Islands at Risk: Coastal Hazard Assessment and Mapping in The Hawaiian Islands

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ABSTRACT

Seven natural phenomena have been identified as posing significant threats to coastal areas of the Hawaiian Islands. These "hazards" include: coastal erosion, sea-level rise, major storms, volcanic and seismic activity, tsunami inundation, coastal stream flooding, and extreme seasonal high wave events. In addition to these phenomena, coastal slope and local geologic setting are important factors for accurately determining the hazard potential for specific areas. To quantify the effects of individual hazards, their past magnitudes and occurrence have been evaluated from historical records and a semiquantitative ranking scheme applied. The intensity of each hazard has been ranked low, moderately low, moderately high, or high using definitions based on their historical occurrence and magnitude. Comparison and statistical ranking and weighting of all hazard rankings for a given segment of coast, combined with geologic character and morphologic slope, are used to define the Overall Hazard Assessment which provides a guideline for management decisions regarding coastal land use and planning.

Key Words: coastal hazards, hazard assessment, hazard mapping, Hawaiian Islands.

INTRODUCTION

> *Hao mai ka makani kuakea ka moana; hao mai ke kai ku ke ko'a I uka.*
>
> "When the gales blow the sea is white-backed; when the sea rises, corals are washed ashore" (Hawaiian Proverb; Pukui, 1983).

The ancient Hawaiians were well aware of the fury of nature and developed a respect for the hazards around them. The siting of villages and structures away from the coast on higher ground demonstrated their understanding of hazard potential and how to avoid severe consequences. In contrast, twentieth century development emphasizes a rather complacent perception of a calm and tranquil paradise, commonly ignoring the fact that the Hawaiian Islands are subject to the adverse effects of a wide variety of natural coastal hazards. Hawaii is the only state in the United States subject to all four of the following natural phenomena: earthquakes, volcanic eruptions, tsunamis, and hurricanes. Additional threats occur from coastal erosion, sea-level rise, coastal stream flooding, and extreme seasonal high wave energy.

The last great tsunami to affect the Hawaiian Islands was in 1960. Since then, there has been widespread and intensive development along the Hawaiian shoreline. Hurricane Iwa, which devastated the island of Kauai in 1982, was the first major damaging hurricane to strike Hawaii in nearly 50 years. Post-Iwa rebuilding on Kauai and leeward Oahu was severely impacted by Hurricane Iniki, which occurred just 10 years later. Coastal stream flooding caused by intense rainfall events are nearly an annual occurrence in the state, as are seasonal high waves generated by north Pacific storms. Coastal erosion has caused beach loss or narrowing on nearly one-quarter of Oahu's beaches and as much as a third of the beaches on Maui (Coyne et al., 1996; Fletcher et al., 1997). As coastal lands increase in both economic and social value, it becomes imperative to develop a better understanding of the processes that shape the coast and impact the people that live there.

Although the various natural processes affecting the coast have long been recognized as having important consequences, there has been no previous systematic attempt to quantify, rank, and map the distribution of Hawaiian coastal hazards. This article describes research that examines the intensity and history of natural hazards in the Hawaiian coastal zone to improve our understanding of coastal processes and their effects on property and the natural environment. The history and character of seven potentially hazardous coastal processes were investigated to provide a sound database for engineers, scientists, planners, and managers. A semi-quantitative hazard ranking system was developed that defines the hazard intensity using historical comparisons and inter-site evaluation. This work incorporates information from many previous investigations by scientific and engineering researchers and county, state, and federal agencies. Prior efforts in documenting Hawaiian coastal hazards and existing knowledge and information were combined into a single coastal hazard database and atlas that is cur-

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rently in preparation (*Atlas of Natural Hazards in the Hawaiian Coastal Zone*; to be published by the U.S. Geological Survey [USGS]). In the following sections, a discussion of each hazard is presented, including the assumptions, limitations, and variables that influenced ranking determinations. Prior to discussing the individual hazards, a brief discussion of the importance and use of the coastal geology and coastal zone slope is provided to demonstrate how the physical setting strongly influences coastal processes.

COASTAL SLOPE AND GEOLOGY

Coastal slope determines the amount of coastal land exposed to extreme coastal processes. For example, along shorelines with cliffs, marine overwash from a hurricane is limited to a very narrow strip, whereas along low-lying coastal plains there may be significant inland incursion of marine water (Jaffe and Richmond, 1992; Fletcher et al., 1995). The water-level elevation of overwash may be much higher on coasts with cliffs, due to steep offshore slopes and low wave energy dissipation, but the amount of land affected can be significantly less than on low-lying coasts. Here, coastal slope zone rankings are made for the coastal plain in the elevation range 0 to 60-m (200 ft) above sea level. Use of the 60-m elevation contour is arbitrary, but in general it represents the maximum inland extent of areas affected by most of the hazards discussed. It also approximately corresponds with the 200-ft contour that is marked on available topographic maps.

Coastal slope was subdivided into one of three values: Number 1 indicates a gentle slope with a gradient less than or equal to 20% ($\leq$11.5°); Number 2 indicates a moderate slope with a gradient greater than 20% and less than 45% ($>$11.5° and $<$26.7°); and Number 3 indicates a steep slope with a gradient greater than or equal to 45% ($\geq$26.7°). In the technical map series, an example of which is shown in Figure 1; the darkest shade indicates the gentlest slope because it is more susceptible than a steep slope with regard to stream flooding, tsunami inundation, storm overwash, erosion, seasonal wave hazards, and sea-level rise. This is in keeping with the color ranking system in which the highest hazard intensity is mapped with the darkest shade.

In many locations, a steep coastal headland or cliff presents an effective barrier to inland storm overwash, tsunami inundation, erosion, stream flooding, and sea-level rise. Because coastal bluffs mitigate against the highest hazard ranking for those processes, they are assigned the highest slope value (3) even where it is $<$60 m high. In other words, in such instances the effective coastal zone slope was mapped, which is often not the average slope of the first 60 m, but instead is the slope of the effective portion of the coast with regard to hazard assessment.

The coastal geology of Hawaii is complex—the determinations of coastal geology are by necessity broad-based and generalized, incorporating those features that are important in assigning hazard severity rankings. Significant features have length scales $>$300 m ($\sim$1000 ft) in most places. The coastal geology was determined using existing topographic and geologic maps, field observations, and analysis of aerial videography of the Hawaiian coastal zone. A complete set of aerial videography depicting the entire Hawaiian coastline was collected from an elevation of 90–150 m (300–500 ft).

Geologic features are depicted on a set of technical maps (Figure 1) using an alpha code with the dominant geology capitalized and associated secondary geologic features in lower case (Table 1). Primary features include beaches, low-lying rocky shorelines, stream mouths, steep rocky headlands, and heavily developed shorelines. Shorelines are further modified by the presence of reefs, embayments, wetlands, smaller streams, and minor development. The developed shoreline designation (D) is used to identify coastlines stabilized with revetments and seawalls. Fringing reef includes seafloor in the coastal zone supporting active coral-algal growth. Typical reef growth within the Hawaiian coastal zone consists of a thin veneer (1–2 m) of coral-algal growth on either a volcanic rock platform or antecedant Pleistocene limestone foundation (Grigg, 1998). Only the well-developed reefs have been mapped, not just areas of coral growth. Examples of the geology code usage are shown in Figure 2.

COASTAL HAZARDS

The primary hazards affecting the Hawaiian coastal zone and the order in which they will be discussed are tsunami inundation, coastal stream flooding, seasonal high waves, high winds and marine overwash associated with storms, erosion of the shore, sea-level rise, and volcanism and seismicity.

Tsunami Inundation

Tsunamis pose a significant hazard in the Hawaiian coastal zone. According to Dudley and Lee (1998), Hawaii has experienced a total of 95 tsunamis in 185 years (1813–1998), or on average one every two years with a damaging tsunami every five years. The last truly large event, however, occurred in 1960. During the tsunami of 1946, generated by an earthquake in the Aleutian Islands, 159 people statewide lost their lives including 15 children and five teachers at Laupahoehoe Peninsula where a 9-m (30-ft) wave washed over the low-lying headland along the east coast of the island of Hawaii.

Tsunamis are caused by the sudden movement of the seafloor in response to faulting, landsliding, or submarine volcanic eruptions or collapse of volcanic edifices. The seafloor movement generates a number of long-wavelength waves that travel across the ocean unimpeded until they reach the coast. Tsunamis affecting the Hawaiian Islands

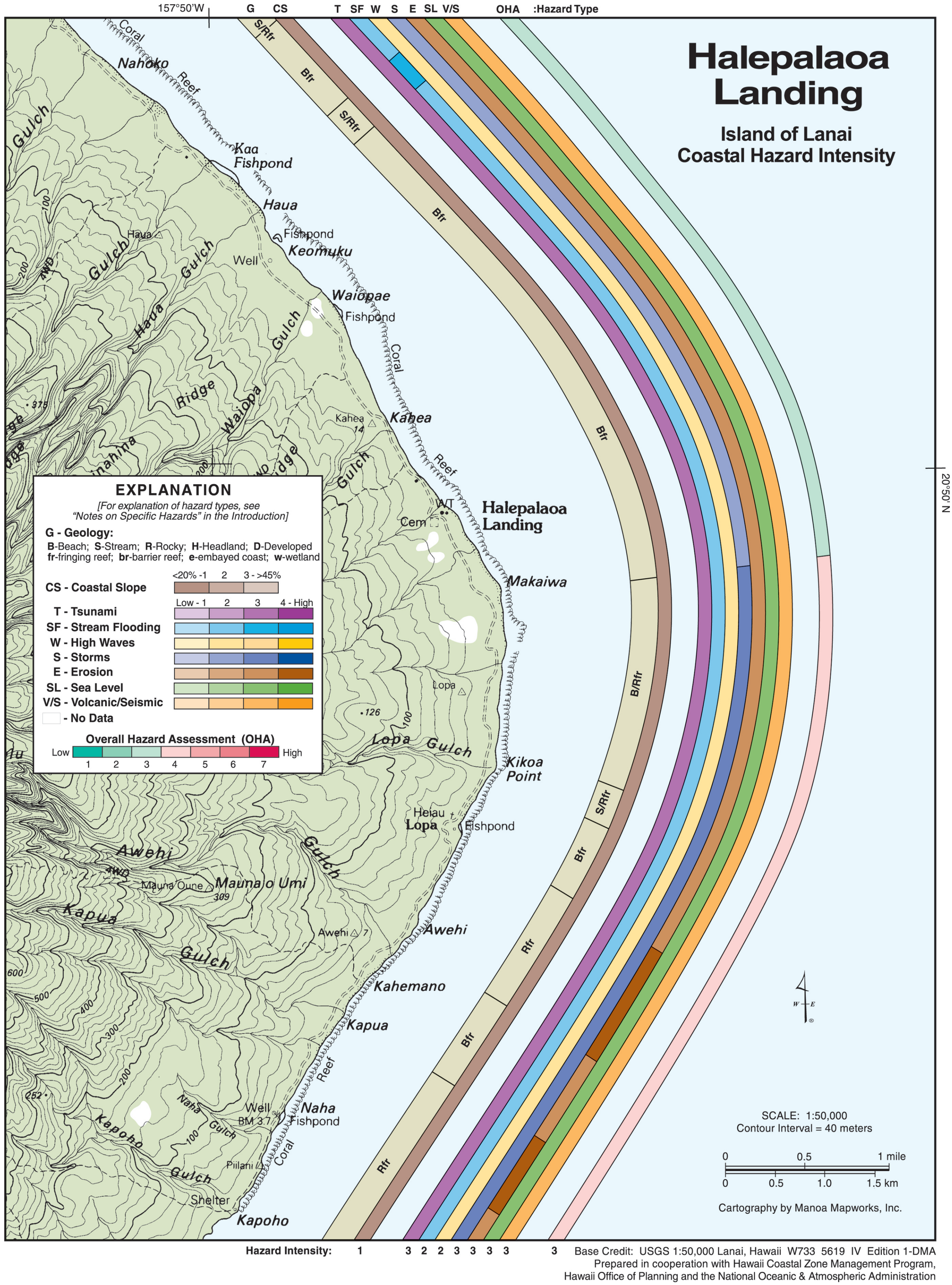

FIGURE 1. Coastal hazard Technical Map of Halepalaoa Landing, eastern Lanai.

TABLE 1. Summary of coastal features mapped and depicted in the Technical Map series. Upper case letters refer to primary features, whereas lower case denotes a secondary feature.

Code	Description
B	Sandy beach, may include minor amounts of beachrock
R	Low-lying rocky shoreline (beachrock, boulder beaches, basalt, or limestone), may include a perched beach above high-tide line on a rocky platform
S	Prominent stream mouth (including adjacent areas subject to stream flooding);
H	Steep and rocky headland, often with a boulder beach or debris cone at its base;
D	Developed shoreline, often where former beach has been lost to seawall construction or former natural environment cannot be determined due to urbanization;
fr	Fringing reef adjacent to shoreline;
br	Barrier reef (the only true barrier reef in Hawaii is in Kaneohe Bay; however, we have mapped Kailua Bay as a barrier reef because the reef there protects a lagoonal region, and effectively dissipates hazardous wave energy similar to a larger barrier);
e	Embayed coast, used to designate pocket beaches, narrow embayments, and coasts leeward of prominent headlands;
w	Wetlands, designating coasts with adjacent terrestrial wetlands, ponds, and anchialine wetlands;
d	Used when development is a secondary feature of the shoreline;
s	Used when a stream mouth is a secondary feature of the shoreline

can either be locally generated or originate far afield throughout the Pacific Ocean basin. Locally generated events are especially hazardous because of the limited warning time. It is thought that catastrophic tsunamis were locally generated during the early geologic history of the Hawaiian Islands when massive portions of the young islands slid into the sea (Moore et al., 1989). More recently, tsunamis that have impacted the Hawaiian Islands have been generated far afield and have taken several hours, or longer, to reach Hawaiian shores.

The geography of the shoreline plays an important role in the form of the tsunami wave. Tsunamis manifest predominantly as a rapidly rising sea level and less commonly as large breaking waves (bores). Tsunami waves may be very large in embayments, typically experiencing amplification in long funnel-shaped bays. Fringing and barrier reefs appear to have a mitigating influence on tsunamis by dissipating wave energy. For example, within parts of Kaneohe Bay that are protected by a barrier reef, the 1946 tsunami reached only 0.6 m (2 ft) in height, while at neighboring Mokapu Head the wave crest exceeded 6 m (20 ft) (Loomis, 1976).

The high degree of volcanism and seismic instability in and around the Pacific basin and the Hawaiian Islands central Pacific location has led to a long history of tsunami occurrences as shown by historical tsunamis impacting the island of Oahu (Figure 3). Hawaii has been struck by more tsunamis than any other region in the world (Dudley and Lee, 1998).

Coastal Stream Flooding

Watersheds in Hawaii are typically small, averaging <2.6 km^2 (1 mi^2; Peterson, 1996), and are characterized by steep slopes with little channel storage. Consequently, intense rainfall events often result in a rapid rise of water level and flash flooding. Coastal flooding of low-lying areas and rapid discharge of sediment into littoral environments are common effects of intense rains.

In a 1983 report, the State of Hawaii Department of Land and Natural Resources reported that previous floods in Hawaii had claimed >350 lives and caused more than \$475 million in damages (Hawaii Department of Land and Natural Resources, 1983). Floods caused by heavy rainfall and

FIGURE 2. (A) The Diamond Head and Waikiki coast on the southern shore of Oahu is an example of a developed coastal plain beach with a broad fringing reef tract (D/Bbrfr). **(B)** Along the northeastern coast of Molokai, embayments comprised of a stream mouth and beach (S/B) are often interspersed between steep headlands (H).

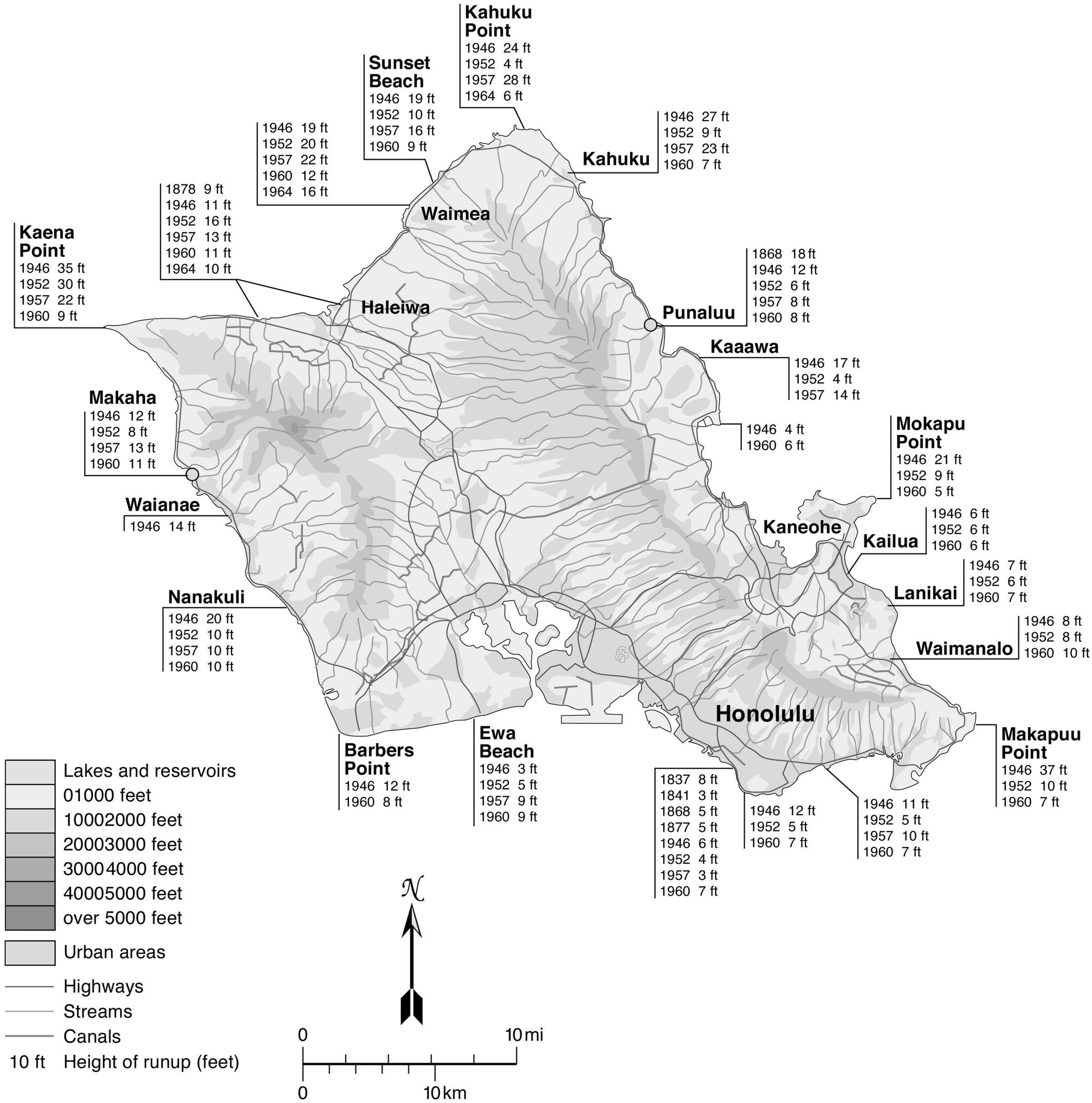

FIGURE 3. Map showing the distribution and height of historical tsunamis for the island of Oahu (after Loomis, 1976).

strong winds typically occur during the winter months, although heavy rainfall can also be associated with the tropical storm and hurricane season between the months of June and November. Kona storms, locally generated storms that typically occur in winter months, are often accompanied by strong winds and heavy rains and approach from leeward (*kona*) directions. Kona storms tend to be less frequent, but more intense, than typical winter cold-front storms. Areas subject to recurrent rainstorm floods are the coastal plains and flood plains of Maui, Kauai, and Oahu. Flooding tends to be less intense by comparison on Hawaii, Molokai, and Lanai although severe flash floods can occur almost anywhere. Regions in Hawaii of high precipitation are typically characterized by deep valleys that channelize floodwaters, thereby reducing flooding. Elsewhere, the high porosity of the volcanic rocks lead to high infiltration rates and are a deterrent to frequent flooding. Although there is no complete official tabulation of flood damages and lives lost for the state, Table 2 provides a historical summary of severe floods in Hawaii.

High Seasonal Wave Energy

Sudden high waves, and the strong currents they generate in the nearshore region, are perhaps the most consistent and predictable coastal hazard in Hawaii. Unfortunately, they account for the greatest number of actual injuries and rescues on an annual basis. It has been said that picking intertidal mollusks (ʻopihi) from coastal rocks is the number one

TABLE 2. Major stream floods and damages, 1915–1998, for the Hawaiian Islands (from an unpublished Hawaii Department of Land and Natural Resources report on Floods and Flood Control, 1983, and monthly storm data from the National Climatic Data Center, National Oceanic and Atmospheric Administration).

Date	Statewide Lives Lost	Location	Damages (1998 $)	Cause
1915	10	Statewide		Cloudburst
1/14/1916		Iao Stream, Maui	$250,000	Heavy rains
1/17/1916	16	Statewide	$1,000,000	Heavy rains
1917	3	Statewide		Heavy rains
1/16/1921	4	Honolulu	$500,000	Heavy rains
1922	1	Statewide		Heavy rains
1927	5	Statewide		Heavy rains
1928	1	Statewide		Heavy rains
1929	1	Statewide		Heavy rains
11/13/1930	30	Kalihi, Moanalua, Halawa valleys, Oahu		Heavy rains
1932	3	Statewide		Rainstorm
2/27/1935	14	Oahu	$1,000,000	Severe rainstorm
1938	2			Severe rainstorm
1/4–5/1947	1	Hawaii, Maui, Oahu	$2,200,000	High seas
1/23–26/1948	1	Hawaii, Maui, Oahu	$250,000	Strong winds and rainstorm
1/15–17/1949	4	Kauai, Oahu	$550,000	Intense Kona storm
11/30/1950	4	Maui, islandwide	$322,120	Heavy rains
3/26–27/51	1	Oahu	$1,303,000	Heavy rains and strong winds
1/21/1954	2	Oahu	$500,000	Heavy rains and strong winds
11/27–28/1954		Kauai, Oahu	$810,000	Heavy rains
12/19–21/1955	7	All islands		Kona storm
1/24–25/1956	1	Wailua, Kauai, Oahu Hawaii	$700,000	Heavy rains
2/25/1956		Sunset Beach, Oahu	$250,000	Flash flood
2/7/1957	2	Honolulu, Waimanalo Aina Haina, Oahu	$400,000	Flash flood
12/1/1957		Kauai, Oahu, Maui,Hawaii	$1,056,000	Hurricane
3/5/1958		Oahu	$500,000	Heavy rain
8/6–7/1958	2	Oahu, Maui,Hawaii	$552,000	Heavy rain, strong wind, and high seas
1/17–18/1959		Oahu, Molokai,Maui, Hawaii	$1,393,000	Heavy rain, strong wind, and high seas
8/4/1959	2	Kauai, Oahu, Maui, Hawaii	$11,524,000	Hurricane
5/12–13/1960		Oahu, Maui	$250,000	Kona storm
4/2–4/1961		Hawaii	$1,744,000	Heavy rains
10/27/1961	1	Oahu, Maui, Hawaii	$2,045,731	Heavy rain, strong wind, and high seas
10/31/1961		Molokai	$1,958,380	Heavy rains
11/1–2/1961		Lahaina, Maui	$1,600,000	Heavy rains
1/15–17/1963	3	All islands	$790,000	Heavy rains and strong winds
4/15/1963		Kauai	$2,192,000	Heavy rains
5/14/1963		Pearl City, Oahu	$300,000	Heavy rains
12/19–23/1964	1	All islands	$439,000	Heavy rains, strong winds, and high seas
2/4/1965		Oahu, Molokai, Maui	$674,000	Heavy rains
4/25/1965		Hana, Maui	$288,000	Heavy rains
5/3/1965		Kahaluu, Oahu	$711,300	Heavy rains
11/10–15/1965	4	Oahu	$500,000	Heavy rains and strong winds
7/25/1965		Hilo, Hawaii	$660,000	Heavy rains
1966	2	Statewide		Heavy rains
12/17–18/1967	1	Kauai, Oahu	$1,354,850	Heavy rain, high seas, and tornado
1/5/1968		Pearl City, Oahu	$1,243,000	Heavy rains
4/15–16/1968		Hana, Maui	$293,000	Heavy rains
10/3–4/1968		Hawaii	$735,000	Heavy rains
11/30–12/1/1968		Kauai	$427,000	Heavy rains
1/5/1969		Barking Sands, Kauai	$359,000	Heavy rains and strong winds
2/1/1969		Keapuka, Oahu	$705,100	Heavy rains
1/28/1971		Maui	$553,000	Heavy rains
1/28/1971	2	Kona, Hawaii	$1,766,550	Waterspout, tornado, and heavy rains
4/19/1974	11	Kauai,Oahu,Maui	$3,868,300	Heavy rains
1/30–2/1/1975		Kauai, Oahu	$566,000	Heavy rains
2/5–7/1976		Oahu	$802,000	Heavy rain, high seas, and strong winds
11/6–7/1976	2	Oahu	$270,000	Heavy rain and strong wind

Continued

TABLE 2. Continued.

Date	Statewide Lives Lost	Location	Damages (1998 $)	Cause
1978	2			Rainstorm
2/17–22/1979		Hawaii	$6,050,000	Heavy rains
11/15–28/1979		Hawaii	$3,752,720	Heavy rains
1/6–14/1980		Statewide	$42,578,000	Heavy rains, high seas, and strong winds
3/14–26/1980		Hawaii	$4,320,1000	Heavy rains
10/28/1981		Waiawa Stream, Oahu	$786,350	Heavy rains
12/26–27/1981		Hawaii	$2,000,000	Heavy rains
11/23/1982	1	Statewide	$307,859,000	Hurricane
12/31/1987–1/1/1988		Oahu		Heavy rains
7/21–23/1993		Statewide		Heavy rains, remnants of hurricane

hazard in the state and has long been recognized by the Hawaiians as signified by the saying: "He i'a make ka 'opihi" (The 'opihi is the fish of death; Pukui, 1983).

The Oahu Civil Defense Agency classifies high surf as a condition of very dangerous and damaging waves ranging in height from 3–6 m (10–20 ft) or more. These waves result from open-ocean swell generated by storms passing across the Pacific. High surf conditions on the northern shores of all islands are most common from October through March. The north shore of Oahu is world renown for its extremely large winter surf (Figure 4), attracting waveriders from around the globe. High surf on the southern shores occurs most commonly in the summer months when storms to the south, including southern hemisphere tropical cyclones, generate wave heights in the range of 1.2–4.5 m (4–15 ft). Tradewind generated waves, usually <2 m in height, occur throughout the year along all windward (east) coasts. The leeward (western) shores can receive wave energy from the north or south depending on local orientation and exposure. Infrequent, locally generated Kona storm waves can be large, up to 4.5 m (15 ft); they are associated with the passage of local fronts or extra-tropical low-pressure systems. Because Kona waves approach from the south to southwest, they impact normally "protected" shorelines and can cause significant erosion/accretion problems.

FIGURE 4. Oblique aerial photograph of Sunset Beach on the North Shore of Oahu—an area famous for its large rideable waves.

Storm Overwash and/or High Winds

The extreme damage and economic losses associated with hurricanes Iwa (1982) and Iniki (1992) have dramatically increased the level of public awareness to the threat from hurricanes in Hawaii. The damage and injury associated with these storms was the result of high wind, extreme waves and marine overwash, and locally heavy precipitation (Schroeder, 1993; Fletcher et al., 1995). Rather than considering and ranking each of these phenomena separately, a single category related to storms consisting principally of the overwash and high wind hazards was created.

Our knowledge of tropical cyclone behavior in the central Pacific has been greatly improved by satellite technology that allows us to track storms across the vast oceans. Shaw (1981) presented a comprehensive survey of documented tropical cyclones (of all intensities) over the period 1832–1979. Using written accounts of various observers, he identified 19 storms between 1832 and 1949 and 17 storms between 1950 and 1959. By 1960, satellite data became available. Thirty-four tropical cyclones were identified between 1960 and 1969, 34 between 1970 and 1979, and 54 storms between 1980 and 1989. Between 1970 and 1992, 106 tropical cyclones were identified in the central Pacific region resulting in an average of 4.5 storms per year (Schroeder, 1993). Of course not all of these storms intersected Hawaii (Figure 5), and actual hurricane strikes on the Hawaiian Islands are relatively rare historically. More commonly, "near-misses" that generate large swell and moderately high winds causing varying degrees of damage are the hallmark of hurricanes passing close to the islands. Impacts from these "near-misses" can be severe and lead to beach erosion, large waves, high winds, and marine overwash, despite the fact that the hurricane did not make landfall. Communities

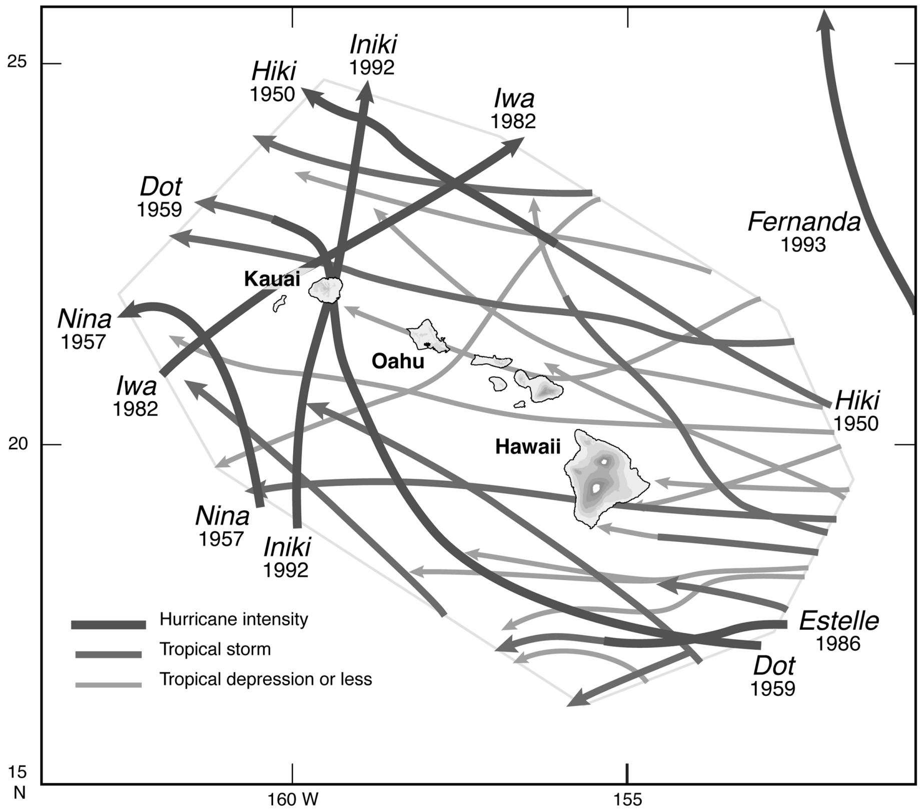

FIGURE 5. Map showing major storm and hurricane tracks near the main Hawaiian Islands (after Schroeder, 1993).

on the Waianae (leeward) coast of Oahu suffered severe damage from hurricanes Iwa and Iniki, yet the eye of neither storm actually made landfall on Oahu. Indeed, the highest wind speeds recorded during Iwa were in windward Oahu where wind accelerated upon crossing and descending the steep cliffs of the Pali (Koolau Range). Storms directed on one side of an island may have significant impact on the other side.

Because the last two hurricanes to hit the islands struck Kauai, there is a common misconception that Kauai lies in a more vulnerable position than the other islands. However, in a recent analysis of Hawaiian hurricanes, Schroeder (1993) concluded that every island has been affected by hurricanes and that no island is without risk. The poorly understood factors that control hurricane tracks play a key role in which islands are at highest risk during any given hurricane. Given minor changes in atmospheric conditions, Iniki could have just as easily come ashore at Oahu or missed the islands altogether. Tropical depressions and storms have intersected Hawaii on windward, northern, and southern coasts throughout history. In the summer of 1992, tropical storms (formerly hurricanes) Fernanda and Eugene passed along both the windward and leeward coasts of all islands within three weeks of each other, clearly demonstrating that either side of any island can sustain a direct hit by a shift in the large-scale atmospheric flow.

Studies in the aftermath of Hurricane Iniki and Typhoon Russ on Guam showed the greatest threat related to hurricane overwash in the Pacific Islands with narrow insular shelves is due to water-level rise from wave forces rather than wind forces (Jaffe and Richmond, 1992; Fletcher et al., 1995). This differs from areas with wide shallow shelves, such as the east and gulf coasts of the United States, where wind set-up or storm surge is the primary type of elevated water levels. During Iniki, the strongest component of the overwash was the result of large waves causing extreme wave run-up and set-up. Other factors influencing coastal overwash are low atmospheric pressure (relatively minor factor), tidal stage, coastal topography, and location relative to the eye of the hurricane.

Coastal Erosion

Coastal erosion and beach loss are chronic and widespread problems in the Hawaiian Islands. Typical erosion rates in Hawaii are in the range of 15–30 cm/yr (0.5–1 ft/yr; Hwang, 1981; Sea Engineering, Inc., 1988; Makai Engineering, Inc. and Sea Engineering, Inc., 1991). Recent studies on Oahu (Table 3; Coyne et al., 1996; Fletcher et al., 1997) have shown that nearly 24% or 27.5 km (17.1 mi) of an original 115 km (71.6 mi) of sandy shoreline (1940s) has been either significantly narrowed (17.2 km; 10.7 mi) or lost (10.3 km; 6.4 mi). Nearly one-quarter of the islands' beaches have been significantly degraded over the last half-century and all shorelines have been affected to some degree. Oahu shorelines are by far the most studied; however,

TABLE 3. Beach narrowing and loss on Oahu (adapted from Coyne et al., 1996 and Fletcher et al., 1997).[a]

Beach Condition and Change	Mokuleia	Kaaawa	Kailua-Waimanalo	Maili-Makaha	Island-wide
Originally sandy (km)	12.2 ± 1.0	7.5 ± 0.6	15.5 ± 1.3	6.0 ± 0.5	115.6 ± 9.8
Narrowed beach (km)	2.1 ± 0.2	3.2 ± 0.3	0.9 ± 0.1	1.3 ± 0.1	17.3 ± 1.5
Lost beach (km)	0.2 ± 0	0.8 ± 0.1	1.6 ± 0.1	0.2 ± 0	10.4 ± 0.9
Degraded beach (%)	18.7	53.6	16.3	24.9	23.9
Short-term, maximum shoreline change rate (m/yr)	−5.1 to 7.7	−5.8 to 14.0	−6.4 to 5.1	−2.2 to 4.0	N.C.[b]
Net shoreline change rate (m/yr)	−0.2 to 0.3	−1.7 to 1.8	−0.9 to 0.6	−0.4 to 0.6	N.C.
Nonarmored mean sandy beach width (m)	26.8	13.2	22.4	43.7	N.C.
Armored mean sandy beach width (m)	12.8	8.9	7.1	24.5	N.C.
Mean long-term shoreline change rate for armored sites (m/yr)	−0.2	−0.3	−0.6	−0.5	N.C.
Range of shoreline change rates for armored sites (m/yr)	−0.1 to −0.3	0 to −1.7	0.2 to −1.8	−0.2 to −1.0	N.C.

[a]97.4 percent of armored beaches experienced chronic erosion prior to the period of narrowing. 92.1 percent of armored beaches experienced long-term (>12 yr) chronic erosion prior to narrowing. Island-wide, all narrowed beaches are on armored shorelines.
[b]N.C., not calculated.

beach loss has been identified on the other islands as well, with nearly 13 km (8 mi) of beach likely lost due to shoreline hardening on Maui (Makai Engineering, Inc. and Sea Engineering, Inc., 1991).

The original sandy shoreline along many segments of coast has been replaced by shoreline hardening structures of various designs and construction materials (i.e., seawalls, revetments, groins of concrete, stone, and wood). The presence of a shoreline structure is indicative of an erosion hazard, but in many places the structure probably exacerbates the problem and changes a condition of shoreline erosion into one of beach loss (Fletcher et al., 1997). Coastal lands are typically composed of carbonate sand in Hawaii; therefore, when they experience chronic erosion and the shoreline shifts landward, a supply of sand is released to the adjoining beach and nearshore region. The beach then remains wide even as it moves landward with the eroding shoreline. If sand is not available to the beach, such as when a wall is built to protect the land (e.g., sand is trapped behind the wall), then beach erosion will ensue as a result of sand impoundment, which leads to beach narrowing and eventually beach loss.

Most beach sand in Hawaii is composed of bioclastic carbonate grains derived from the skeletons of corals, mollusks, algae, and other reef-dwelling, carbonate-producing organisms. Sand supplies are limited relative to mainland coasts where terrigenous sand derived from large rivers and other sources dominate. The formation of beachrock, storage of sand in coastal dunes, and irretrievable sand loss to deeper water beyond the reef crest all contribute to relatively low volumes of sand available to the system. On many Hawaiian beaches, the available sand ends beyond the toe of the beach in a water depth of 1.2–1.8 m (4-6 ft) where the bottom becomes reef or a reef pavement. In contrast, on mainland beaches the sand deposits often extend a considerable distance (hundreds to thousands of meters) offshore.

Causes of coastal erosion and beach loss in Hawaii are numerous but, unfortunately, are poorly understood and rarely quantified. Construction of shoreline hardening structures limits coastal land loss but does not alleviate beach loss and may actually accelerate the problem by prohibiting sediment deposition in front of the structures. Other factors contributing to beach loss include reduced sediment supply, large storms, and sea-level rise. Reduction in sand supply, either from landward or seaward (primarily reef) sources, can have a myriad of causes. Obvious causes such as beach sand mining and structures that prevent natural access to backbeach deposits remove sediment from the active littoral system. More complex issues of sediment supply can be related to reef health and carbonate production which, in turn, may be linked to changes in water quality. Second, the accumulated effect of large storms is to transport sediment beyond the littoral system. Third, rising sea level leads to a landward migration of the shoreline (see next section).

Dramatic examples of coastal erosion, such as houses and roads falling into the sea, are rare in Hawaii, but the impact of erosion is still very serious. The signs of erosion are much more subtle and typically start as a “temporary” hardening structure designed to mitigate an immediate problem which, eventually, results in a proliferation of structures along a stretch of coast. The natural ability of the sandy shoreline to respond to changes in wave climate is lost. It appears obvious that the erosion problem in Hawaii would be much less severe if adequate setback rules were established.

Sea-Level Rise

Tide gauges located on the islands of Kauai, Oahu, Maui, and Hawaii record fluctuations in local sea level and analysis of these records provides rates of long-term (last several decades) sea-level variation around the state (Fletcher, 2000). Results show that each island has its own rate of rel-

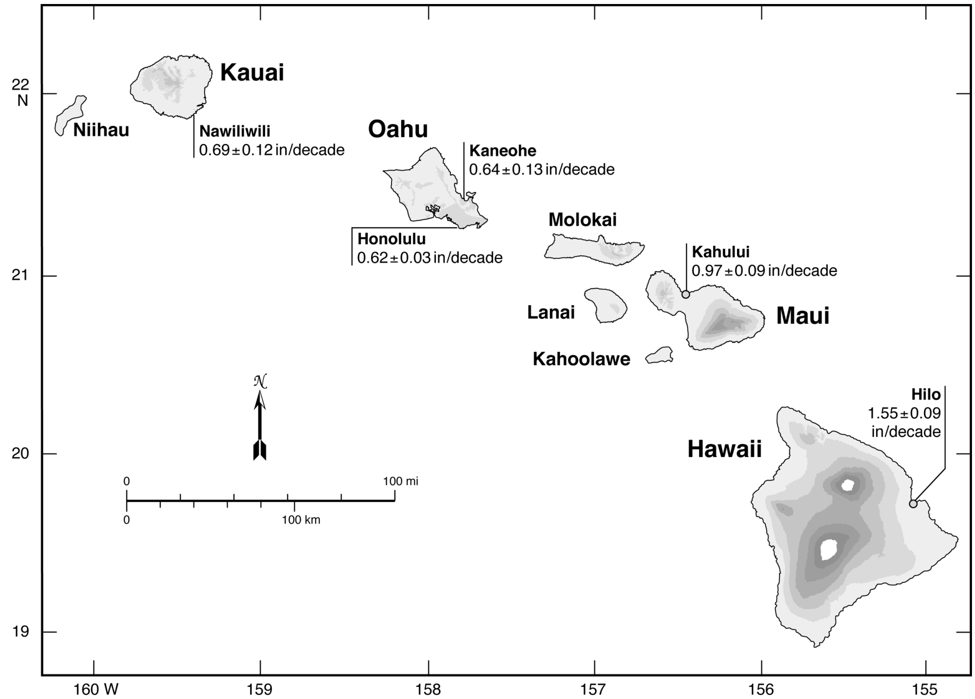

FIGURE 6. Variation of sea-level rise in the main Hawaiian islands based on tide gauge records (after Hwang and Fletcher, 1992).

ative sea-level rise (Figure 6) due to the local isostatic response. Hawaii, because of the heavy load of geologically young volcanic material, is flexing the underlying crust causing the island to subside, creating a comparatively rapid rate of relative sea-level rise, on the order of 3.9 mm/yr (1.5 in./decade). Because it lies near Hawaii and is still historically volcanically active, Maui is also affected by the flexure process and is experiencing rapid sea-level rise, nearly 2.54 mm/yr (1 in./decade). Oahu and Kauai lie outside the area of subsidence and have lesser rates of relative sea-level rise, ~1.5 mm/yr (0.6 in./decade).

The prospect for continued beach degradation and coastal land loss is strongly dependent upon continued sea-level rise. There is no evidence, or theory, suggesting that this trend will do anything other than continue through the near future. Although future rates of rise resulting from an enhanced greenhouse effect have been discussed by scientists, planners, and policymakers throughout the 1980s and 1990s, scientific consensus has settled on a 50 cm rise by the year 2100 with a range of uncertainty of 20–86 cm (Warrick et al., 1996). Should sea-level rise accelerate in the future, low-lying, low-relief, readily erodable, and gentle-slope coasts would be the most vulnerable to sea-level hazards. A more complete discussion of future sea levels and impacts is available in Fletcher (1992).

Despite the uncertainties of predicting future sea levels, the present rate of rise is sufficiently rapid to cause coastal retreat at significant rates. The commonly used "Bruun Rule" method (Bruun, 1962, 1983) of relating sea-level rise to beach retreat has been used to predict a retreat of 1.2–1.5 m (4–5 ft) per decade on Oahu and Kauai (Hwang and Fletcher, 1992). This finding is supported by aerial photographic measurements of beach retreat and suggests that presently narrow beaches fronting seawalls on these islands are likely to be lost over the next quarter century.

Seismicity and Volcanism

The Hawaiian Islands are located in a more complex and hazardous seismic setting than is generally realized (Figure 7). Volcanism is the source of energy for ~95% of the earthquakes on the island of Hawaii. According to Heliker 1997, the Island of Hawaii experiences thousands of earthquakes each year and is, in fact, the most seismically active place in the United States. Although most are small and go unnoticed, one or more earthquakes are felt in the state annually, and minor damage resulting from a stronger shock is not infrequent. The majority of Big Island seismicity is related to the movement of magma within Kilauea or Mauna Loa volcanoes. A few quakes have been related to movements along fault zones located at the base of the volcanoes or deeper within the crust. Seismic tremors on Hawaii have caused ground cracks, landslides, ground settlement, damaging tsunamis, and mudflows as well as damage to buildings and other structures. Strong earthquakes of magnitude 5 or higher (Richter Scale) can cause property damage and endanger people. Because much of the Big Island is rural and sparsely developed, significant damage is usually found only with larger earthquakes. Two damaging earthquakes on the Big Island are especially notable, the Great Ka'u Earthquake of 1868 and the Kalapana Earthquake of 1975. These were the most destructive earthquakes in recorded

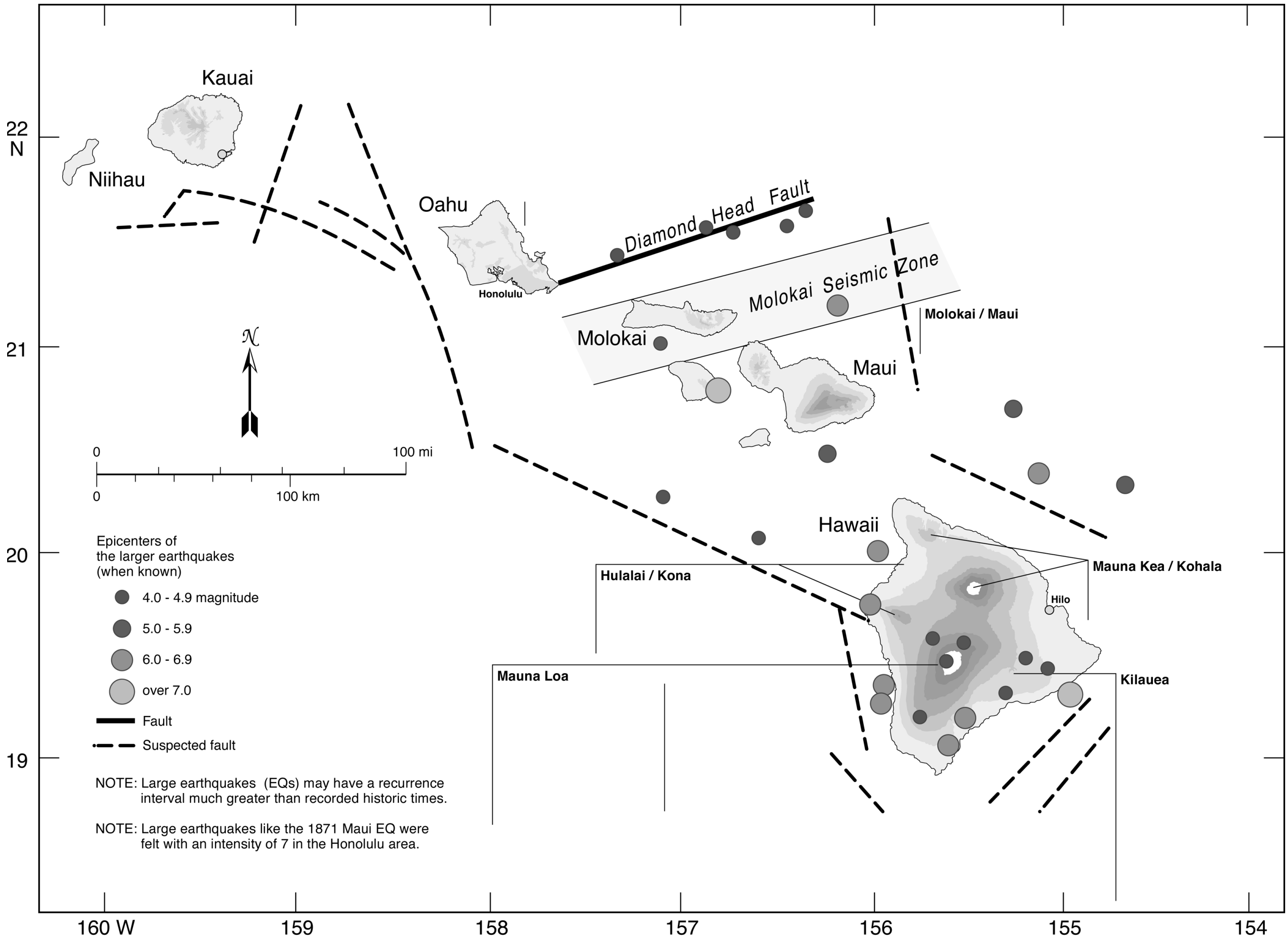

FIGURE 7. Map depicting volcanic and seismic hazards of the main Hawaiian Islands (after Furumoto et al., 1990 and Heliker, 1997).

Hawaiian history. Both tremors caused extensive damage to both wooden and stone houses, and each generated locally destructive tsunamis.

Furumoto et al. (1990) analyzed the record of Big Island seismicity and found that earthquakes of magnitude 6 or greater tend to occur in clusters with recurrence intervals of 10–12 years. Wyss and Koyanagi (1988) identified two regions, the East Kona Block and the South Kona Block, as not having seismically ruptured in the last 100 years.

In the Central Region, defined by Furumoto et al. (1990) as the area encompassing Maui and Oahu, the seismicity is generally related to tectonic activity on the seafloor near the Hawaiian Islands, although the potential for volcanic-related seismicity on Maui's Haleakala Volcano is considered significant. The region has experienced three damaging earthquakes within historical times. Tectonic activity capable of generating hazardous earthquakes in the Central Region is related to seafloor fractures and faults around the islands. The largest of these, the Molokai Seismic Zone and the Diamond Head Fault have been the locus for a number of earthquakes of 4.0 magnitude or higher (Furumoto et al., 1990).

Klein et al. (2000a, 2000b) recently mapped the probability distribution of seismic hazards among the main Hawaiian Islands, utilizing improved earthquake catalogues and giving special consideration to the variation in seismic activity found among the different source areas surrounding the island chain. They gave 10 and 2% probability of peak ground acceleration exceeding predicted values in 50 years, which correspond to recurrence times of ~500 and 2500 years, respectively. The hazard assessments are for firm rock conditions so the predicted motions for unconsolidated sediments that characterize a significant portion of the Hawaiian coastal zone, including the filled region of downtown Honolulu (Cox, 1986), should be considered minima. Whereas subtle lithospheric variations certainly must exist and result in distinct seismic responses on a local scale, a general predicted trend exists. The seismic hazard is highest along the southeast coast of the Big Island, followed by the Kona coast, and gradually decreases exponentially toward the northwest, such that a value of 13% is predicted at Honolulu for peak ground acceleration with a 10% probability of exceeding that acceleration.

The northwestern or Kauai-Niihau region has experienced tremors from earthquakes originating farther south, but no known seismic activity has originated among these northern islands. The earthquake risk for the northwestern islands has been evaluated as minimal.

Volcanic hazards are, of course, greatest on the southern shore of Hawaii, but active seismicity on Haleakala and on Mauna Loa indicate that these volcanoes should continue to be perceived as potentially hazardous. The USGS has completed an extensive mapping program to determine the history and severity of the volcanic hazard on the Island of Hawaii (Wolfe and Morris, 1996). Hawaiian volcanoes erupt either at their summits where lava collects, and may overflow from calderas, or along their flanks where lava issues through zones of weakness in the volcano, called rift zones. The volcanic hazard is associated with lava flows, explosive eruptions, airborne lava fragments, poisonous and corrosive volcanic gases, and ground cracks and settling.

Lava flows present the most frequent hazard associated with Hawaiian volcanoes; however, they rarely endanger human life. Property loss and economic devastation are the most frequent consequence of lava movement. Airborne ash, cinders, and other lava fragments are usually only hazardous in the immediate vicinity of an eruption. Volcanic gases generated by the present eruptions at Kilauea are composed mostly of water vapor, with lesser amounts of sulfur dioxide, carbon dioxide, and hydrogen. Small quantities of carbon monoxide, hydrogen sulfide, and hydrogen fluoride have been measured, but not in health-threatening concentrations. These gases, particularly sulfur dioxide, can mix with rain water to create a corrosive acid rain downwind of the Kilauea eruptions, and higher than average acidity has been documented in drinking water samples, but not at hazardous doses. Water-catchment systems, however, often have leached lead-based metals (e.g., from roof flashing, lead-headed nails, and pipe solder).

Explosive eruptions are not common at Kilauea, but they have occurred within historical times. The interaction of groundwater and hot magma is the usual mechanism leading to an explosion, and the resulting magnitude of the event can be catastrophic in certain circumstances. In 1790, turbulent avalanches of hot gases and rock fragments created pyroclastic surges that flowed several miles to the southwest from the summit of Kilauea. A group of ~80 Hawaiian warriors traveling from Hilo to the Ka'u District at the time to engage King Kamehameha in battle were killed by one of these surges. Geologists have analyzed thick deposits from pyroclastic flows around both Mauna Loa and Kilauea and determined that large surges have occurred in the recent past.

HAZARD RANKING AND INTENSITY

Ranking hazard intensity in a region requires applying scientific judgement grounded in a thorough understanding of the specific history of hazardous phenomena and a familiarity with local environmental processes. Consequently, a major effort of this study was the compilation and construction of a history of hazards in the Hawaiian Islands. Scientific literature, agency reports, newspaper accounts, and miscellaneous records of hazardous events since the beginning of the nineteenth century were used to construct the timing and magnitude of events.

There exists no established methodology for determining the hazardous nature of a coastline. This system was designed following the general procedure used in the National Coastal Hazard Map (Kimball et al., 1985) in the USGS National Atlas. Our design has the advantage of being tailored specifically to the Hawaiian coast and the drawback that it does not benefit from a history of testing and revision that leads to improvement and optimization. We sought to design a methodology subject to the standard tests of scientific validity, which are reproducibility and testability. This ranking method is reproducible through the specific definitions of each hazard intensity (Table 4), and it is subject to the test of time (comparison of rankings to future events) and the constraints of the historical database. Although certain hazards such as stream flooding frequency and hurricane overwash can be successfully modeled, it is beyond the scope of this project to construct numerical approximations of each hazard for the entire Hawaiian coast. Rather, the goal is to present a usable, understandable, yet detailed characterization of coastal hazards within a scientific framework and with historical accountability.

Ranking hazard intensity is based on a number of variables, some of which are not always available for consideration because much of the Hawaiian coast is remote and little is known about its hazard history. In many cases, the option of mapping intensity was "no data available," but this would run counter to the spirit and intent of the project. Thus, in nearly all settings lacking historical data, environmental features and regional patterns were used as a sufficient basis for determining the likely intensity of each hazard. For example, beach erosion rates are not known for the entire state, yet there are some beaches where abundant beachrock is exposed, and the vegetation line is awash during high tide. These are strong environmental indicators of chronic erosion. In such localities, these are sufficient data for assigning a ranking of 3 or even 4 to the beach erosion hazard. Elsewhere, for instance, on the remote northeastern coast of Maui, low-lying stream valleys surrounded by steep-cliffed shorelines are clearly susceptible to high tsunami run-up and storm overwash and thus were assigned a higher, rather than a lower, ranking despite the absence of direct historical data. That is, the likelihood of severe impacts if a tsunami or storm were to strike are high here.

Hazard intensity rankings for each process are summarized in Table 4 and following is a brief description of how each intensity ranking was developed.

TABLE 4. Hazard intensity rank definitions.

Threat	Low (1)	Moderately Low (2)	Moderately High (3)	High (4)
Tsunami inundation	No history of tsunami activity and no reasonable basis for expected activity	History of minor tsunami flooding (≤10 ft elevation); future flooding hazard is low because of a steep coastal zone (≥45%) or some other mitigating factor (tsunami barrier)	History of major flooding (>10 ft elevation) but historical damage, and expected future damage is slight because the steep coastal zone slope (≥45%) makes development unlikely	History of major flooding (>10 ft elevation) with significant damage because of a moderate to gentle slope (<45%)
Coastal stream flooding	No history of coastal stream flooding and no reasonable basis for expected flooding due to low seasonal rainfall in water shed (monthly maximum <4.9 in.); or steep coastal slope (>45%)	History of nondamaging flooding where streams or highlands with seasonal high rainfall are present (monthly maximum >7.9 in.) and coastal slope >20%; or history of flood damage with full mitigation since last major flood	Abundance of streams and high seasonal rainfall in watershed (monthly maximum >7.9 in.) and history of damaging floods with partial mitigation; or no mitigation where slope >20% and <45%	Historically high flood damage on gentle slope, watershed rainfall (monthly maximum >7.9 in., no mitigation efforts or improvements since last damaging flood
High waves	No reasonable basis to expect high waves	Seasonal high waves 4–6 ft	Seasonal high waves 6–8 ft with hazardous run-up and currents	Seasonal high waves >12 ft, characterized by rapid onset
Storm overwash and/or high winds	No history of overwash or high winds, and no reason to expect them	Minor historical overwash (≤10 ft), and/or high winds (∼40 mph gust)	Historical overwash >10 ft on steep slope,and/or high winds with localized (isolated cases) structural damage(∼40 mph sustained)	Historical overwash >10 ft on moderate to gentle slope, and/or high winds with widespread structural damage (∼75 mph gust)
Coastal erosion	Long-term accretion (>10 yr) with no history of erosion, or dynamic cycles with consistent annual accretion	Long-term stable, or minor erosion/accretion cycles with erosion fully recovered by accretion; low rocky coasts; perched beaches	Long-term erosion rate ≤1 ft/yr; or highly dynamic erosion/ accretion cycles with significant lateral shifts in the shoreline	Chronic long-term erosion >1 ft/yr, or beach is lost, or seawall at waterline for portions of the tidal cycle
Sea-level rise (0.04 in. = 1 mm)	Steep coastal slope where rise>0.04 in./yr or gentle slope where rise <0.04 in./yr	Gentle or moderate slope where rise >0.04 in./yr or steep slope where rise >0.08 in./yr	Gentle or moderate slope, where rise >0.08 in./yr or steep slope where rise >0.12 in./yr	Gentle or moderate slope where rise >0.12 in./yr
Volcanism and/or seismicity	No history of volcanic or seismic activity seismic probability zone 0	No volcanic activity in historic times; seismic probability zone 1, minor historic seismic damage	Limited history of volcanism, seismic probability zones 2 or 3 recommended (historic seismic damage)	Frequent volcanism, seismic probability zones 2 or 3 recommended (frequent historic damage)

No safe place during a tsunami exists near sea level on the coast. On low-lying shorelines, such as in the river and stream valleys that characterize so much of Hawaii, a tsunami may occur as an extremely rapid rise and fall of flood waters characterized by high velocity and turbulent flow. At headlands, the refractive focusing of the wave crest can lead to energy concentration and high magnitude run-up heights. Intensity definitions are conservative. The highest tsunami hazard intensity rating (4) was assigned to areas with an historical run-up height of ∼3 m (10 ft) and a gentle to moderate coastal zone slope. Mitigating factors include large headlands, barrier or broad fringing reefs, and protective structures such as jetties and breakwaters. The ranking of 3 is assigned to localities where there may be a history of high tsunami run-up heights, but little chance of damage because of the presence of an exceedingly steep slope preventing placement of structures. The 3-m criteria is derived from the minimum overwash elevation during Hurricane Iniki that produced significant damage to the first row of dwellings. In general, it was assumed that overwash and tsunami run-up will be similarly influenced by coastal slope and elevation. This is also a reasonable estimate of the elevation of many beachfront homes and structures in Hawaii.

Coastal stream flooding is only ranked in the immediate coastal zone, up to the 200 ft contour (60 m). The hazard ranking for stream floods depends on a number of factors including the history of flooding at the site, coastal zone slope, the seasonal rainfall in the adjacent watershed, and the level of mitigation by the U.S. Army Corps of Engineers and/or the county public works departments. The highest intensity ranking is applied to low-lying streams with high rainfall watersheds (seasonal monthly maximum >200 mm; 7.9 in.) where a historically high level of flooding has occurred and where no mitigation improvements have been attempted since the most recent damaging flood. Lower rankings are based on flood history, watershed climatology, and mitigation levels.

The highest ranking (4) for seasonal high surf is reserved, in most cases, for north-facing shorelines exposed to winter swell that commonly have wave heights exceeding 3.6 m (12 ft); often exceeding 6 m (20 ft). Because of the narrow insular shelves, there is little dissipation of wave energy as the swell generated from North Pacific storms approach the coast. Wave height at the coast can change rapidly, often catching unaware swimmers, fishers, and hikers walking along the shoreline. Wave set-up and run-up associated with sets of large waves creates strong nearshore currents that are extremely hazardous for swimmers. It is not unusual for lifeguards to perform a dozen rescues in one day under these conditions. Lower rankings of the wave hazard are based on reduced wave heights, such as swell generated by southern storms in the summer that can reach a height of 4.5 m (15 ft) along south-facing coasts. Ranking No. 2 typically characterizes windward coasts, which can have large waves of 2 m (7 ft) generated by hurricanes passing to the east of Hawaii but normally do not exceed 1.5 m (4 ft).

Storm overwash and high wind ranking indices are based on levels of windspeed, historical structural damage, and overwash elevation. In the absence of meteorological data or process to the contrary, it is assumed that all Hawaiian coasts are equally vulnerable to hurricane impacts and that the only mitigating variables are local in nature (e.g., slope, elevation, geology, and offshore barriers). The highest intensity ranking (4) is based on overwash exceeding 3 m (10 ft) above low tide which is sufficient on most Hawaiian beaches and low-lying coastlines to flood the area landward of the beach. Where structures are present, the lower levels can be flooded as happened on Kauai during both Hurricanes Iwa and Iniki. A wind gust value of ~120 km/hr (75 mph) is included as an approximation of the minimal speed that will cause extensive structural damage to single family homes and other small dwellings. Intensity No. 3 is also related to an overwash above 3 m (10 ft) in elevation and sustained windspeeds sufficient to cause localized damage to individual dwellings (T. Schroeder, 1995, personal communication) estimated to be ~65 km/hr (40 mph). Sustained winds of 60–120 km/hr (39–73 mph) are used by meteorologists to classify tropical storms, whereas hurricanes have sustained wind speeds of 120–240 km/hr (74 to 149 mph).

Historical erosion rates for Hawaiian sandy shorelines have been derived primarily from aerial photograph interpretation (Hwang, 1981; Makai Engineering, Inc. and Sea Engineering, Inc., 1991; Coyne, et al., 1996, 1999; Fletcher et al., 1997). In areas lacking historical studies, environmental indicators of shoreline erosion, such as the presence of beachrock, seawalls, and/or revetments, and narrow beaches in front of vegetation lines that have been abraded or clearly subject to wave wash, were used to assign rankings. The highest erosion category (4) is defined as long-term erosion at a rate exceeding 0.3 m/yr (1 ft/yr.) or a seawall or revetment without a beach where one was formerly located. Seawalls, which are popularly described as "stabilizing" a shoreline, may actively contribute to beach erosion where sand supply is limited and there is a net landward movement of the shoreline (U.S. Army Corps of Engineers, 1991). Unfortunately, these are typical conditions for the Hawaiian coast where it is affected by long-term sea-level rise and a history of shoreline retreat. Seawalls that intersect the waterline at some point during the tide cycle are, by their very presence, a sign of past or current erosion. Therefore, this report considers coastal segments where seawalls occur near the waterline as highly endangered by erosion, and the erosion severity ranking was assigned a 3 or 4. Moderately high category 3 rankings (erosion <0.3 m/yr) are related to highly dynamic erosion/accretion cycles that cause significant shifts in the waterline. This is a hazardous situation that often leads to rapid upland erosion and structural undercutting frequently resulting in seawall construction and eventual beach loss.

Sea-level rise has not been evaluated here as a dynamic or energetic hazard. It is, however, an agent in exacerbating, rather than mitigating, each of the other hazardous processes. Where the rate of sea-level rise is high (>3 mm/yr; 0.12 in./yr) and the coastal zone slope is low, sea-level rise is ranked at high intensity. Moderate rates of rise on steeper slopes define less intense ranking levels.

Volcanism and seismicity pose a significant risk in the Hawaiian Islands. Areas with frequent volcanism and historical seismic activity are assigned the high hazard intensity of 4 and include large segments of the island of Hawaii. Because the hazard intensities are based on the historical record, the eruption on the southwestern flank of Haleakala on Maui, ~1790, elevates that region to a high ranking for volcanism and seismicity. Limited history of volcanism, but a history of earthquakes, characterizes hazard zone 3. Recommendations contained within the Uniform Building Code are incorporated into this ranking of the volcanic and seismic risk hazards and assigned a ranking of 3 to the southern half of Oahu from Makaha around Diamond Head and Makapu'u Head to Kaneohe Bay. The remainder of the island is given a seismic rank of 2, no historical volcanic activity and low seismic probabilities.

OVERALL HAZARD ASSESSMENT

In addition to ranking individual hazards, a nominal overall hazard assessment (OHA) for the coast was calculated by combining individual assessments and applying a weighting scheme to emphasize dynamic hazards. The OHA was determined by squaring each intensity value, doubling the squared value of the dynamic hazards, and averaging the seven weighted values. Squaring each intensity level gives greater emphasis to high-intensity hazards that generally constitute the greatest threat. Certain hazards are more dynamic than others, including volcanism and seismicity, coastal stream flooding, seasonal high waves, marine overwash and high winds, and tsunami inundation. These hazards may achieve a high level of severity in a relatively short time. The hazards of long-term sea-level rise and beach erosion do not constitute a life-threatening hazard, although they certainly may exacerbate other hazards. For example, a healthy beach acts as a natural buffer protecting the coast during extreme events, but when in an eroded state little protection is provided. The dynamic hazards constitute a greater risk and thus are assigned an additional weighting factor of 2×, after they are squared. The sum of the squared and doubled values are averaged and the resulting value used to assign a nominal overall hazard rank (Table 5).

CONCLUDING REMARKS ●

Part of the criteria in assigning severity rankings is based on historical observations of hazard intensity and magnitude. The damage history related to all hazards only covers the late nineteenth to twentieth centuries, and only the era of satellite technology (1960 to present) allows controlled coverage of meteorological hazards. For instance, volcanic and seismic hazards certainly have longer recurrence intervals than reported in the short history available for this study. Also, hurricanes and other meteorological events have only been uniformly detected since 1960. The understanding of storm intensity and frequency therefore is skewed toward the available data, and a broader understanding of hazard history in Hawaii is not possible.

Damage in areas hit by natural hazards during early years (prior to 1960) was only recorded for then populated regions; thus, a significant (and unknown) hazard history may exist for areas that were more recently populated. Because of this, newly populated areas may have been assigned a lower severity ranking than may be appropriate. Every hazardous phenomenon described here, and others such as subaerial slope failure and shoreline collapse, need to be more carefully quantified, forecast, and mitigated. Identification of extreme events through careful geologic mapping is one method extending the record of hazard event history. The best way to avoid coastal hazards is to avoid inappropriate development in the coastal zone.

TABLE 5. Values used to determine the OHA.

Value	OHA
2–4	Very low hazard
4–8	Low hazard
8–12	Moderate to low hazard
12–16	Moderate hazard
16–20	Moderate to high hazard
20–24	High hazard
24–28	Very high hazard

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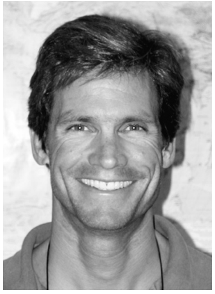

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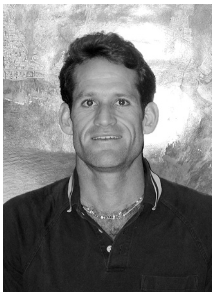

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