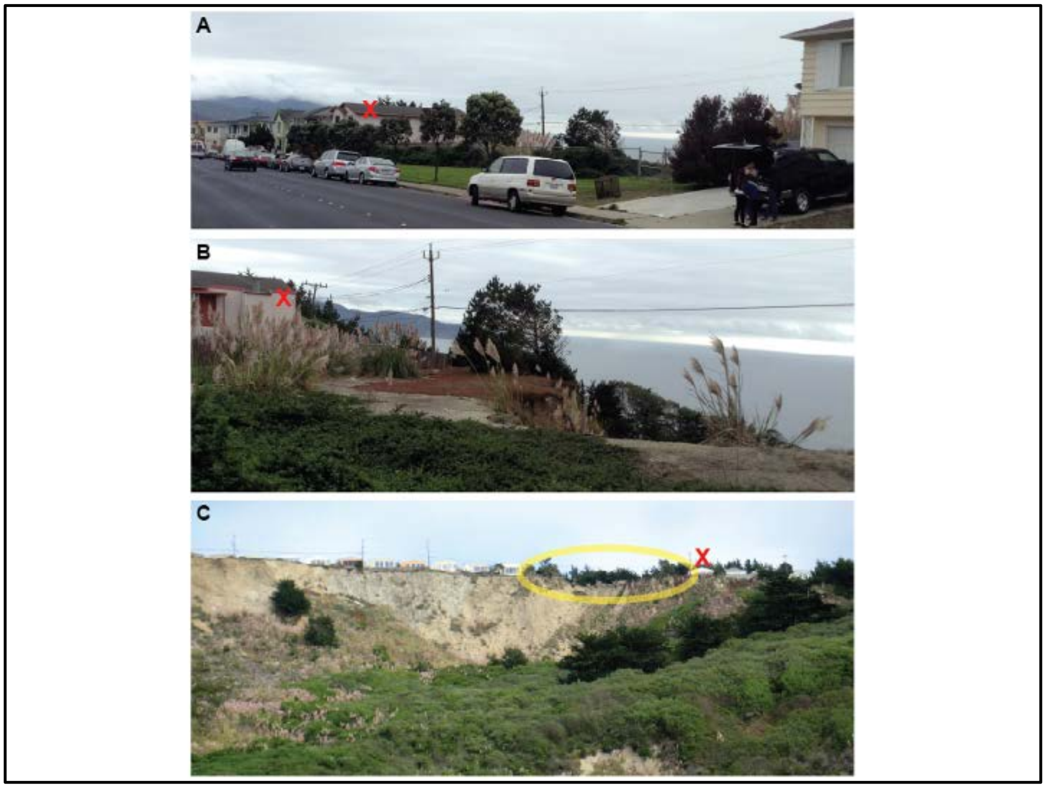

Figure 12. Photographs (Daly City, California, 2013) showing the area of missing houses at site 3 in Figure 10C. For reference, the house marked with the red X is the same in all three photos. A) View from the street looking southwestward towards the ocean showing an odd gap in the pattern of closely-spaced homes. B) View at the site itself showing the advancing head of the scarp. C) View of the gap (marked in yellow) looking upward and eastward from the base of the landslide. (Photos: M.A. Kruge)

court ruled to be *force majeure* (an "act of God"), thereby relieving the defendants of responsibility in this instance (Montoro Chiner, 1997).

1.4 Coastal Processes and Environmental Management

Coastal regions not threatened by major volcanic or seismic events may nonetheless be exposed to significant risks. Urbanization may encroach upon zones vulnerable to storm damage, exacerbated by the prospect of rising sea levels due to *global climate change* (Gornitz et al., 2001). Narrow highways on populated *barrier islands* and *spits* may prove to be inadequate evacuation routes in the face of an approaching major storm. The population of shore areas may swell with vacationers and temporary residents during warmer months, complicating emergency procedures should dangerous weather events require them. In spite of potential hazards, the beauty of coastal areas make them attractive to visitors and property owners alike. Inevitably, complex environmental management issues arise, such as the conflict between the need for public open space and private property rights.

1.4.1 Coastal Sediment Transport Dynamics and Engineered Shore Structures

Frequent visitors to a coastal area may casually notice changes at a familiar beach, such as losses of sand after a winter storm. Residents of seaside vacation homes often demand governmental protection of their private property, by means of *beach nourishment* (sand replenishment), *dune* construction, or installation of durable *groins*, *jetties*, *sea walls*, *breakwaters*, and *revetments*.

The Atlantic shores of Long Island (New York) and New Jersey offer good examples of human interaction with dynamic coastal processes. For instance, in Atlantic Beach, New York, a series of groins was constructed along the beach to protect it from marine *erosion* (Fig. 1-13). Each groin was formed by piling large boulders in a line about 70 m long reaching out into the sea, spaced at intervals of about 200 m. At this location on the south shore of Long Island, the *longshore current* moves from east to west (right to left in the image), in turn transporting sediment (*longshore drift*) along the beach in the same direction. The groins, affixed perpendicularly to the shore, interfere with this process and thus sand accumulates on their *updrift* (east) sides, while sand is removed from the *downdrift* sides. If groins are correctly sized and spaced, they should have the intended overall effect of capturing the laterally migrating sand, protecting the beach as a whole. However, adjacent unprotected beaches, particularly those downdrift of the groin field, may suffer increased erosion, a case of "robbing Peter to pay Paul" (Kana, 1995; Gornitz et al., 2002).

The *sediment budget* is of great concern to coastal planners, particularly along the eastern seaboard of the United States, who are in many instances compelled to repeatedly undertake expensive artificial beach nourishment operations when the natural sand supply fails to keep pace with erosion. Montauk Point, New York, forms the easternmost tip of Long Island's South Fork, jutting out like the prow of a ship into the open Atlantic Ocean. This narrow peninsula is an eroding *headland* and is a principal natural source of sediment for the Long Island beaches to the west (McBride and Moslow, 1991). Like all of Long Island, Montauk is comprised of poorly-consolidated *glacial till* and *outwash*,

Figure 13. Aerial view of Atlantic Beach, New York, in 2010 showing how groins perturb patterns of sand deposition on the beach. The four groins in this photo are the dark, linear features perpendicular to the shoreline about 70 m long, constructed by piling large boulders. Sand is being transported westward by the longshore current (from right to left in the photo) and accumulates preferentially on the east sides of the groins, while the west sides are correspondingly starved of sand. (Base image: U.S. Geological Survey)

abandoned in place as the leading edge of the continental ice sheet began to melt back, some 20,000 years ago during the Pleistocene Epoch (Kana, 1995). The 18th century lighthouse at Montauk Point, commissioned by President George Washington, is an important historical landmark and continues to provide navigational guidance. Its site is highly vulnerable to erosion by deep ocean waves approaching from the east and south, so environmental engineers undertook to preserve it by cloaking the soft glacial bluffs at its base with a massive, high revetment of large boulders (Fig. 1-14). Revetments are not a permanent solution in dynamic coastal settings and they require periodic maintenance and replacement of displaced boulders (Yang et al., 2012).

A prominent feature of the Atlantic coast from Long Island to Florida is the presence of numerous long, narrow barrier islands and spits oriented parallel to the mainland. Both are similar in their appearance, sediment dynamics, and environmental issues, except that spits are peninsulas attached at one end to the mainland. Atlantic Beach (Fig. 1-13) sits on Long Beach, one such barrier island. To the east lies Fire Island, measuring some 50 km from east to west, the longest barrier island in the New York/New Jersey region (Fig. 1-15). A barrier island separates the open ocean from a *lagoon* (here the Great South Bay), on the other side of which sits the mainland. As is typical of a barrier island or spit, Fire Island is very narrow: a half kilometer or less along much of its extent. The sea connects with the lagoon via inlets at both ends of the island, which are important conduits for tidal transport of sediments in both directions (Leatherman, 1985; Kana, 1995; Lentz et al., 2013). Inlets are ephemeral features and will tend to migrate laterally along the island as a function of sediment transport, in this instance the predominantly westward longshore drift. Historical records document that Fire Island Inlet migrated 8 km towards the west between 1825 and 1940, at which time engineers constructed a rock jetty at the western margin of the island to "lock" the channel in place for navigational convenience. As with other such artificial hardening measures, this produced unintended consequences and created the need for continual maintenance, in this case dredging the sand deposited by the westward drift (Leatherman, 1985). Sediments also migrate westward through the lagoon, entering via Moriches Inlet and exiting at Fire Island Inlet. There they accumulate as an *ebb tidal delta*, left behind by the falling tide just seaward of the inlet. In addition to the headlands to the east, Pleistocene glacial deposits a short distance offshore provide a natural source of sediment (Lentz et al., 2013).

Fire Island constitutes part of the Gateway National Seashore, which entails a complex framework of land management issues, as the island has wilderness areas, federal, state, and county parkland, and private communities. While new hardening measures are forbidden, beach replenishment and *beach scraping* (to obtain sand to enlarge protective dunes in residential zones) are ongoing. Dredging of inlets and offshore *borrow pits* provides the material for beach nourishment (Lentz et al., 2013). These artificial means are employed since the sand budget reflects a deficit, i.e., the rate of erosion for the system as a whole exceeds the natural sediment supply (Kana, 1995). Sand suitable for replenishment is becoming increasingly difficult to acquire along the U.S. Atlantic Coast, leading in some cases to conflict between neighboring communities. Officials in Florida have in fact proposed using crushed recycled glass as a sand substitute (Dean, 2012; Alvarez, 2013).

1.4.2 Coastal Sediment Transport Dynamics in Response to Major Storms and Sea Level Rise

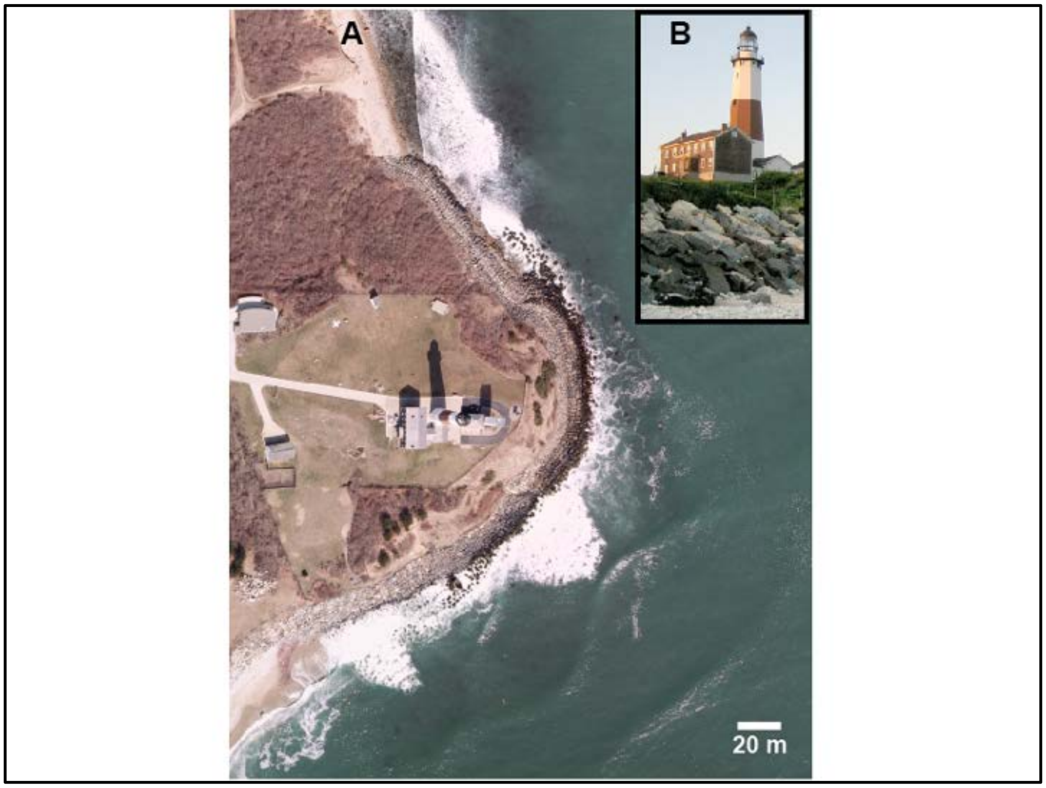

Figure 14. At Montauk Point, New York the historical landmark lighthouse is protected from the Atlantic Ocean by a massive revetment of large boulders. A) Aerial view from a 2010 high resolution orthophoto (U.S. Geological Survey). B) View looking northward from the beach in 2011 (Photo: M.A. Kruge).

Figure 15. Satellite view of south-central Long Island, New York in 2013 showing Fire Island. This barrier island was breached (where marked by yellow oval) in 2012 during Hurricane Sandy. (Natural color Landsat image: U.S. Geological Survey)

Coastal barrier islands are impermanent features, subject to landward migration (*"rollover"*) in response to sea level rise. In the absence of a human population, the ocean beach would continue to exist, progressively repositioned closer to the mainland, as the lagoon either shrank or *transgressed* in turn upon the shore behind it. Environmental management issues arise when buildings and infrastructure are placed on an ephemeral entity, particularly one that might appear relatively stable for years (Gornitz et al., 2002). Barrier island rollover is episodic, most dramatically in evidence after a major storm event, during which the narrow island may experience *overwash* in which powerful, storm-driven waves completely swamp a segment of the island. These waves erode the ocean beach and transport the sediment all the way across the island to the lagoon, in effect shifting the island's position bit by bit (Lentz et al., 2013).

Hurricane Sandy struck coastal New York and New Jersey in 2012 while it was in its *post-tropical cyclone* phase, having migrated northward from its tropical zone of origin retaining tremendous strength. In part due to seabed morphology, the eastern portion is the most overwash-prone section of Fire Island (Leatherman, 1985; Lentz et al., 2013). Indeed, Hurricane Sandy opened a new inlet there some 260 m wide, at a locality unsurprisingly called Old Inlet (yellow oval, Fig. 1-15). It remained open in 2013, noticeably improving water quality in the lagoon due to increased water circulation (Foderaro, 2013). Engineers normally close new inlets quickly, since they counteract beach nourishment measures, transporting sand from the ocean beach to the lagoon to form *flood tide deltas* on the bay side of such inlets (Kana, 1995).

While there were no structures damaged during the formation of the new Fire Island inlet, that is unfortunately not always the case. During a 1992 *extratropical cyclone* (locally known as a *nor'easter*), overwash on the barrier island at Westhampton (just east of Fire Island) destroyed 60 homes. The resulting breach was soon filled and new homes were built on the very spot. That location lies immediately downdrift of a large groin field, which may increase its vulnerability (Gornitz et al., 2002). In Mantoloking, situated on a narrow spit along the New Jersey shore, Hurricane Sandy overrode beach dunes, heavily damaging beachfront properties and flooding homes on the lagoon side (Fig.1-16). While the adjacent municipality of Bay Head was also flooded, the destructive force of the storm waves was moderated by a forgotten 130 year old stone seawall hidden beneath the town's coastal dunes, illustrating the advantage of well-built hard coastal defenses at least for the properties directly protected by them (Irish et al., 2013).

Large-scale hard defenses, such as those in the Netherlands or the MOSE project in Venice, Italy, represent one extreme in coastal environmental management, with its advocates proposing a similar approach for the New York region (Ghezzo et al., 2010; Kleinfield, 2012). Property owners often clamor for smaller scale hard structures (stone groins, seawalls, etc.) to protect their slice of the coast. However, armoring may have deleterious side-effects, increasing the erosion rates on adjacent beaches as was discussed above. Beach nourishment and dune enhancement are effective, softer measures, but are only temporary and must be repeated. Stricter building codes are obviously beneficial in stipulating the elevation of structures and mechanical systems for new construction as well as retrofits. Building owners in New York City who voluntarily exceeded existing code requirements fared better in

Figure 16. Oblique low altitude airphoto looking westward at Mantoloking, New Jersey in the aftermath of Hurricane Sandy, 2012. The houses in the foreground face the Atlantic ocean. The streets between the rows of houses are flooded and littered with debris. The flooded houses in the background are on the lagoon (Barnegat Bay) side of the narrow peninsula, only about 200 m wide at this location. (Photo: U.S. Air Force)

Hurricane Sandy (Navarro, 2012). While some may consider New Jersey and Long Island beaches to be functionally "infrastructure" due to their importance to local economies (and thus worthy of costly maintenance), others advocate a *strategic retreat* from shore areas, cognizant of an expensive and ultimately futile battle in which nature has the advantage (Pilkey, 2012; Dean, 2013).

All of this is occurring in the context of ongoing sea level rise in the New York City region, which locally totals about 2.7 mm yr^{-1} (half of which is due to global sea level rise, the remainder to local land *subsidence*). The rate is expected to increase throughout the 21st century according to global climate projections. Even if major storms do not increase in intensity or frequency, they will wreak greater destruction in low-lying areas, since a higher base sea level will increase the likelihood of flooding. Costs for coastal protective measures, be they hard or soft, will likely increase under this scenario (Gornitz et al., 2002). The legal challenges involved will likely be complex and divisive. An example is the proposal by Titus (1998) for *rolling easements* by which shore property owners would not be allowed to employ durable measures against sea level rise, thus preserving public access to the water as the private lots receded. In the U.S., this would no doubt lead to a contest between those claiming the primacy of the constitutional proscription of "takings" and those favoring the common law tradition of open waterfronts. As in regions confronting volcanic and seismic hazards, effective environmental management of vulnerable coastal areas will demand broad-based knowledge, wisdom, and political skills.

1.5 Environmental Management of Rivers and Lakes

Rivers and lakes are economically important as sources of drinking and irrigation water, as navigation routes, as fisheries, and as tourist destinations. Their banks and shores host numerous human settlements, large and small. Rivers have commonly been a source of hydropower, from traditional water wheels to large, modern hydroelectric plants. Artificial canals and reservoirs may also be included in this category.

Episodic flooding by rivers has caused great loss of life and destruction of property. Droughts will reduce river flows and lake levels, impairing the activities enumerated above. All types of terrestrial surface water bodies may be afflicted by industrial and urban pollution. *Eutrophication* (excess of aquatic nutrients) of lakes, reservoirs, and lagoons can produce noxious algal blooms.

In the case of these important water resources, effective environmental management, as always, would both protect the environment from undue anthropogenic pressure and reduce environmental risks to inhabitants.

1.5.1 Flooding Hazards

In 1955 Hurricanes Connie and Diane struck the northeastern United States several days apart. The *runoff* from the storms surged down river systems in Connecticut. The heavily industrialized Naugatuck River valley was among those strongly impacted. Factories including rubber, brass, and steel rolling mills dotted the river's *flood plain* and many were quickly overwhelmed by the rising waters (Fig.

1-17). This event provides us with a compact case study of engineered responses to flooding hazards. As with the California landslide problem, it is instructive to view aerial images in sequence, in this case before and after the 1955 flood (Fig. 1-18). The views, taken in 1949 and 1972, show the same 1.5 km stretch of the Naugatuck River in the small industrial city of Ansonia, depicting roads, railways, factories and housing. The flood plain ("u", Fig. 1-18A) on the inside of the river's broad *meander* had been wisely left largely vacant prior to the flood, but other low-lying areas (e.g., "t" across the river) were densely developed with commercial and residential structures. These buildings were heavily damaged by the flood, so they were all condemned, demolished and replaced by a shopping center, smaller commercial establishments, and a new street pattern ("t", Fig. 1-18B). The roadway bridge ("v") at the bottom of the images was replaced by a more substantial one after the event. Most notably, an intensive engineering intervention drastically modified the river along this stretch. A straightened and widened channel, a massive concrete and stone revetment on the west bank ("x"), and high concrete *flood wall* on the east bank ("y") are clearly evident in Figure 1-18B. The small *tributary* stream on the east side ("w") was armored with its own flood wall. A modern sewage treatment plant was established in zone "u" in the flood plain, now protected by the revetment (Fig. 1-18B). More recently, the factories ("s") were demolished and new retail, commercial, and light industrial facilities were constructed in zones "t" and "u", with the confidence provided by the hard flood control structures (Fig. 1-19).

Despite engineered flood control measures instituted on rivers across the United States, flooding continues to exact a toll in lost lives and property. Expert consensus indicates that one of the best remedies is to restrict construction on hazardous flood plains, yet such development persist (Dierauer et al., 2012). Large rivers (e.g., Mississippi and Rhine) are extensively lined with *dikes* and *levees*, hard raised structures designed to confine the flow to the channels during high water events. Channel volume is nonetheless finite and *overtopping* may still occur during extreme cases. One solution is levee *setback*, by which the barriers are rebuilt farther back from the riverbed. This would increase the maximum channel volume (m^3) available during a high flow event and consequently permit a higher flow rate (m^3 sec^{-1}), allowing excess *discharge* to pass safely without flooding. However, structures currently protected could find themselves on the wrong side of a new relocated levee, meaning that *buyouts* would have to be considered in the cost-benefit analysis. Modeling that considers terrain characteristics, historic discharge rates, flood recurrence intervals, and land use would be effective as environmental managers weigh the expense of new infrastructure versus the cost of flood damage that would otherwise be incurred. Since many existing levees along the Mississippi River are aging and in need of repair, now is an opportune moment to consider the alternative of repositioning them (Dierauer et al., 2012).

1.5.2 Eutrophication - "Too Much of A Good Thing"

Nitrogen (N) and phosphorus (P) are nutrients essential for plant growth and are liberally applied to soils as fertilizers in the course of agricultural and horticultural activities. Excess nutrients not absorbed by the cultivated plants may escape via runoff and produce eutrophication in lakes within the *drainage basin*. This nourishment is essential for the growth not only of terrestrial plants, but for

Figure 17. Oblique low-altitude aerial view showing the flooded industrial zone along the Naugatuck River in Derby, Connecticut in the aftermath of back-to-back Hurricanes Connie and Diane in August, 1955. (Photo: Collection of the Derby Public Library)

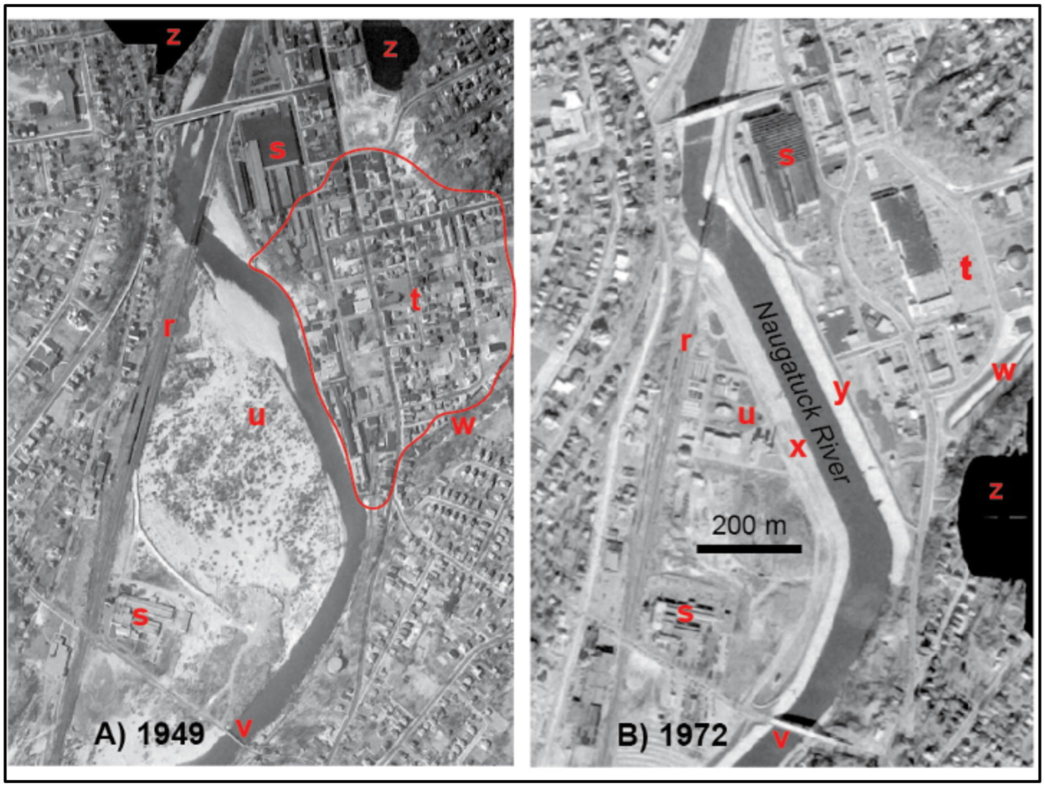

Figure 18. Aerial images of Ansonia, Connecticut showing A) the conditions in 1949, before the devastating 1955 Naugatuck River flood and B) the same area in 1972, after completion of the flood control projects undertaken in response to the 1955 flood. River flow is from north to south (top to bottom in these images). r: railroad. s: large factories. t: low-lying zone demolished and redeveloped as a shopping center and industrial park after the flood. u: flood plain largely vacant before 1955, but later the site of a sewage treatment plant. v: bridge over the Naugatuck River that was replaced after the flood. w: small tributary creek with a flood wall constructed after 1955. x: west bank of the river armored with a concrete and rock revetment after the flood. y: massive concrete flood wall on the river's east bank built after 1955. z: clips used during photographic processing. (Base images: U.S. Geological Survey).

Figure 19. View of the Naugatuck River in Ansonia, Connecticut in 2001, looking upriver, just north of the area depicted in Figure 18, showing the continuation of the rock and concrete revetment on the west bank and the high concrete flood wall on the east bank. (Photo: M.A. Kruge)

aquatic algae and vascular plants as well, masses of which may swell into noxious blooms in waters overloaded with nutrients. Rivers and marine systems can be similarly afflicted, particularly marine and *estuarine* lagoons behind barrier islands in urban areas (Kruge, 2013). In addition to applied fertilizers, the combustion of fossil fuels produces nitrogen emissions into the atmosphere, some of which returns to the surface. Phosphorus has been an important ingredient in household detergents, but many jurisdictions have now mandated reduction in its concentration or elimination from cleaning products. Municipal wastewater effluents contribute both N and P, as do animal manures accumulating in large feedlots. Eutrophic lakes have total N and P concentrations in excess of 650 and 30 mg m^{-3}, respectively, while for marine systems the threshold is somewhat lower and for the moving waters of a river, somewhat higher (Smith et al., 1999).

The sources of N and P (as well as other pollutants) to aquatic systems can be *point* or *non-point*. Point sources are single, discrete locations, such as wastewater treatment plants, waste disposal sites, animal feedlots, mines, and *combined sewer overflows* (CSO's). In environmental management terms, point sources are more amenable to engineered control than diffuse, widespread non-point sources, such as run-off from cultivated lands, pastures, suburban lawns, poorly-functioning septic systems, and construction sites, as well as atmospheric deposition (Smith et al., 1999). CSO's are a particularly vexing problem in cities like New York, which have older systems in which storm sewers are interconnected with the sanitary sewers. During a heavy rainstorm, runoff will overwhelm the system, resulting in the discharge of raw sewage into local water bodies.

In the United States eutrophication is the most common water quality issue and is not merely an esthetic concern or a nuisance. Drinking water may develop taste and odor problems or even health risks, while water intake systems may clog with biomass. Fisheries and tourist-dependent enterprises may suffer losses. In the extreme, blooms may be due to highly-toxic species of *cyanobacteria*. To prevent or reverse eutrophic conditions, reducing nutrient discharges at known major point sources (e.g., by upgrading wastewater treatment plants) is an important and obvious first measure. Since both N and P are limiting (essential) nutrients, it may be sufficient to reduce only one of them below the critical threshold (Smith et al., 1999). However, long-term success may be elusive. For example, Lake Erie (the Great Lake situated between the Canadian province of Ontario and the U.S. state of Ohio) is once again plagued by massive summer algal blooms after decades of successful suppression efforts on both sides of the international border (Wines, 2013a). *Beneficial use* may provide a way to profit from what otherwise is problematic. In one innovative example, algal biomass from blooms in Orbitello Lagoon (Italy) has been harvested as a feedstock for *biofuel* (Bastianoni et al., 2008).

1.5.3 Lakes in Arid Regions

A *desert* is a region in which the sparse rainfall (generally < 250 mm yr^{-1}) is largely lost to evaporation, with little accumulating in streams, in lakes, and underground (Pipkin et al., 2008). Contemporary desert lakes in the western United States are often relicts of much larger freshwater bodies that formed during the cooler, wetter Pleistocene Epoch. As *desertification* proceeds, lake waters evaporate and precipitate mineral salts (*evaporites*), while the residual waters becomes increasingly saline or even *hypersaline*. An example is Mono Lake, a fairly large (160 km^2) hypersaline lake in the high desert of eastern California, the low point in an enclosed drainage basin with no outlet to the sea (Fig. 1-20). It has high concentrations of sodium, chloride and carbonate *ions*, among others, and an alkaline *pH* of about 10 (Jellison and Melack, 1993). Close examination of Figure 1-20 reveals concentric bands parallel to the present lake shore marking higher past strand lines, most visible extending for several kilometers to the northeast.

In 1941, the city of Los Angeles, some 400 km to the south, began to divert freshwater streams in the Mono Basin to enhance its municipal water supply (Jellison et al., 1996). Mono Lake water levels soon began a precipitous decline, dropping 14 m over the next 30 years (Fig. 1-21) and reducing lake surface area by about one third. The ensuing popular outcry eventually had an effect in 1994, when the California State Water Resources Control Board instituted limits on water withdrawals applicable if lake levels fall below 1948 m (Jellison et al., 1998). Since that time, water levels have risen, but they remain the below the regulatory threshold, which in turn is well below the historical lake level maximum recorded during the 1920's (Fig. 1-21).

The higher-than-normal precipitation of the 1982-1983 ENSO event freshened the uppermost layer of lake water (*epilimnion*), while the deeper waters (*hypoliminion*) remained saline, and led to a temporary lake level rise of about 2 m (Fig. 1-21). This *meromictic* state, in which the less dense, fresher waters buoyantly remained "floating" above the denser, saltier water below, induced a *stratification* of the lake waters that persisted for several years thereafter. During this period, the layers in the lake coexisted essentially unmixed and isolated from one other. Nutrients, particularly N, remained in the upper waters, prompting algal blooms (Jellison and Melack, 1993). Ironically, the subsequent rise in lake level due to the water diversion restrictions has triggered a recurrence of meromixis (Jellison et al., 1998). The decision that mandated the 1948 m minimum lake level was evidently the result of political compromise attempting to balance the water needs of Los Angeles with the ecological requirements of a healthy lake system. Although the Mono Lake area is sparsely populated with limited agricultural activity, human influences indirectly perturb the natural system in unexpected ways. It remains an interesting and important challenge for environmental managers.

1.6 Groundwater Management and Karst Hazards

Groundwater (subsurface water flowing slowly through *porous* and *permeable* soil, sediment and rock) is one of the largest sources of freshwater available for use by humankind (Pipkin et al., 2008). Assuring adequate supplies of groundwater, discouraging its overuse, and safeguarding the resource from contamination are all important environmental management concerns. *Karst* topography develops in areas underlain by the more soluble types of *bedrock*, namely, *limestone* and evaporites. Groundwater can slowly dissolve such rocks to form caverns. A cavern may grow large enough to undermine the ground above, which can collapse without warning and form a *sinkhole* that can be large enough to swallow a building.

1.6.1 Groundwater Overdraft - Impact on Agriculture and Municipal Water Supplies

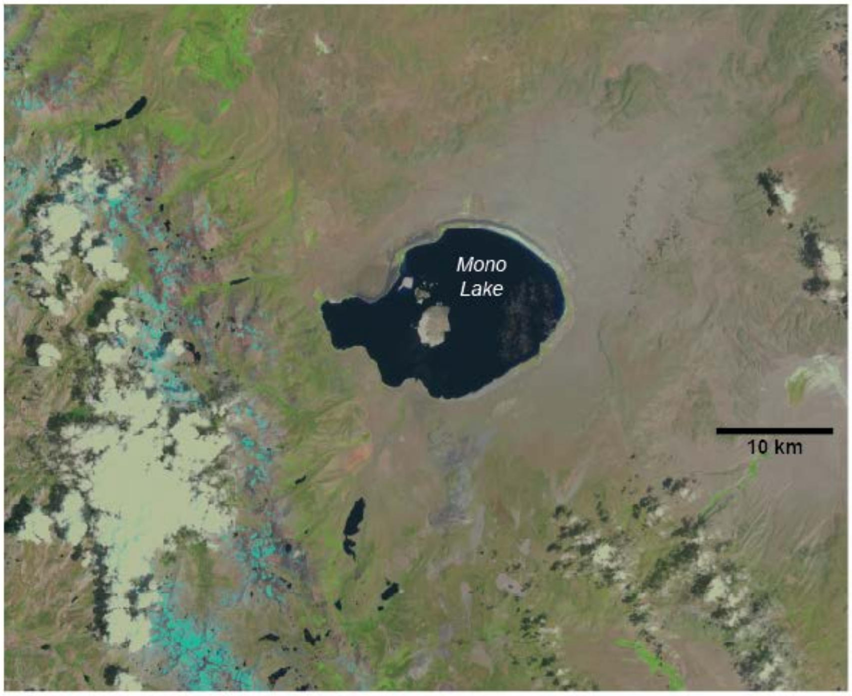

Figure 20. Satellite view of Mono Lake, California and environs in July, 1999. In the false color scheme employed, water appears black, the bare desert surface appears tan shading to mauve in the dry outer margins of the lake bed, vegetation appears green, patches of snow lingering on the high Sierra Nevada mountain peaks along the west side are turquoise blue, and clouds appear white. The shrinkage of the lake due to declining water levels is most visible on its northeastern margin. (Landsat image: U.S. Geological Survey)

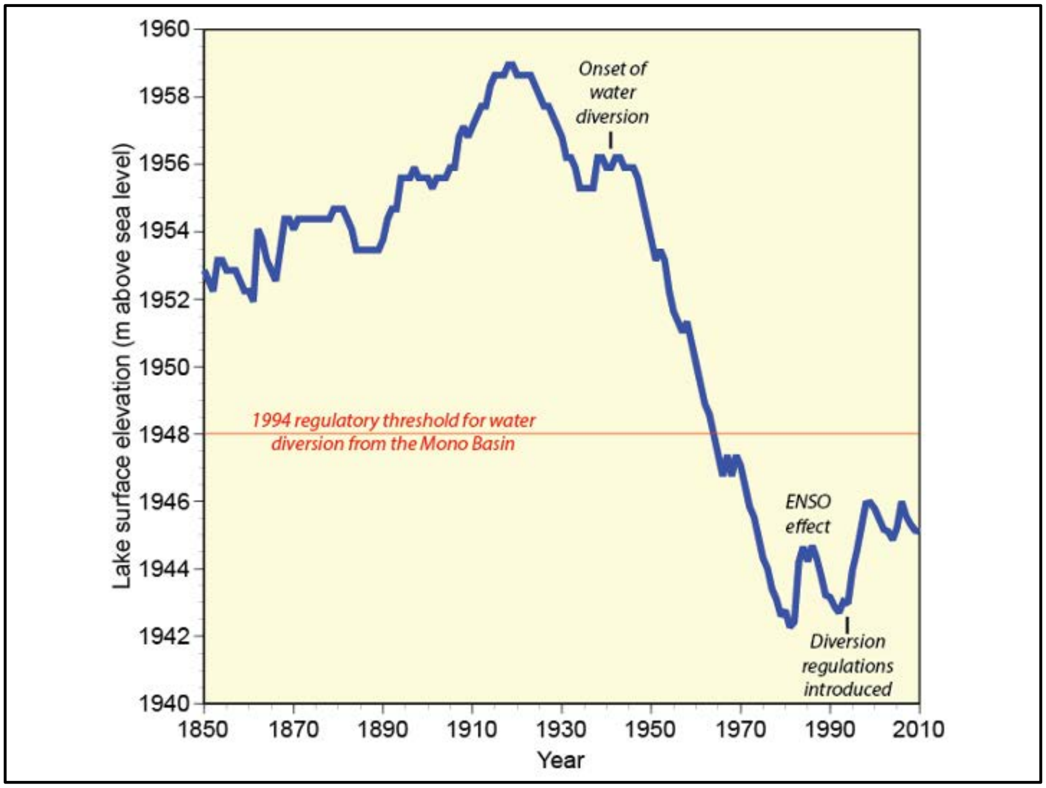

Figure 21. Fluctuations in Mono Lake water levels from 1850 to 2010. (Data source: Mono Lake Committee, Mono Basin Clearinghouse)

Some of the water falling as precipitation on the surface infiltrates into the ground and thereby *recharges* the groundwater resources below. Groundwater migrates in the subsurface, but slowly, on the order of centimeters or even millimeters per day, as it passes through tiny, convoluted *pore* space networks within soil, sediment, or suitable rock such as *sandstone*. The uppermost layer of material encountered generally has both air and water within its pore spaces and is termed the *vadose or unsaturated zone*. Below that the available pore spaces are saturated with ground water within the *saturated zone*. The *water table* is the boundary surface between the unsaturated zone above and the saturated below, moving up or down within the body of the porous, permeable *aquifer* over time as a function of the recharge rate. During periods of heavy rainfall, the water table (i.e., the top of the saturated zone) will rise and may even reach the surface. During *droughts*, the water table will fall and water wells may go dry if they are not deep enough. Ideally, recharge by precipitation or melting snow will keep pace with groundwater withdrawal from wells. Otherwise, conditions known as *overdraft*, *overpumpimg*, or *groundwater mining* may develop, leading to depletion of the resource and possible scarcity.

The productivity of the vast grain fields of the American Middle West has been increasingly sustained by irrigation, which taps into the High Plains aquifer system (also known as the Ogallala aquifer) stretching from Texas to South Dakota. *Central pivot irrigation* systems imprint the landscape in these states with large green circles of growing crops on the order of a kilometer in diameter, easily visible from high-flying aircraft. The increased use of these systems is readily apparent when comparing aerial images taken of the same part of western Kansas two decades apart (Fig. 1-22). In 1991, there were only three circles (highlighted in yellow on the black and white image) irrigated by central pivot mechanisms, whereas by 2010 there were 39 in the same area, some with double the diameter of the earlier fields. A central pivot system operates by withdrawing water from a well drilled in the center of the field. Water is delivered to the crops via perforated piping on wheels that slowly rotates around the well (Fig. 1-23A). The effect on the High Plains aquifer of water withdrawals in Kansas over a 66 year period is a steep and continuing drop in the water table of about 10 m at this location (Fig. 1-23B), indicating that groundwater consumption is outstripping the recharge capabilities of the system. The drier southern areas overlying the High Plains aquifer are being particularly impacted, forcing the reduction or even cessation of irrigation activities and switching from maize to less water intensive crops such as sorghum or to livestock (Wines, 2013b).

Central pivot irrigation is employed even in the arid southwestern United States (Fig. 1-24). This aerial image depicts several irrigated circles (about the same size as the ones in Kansas) under cultivation in the Nevada desert. They are sited in a river valley that remains dry for much of the year, but where the water table is evidently high enough to be reached by wells. Timely groundwater recharge in dry country is not to be taken for granted. Farmers there must be particularly careful to employ *sustainable* practices and avoid groundwater mining, as the water resources that they are exploiting were likely emplaced during the wetter climate of the Pleistocene ice age and thus will essentially be irreplaceable for the foreseeable future (Pipkin et al, 2008).

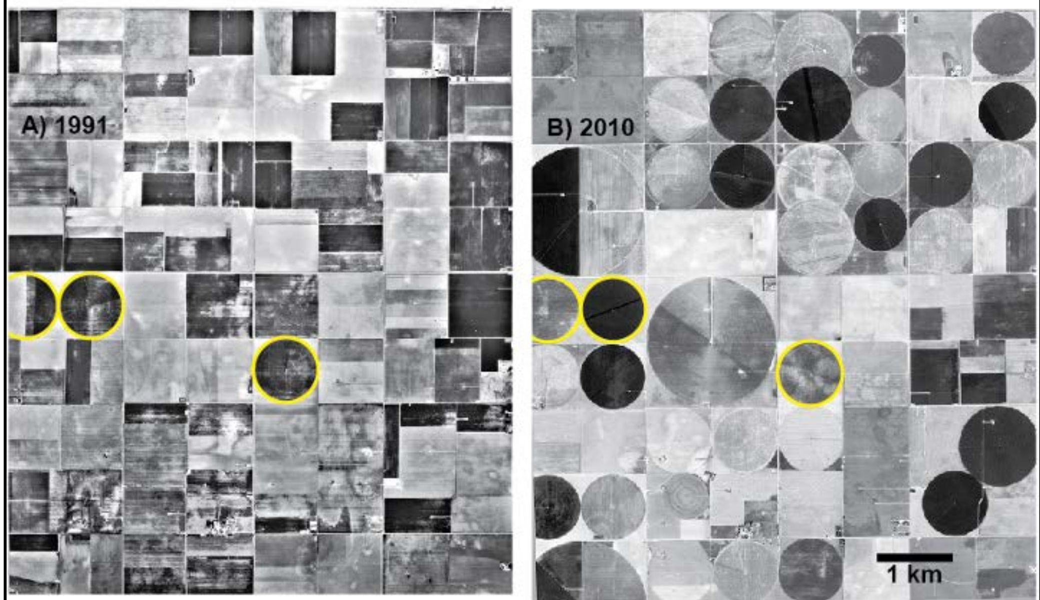

Figure 22. Two aerial images documenting the increased use of center pivot irrigation on southwestern Kansas farms (near Haskell, about 83 km southwest of Dodge City) with water withdrawn from the High Plains aquifer. For reference, the same three irrigated circles are marked in yellow on both images. A) View in 1991. B) View of same area in 2010. (Base images: U.S. Geological Survey)

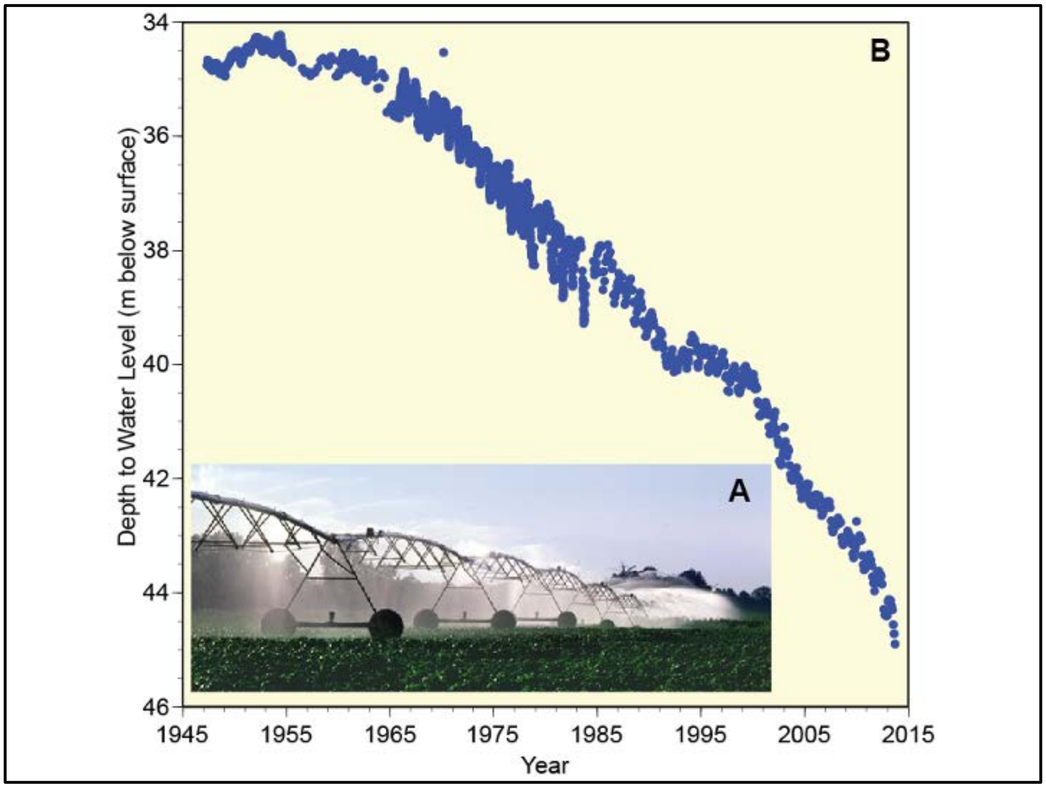

Figure 23. A) Central pivot irrigation system in operation (Photo: U.S. Dept. of Agriculture). B) High Plains aquifer monitoring well data documenting a progressive 10 m drop in water level from 1947 to 2013, Colby, Kansas. (Data source: U.S. Geological Survey).

Figure 24. Oblique aerial photograph of an irrigated zone within a dry river valley in the Nevada desert, 38 km northwest of Tonopah, September, 2013. The large center pivot field (marked by green arrow) is about 800 m in diameter. Note the large thermal solar electrical generating station (red arrow) under construction in the background. (Photo: M.A. Kruge)

The U.S. northeastern states normally have ample rainfall, nonetheless if withdrawals exceed recharge, groundwater overdraft problems will occur there as well. On western Long Island, New York early European settlers produced groundwater from shallow wells in the Upper Glacial aquifer (Fig. 1-25). The aquifer was recharged by precipitation and infiltration from septic systems, but the latter also caused groundwater contamination, which became more severe as the population increased. To alleviate the pollution problem, municipal wells were drilled to tap the deeper Jameco and Magothy aquifers, shielded from surface contamination by the overlying impermeable Gardiners Clay *aquiclude*. The aquiclude also shields the deeper aquifers from ready groundwater recharge from above, resulting in a *hydrologic* imbalance in which deep well withdrawal rates exceeded recharge. The recharge deficit was exacerbated as individual septic systems were replaced by large municipal wastewater treatment plants (which release their effluent directly to the sea precluding recharge) and as suburban developments superseded farmlands, impeding water infiltration with impervious paved surfaces and buildings (Cohen et al., 1968).

As a further complication, freshwater aquifers in coastal regions are particularly vulnerable to salt water intrusion (Oude Essink, 2001). A cross-section running northward 14 km from Atlantic Beach on the Long Beach barrier island depicts southwestern Long Island's four main freshwater aquifers in light blue (Fig. 1-25). The drawing shows the status in the mid-20th century when overpumping was drawing salt water into the freshwater aquifers from the south, intruding as three wedges shown in dark gray and advancing northward as rapidly as 100 m yr^{-1} during the 1950's. Overpumping also created a *cone of depression* in the Jameco Aquifer (highlighted in yellow) such that the wells at that location began to produce saline water, detected during water quality testing as increasing chloride ion contents (Cohen et al., 1968). Queens County was ultimately connected to the New York City surface water reservoir system, thus alleviating their groundwater problems, whereas Nassau County still relies on groundwater and must vigilantly work to avoid contamination and overpumping problems.

1.6.2 Karst Topography and Sinkhole Hazards

Much of the U.S. state of Florida is underlain by limestone bedrock, which is predominately composed of *calcite*, a calcium carbonate mineral. Carbonate rocks are susceptible to slow dissolution by groundwater, the source of which is rainwater that is normally slightly acidic. Sinkholes produced by collapse of caverns in this karst terrain are particularly prevalent in central Florida. A satellite view of the city of Winter Haven is typical, showing dozens of large and small sinkholes (flooded and appearing deceptively as picturesque lakes) within the ≈ 40 km^2 area of the image (Fig. 1-26). Seen from the air, sinkhole lakes have characteristically rounded margins, collectively presenting a "Swiss cheese" appearance in map view. Sinkhole formation mechanisms include direct roof collapse, slippage of unconsolidated soil or sediment into a cavernous void below, and a passive sagging of the surface materials (Gutiérrez et al., 2008a).

The sudden ground failure forming a new sinkhole can be frightening, costly, and even fatal to residents. In 2013, a recently built multi-unit structure at a Clermont, Florida resort complex some 40

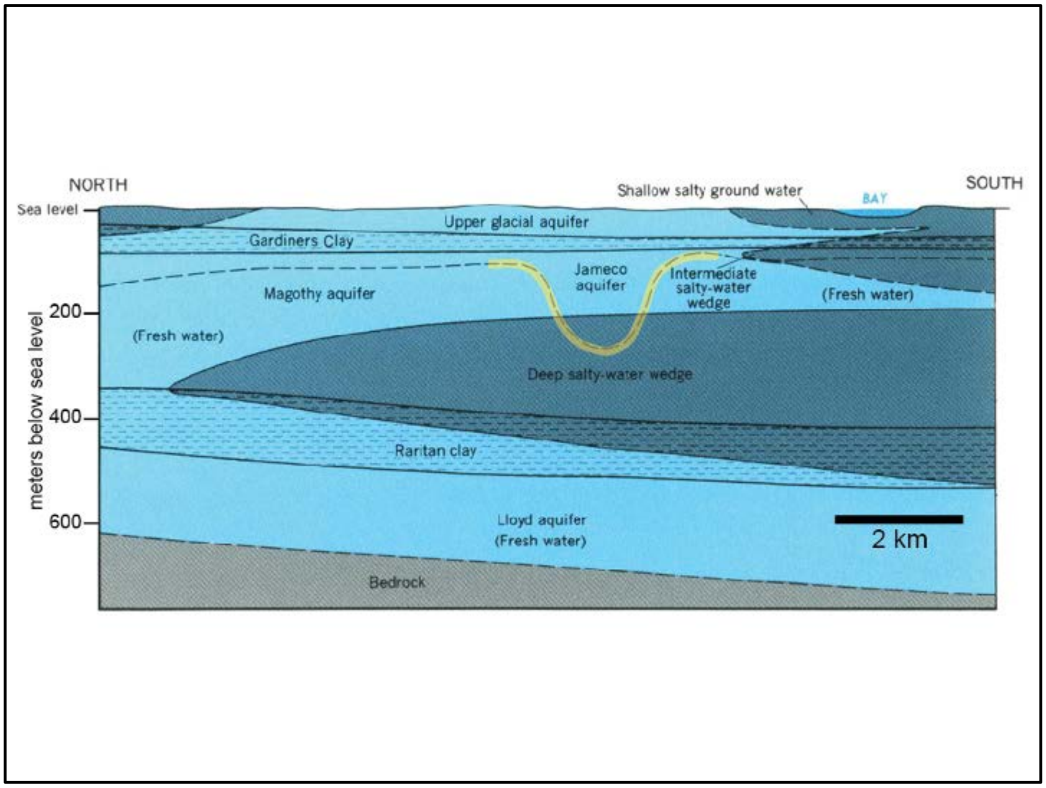

Figure 25. Cross-section illustrating groundwater problems on Long Island, New York in 1961. Three salt water wedges (shallow, intermediate, and deep, shown in dark gray) invaded the Upper Glacial, Jameco, and Magothy freshwater aquifers (light blue) due to overpumping, which also resulted in a cone of depression (highlighted in yellow). The section goes from Atlantic Beach (Fig. 13) northward to Valley Stream. (Modified from Cohen et al., 1968)

Figure 26. Satellite image of Winter Haven, Florida taken in 1994. The "Swiss cheese" landscape is pockmarked with flooded sinkholes forming lakes of varying sizes. In this false color image, water appears dark gray to black and vegetation appears red, while streets and larger buildings appear pale bluish-gray. (Base image: U.S. Geological Survey)

km north of Winter Haven collapsed without warning, fortunately with no loss of life (Liston, 2013). The ruined building (Fig. 1-27) was sited upon terrain that is clearly karstic with many sinkhole lakes in the vicinity (Fig. 1-28). Within the frame of the aerial view, roughly one square kilometer in area, numerous small sinkholes are clearly visible in the image from 1952, prior to any real estate development (Fig. 1-28A). The large lake in the center may have formed by the coalescence of several sinkholes, but further evidence would be needed for confirmation. Six decades later, the resort complex is occupying a swath of higher ground between lakes in the eastern portion of the image (Fig. 1-28B). Some of the sinkholes are less evident, partially obscured by vegetation or fill, but they are still discernable, especially when the two images are viewed side-by-side. The site of the collapsed structure (still intact in Figure 1-28B) is marked by a red rectangle on both images. The environmental management questions become 1) to what extent should the developers have anticipated further sinkhole formation and 2) to what extent the responsible government entities should have restricted construction based on the risk. This then leads to considerations of appropriate building codes, structural retrofitting, insurance, and liability in the event of damages (Zisman, 2013) - essentially the same concerns evoked by earthquakes, flooding, and the other risks presented above.

Evaporites are even more prone to sinkhole formation than carbonate rocks. Common evaporite minerals such as *gypsum* and particularly *halite* (calcium sulfate and sodium chloride, respectively) are considerably more water-soluble than calcite with lower mechanical strength, producing sinkholes that are more active and diverse (Gutiérrez et al., 2008a). Evaporite bedrock underlies about 7% of Spain, where the Zaragoza metropolitan area is particularly vulnerable, having evaporites overlain by permeable *alluvial* aquifers (Gutiérrez et al., 2008b; c). In a recent instance, sinkhole-induced damage to a relatively new apartment building in the Zaragoza area led municipal authorities to condemn the structure and relocate the inhabitants, due to imminent risk to their safety (Portella, 2013). Ironically, the sinkhole in this zone was well-studied, having created problems for decades leading to the demolition of a factory on a neighboring property. The successor building at that site is a department store, constructed on a foundation of deep pilings reaching to solid bedrock below and thus remains undamaged. The affected apartment building was constructed with only a concrete slab foundation (Gutiérrez et al., 2009).

All geotechnical means of sinkhole risk evaluation have their limitations and thus investigations are best done using a combination of methods, using essentially the same tools as are used in paleoseismic and landslide studies. Examination of a series of aerial photographs taken over a period of decades (e.g., Fig. 1-28) and of maps prepared over the years is a logical early step. *Boreholes* should be drilled and the vertical sequence of materials characterized and *logged*. *Geophysical* surveys are non-intrusive and relatively inexpensive. These include *ground-penetrating radar* and *electrical resistivity* measurements. These are particularly effective in conjunction with trenching and together permit 2-D (Fig. 1-29) and even 3-D visualization of the zone (Gutiérrez et al., 2009; Zisman et al., 2013). Another approach employs satellite-based *synthetic aperture radar*, with data from repeated passes of the satellite over the same area processed by differential interferometry to produce high resolution imagery and quantitative measurements of subsidence (Tomás et al., 2014). If sinkhole damage to an existing building is suspected, a forensic evaluation of the structure is also warranted to confirm that the damage

Figure 27. This building at the Summer Bay Resort in Clermont, Florida suddenly collapsed in 2013 when a sinkhole opened beneath it. (Photo courtesy of the Orlando Sentinel)

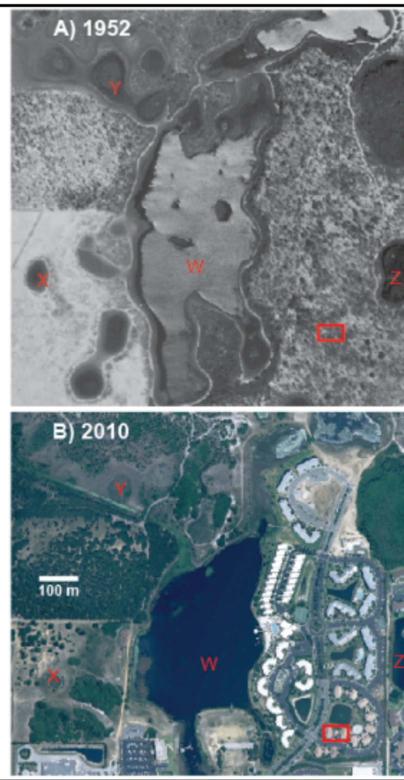

Figure 28. Aerial images showing the distribution of sinkholes on the land surface in the vicinity of the Summer Bay Resort collapse site (red rectangle) in Clermont, Florida (Fig. 23). For reference, three smaller sinkholes (here labeled X, Y and Z) are marked on both images. A) In 1952, the area was almost entirely undeveloped. A large lake (w) with two embayments on its southern end dominates the center of the image. B) In 2010, while much of the land remains undeveloped, the Summer Bay Resort complex occupies the eastern third of the image, constructed upon what appeared to be a solid swath of land in 1952 (Fig. 24A). The large lake (w) has shrunk and the sinkholes x, y and z are less apparent in the later image. Several ponds were constructed amid the buildings, one notably next to the collapse site. (Base images: U.S. Geological Survey)

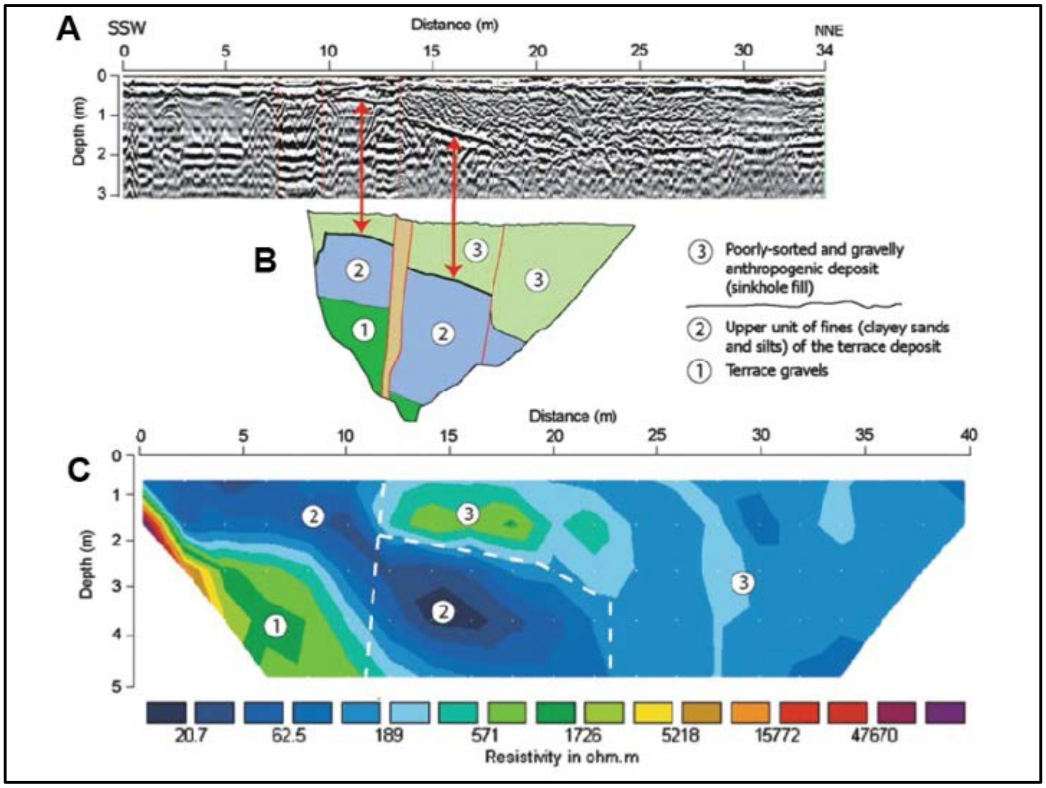

Figure 29. Geophysical methods used in the investigation of a large active sinkhole, Zaragoza, Spain. a) Ground-penetrating radar profile. b) Profile of excavated trench c) Electrical resistivity profile. (Gutiérrez et al., 2009)

is not due to other unrelated factors, which could lead to unnecessary litigation and provide opportunities for unscrupulous building and repair contractors (Zisman, 2013; Zisman et al., 2013). As with all the hazards discussed above, the safest and least expensive risk reduction strategy is to not build in such unstable areas in the first place (Gutiérrez et al, 2009).

1.7 Geological Factors Impacting Waste Management

Human populations worldwide generate an ever-increasing amount of municipal solid waste, estimated at 1.7 billion tonnes per day in 2008, some 95% of which was being consigned to *landfills* (Foo and Hameed, 2009). High level, long-lived nuclear wastes, although produced in much smaller quantities than municipal wastes, pose special and particularly difficult problems of their own. In both cases, potential groundwater and surface water contamination are of paramount concern.

1.7.1 Municipal Solid Waste Disposal and Landfill Leachate

Until recently, the uncontrolled disposal of municipal solid waste by filling low-lying areas or dumping on lands considered to be of little value was a common practice (Foo and Hameed, 2009). A case in point is the now-abandoned Malanka landfill in the Hackensack Meadowlands of New Jersey (Fig. 1-30). Precipitation can freely infiltrate and percolate through the buried waste, leaching contaminants into the groundwater system and surrounding estuary. To avoid the migration of the polluting *leachate* into the environment, it is important to design and construct a properly engineered landfill (Fig. 1-31). When initially siting a landfill, the first considerations include the nature of the host materials and the groundwater dynamics. The landfill should be placed within clay-rich sediments or soil, which functions in the groundwater system as low-permeability, passive barrier to the movement of leachate. However, it should be noted that even very thick, low-permeability, and competent clay units may have very small secondary pathways such as fractures or root burrows that act as significant conduits for contaminant flow (Pankow and Cherry, 1996). A porous and permeable sand layer would be a worse choice, although it could provide limited natural filtration of the leachate. Karst terrain would perform even more poorly, as contaminated groundwater would pass readily through its open subsurface conduit network with little filtration (Lindsey et al., 2010). Once chosen, the site should be excavated and lined with clay and synthetic barrier layers as additional insurance, then with a porous sand layer and piping to collect the leachate. After the landfill has been filled to capacity with waste, it should be sealed with an impermeable upper layer, covered with topsoil and revegetated. As leachate forms, it accumulates at the base of the landfill to be withdrawn via the pipe network for treatment. Wells around the perimeter monitor groundwater quality and for any fugitive leachate (Pipkin et al., 2008).

Aerobic degradation is the initial phase of waste decomposition in a landfill, producing volatile *fatty acids* that *biodegrade* relatively readily. Two of the parameters routinely measured during landfill monitoring (as well as more generally in other environmental investigations) are *biological oxygen demand (BOD)* and *chemical oxygen demand (COD)*. The aerobic phase is characterized by a relatively

Figure 30. Abandoned Malanka Landfill, Secaucus, New Jersey. (Photo: M.A. Kruge)

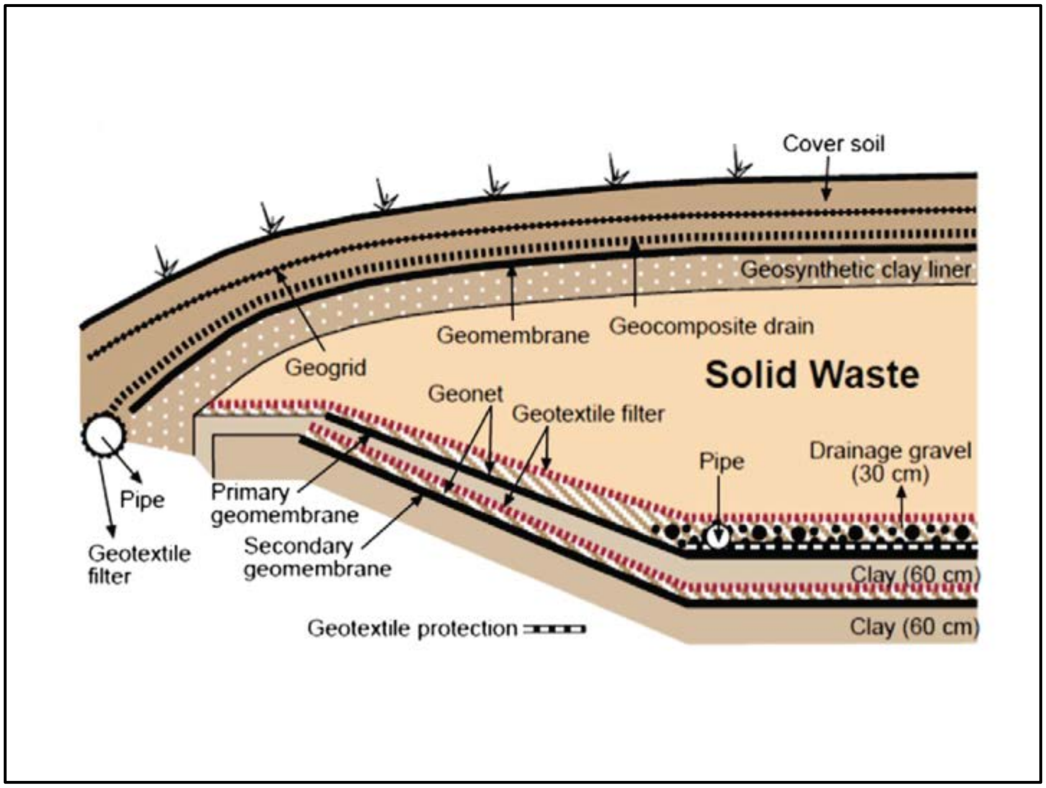

Figure 31. Cross-section of a landfill lined with clay and synthetic materials (geogrid, geomembrane, geotextiles, etc.) to prevent groundwater contamination, with piping systems engineered to collect leachate for treatment (Ersoy et al., 2013). In addition, the decomposing waste can be tapped to produce methane gas, which can be used beneficially as a fuel.

high BOD/COD ratio. Once the available oxygen has been consumed, the *anaerobic* degradation phase begins, favoring *methanogenic* bacteria. The BOD/COD ratio falls and high molecular weight *humic substances* become the dominant organic components (Kurniawan et al., 2006). Microbial methane accumulations may be hazardous, but the gas can be withdrawn via wells in the landfill and beneficially used as fuel.

Associated pollutants in landfill leachate pose additional concerns. These include ammoniacal-nitrogen, *heavy metals* and metalloids (such as As, Cd, Cr, Co, Cu, Hg, Ni, Pb, Zn), and *persistent organic compounds* (including aromatic hydrocarbons, phenols, halogenated compounds, pesticides). The collected leachate must be chemically and physically treated to stabilize these contaminants, employing methods including coagulation-flocculation, chemical precipitation, ammonium stripping, micro-, ultra- and nanofiltration, activated carbon absorption, and ion exchange. The concentrated sludge produced during these steps must in turn be sequestered or destroyed safely (Kurniawan et al., 2006; Foo and Hameed, 2009). From an environmental management perspective, it would be sensible to minimize the need for complex, expensive engineered landfills through composting of organic wastes, recycling, and more sustainable production-consumption systems.

1.7.2 Nuclear Waste Disposal

Nuclear waste presents special disposal problems, as some of the constituent isotopes may have very long *half-lives* and thus remain dangerously radioactive for hundreds or even thousands of years. Radioactive wastes are generated by nuclear power stations (directly and by the associated fuel processing), in weapons production, at research facilities, in industrial processes, and by medical usage. Since there is a great diversity of nuclear waste types, a classification scheme is employed to properly guide the disposal process, based on the level of radioactivity (high, medium, or weak) and the half-life (long, short, or very short). Wastes may include relatively pure substances, contaminated components from decommissioned facilities, or protective clothing and tools that were in contact with nuclear materials (ANDRA, 2012).

The long-term fate of spent nuclear fuel and high-level radioactive waste in the United States remains unresolved, the subject of both scientific research and political controversy. Yucca Mountain, Nevada was chosen by the U.S. Congress in 1987 as the single repository in the country for all such waste, after a decade of site evaluation. It is a ridge of volcanic *tuff* (consolidated pyroclastic ash) situated in the sparsely-populated Nevada desert roughly 120 km northwest of Las Vegas (Fig. 1-32A). The potential migration of *radionuclides* via dissolution in groundwater was a foremost concern during the evaluation. Having currently a semi-arid climate, precipitation at the site is minimal and thus so is groundwater recharge. The thick vadose zone would isolate the subterranean repository high above the present water table, in galleries excavated deep into the mountain (Fig. 1-32B). In addition to these natural impediments to radionuclide migration, the waste would be packaged in robust, impermeable materials to create an engineered barrier to migration (Bodvarsson et al., 1999). Specific factors evaluated included the possibility of future *magmatic* activity at the site, earthquakes, climate change leading to more abundant rainfall, and human intrusion (Rechard et al., 2014a)

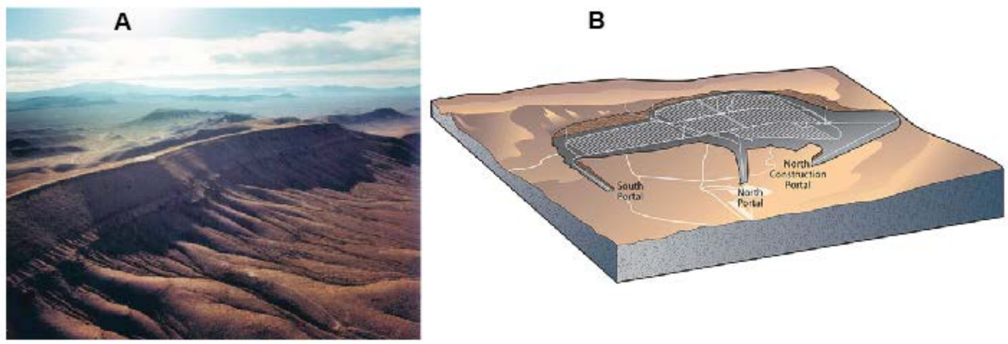

Figure 32. Proposed high level nuclear waste storage site, Yucca Mountain, Nevada. A) Oblique aerial photograph of the mountain. B) Plan of the underground storage site. (Images: Los Alamos National Laboratory)

The initial standard for a disposal site was to limit radionuclide leakage to a 5 km radius over 10,000 years. Later, a more stringent 18 km over 1,000,000 year limit was set (Rechard et al., 2014b). Since 1983, $15 billion has been spent on the evaluation of the Yucca Mountain site and, although the scientific knowledge base was greatly enhanced, political opposition ultimately led to suspension of the project. Evaluation of a new site will not proceed unless it is first welcomed by its host community and sanctioned by local authorities (Rechard et al., 2014c).

1.8 Energy Resource Extraction and Its Environmental Consequences

Our civilization is strongly dependent on the combustion of vast quantities of *fossil fuels* (*coal*, *petroleum*, *natural gas*). One result of their utilization on such a scale is the continuing increase in atmospheric concentrations of the *greenhouse gas* carbon dioxide, in turn observed to provoke global climate change (IPCC, 2007). However, the emphasis in this section will be geological setting of the resources and the environmental consequences of their extraction.

1.8.1 Coal and Coal Mining

Coal *seams* are layered *sedimentary* rocks composed mostly of fossil organic matter, usually derived from ancient *terrestrial* swamp and bog plants. Microscopic examination of coal reveals fossil wood, charcoal, spores, pollen, roots, bark, tree resins, leaves, and algae, along with minor amounts of mineral matter (Killops and Killops, 2005). The ample *bituminous* coal resources in the eastern United States are predominantly of *Upper Carboniferous* age (roughly 300 million years old) with large, economically significant deposits in the Appalachian and Illinois Basins. In addition to more traditional underground mining, coal is also extracted less expensively from large *open-pit* or *strip mines* on the surface in places where the seam is not too deeply buried. Enormous *draglines* remove the *overburden* to reveal the coal, which is then excavated and hauled out of the mine (Fig. 1-33A). Regulations stipulate that after the mine has been closed, the site should be *reclaimed*, with the ground surface restored to its original topographic contour and re-vegetated (Pipkin et al., 2006). Prior to the institution of these policies, mine operators simply abandoned worked-out strip mines, leaving barren piles of *tailings* and flooded pits (Fig. 1-33B).

Some coal seams may contain up to several percent sulfur. These high-sulfur coals were formed when their precursor coastal peat swamps were submerged during periods of sea level rise and the dissolved sulfate in the seawater subsequently reacted with the peat. The coal thus produced contains microscopic crystals of *pyrite* and other iron sulfide minerals, along with various organic sulfur forms (Gluskoter and Simon, 1968). The abandoned tailings of high-sulfur coal mines produce *acid mine drainage*, in which the sulfide minerals are oxidized to sulfate in the presence of the oxygenated surface water:

$$FeS_2 + 7/2\ O_2 + H_2O \Rightarrow Fe^{2+} + 2\ SO_4^{2-} + 2\ H^+$$

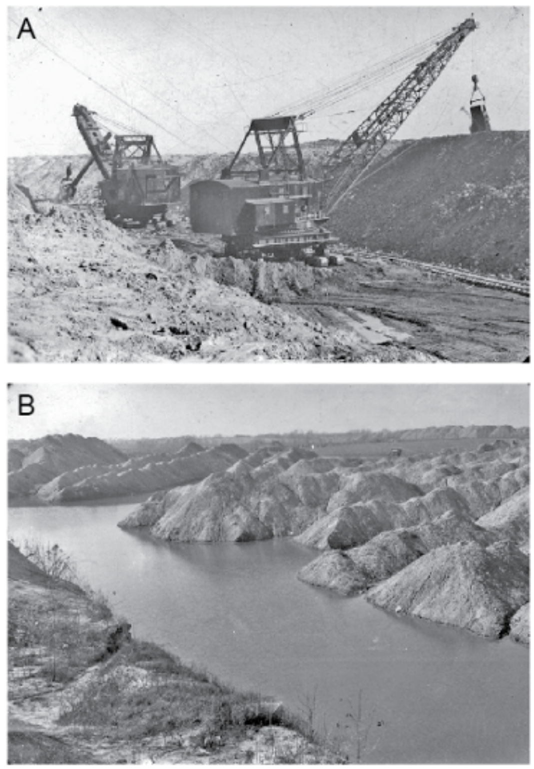

Figure 33. Open-pit coal mine, Wilmington, Illinois. A) Active mining in 1938. B) "Moonscape" of barren spoils piles and flooded pit after the mine was abandoned shortly thereafter. (Photos: G. Langford)

Similar problems arise from the tailings of mines producing copper, lead, zinc, and other metals with sulfide ores (Johnson and Hallberg, 2005; Akcil and Koldas, 2006). The abandoned Will Scarlet open-pit coal mine in southern Illinois is a case in point, flooded with multi-hued acidic waters (Fig. 1-34). It has been deemed one of the worst cases of acid mine drainage in the U.S., with streams nearby essentially devoid of aquatic life. The Land Reclamation Division of the Illinois Department of Natural Resources has been empowered to treat such abandoned properties, but funding is insufficient (Fitzgerald, 2012). Treatment strategies include physical, chemical and biological methods. For older sites that were never reclaimed by their original operators, diverting streams or even groundwater flow may be helpful, although difficult. Chemical treatments seek to raise the pH and precipitate the iron compounds. Lining a streambed with limestone is a hybrid physical/chemical approach (Akcil and Koldas, 2004). Biological treatments include the creation of wetlands, permeable reactive barriers, and iron-oxidation bioreactors. In an instance of beneficial use, iron-rich sludge from an abandoned coal mine was used to produce paint pigment (Johnson and Hallberg, 2005).

Mountaintop removal-valley fill is a more recently developed surface coal mining method, on a dramatic scale comparable to or greater than open-pit mining, especially in West Virginia (Fig. 1-35). To accomplish this, the higher elevation overburden is removed with explosives to expose the coal, then dumped over the edge of the cut to fill adjacent valleys, obliterating or altering the stream drainage and groundwater infiltration systems therein (McGriffith et al., 2012). This has accelerated rates of production of highly marketable coal from low-sulfur seams in West Virginia (Fedorko and Blake, 1998). (In addition to its potential to produce acid mine drainage, high-sulfur coal generates sulfate upon combustion in coal-fired power plants. *Acid rain* will result if the exhaust gases are not *scrubbed* to remove the sulfate. Low-sulfur coal reduces the need for scrubbers.) Arsenic, chromium, manganese, nickel, lead and other trace elements are present in West Virginia coals in mean concentrations ranging from <1 to about 22 mg kg^{-1} (Fig. 1-36). Mountaintop removal mining-valley fill operations may lead to increase *bioavailability* of some of these elements in downstream ecosystems and a possible increase in human birth defects (Pumure et al., 2010; Ahern et al., 2011).

The extent of old subsurface coal mines is often poorly known, a casualty of inaccurate or missing documentation, some mines having been abandoned generations ago. Surface subsidence above such old mines is a continuing environmental issue in coal regions, creating problems reminiscent of those plaguing karst terrains (Fig. 1-37). The Indiana Geological Survey has spent decades creating maps to help combat the hazard, which has damaged homes, schools, and other structures (Blackford, 2012; Harper, 2011). Once a subsiding mine site has been recognized, it can be monitored for continuing movement by instrumentation (O'Connor and Murphy, 1997).

1.8.2 The Petroleum System

Commercial *petroleum* accumulations develop within large, layered *sedimentary basins*. The *petroleum system* is the conceptual framework used currently to understand the occurrence of conventional and non-conventional oil and gas resources in these basins (Hunt, 1996). It has five

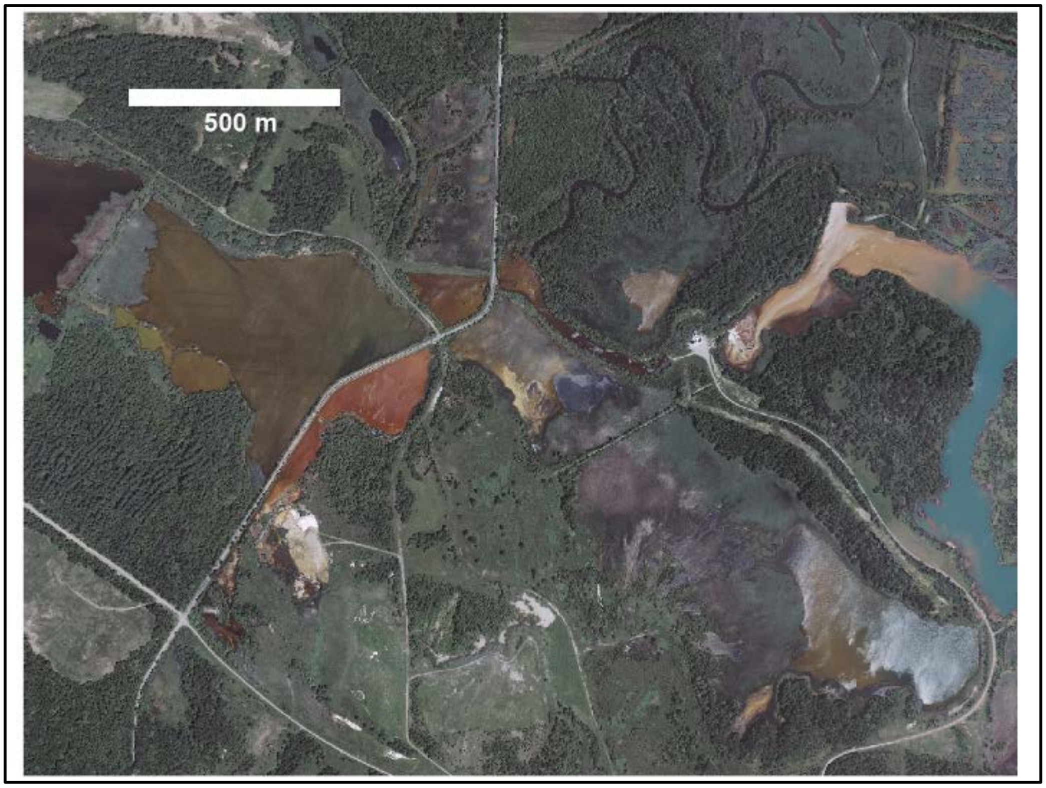

Figure 34. Aerial image of the abandoned Will Scarlet open-pit coal mine in Williamson County, Illinois. The unreclaimed pits have flooded with water, multi-colored due to the high acidity. Forests and fields appear dark green in contrast. (High resolution orthophoto: U.S. Geological Survey)

Figure 35. Oblique aerial photo of a mountaintop removal coal mining operation in January, 2006, Kayford Mountain, West Virginia. (Photo: V. Stockman)

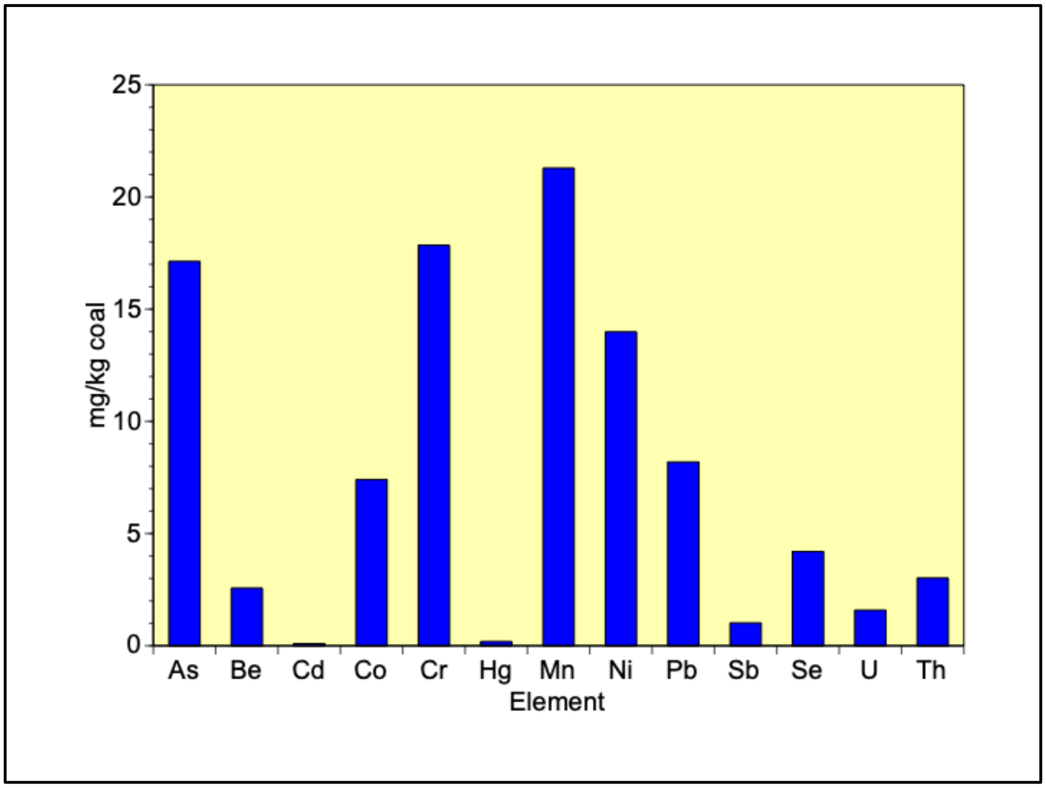

Figure 36. Average distribution of potentially hazardous trace elements in West Virginia coals. (Data: West Virginia Geological and Economic Survey)

Figure 37. Subsidence of an abandoned underground coal mine in an Indiana farm field. Photo: Indiana Geological Survey (Harper, 2011).

components or phases: aquatic biomass formation, biomass preservation in sediments, generation of petroleum, migration of petroleum, and trapping.

Whereas coal deposits derive most frequently from fossilized terrestrial plant remains, petroleum begins with microorganisms, especially algae, floating in the shallow *photic zone* in oceans and large lakes. If natural eutrophic conditions develop, algae will bloom in the surface waters and it is their biomass that provides the essential raw material for petroleum and natural gas formation. If the blooms are sufficiently massive, the responding scavengers, particularly aerobic bacteria, may consume the available dissolved oxygen in the water faster than it can be replenished by marine currents, suppressing the scavenging processes. The biomass will then be able to settle to the bottom sediments before it can be fully recycled. There it will be buried and preserved as sedimentation proceeds, completing the second phase of the process. As more sediment accumulates above it, the third phase begins. Progressively deeper burial leads to *geothermal* heating of the preserved *organic matter*, transforming the biomass into *kerogen* via the process of *diagenesis*. Then, with continued heating at yet higher temperatures (roughly 100 to 120 °C, as are encountered typically at burial depths of several thousand meters in a sedimentary basin) the process known variously as *catagenesis, thermal maturation,* or *oil generation* cracks the kerogen into the constituent molecules of petroleum (mostly *hydrocarbons* containing 5 to 40 or more carbon atoms) or natural gas (predominantly methane with other small hydrocarbons). The clay-rich sediments that mixed with the biomass on the seafloor have by now hardened into *shale* and *mudstone* rich in organic matter and are called the *source rock* (Tissot and Welte, 1984; Hunt, 1996). Within the complex mixture of compounds present in petroleum, it is remarkable that molecules of obvious biological origin (such as *steroids*) are still preserved (Ourisson et al., 1984).

Once the oil and/or gas have been generated, the fourth phase begins, which is the *expulsion* out of the impermeable source rock into an adjacent porous, permeable rock such as a sandstone. There it will interact with the water already present within the pore network and gradually rise, since gas and many types of petroleum are less dense than water. The hydrocarbons will continue to *migrate* upward through the permeable strata until their path is blocked by a overlying layer of impermeable rock, such as another shale. The oil and gas will then accumulate in the permeable *reservoir rock* beneath the *trap* in the fifth and final phase. To develop a conventional oil or gas deposit, all five phases of the petroleum system must be completed in sequence, a process that requires millions of years (Hunt, 1996).

1.8.3 Petroleum and Natural Gas Extraction - Environmental Considerations

A reservoir rock beneath a trap is the classic target sought for petroleum exploitation, whether the ancient sedimentary basin is presently onshore or offshore. Onshore exploration and production tends to be lower in cost, particularly if the location is not a remote one with a harsh climate. Offshore development of the resource began modestly, in shallow waters. Gradually, methods became more sophisticated and capable, with taller platforms that could stand in deeper waters. More recently, the development of floating platforms permits work in even deeper waters beyond the continental shelf, but at proportionately greater risk. In 2010, the *Deepwater Horizon* offshore oil platform caught fire in the

Gulf of Mexico and sank with the loss of 11 crew members, as the well was being closed pending later production (Fig. 1-38A). The platform was operating in a water depth of roughly 1600 m with the target oil reservoir at about 4000 m below the sea bed, thus the work was at such great depths that it was pushing the technological limits. Contributing factors to the disaster include a poor job installing and cementing the steel *casing* that lined the well bore and the failure of the *blowout preventer*, a device designed to quickly close the well in the event of an emergency. The fundamental problem leading to the fatal loss of control was the failure of oversight and supervision to keep pace with advances in a technology that had not yet been fully proven. While the tragedy aboard the platform would have been bad enough, there was more to come. The well immediately began to leak oil into the Gulf, ultimately spilling an estimated 800,000 m^3 over a five-month period before desperate attempts to staunch the flow finally succeeded. This caused grave disruption to coastal ecosystems and fisheries in Louisiana and neighboring states (Fig. 1-38B) (Graham et al. 2011).

A disaster of the magnitude of the *Deepwater Horizon* story is fortunately rare, but there are fundamental issues that a society dependent on petroleum for much of its energy needs must face. While petroleum continues to be generated in the subsurface, the process is a very slow one, such that the present rate of consumption far surpasses the natural rate of replenishment. Thus, petroleum is for all practical purposes a *non-renewable resource*. The questions regarding how much extractable oil remains and how long it will last remain elusive, particularly as new technologies such as offshore drilling increase *proven reserves*. An early attempt (Hubbert, 1956) to predict the trajectory of future global output concluded that peak oil production would occur in about the year 2000 followed by decades of slow decline (Fig. 1-39). This approach was based on extrapolation of the behavior of individual oil wells and fields over their productive lifetimes, which showed initial increases up to a maximum then a gradual decrease. Petroleum engineers developed ever more sophisticated methods for *secondary* and *tertiary recovery*, dramatically extending oil field lifespans. Nevertheless, production decline inevitably takes its toll. The Hubbert approach was recently revisited (Nashawi et al., 2010), with surprisingly similar results (Fig. 1-39). They predict global *"peak oil"* in about 2015, followed by a century of decline, although cumulative production in their scenario is several times that of the Hubbert original. If these models are reasonably correct and peak production is imminent, the search for alternatives to petroleum should be given greater impetus.

Nashawi and coworkers (2010) did not consider the implications of the latest technical developments in oil and gas extraction from so-called "*tight formations*" (rocks of low permeability) such as the *Marcellus Shale* of the northeastern United States (Fig. 1-40A). Hydrocarbons can be produced from such rocks after artificially inducing fracturing by forcing large volumes of a mixture of water and other substances into the well bore under high pressure ("*fracking*"), thereby increasing the permeability. Applying a second innovation, *horizontal drilling*, in tandem with hydraulic fracturing further increases production from tight shales (Fig. 1-40B). This new technique permits the well operator to change the direction of the drillbit to remain within the target formation, following it laterally to expose more of the productive horizon to the well bore (Soeder and Kappel, 2009). If one considers this approach within the conceptual framework of the petroleum system, it is essentially an intervention in the system after the third phase, obviating the need for migration and trapping. In

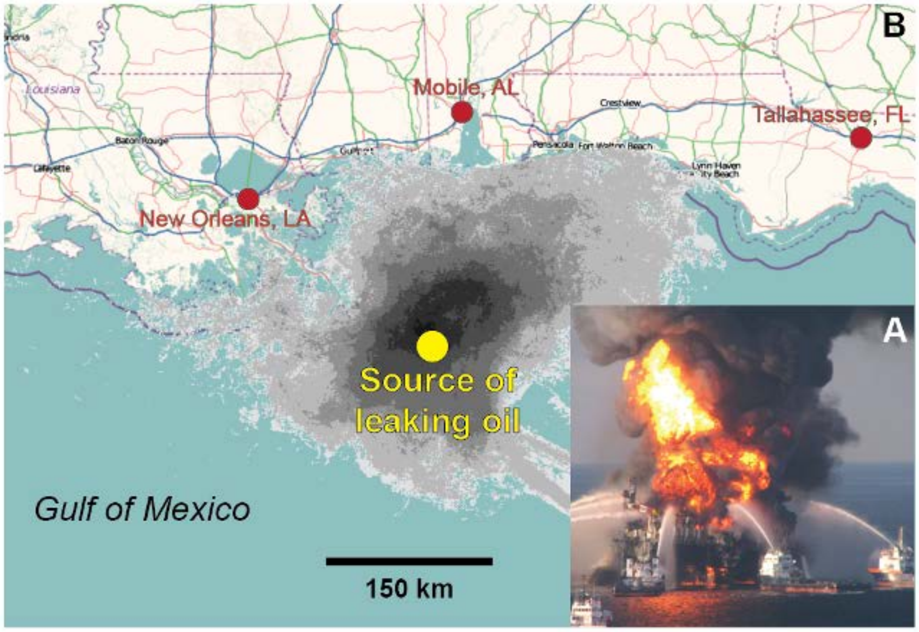

Figure 38. A) The *Deepwater Horizon* offshore oil platform caught fire and sank with the loss of 11 crew members in 2010, as the well was being closed pending later production (Photo: U.S. Coast Guard). B) Cummulative oil spill map for the *Deepwater Horizon* incident for which the darker gray colors indicate more days of sea surface oiling reported (National Oceanic and Atmospheric Administration, 2014).

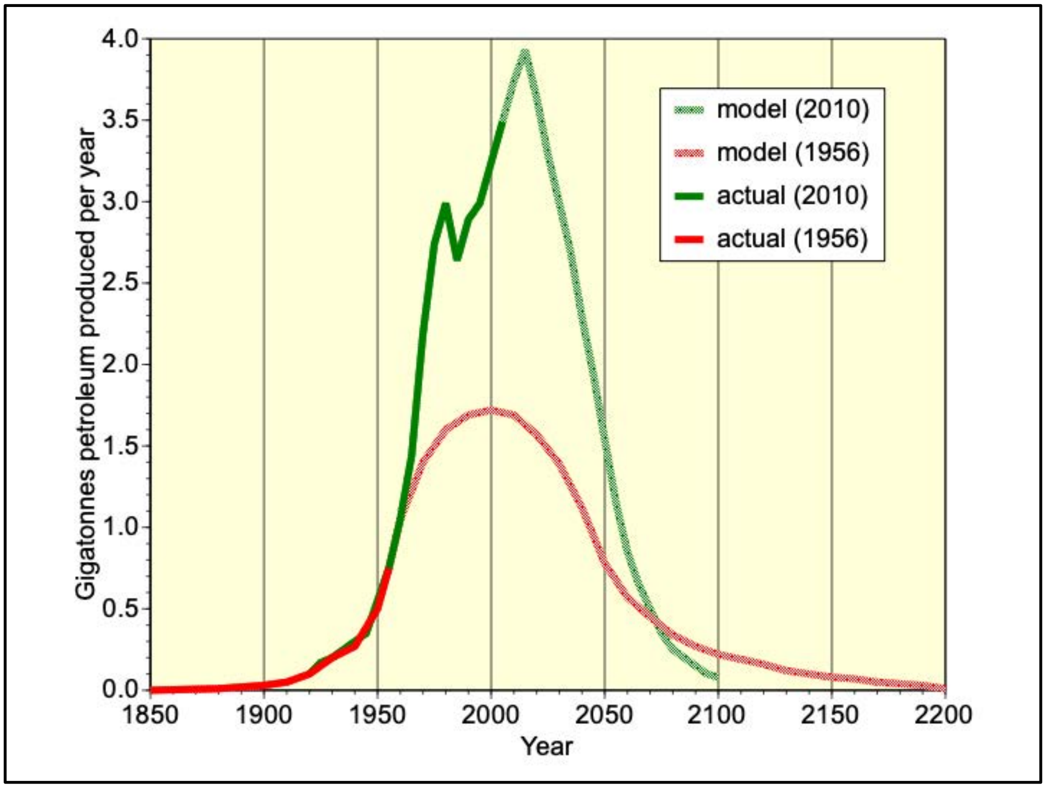

Figure 39. World petroleum production history and predictions showing peak oil production occurring in about the year 2000 (in red, as predicted by Hubbert, 1956) and in about 2015 according to more recent modeling (green, Nashawi et al., 2010). Dark colors indicate actual production data. Light colors indicate model predictions.

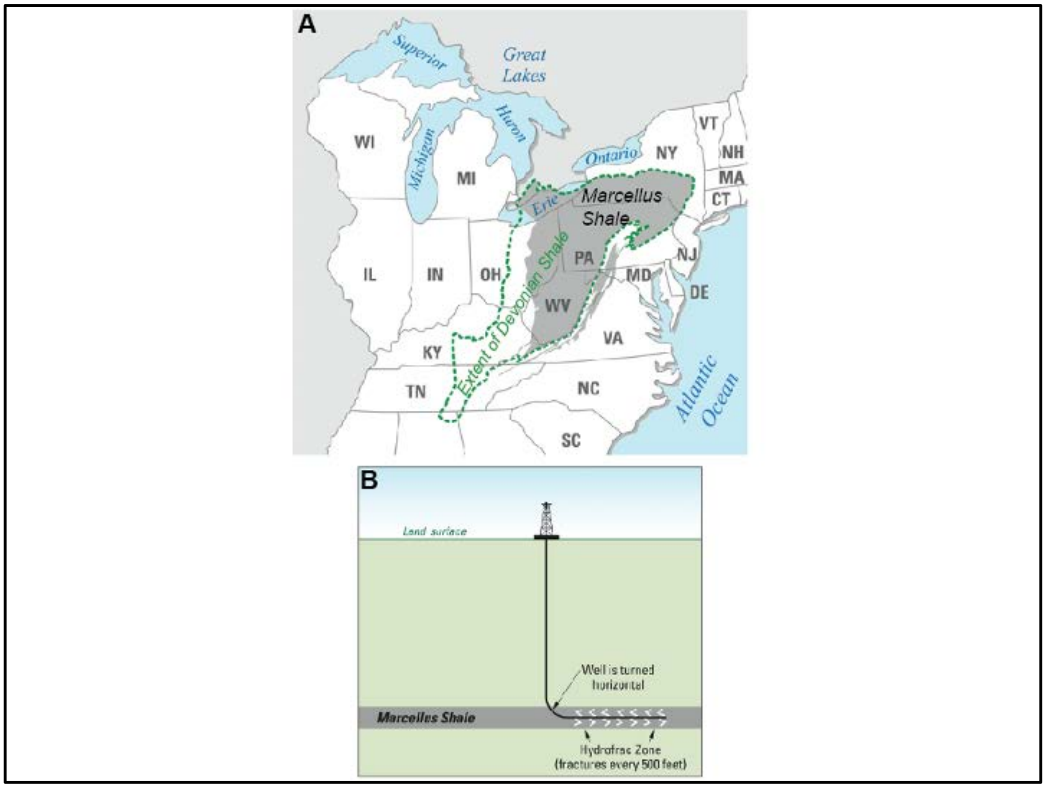

Figure 40. Marcellus Shale “tight gas” exploitation. A) Map of the northeastern United States showing the extent of shales of Devonian age in the Appalachian Basin (outlined in green), of which the Marcellus Shale (in gray) constitutes a major part. B) Schematic of the horizontal drilling and hydraulic fracturing (“fracking”) techniques used to exploit natural gas deposits in the Marcellus Shale. (after Soeder and Kappel, 2009)

essence, the source rock also functions as the reservoir rock. There are many sedimentary basins in the world with mature source rock but without the geological components necessary for migration and trapping. Thus there are now many more possibilities for hydrocarbon exploration and development.

High volume hydraulic fracturing is not without its problems. The first is the large amount of water needed, particularly problematic in dry areas already straining to meet agricultural demand for water (Section 1.6.1), such as western Texas where the Eagle Ford Shale is a principal drilling objective (Galbraith, 2013; Barringer, 2013). More vexing is the question of water contamination (Urbina, 2011; Joyce, 2012), particularly from the *flowback* of the hydraulic fluids to the surface and the natural *produced waters* from deep underground that rise up the well with the hydrocarbons. Both classes of water are extremely saline, with up to 300 g L^{-1} of total dissolved solids, creating concerns over their proper disposal (Rahm et al., 2013). The precise nature of the hydraulic fluids is guarded as a trade secret by operators and that in itself creates mistrust in the community. Chloride and bromide are among the major components present, for which Sun and others (2013) have recently proposed wastewater treatment methods. Cross-contamination of overlying freshwater aquifers is also a concern, whether by the brines or by methane (Vengosh et al., 2013). There have been reports of small earthquakes possibly induced by fracturing via reactivation of faults (Fountain, 2011; Rutqvist et al., 2013). In the United States, Texas and Pennsylvanian have seen the most widespread use of high volume hydraulic fracturing, while other states such as New York as well as other countries have been proceeding more cautiously as they develop their regulatory frameworks (Rahm, 2011; Eaton, 2013). Relatively clean-burning natural gas, including that potentially producible in large volumes via hydraulic fracturing, may serve as an intermediate bridging step to a future state with a greater reliance on *renewable* energy sources (Eaton, 2013). The potential for deleterious effects of the fracturing process should encourage environmental managers to foster a science-based arrangement to maximize resource utilization while minimizing harmful consequences.

Another example of massive unconventional petroleum exploitation is the *oil sand* deposit in Alberta, Canada. Viewed within the conceptual framework of the petroleum system, this is a case for which the fifth phase, the trap, is missing. The permeable sandy reservoir is exposed at the surface, where the oil has been converted into a viscous tar by microbial biodegradation. Hence the oil sands must be strip-mined like coal then steam-treated and refined to create a marketable liquid product (Fig. 1-41). The energy consumed in the mining and thermal treatment is costly but oil prices are currently high enough to make this economically feasible. Of great concern is, that when the carbon dioxide generated by mining and treatment is included, the net greenhouse gas emissions from the exploitation of this resource are nearly triple that of conventionally-produced petroleum (Kunzig, 2009). Public objections arising from these worries have delayed the completion of a pipeline designed to bring the Alberta oil into the United States (Frosch, 2013).

1.8.4. Consideration of Externalities

Cost-benefit analyses performed by the energy industry regarding the utilization of nuclear power, coal, conventional petroleum and natural gas, hydrocarbons from hydraulic fracturing, and oil

Figure 41. Oil sand refinery on the banks of the Athabasca River 30 km north of Fort McMurray, Alberta, Canada. Dikes separate the river from the ponds of oily water used in the refining process. (Aerial photo: P. Essick)

sands often ignore *externalities*. These are the damages to the environment and burdens placed upon society that are not reflected in the market price of the energy (Schleisner, 1999). Long-term planning decisions should be made with externalities in mind when comparing the economics of fossil energy systems with those of renewable energy sources, be they solar (Figs. 1-24 and 1-42), hydropower, wind, tidal, biomass, or waste-to-energy.

1.9 Concluding Remarks

In the course of this overview, the emphasis has been upon the geological basis of a number of major environmental management issues. Throughout, the perspective has been grounded in the belief that populations should be protected from undue exposure to natural hazards and that natural systems should likewise be shielded from undue anthropogenic pressure. Whether the threats were volcanic eruptions, earthquakes, floods, landslides, or subsidence, it has been emphasized that geological and environmental methodologies and knowledge can serve to provide a sensible means for risk reduction. Given that some human settlements will likely continue to be situated in hazardous areas, engineered approaches to protection of life and property will be beneficial if properly applied. Armed with both knowledge and political sensitivity, environmental managers will have opportunities for positive social impact in negotiating the challenges as they weigh costs, risks, and benefits. When considering natural resource and energy issues, environmental managers should foster science-based solutions to maximize resource utilization while minimizing harmful consequences, bearing in mind externalities and long-term impacts. As with the debate over strategies to cope with natural hazards, the course of future energy policy will be determined by the complex and contentious interplay of the scientific/technical, economic, and political drivers. At these critical junctures, it is evident that environmental managers have an important role to play.

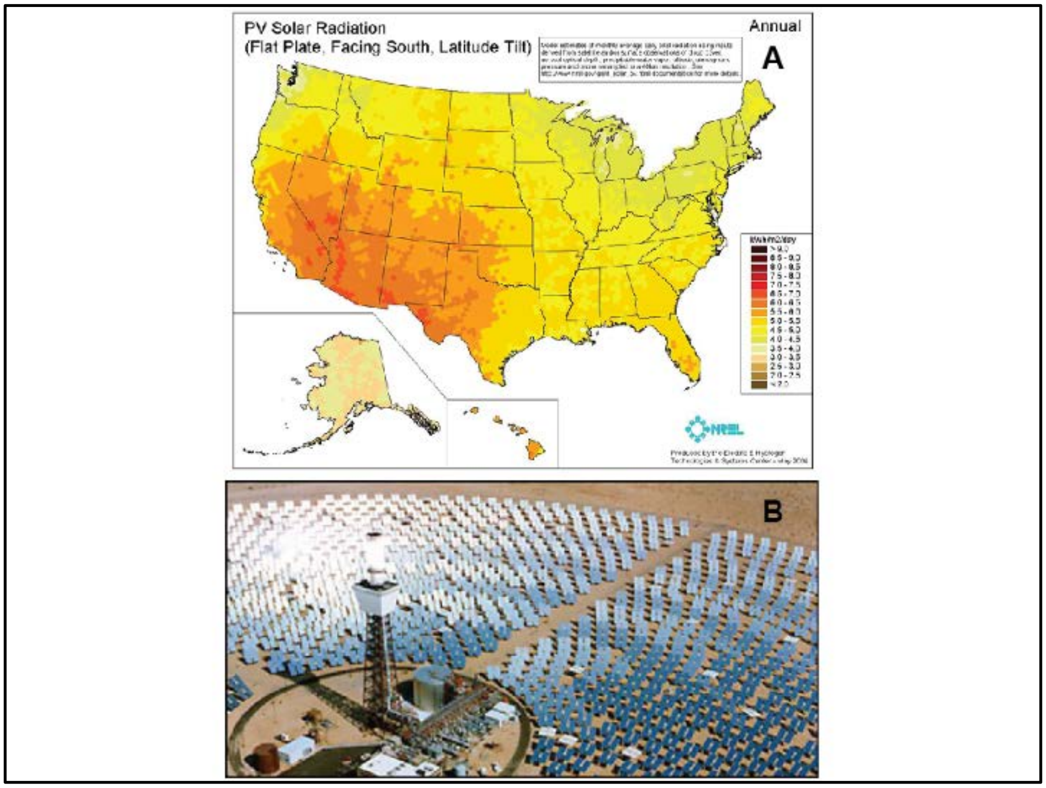

Figure 42. A) Map of solar energy potential in the United States. The desert southwest has the greatest potential, as indicated by its red and orange colors on the map. B) Tower and surrounding field of mirrors at the experimental thermal solar electrical generating plant “Solar Two” in the Mojave Desert, California. (Images: National Renewable Energy Laboratory, U.S. Dept. of Energy)

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Appendix. Geographic Coordinates of the Examples Presented.

This table presents the geographic coordinates of the examples given in the text for further exploration by the reader, keyed to figure number. The digital degree format is used, such that south latitude and west longitude values are written as negative numbers. This is generally simpler to use than the degrees-minutes-seconds format and can be employed with Google Earth or other geographic information utility if the preferences are set to accept them.

Location	Figures	Latitude (°N)	Longitude (°E)
Mt. Vesuvius, Italy	2	40.8196	14.4281
Eyjafjallajökul Volcano, Iceland	3	60.6308	-19.6008
Mt. Rainier, Washington	4	46.8537	-121.7589
Mt. Ruapehu, New Zealand	5	-39.2836	175.5667
Otsuchi, Japan	6	39.3582	141.8994
San Francisco, California	7-9	37.7749	-122.4194
Daly City, California	10-12	37.6672	-122.4890
Atlantic Beach, New York	13, 25	40.5852	-73.7255
Montauk Lighthouse, New York	14	41.0708	-71.8570
Fire Island, New York	15	40.7231	-72.8907
Mantoloking, New Jersey	16	40.0438	-74.0487
Ansonia/Derby, Connecticut	17-19	41.3362	-73.0787
Mono Lake, California	20-21	38.0070	-119.0122
Haskell, Kansas	22	37.5262	-100.9067
Colby, Kansas	23	39.3914	-101.0672
NW of Tonopah, Nevada	24	38.3670	-117.4299
Winter Haven, Florida	26	28.0222	-81.7328
Clermont, Florida	27, 28	28.3494	-81.6584
Zaragoza, Spain	29	41.6427	-0.9356
Landfill, Secaucus, New Jersey	30	40.7534	-74.0855
Yucca Mountain, Nevada	32	36.8524	-116.4288
Mine, Wilmington, Illinois	33	41.2923	-88.1863
Will Scarlet Mine, Illinois	34	37.6525	-88.7232
Mine, Kayford Mountain, West Virginia	35	37.9698	-81.3818
Deepwater Horizon site, Gulf of Mexico	38	28.7381	-88.3659
Refinery, near Fort McMurray, Alberta	41	57.0050	-111.4816
Solar Two project, Barstow, California	42	34.8719	-116.8342