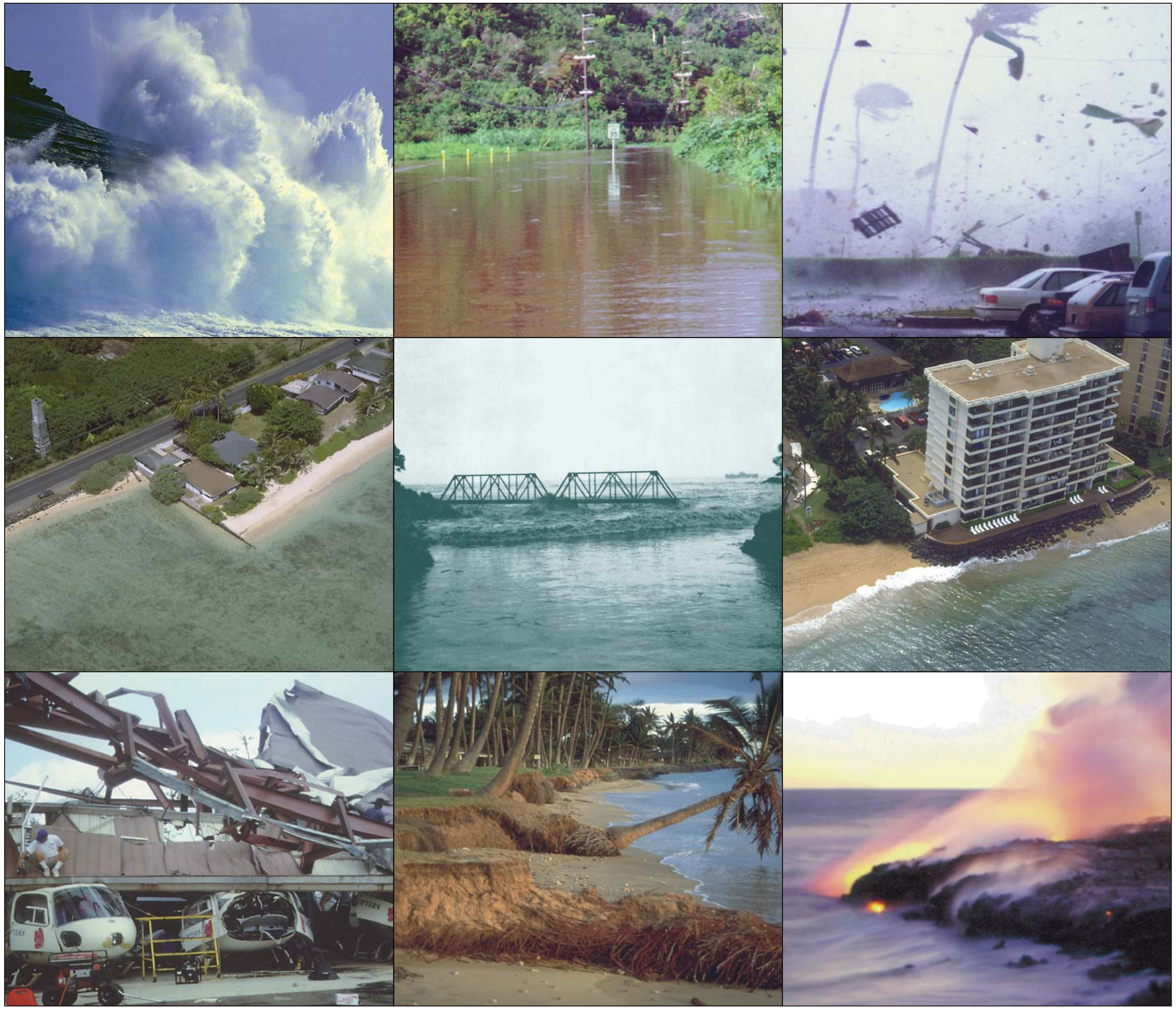

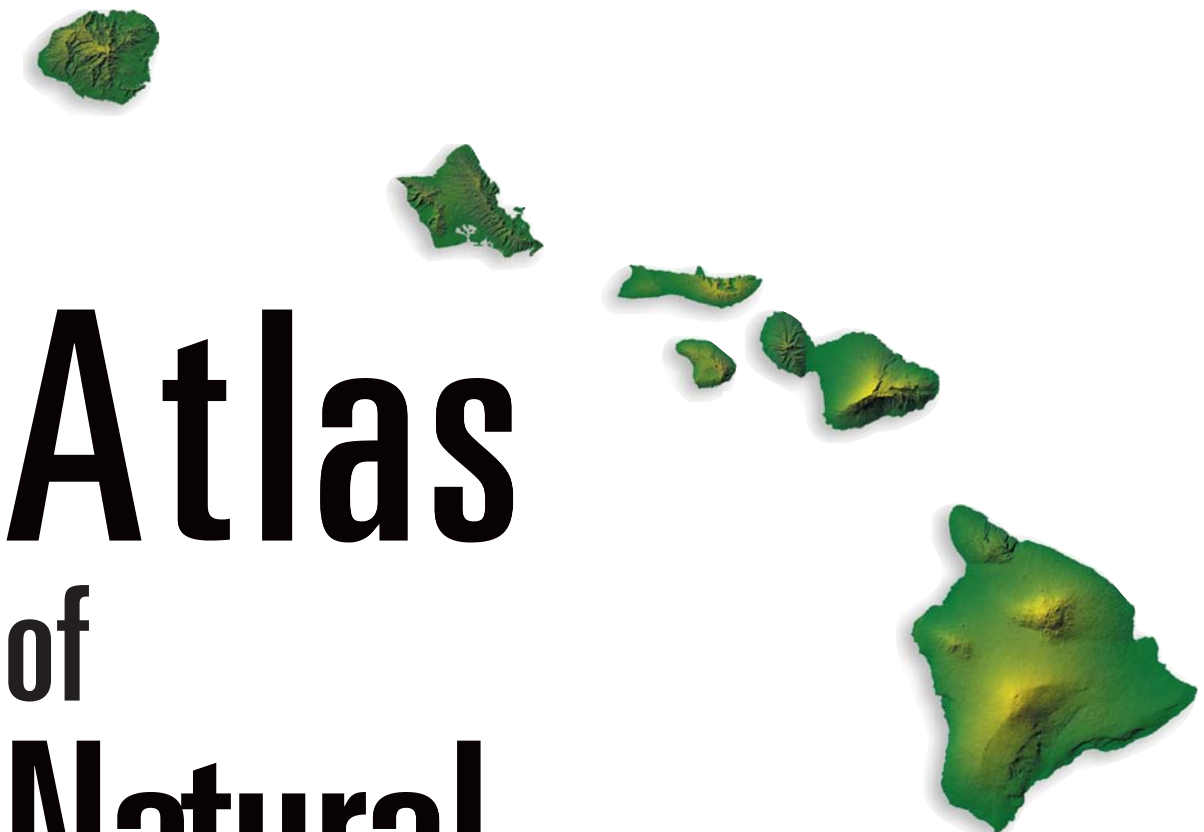

Atlas of Natural Hazards in the Hawaiian Coastal Zone

U.S. Department of the Interior
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Geologic Investigations
Series I-2761

Cover Photos

High waves at Koko Head, Oahu. (Photo, Steve Businger.)	Stream flooding along the Hanalei River, Kauai. (Photo, Scott Calhoun.)	Flying debris in Lihue, Kauai, during Hurricane Iniki. (Photo, Bruce Asato.)
Beach loss is more common along hardened shorelines (left) than along unhardened shorelines (right), Kaaawa, Oahu. (Photo, Charles Fletcher.)	Tsunami bore entering the mouth of the Wailuku River, Hilo, Hawaii, on April 1, 1946. (Photo, Shigeru Ushijima.)	Sea-level rise and coastal erosion threaten much of the coastline and infrastructure in Hawaii, Honokowai Point, Maui. (Photo, Charles Fletcher.)
Destruction at Princeville Airport, Kauai in the wake of Hurricane Iniki. (Photo, Bruce Richmond.)	Coastal erosion at the Halama shoreline in Kihei, Maui. (Photo, Charles Fletcher.)	Lava entering the sea near Kalapana, Hawaii. (Photo, Scott Rowland.)

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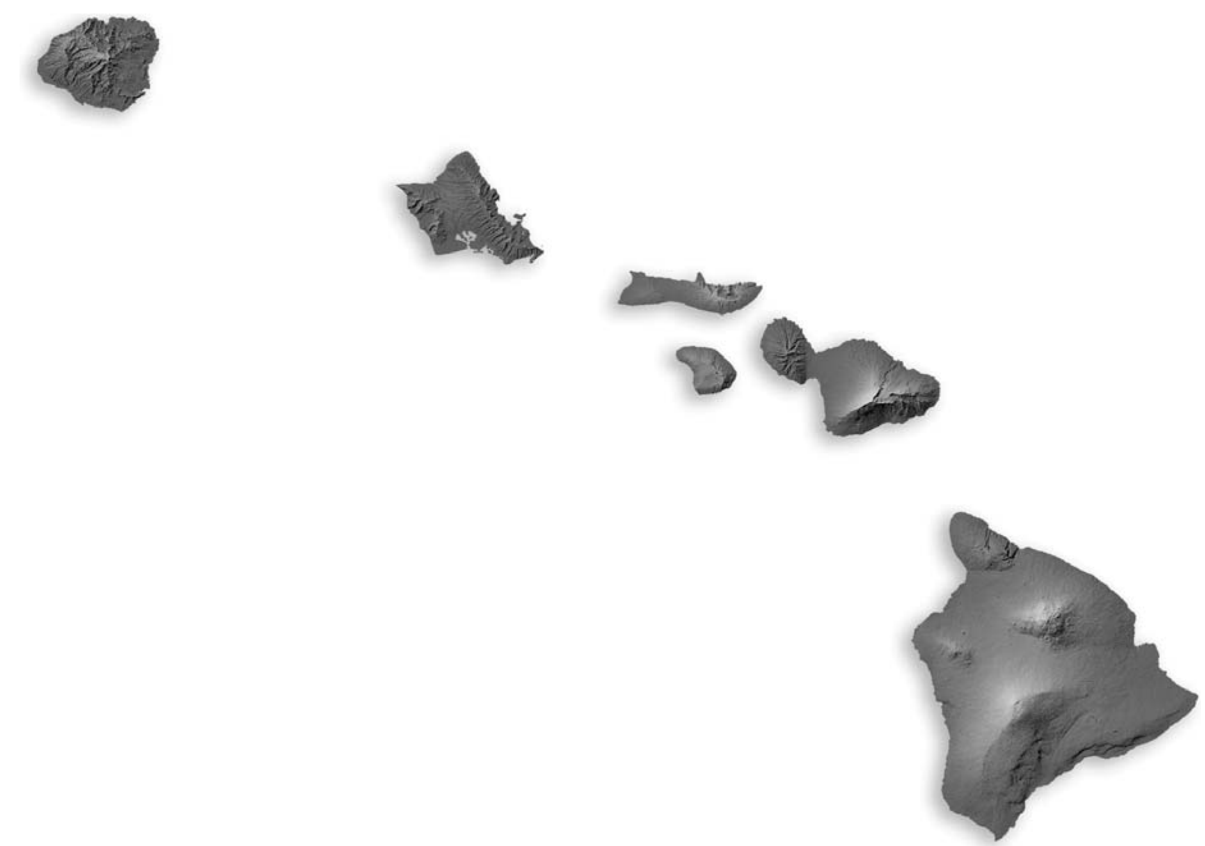
By Charles H. Fletcher III, Eric E. Grossman, Bruce M. Richmond, and Ann E. Gibbs



Prepared in cooperation with University of Hawaii, State of Hawaii Office of Planning, and National Oceanic and Atmospheric Administration

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Purpose and Structure

This atlas reports on a program of research that assigns a relative ranking scale to seven natural coastal hazards. The ranking is based on the historical trends and natural factors influencing site vulnerability and hazard intensity in the Hawaiian coastal zone.

The Hawaii Coastal Zone Management Program (Office of Planning) has identified the prevention and minimization of threats to life and property from episodic and chronic coastal hazards as a priority deserving research and scientific definition. Other than the general requirements of the state shoreline setback provisions and the National Flood Insurance Program, Hawaii lacks specific policies regarding rebuilding storm-damaged structures away from high-hazard areas. There is no restriction on the use of public funds for projects that allow or encourage development in high-hazard areas. Without specific policies or restrictions, development will continue to occur in high-hazard areas at the taxpayer's expense (U.S. Fish and Wildlife Service, 1993).

Introduction

Coastlines are nature's great laboratory of equilibrium. Coastal environments have the capacity to undergo swift and powerful changes in response to meteorological and oceanographic forces. Consequently, students of coastal processes learn that the first principle of coastal science is, "The only reliable constant on the shoreline is a condition of perpetual change." A healthy coastal environment is one with the ability to change when change is needed. Sea levels rise and fall, storms come and go, beaches retreat and advance, and change occurs on timescales from a few seconds to the entirety of Earth history.

Unfortunately, the same dynamic natural processes that characterize coastlines also pose a hazard to the human use of coastal resources. The citizens of Hawaii live and play along island shores. Their right to use the coast and enjoy its benefits are guaranteed in the state constitution, which entrusts the state with the obligation to conserve coastal lands for the people of Hawaii. Yet the coast can be a hazardous environment with a capacity for swift change that can threaten life and property.

To improve our understanding of this problem and its remediation, we have investigated the history and character of natural hazards on the Hawaiian coast. This report contains a history and ranks the intensity of seven potentially hazardous coastal processes in Hawaii. These hazards are:

1.) Tsunamis
2.) Stream flooding
3.) High waves
4.) Storms
5.) Erosion
6.) Sea level
7.) Volcanic/seismic

All sectors of the Hawaiian coast have some degree of hazard history and vulnerability. The responsibility, then, is on the land user or developer to shape their development plans to reduce the impact of a recurrence of specific hazards with high-ranked intensity on human life and economic investment. Those coastal segments that have a high or very high overall hazard ranking must be viewed as especially dangerous for human use or development. A high ranking in any one of the individual hazard categories warrants cause for heightened awareness and concern for implementing mitigation with specific design elements into user plans.

Purpose

The purpose of this report is to communicate to citizens and regulatory authorities the history and relative intensity of coastal hazards in Hawaii. This information is the key to the wise use and management of coastal resources. The information contained in this document, we hope, will improve the ability of Hawaiian citizens and visitors to safely enjoy the coast and provide a strong data set for planners and managers to guide the future of coastal resources.

This work is largely based on previous investigations by scientific and engineering researchers and county, state, and federal offices and agencies. The unique aspect of this report is that, to the extent possible, it assimilates prior efforts in documenting Hawaiian coastal hazards and combines existing knowledge into a single comprehensive coastal hazard data set. This is by no means the final word on coastal hazards in Hawaii. Every hazardous phenomenon described here, and others such as slope failure and rocky shoreline collapse, need to be more carefully quantified, forecast, and mitigated. Our ultimate goal, of course, is to make the Hawaiian coast a safer place by educating the people of the state, and their leaders, about the hazardous nature of the environment. In so doing, we will also be taking steps toward improved preservation of coastal environments, because the best way to avoid coastal hazards is to avoid inappropriate development in the coastal zone.

Technical Map Series

We have chosen maps as the medium for both recording and communicating the hazard history and its intensity along the Hawaiian coast. Two types of maps are used: 1) small-scale maps showing a general history of hazards on each island and summarizing coastal hazards in a readily understandable format for general use, and 2) a large-scale series of technical maps (1:50,000) depicting coastal sections approximately 5 to 7 miles in length with color bands along the coast ranking the relative intensity of each hazard at the adjacent shoreline.

The authors intend for this report to be used as a reference atlas of coastal hazards in Hawaii. We have constructed a set of technical hazard maps (example follows) of the entire shoreline of the islands of Kauai, Oahu, Molokai, Lanai, Maui, and Hawaii at a scale of 1:50,000 (1 inch on the map equals approximately 0.8 miles). The technical map series displays the nominal relative intensity (on a ranked scale of 1 to 4, where 4 is most intense) of each of the seven hazards following a set of specific definitions (Table 1). These are used as a guide in assigning an intensity level to each hazard. Where a lack of data precludes establishing a specific ranked definition, the rankings are applied as a relative scale based on a logical interpretation of environmental variables. Each map also depicts the geology of the coast using a simple alphabetical code. In addition, the slope of the coastal zone is mapped from sea level to an elevation of approximately 200 feet, or the first major change in slope. Both geology and slope are important variables in determining the hazardous character of the coastal zone.

Ranking Hazard 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 episodes since the beginning of the nineteenth century are compiled here into a single report. It is our hope that the hazard data set will continue to be maintained and updated in the interest of eventually achieving a statistically robust capability to predict hazard chronology and intensity.

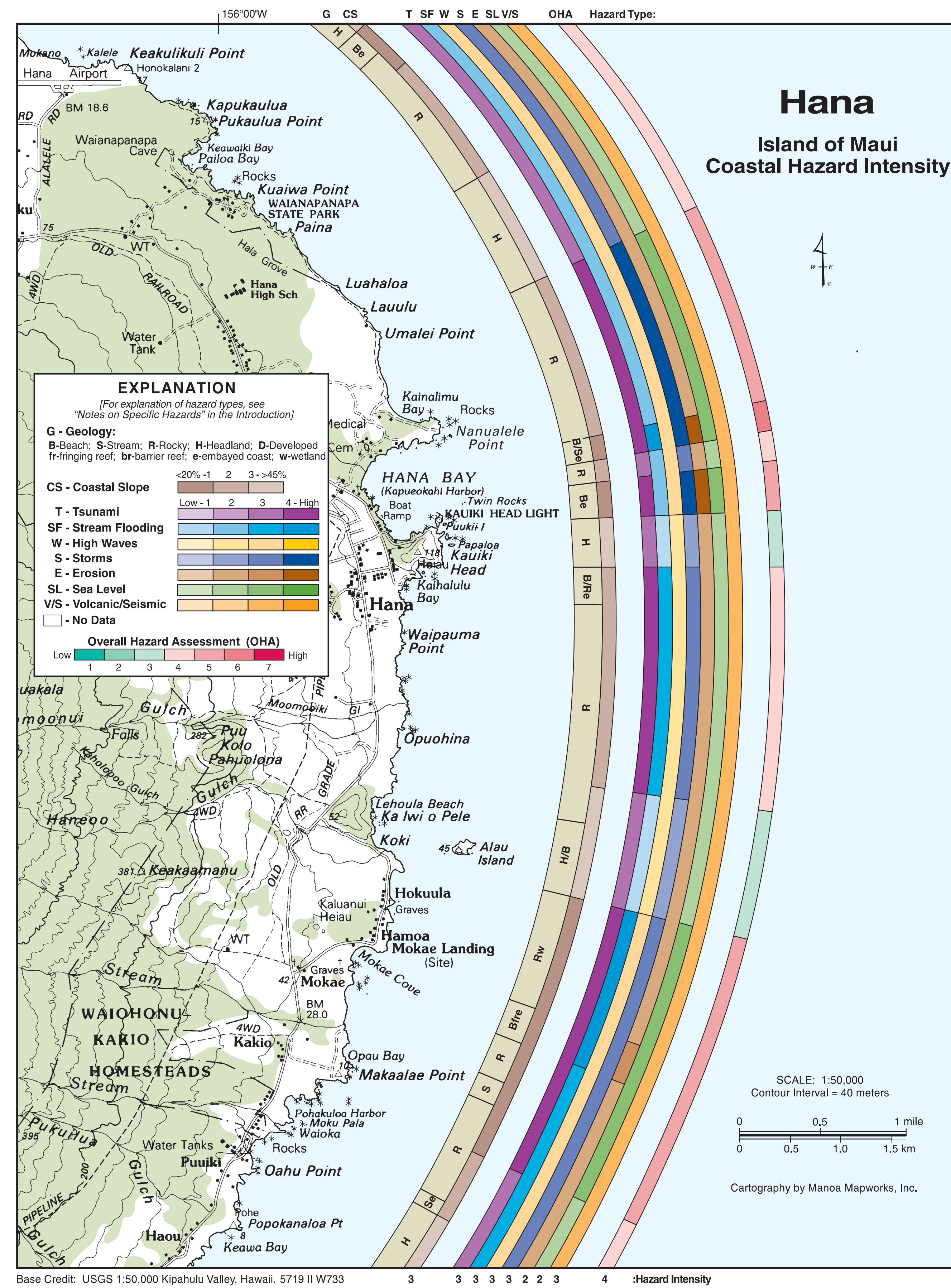
There exists no established methodology for determining the hazardous nature of a coastline. We have designed our system following the general procedure used by the U. S. Geological Survey in their National Coastal Hazard Map (Kimball and others, 1985). Our design has the advantage of being tailored 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. We were successful in this. Our ranking method is reproducible through the specific definitions of each hazard intensity (Table 1), and it is subject to the test of time (comparison of our rankings to future events) and the constraints of the historical data. 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, our 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 (Table 1), 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. However, in nearly all settings lacking historical data we have been able to use environmental features and regional patterns 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, this is sufficient data for assigning a ranking of 3 or even 4 to the beach erosion hazard.

TABLE 1
Hazard Intensity Rank Definitions

Hazard	Low (1)	Moderately Low (2)	Moderately High (3)	High (4)
Tsunami	no history of tsunami flooding; steep coastal zone slope (≥45%)	history of tsunami flooding; steep coastal zone slope (≥45%)	history of tsunami flooding; historical damage; steep coastal zone slope (≥45%)	history of tsunami flooding; historical damage; gentle slope (<45%)
Stream Flooding	no history of coastal stream flooding and no reasonable basis for expected flooding due to low seasonal rainfall in watershed (<4.9 in per month); or steep coastal slope (>45%)	history of nondamaging flooding where streams or highlands with seasonal high rainfall are present (>7.9 in per month) 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 (>7.9 in per month) and history of damaging floods with partial mitigation or no mitigation where slope >20% and <45%	historically high flood damage on gentle slope, high watershed rainfall (>7.9 in per month) and 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
Storms	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)
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 water-line for portions of the tidal cycle
Sea Level (0.04 in=1mm)	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/yr or steep slope where rise >0.12 in/yr	gentle or moderate slope where rise >0.12 in/yr
Volcanic/ Seismic	no history of volcanic or seismic activity, *UBC seismic zone factor ≤ 2	no volcanic activity in historical times; *UBC seismic zone factor ≤ 2, minor historic seismic damage	limited history of volcanism, *UBC seismic zone factor ≥ 2 recommended, historic seismic damage	frequent volcanism, *UBC seismic zone factor ≥ 2 recommended, frequent historic damage

*UBC, Uniform Building Code seismic zone factor



Intensity Variables

Variables that were considered when assigning hazard intensities include the history of a particular hazard, local and regional environmental processes, arguments for or against future occurrences of the hazard, and mitigating or exacerbating circumstances that are relative to future hazard intensity. For example, throughout the state a number of streams with a history of flooding have undergone channelization by the U.S. Army Corps of Engineers to mitigate the threat of future flooding. These efforts are generally successful measures in decreasing the downstream flood hazard to local residents. We have ranked the intensity for these locations with consideration of the level of mitigation and the flooding history since mitigation was enacted. Some of these locations are also subject to flooding because of extremely heavy rainfall that quickly collects on the ground due to insufficient permeability in the underlying substrate. This is different than stream flooding. Clearly, in these regions, stream channelization does not fully mitigate the flooding hazard. Thus a region may be fully channelized, but the hazard is only partially mitigated. Our ranking depicts the continued presence of a hazard despite the mitigation effort.

Overall Hazard Assessment

In addition to ranking individual hazards, we have calculated a nominal Overall Hazard Assessment (OHA) for the coast 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, which 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. Long-term sea-level rise and beach erosion do not constitute a life-threatening hazard, although they certainly may exacerbate the others. The dynamic hazards constitute a greater risk and thus are assigned an additional weighting factor of x2, after they are squared. The sum of the squared and doubled values are averaged and the resulting value is used to assign a nominal overall hazard rank with the following guidelines:

Rank	OHA	Level
1	2-4	Very Low OHA
2	4-8	Low OHA
3	8-12	Moderate to Low OHA
4	12-16	Moderate OHA
5	16-20	Moderate to High OHA
6	20-24	High OHA
7	24-28	Very High OHA

Report Structure

The main body of this report presents an island by island review of coastal hazards. Each island is given its own chapter beginning with a general introduction that presents a brief but informative review of each hazard. The centerpiece of the discussion is a series of historical summary maps describing the intensity, date, and known consequences of island hazard history. These maps are provided in color as a means of optimizing the relative information, yet they readily reproduce to black and white for ease of distribution.

The second section of each chapter provides technical maps of relative hazard intensity. More than 120 maps have been constructed that depict relative hazard intensity, coastal geology and slope, and the Overall Hazard Assessment, which is a weighted average of all seven hazards (as previously discussed).

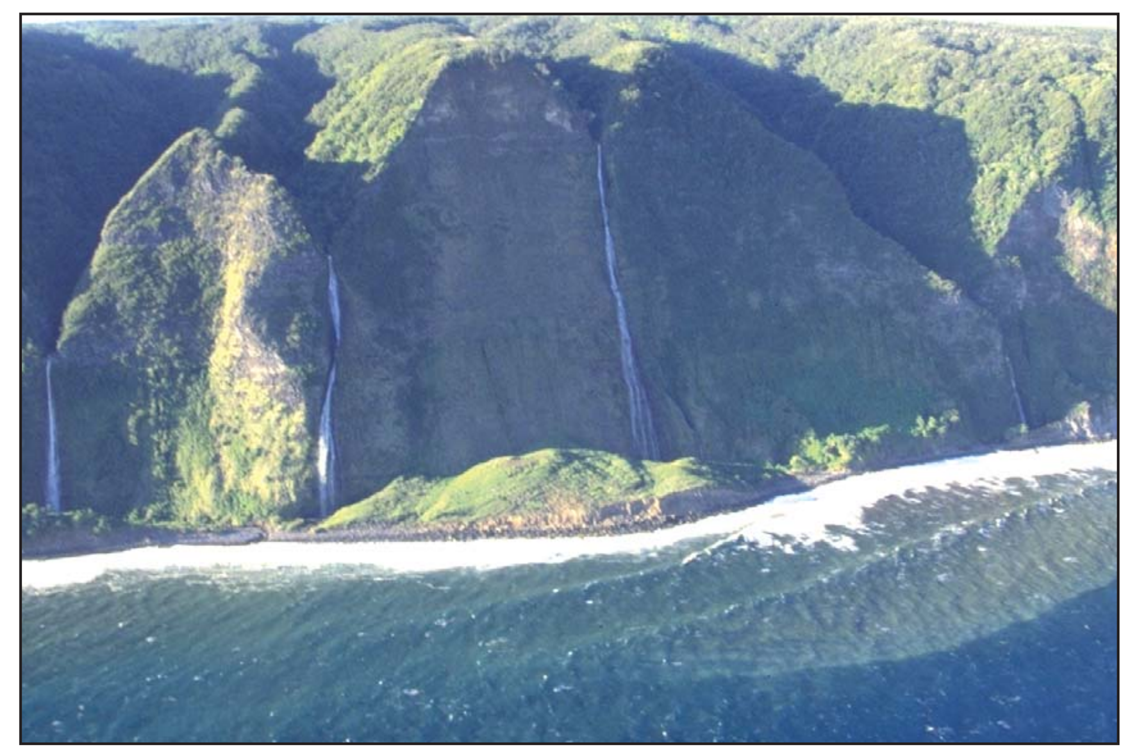
Notes on Specific Hazards

The following discussion details the assumptions, limitations, and variables that influenced our ranking determinations and the mapping of coastal geology and coastal zone slope. Although understanding the technical mapping format may initially require a period of familiarization, once learned, each map embodies a large amount of detail and becomes a rapid and ready source of information.

Coastal Slope

The coastal-slope ranking assignments are made for the coastal plain in the elevation range of 0 to 200 ft above sea level. In many locations, a steep coastal headland or cliff less than 200 ft high presents an effective barrier to inland storm overwash, tsunami inundation, erosion, stream flooding, and sea-level rise. Because this mitigates against the highest hazard ranking for those processes it is assigned the highest slope value (no. 3) even though it is less than 200 ft high. In other words, in such instances we have mapped the effective coastal slope, which is often not the average slope of the first 200 ft but instead is the slope of the effective portion of the coast with regard to hazard mitigation.

Technical maps, showing intensity rankings, depict the coastal zone slope in one of three shades of brown (see technical map example, p.3): the darkest shade (no. 1) indicates a gentle slope with a gradient less than or equal to 20% (<11.5°); the middle shade (no. 2) indicates a moderate slope with a gradient greater than 20% and less than 45% (>11.5° and <26.7°); the lightest shade (no. 3) indicates a steep slope with a gradient greater than 45% (>26.7°). We use the darkest shade for the gentlest slope because it is more hazardous 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 wherein greatest hazard intensity is mapped with the darkest shade.



The Hamakua shoreline, on the northeast coast of the Big Island, displays both gentle and steep coastal zone slopes.

Geology

The geologic framework of the Hawaii coast is complex and exhibits frequent changes and a variability in detail that is not fully mappable at a 1:50,000 scale. Our determinations of coastal geology are broad based and generalized, incorporating those features that are important in assigning hazard severity rankings. These features have lengths greater than 1000 ft in most instances.

The coastal geology was mapped in a field program using aerial videotapings of the Hawaiian coastal zone from an elevation of 300-500 ft, at an airspeed averaging 70-100 knots. These tapes are available from the Office of State Planning. They provide an excellent and detailed archive of the Hawaiian coastal environment in late 1993.

We recommend that a more comprehensive geologic mapping research program be implemented to determine those variables that may play an additional role in hazard severity such as risk from slope instability, grain size variations that may control oil spill clean-up efforts, freshwater discharge sites that modify reef character and coastal sedimentology, channel systems in fringing reefs that allow high onshore wave energy, rocky sectors of shoreline that may be seasonally exposed by shifting sands, and other geologic variables. We have used the developed shoreline designation (D) to identify coastlines stabilized with revetments and seawalls. Fringing reef (fr) includes seafloor in the coastal zone supporting a shallow reef platform.

Geologic features (Table 2) are depicted using an alpha code with the dominant geology capitalized and associated secondary geologic features in lower case:

TABLE 2
Geology

(Upper Case = primary feature)

B - sandy beach, may include minor amounts of beachrock
R - low-lying rocky shoreline (beachrock, boulder beach 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

(lower case = secondary feature)

fr - fringing reef adjacent to shoreline
br - barrier reef (only one barrier reef is found in Hawaii; it is along the seaward margin of Kaneohe Bay, Oahu)
e - embayed coast, designates pocket beaches, narrow embayments, and coast leeward of prominant headlands
w - wetlands, designates coasts with adjacent terrestrial wetlands and ponds
d - development is a secondary feature of the shoreline
s - stream mouth is a secondary feature of the shoreline

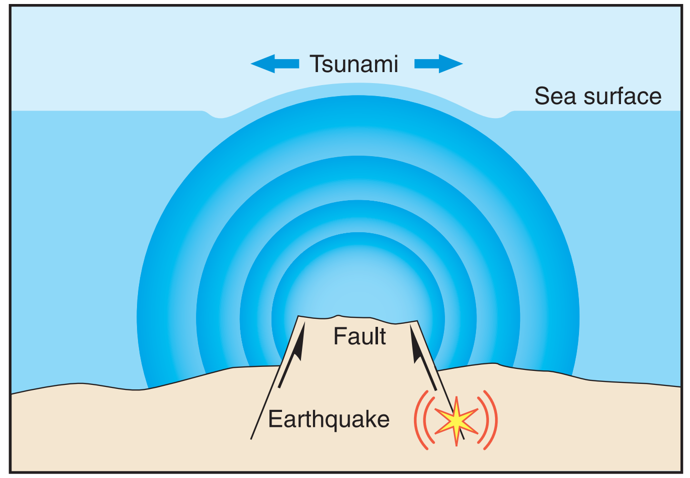
The Diamond Head and Waikiki coast on Oahu is an example of a developed coastal plain with beaches and a broad fringing reef tract (D/Bfr).

Along the Hamakua and Upolu coasts of the Big Island, embayments comprised of a stream mouth and beach (S/Be) are often interspersed between steep headlands (H).

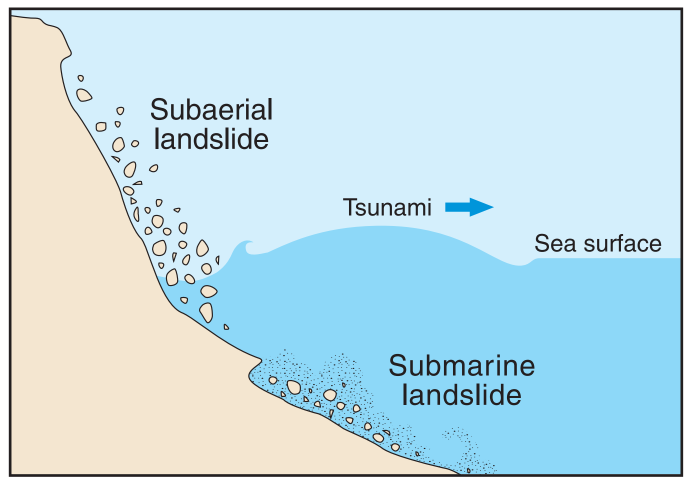
Tsunamis

Tsunamis are caused by a sudden movement of the seafloor that generates a wave, or actually a series of waves, that travel across the ocean until they reach a coast. Seafloor movements may include faulting, landsliding, or submarine volcanic eruptions. Submarine faulting, often consisting of the vertical movement of a block of oceanic crust, may cause the seismic tremors that are known as earthquakes. The tsunami, then, is the result of the faulting, not the earthquake. Landslides originating either under the sea or above sea level and then sliding into the water may also generate a tsunami. On July 9, 1958, a massive rockslide at the head of Lituya Bay, a fjord in Alaska, produced a tsunami that surged more than 1,700 ft up an adjacent hillside. It is thought that large tsunami were generated from time to time during the early history of the Hawaiian Islands when massive portions of the young islands slid into the sea. Tsunami are also caused by explosions or sudden seafloor movements related to submarine volcanism. The violent explosion of the island volcano Krakatoa in 1883 produced tsunami waves 130 ft high on the shores of Sumatra and Java, killing over 36,000 people in all. The high degree of volcanism and seismic instability in and around the Pacific Ocean have led to a long history of tsunami occurrences. Because this is one of the most geologically active regions on Earth, the Hawaiian coast is under the continuous threat of tsunami inundation.

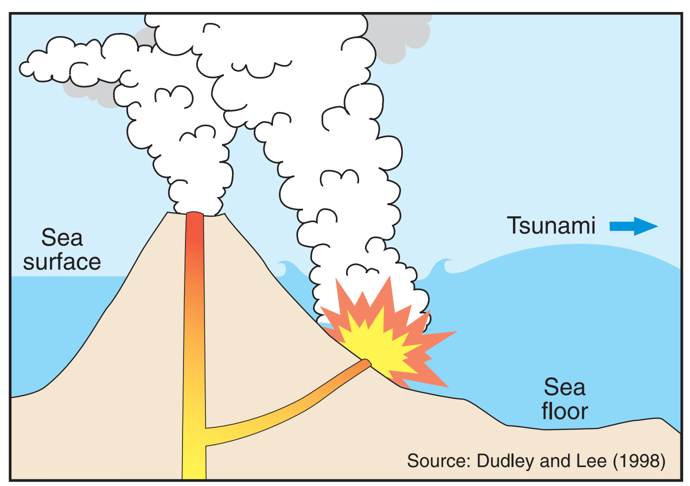
Submarine faulting, landslides, submarine slides, and submarine volcanism are common geologic processes in Hawaii, and all are capable of generating hazardous tsunami. In addition, these processes acting on coastlines around the Pacific have historically produced tsunami that traveled to Hawaii resulting in massive damage and loss of life.



Faulting of the ocean floor may produce a tsunami.

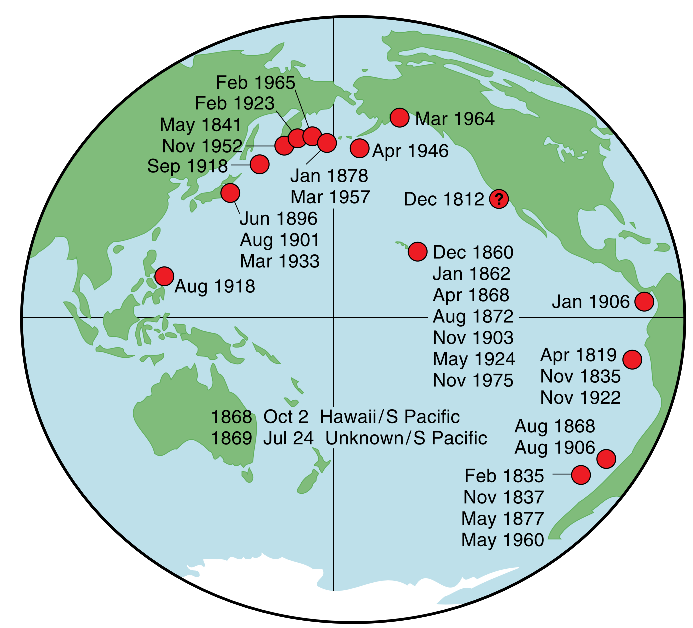


Subaerial or submarine landslides may produce a tsunami.



A submarine volcanic explosion may produce a tsunami.

Laupahoehoe Peninsula, north of Hilo on the Big Island, experienced waves 30 ft high during the Aleutian tsunami of 1946. Twenty-one people lost their lives here, 16 school children and 5 teachers. Statewide 159 people died in the disaster.



Tsunami-generating earthquakes in the Pacific basin and their epicenters (red dots).

Tsunami pose a significant hazard in the Hawaiian coastal zone. According to Dudley and Lee (1998) Hawaii has experienced a total of 95 tsunami in 175 years (1813-1988), however, for our analyses we have adopted the listing of Lander and Lockridge (1989). The last truly large seismic sea wave was in 1960. Tsunami manifest themselves as either large breaking waves, often largest around headlands where they are concentrated by wave refraction, or as rapidly rising sea level like a flooding tide. The geography of the shoreline often plays an important role in the form of the tsunami. Unlike storm waves, tsunami waves may be very large in embayments, actually experiencing amplification in long funnel-shaped bays. Fringing and barrier reefs appear to have a mitigating influence on tsunamis by dispersing the wave energy. Within Kaneohe Bay, Oahu, protected by a barrier reef, the 1946 tsunami reached only 2 ft in height, while at neighboring Mokapu Head the wave crest exceeded 20 ft. Despite complex differences in the geography and orientation of Hawaii's many coastlines, several locations have historically been subject to severe tsunami impacts, including Hilo Bay, Hawaii; Kahului Bay, Maui; and Kakiaka Bay, Oahu.

At sea level on the coast there is no safe place during a tsunami. On low-lying shorelines such as in the river and stream valleys that characterize so much of Hawaii, a tsunami may occur as a rapidly growing high tide that rises over several minutes, perhaps 10 minutes, and inundates low coastal regions. The return of these flood waters to the sea causes much damage. At headlands the refractive focusing of the wave crest leads to energy concentration and high magnitude run-up. Our intensity definitions are conservative. With an historical run-up height of approximately 10 ft (3 m above low tide) and a gentle to moderate coastal zone slope, in the absence of mitigating factors we assign our highest intensity (no. 4) to the tsunami hazard. Mitigating factors include large headlands, barrier or broad fringing reefs, and protective structures such as the jetties and breakwaters found in Hilo and Kahului harbors. The ranking of 3 is assigned to localities where there may be a history of high tsunami run-up, but little chance of damage because of the presence of an exceedingly steep slope preventing building development. Our 10-ft criteria is guided by the minimum overwash elevation during Hurricane Iniki that produced significant damage to the first row of dwellings. This is also a reasonable estimate of the elevation of many beachfront homes and structures in Hawaii.

Stream Flooding

Coastal stream flooding is only ranked in the immediate coastal zone, up to the 200-ft contour. In certain localities, such as eastern Maui, the Big Island Hamakua coast, and north Kauai, streams hang above the sea in valleys that discharge as waterfalls rather than as tidal stream mouths. Although these localities may be susceptible to flooding, we have not ranked them as high hazard sites because they are not at sea level and the flooding hazard is a terrestrial process rather than a coastal process.

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 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 max. >7.9 in [200 mm]) where an 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.

In 1983 the Department of Land and Natural Resources (DLNR) reported that floods in Hawaii had claimed more than 350 lives and caused more than $475 million in damages. Planning for flood control strategies requires a consideration of accommodating development in flood-prone regions through measures such as building code requirements, land use regulations, relocation, and emergency evacuation. In addition, an approach consisting of mitigants such as levees and dikes, improved channels, flood water storage structures and other types of drainage diversion features are employed. Together these two approaches constitute the flood control and flood plain management approach typically utilized by regulatory authorities. Little effort has been made by authorities to lessen the impact of these mitigations on riverine and paludal ecosystems. In fact, little is known of the long-term degradation to both freshwater and coastal saltwater ecosystems that results from the widespread use of flood control techniques (Hawaii Stream Assessment, 1990).

Floods caused by heavy rainfall and strong winds normally occur during the winter months with January typically being the most frequent flood period. Heavy rainfall can also be associated with the tropical storm and hurricane season between the months of June and October. 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. Lanai, lying in the rain shadow of Molokai receives relatively less precipitation. Molokai is relatively unpopulated and the town of Kaunakakai has adequate flood control measures so that flood damage on the island is effectively reduced. The sparse population in the humid regions of Molokai presently reduces the flood hazard, but is no guarantee for the future. On the Big Island, regions of high precipitation are characterized by deep valleys that effectively channelize floodwaters. Elsewhere, the high porosity of the geologically young lavas are a deterrent to frequent flooding. Hilo is susceptible to periods of heavy rainfall and may experience flooding on the low coastal plain. Exceptionally heavy flooding from intense rainfall in the Hilo area in November 2000 led to a declaration of a state of emergency. Damage to bridges and roadways reached $20 million.

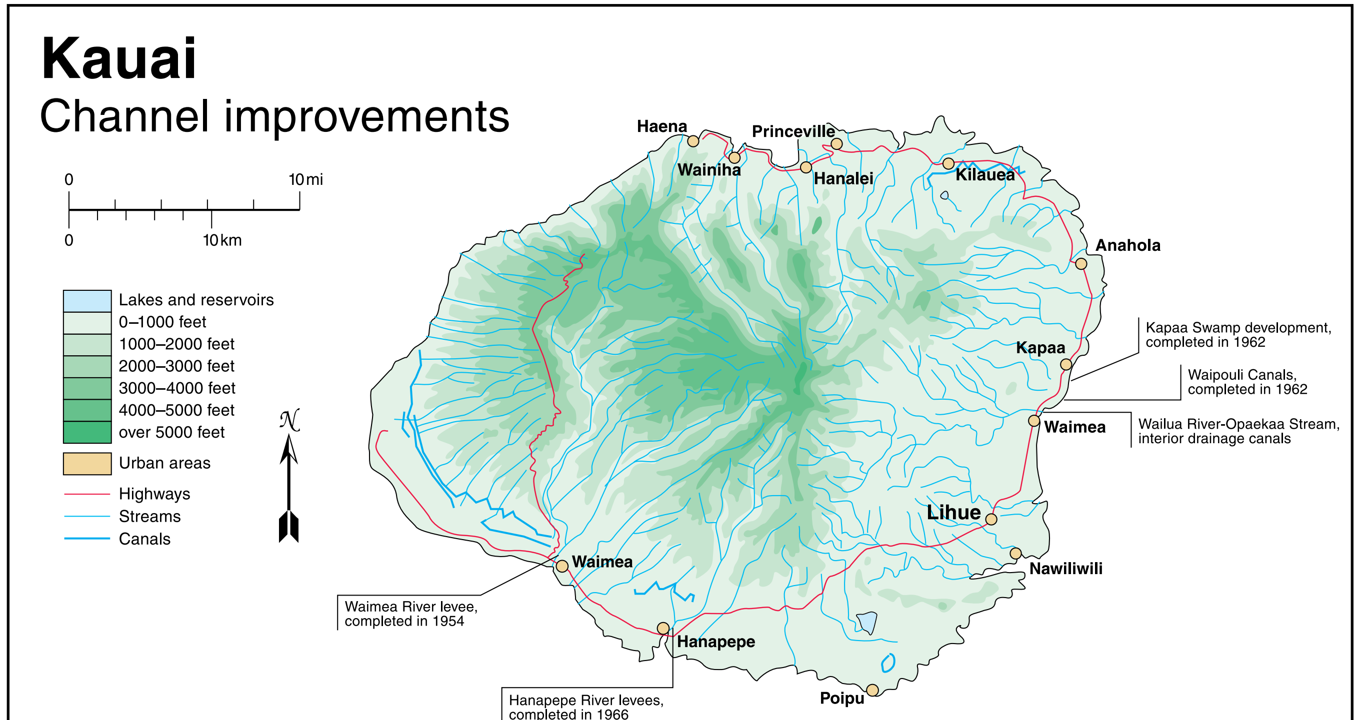
Table 3 is an unofficial tabulation of flood damages and lives lost for the state derived from the 1983 DLNR Report on Floods and Flood Control and the monthly Storm Data publication of the National Climatic Data Center, National Oceanic and Atmospheric Association (NOAA) (visit their web site at http://www.ncdc.noaa.gov/ol/ncdc.html). These data provide an effective summary of the severity of the flood hazard in Hawaii.

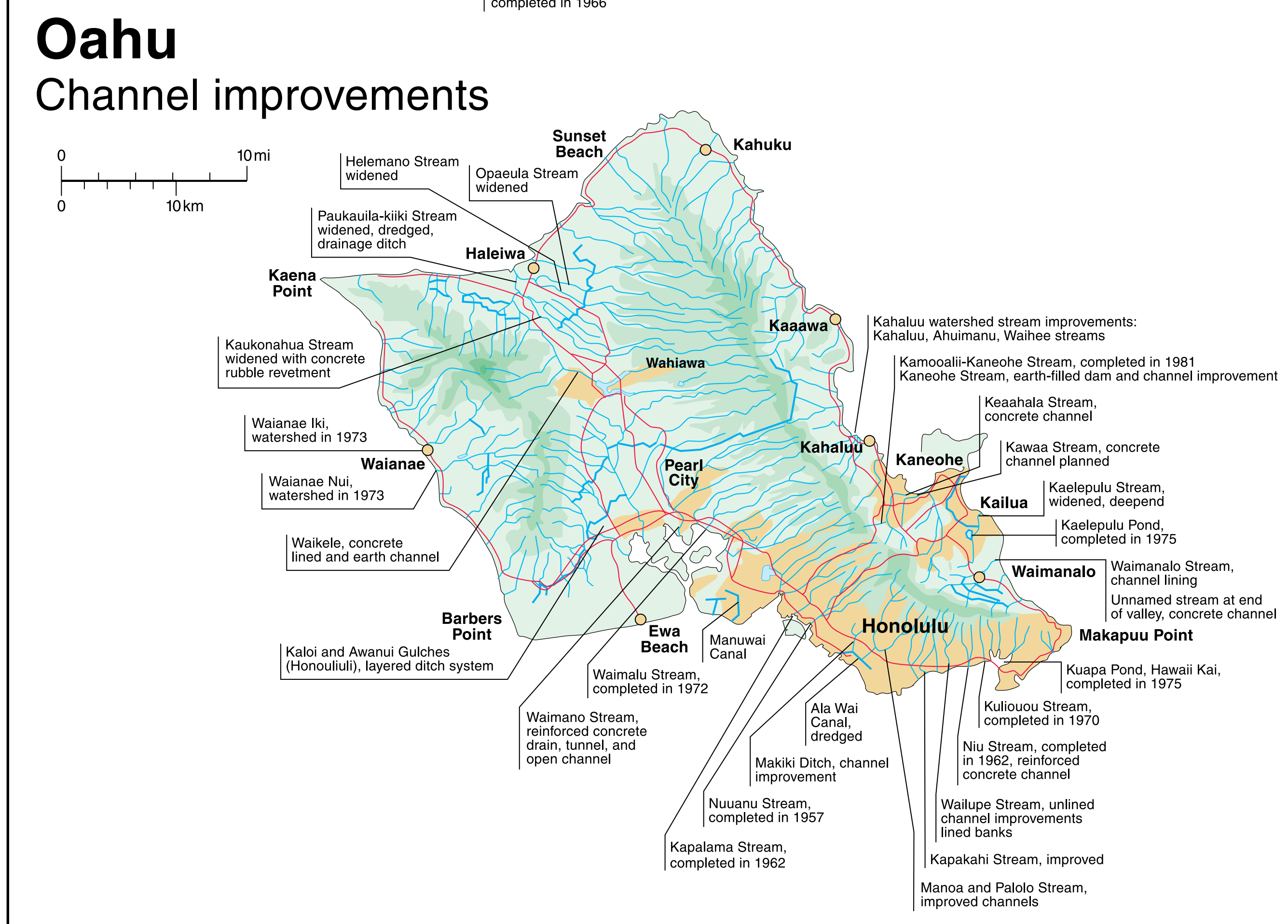
Heavy rainfall combined with an abrupt transition in coastal slope often leads to coastal stream flooding in Hawaii's low-lying coastal zones including Hanalei, Kauai.

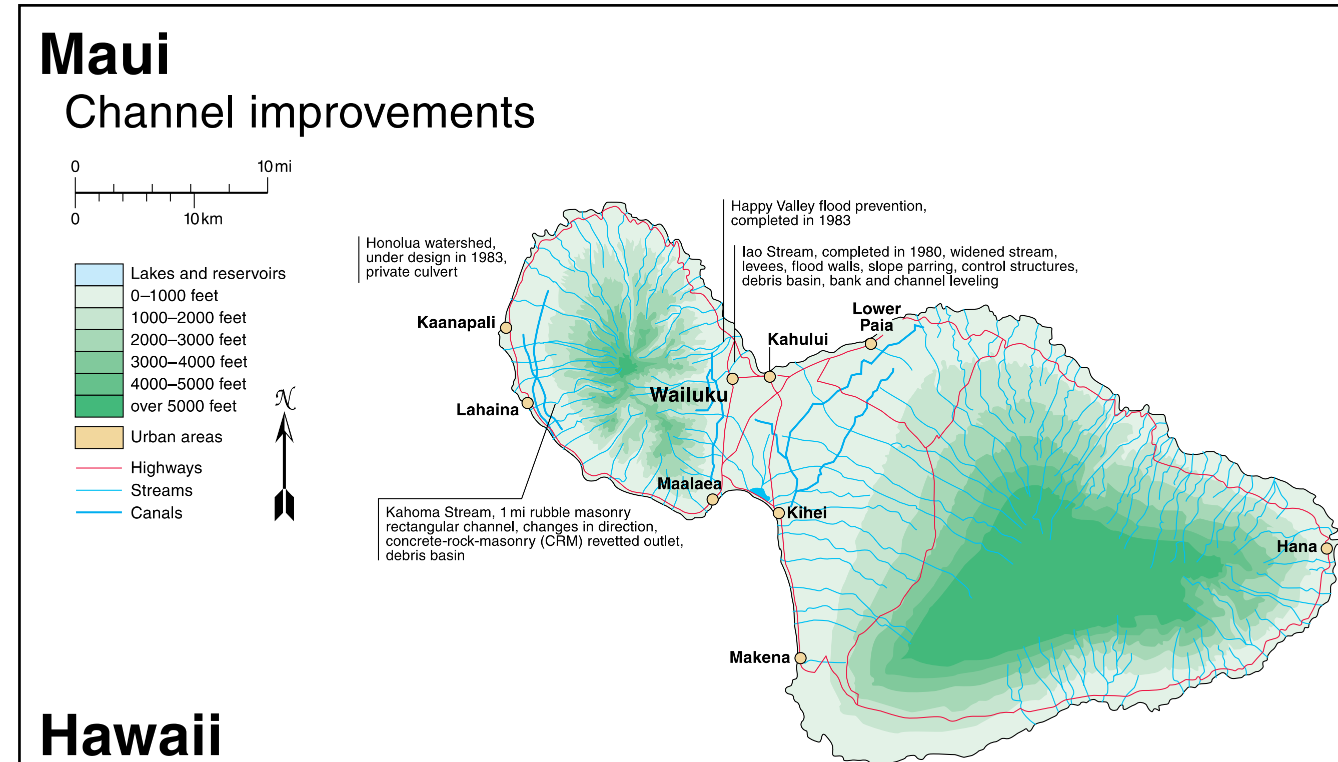
TABLE 3
Major Stream Floods and Damages, 1915-1998 (- , no data available)

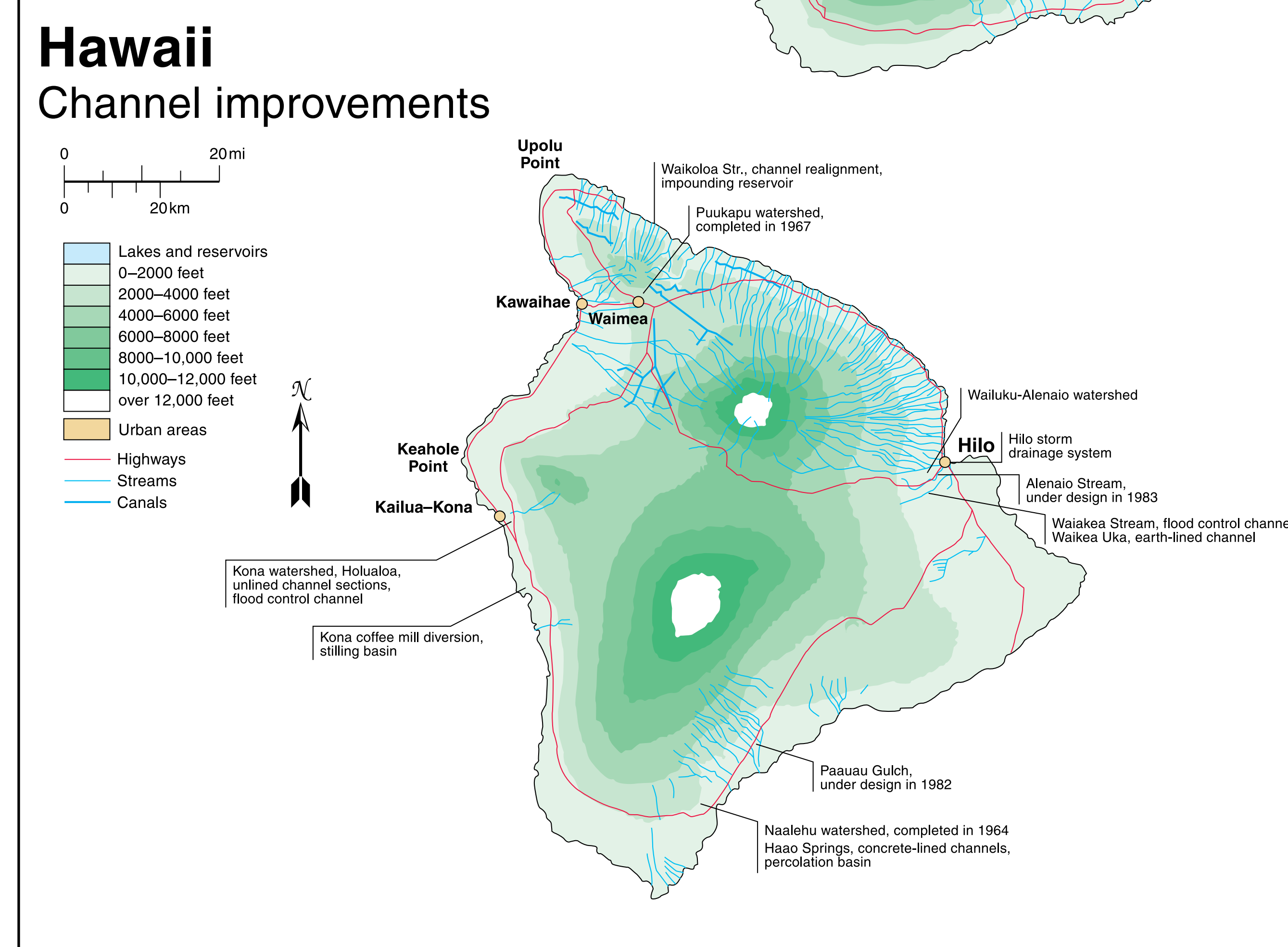
Date	Statewide Lives Lost	Location	Damages 1998 $	Cause
1915	10	Statewide	-	Cloudburst
1/14/1916	-	Iao Stream, Maui	$250,000	Heavy rains
1/17/1916	16	Statewide	$1,000,000	Heavy rains
1917	3	Statewide	-	Heavy rains
1/16/1921	4	Honolulu	$500,000	Heavy rains
1922	1	Statewide	-	Heavy rains
1927	5	Statewide	-	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	Statewide	-	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	Statewide	-	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, high seas
1/17-18/1959	-	Oahu, Molokai, Maui, Hawaii	$1,393,000	Heavy rain, strong wind, 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, 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	Statewide	$790,000	Heavy rains, 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	Statewide	$439,000	Heavy rains, strong winds, 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, 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, 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, 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, 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, strong winds
11/6-7/1976	2	Oahu	$270,000	Heavy rain and strong wind
1978	2	Statewide	-	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, 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

*Kona storms are storms associated with the passing of mid-latitude fronts (low pressure) in the vicinity of Hawaii.









Stream channelization projects by the U.S. Army Corps of Engineers have provided important mitigation for much of the stream flooding hazard in populated regions of the Hawaiian coast. However, these have caused the loss of miles of natural ecosystems in wetlands and stream channels.

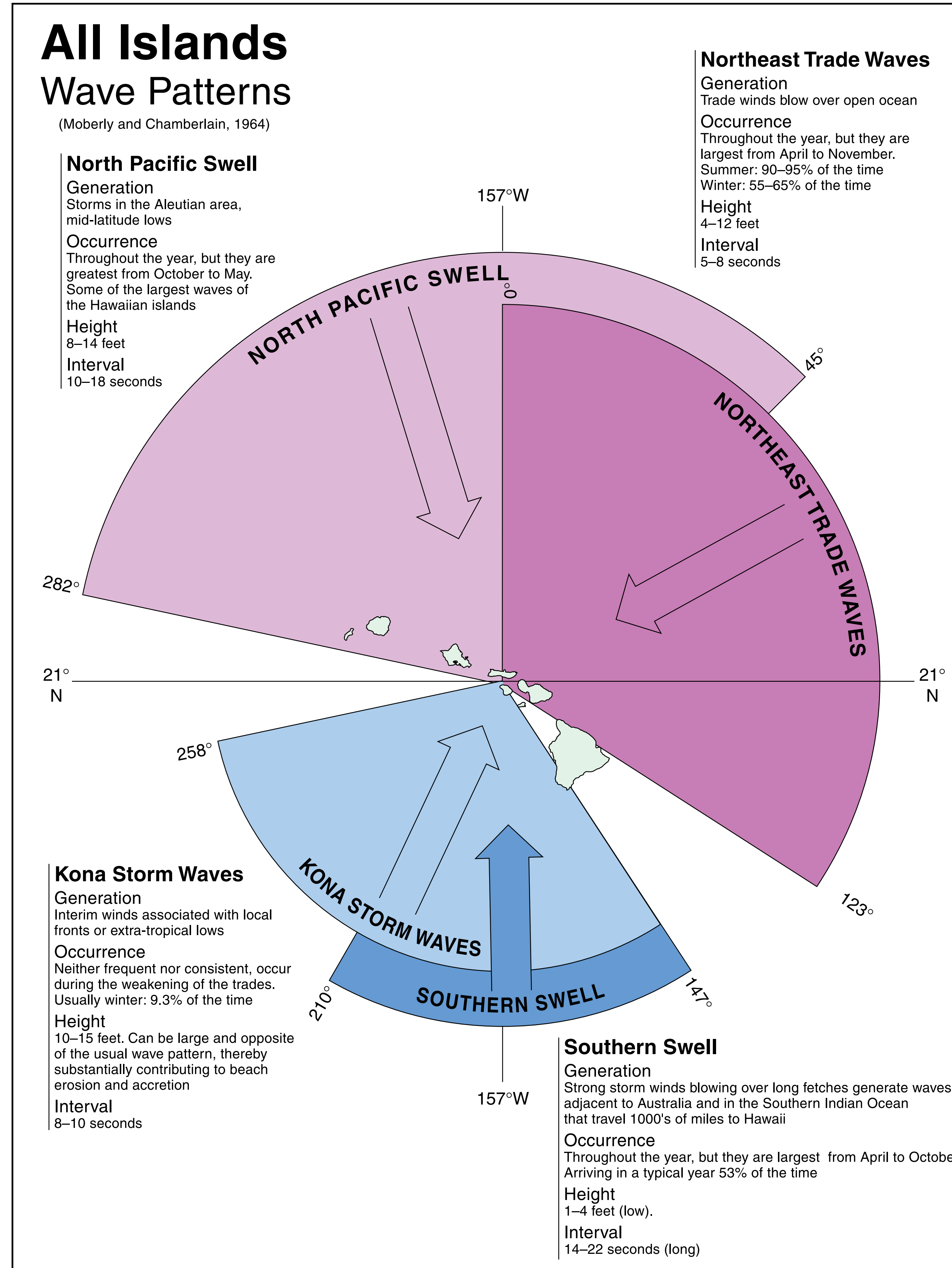
High Waves

Sudden high waves, and the strong currents they generate in the nearshore region, are perhaps the most consistent and predictable coastal hazard in Hawaii. They account for the greatest number of actual injuries and rescues on an annual basis than the other hazards. It has been said that picking intertidal molluscs (opihi) from coastal rocks is the number one hazard in the state. The Oahu Civil Defense Agency classifies high surf as a condition of very dangerous and damaging waves ranging in height from 10 ft to 20 ft or more. These waves result from open ocean swell generated by storms passing through the north and south Pacific Oceans.

Annually, waves that reach Hawaii's shores originate from four primary sources, north Pacific swell, northeast trade wind swell, south swell, and Kona storm swell. Hurricanes and tropical storms are also important sources of waves that impact Hawaii's coasts on an interannual basis. North Pacific swell deliver the highest waves annually (8-20 ft) with moderate- to long-wave periods (10-18 seconds), due to the high intensity and proximity of sub-polar and mid-latitude storms in the north Pacific. North swell occur throughout the year, but are most common between October and May and have the greatest impact on north-facing coasts. Northeast trade-wind swell range 4-12 ft in height ~70% of the year (April to November) and can reach slightly greater heights during intense trade-wind events that occur for 1-2 weeks each year. Because trade wind waves have short wave periods (5-8 seconds), they are only moderately energetic when they reach the shoreline. Waves from south Pacific swell travel great distances and have very long wave periods (14-22 seconds) and moderate wave heights (1-4 ft). Long-wave periods associated with south swell, however, translate into very energetic waves when they reach Hawaii's shores, especially along south-facing coastlines. South swell is most common between April and October, but occur all year. Waves from Kona storms, central Pacific storms associated with fronts passing just north of the main Hawiian Islands, are commonly very steep with moderate heights (10-15 ft) and short to moderate periods (8-10 seconds). Kona storm waves have the greatest impact on south- and west-facing coasts. Waves from hurricanes and tropical storms (June-November) can reach extreme heights (10-35 ft) and occur mostly on east-, south-, and west-facing coastlines, however, occasionally north-facing shores are impacted.

Our ranking no. 4 is reserved in most cases for north-facing shorelines where winter swell arrives with regularity in heights exceeding 12 ft (often exceeding 20 ft). Sets of these large waves are characterized by rapid onset so that within a few seconds they can double in size, often catching unaware swimmers, fishermen, and hikers walking along the shoreline. The water level on the coast increases with these sets of large waves and rip currents are generated as this excess water surges seaward. Although rip channels are used by experienced surfers as a free ride offshore, they are extremely hazardous for the tired swimmer to navigate. 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 8 ft along south coasts. Ranking no. 2 typically characterizes windward coasts, which can have large waves of 6 ft, but normally do not exceed 4 ft, generated by hurricanes passing to the east of Hawaii. These are also hazardous to the uninformed who use the coast for recreation. The sad aspect of this hazard is that most injuries and drownings could be avoided if only the recommendations of lifeguards were more carefully heeded.

Annual high waves from both north and south swell are common in the Hawaiian coastal zone and pose a significant hazard, especially where they break at the shoreline.

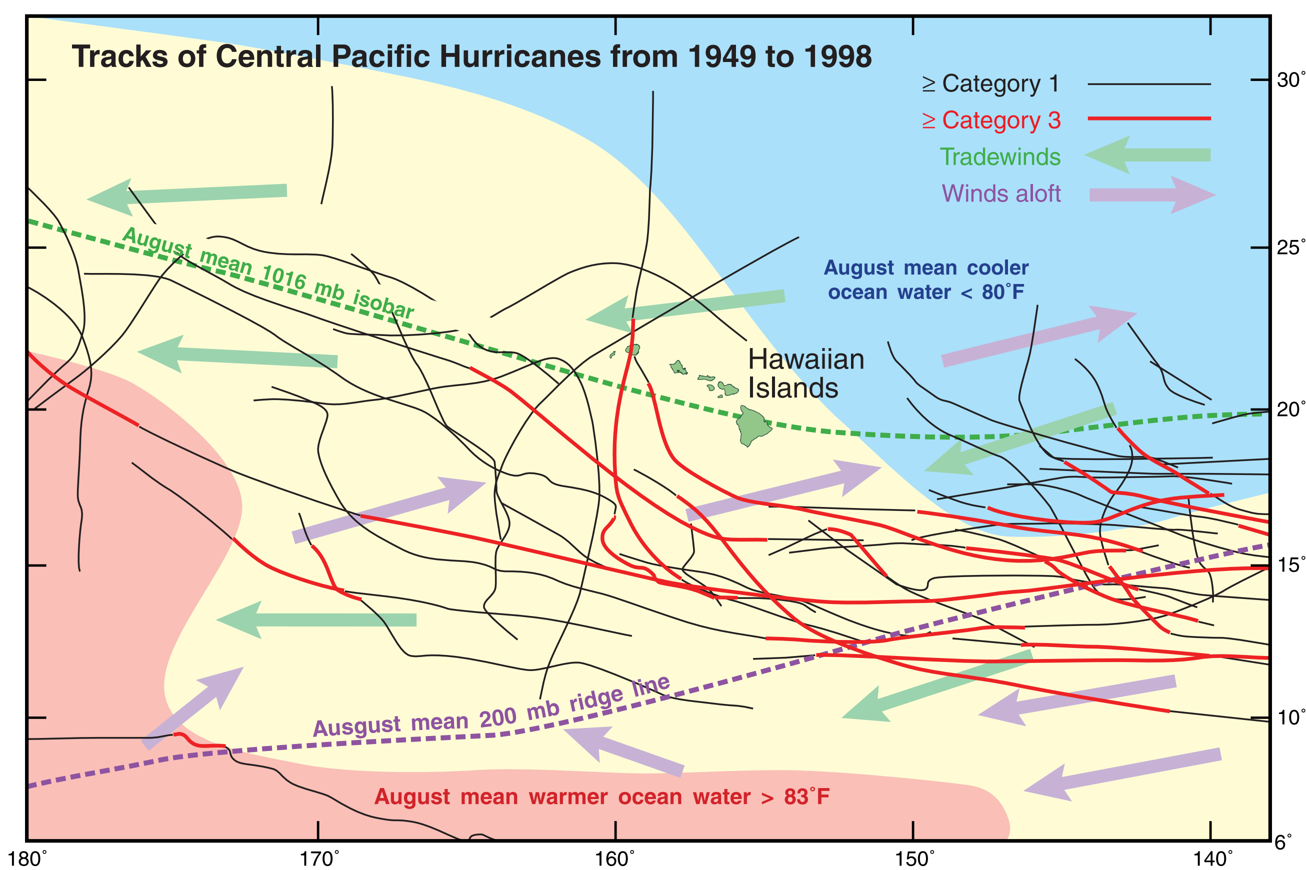


Storms

The extreme damage and economic loss associated with hurricanes Iwa (1982) and Iniki (1992) have increased the general level of public awareness of the threat from tropical cyclones (hurricanes, tropical storms, and tropical depressions) and Kona storms (storms associated with passing of mid-latitude low pressure fronts) in Hawaii. The damage and injury associated with these meteorological phenomena is the result of high winds, marine overwash, heavy rains, tornadoes, and other intense small-scale winds and high waves (Schroeder, 1993). Rather than ranking each of these phenomena separately, we have created a single category consisting principally of the overwash and high wind hazards related to storms.

Research by T.T. Fujita at the University of Chicago has identified the important role of dangerous high intensity, small-scale wind bursts during hurricanes in producing high levels of damage. Termed microbursts and mini-swirls, these localized winds may reach speeds in excess of 200 mph. In the wake of Hurricane Iniki, Fujita identified damage patterns and debris indicating that as many as 26 microbursts (sudden intense downdrafts) and two mini-swirls (a violent whirlwind, not a tornado) had occurred on the island of Kauai. In addition, it was found that downslope winds were more damaging than upslope winds. Mitigation against such high winds is difficult, but numerous and relatively simple construction and retrofit techniques (FEMA Construction Manual) can significantly increase the ability of a building to withstand hurricanes.

Our historical knowledge of tropical cyclones in the central Pacific is a direct function of technology (Table 4). Samuel Shaw of the Central Pacific Hurricane Center has written a comprehensive survey of documented tropical cyclones (of all intensities) over the period 1832 through 1979 (Shaw, 1981). Using written accounts of various observers he records nineteen storms over the period 1832-1949 and seventeen storms between 1950 and 1959. By 1960 early satellite data became available and thirty-four tropical cyclones were identified between 1960 and 1969. The following decade (1970-1979) again produced thirty-four identified tropical storms in the central Pacific, and during the decade of the 1980's (1980-1989) the number increased to fifty-three storms. Between 1970 and 1992, 105 tropical cyclones have been identified in the central Pacific region at an annual average of 4.5 storms (Schroeder, 1993). Damaging hurricanes and tropical storms that have affected the Hawaiian islands are listed in Tables 5 and 6.



Hurricanes in the Central Pacific (140° W to 180 ° W) generally travel from east to west, however, some including Hurricanes Iwa (1982) and Iniki (1992) track in a northerly direction. (mb, pressure in millibars).

TABLE 4
Total tropical cyclones in the central Pacific 1970-2000

Year	Total Storms
1970	5
1971	5
1972	7*
1973	2
1974	3
1975	1
1976	4*
1977	0
1978	7
1979	0
1980	2
1981	2
1982	10*
1983	6
1984	5
1985	8
1986	7*
1987	4
1988	5
1989	4
1990	4
1991	3
1992	11*
1993	5
1994	10*
1995	1
1996	0
1997	7*
1998	3
1999	3†
2000	4

138 storms in 31 years. [*- El Niño onset year; † - third storm died soon after entering central Pacific waters] (source: Schroeder, 1993; National Weather Service, Storm Reports, 2000)

Of course not all of these storms intersect Hawaii, and actual hurricane strikes on the Hawaiian Islands are relatively rare in the modern record (Schroeder, 1993). 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 can be severe and lead to beach erosion, large waves, high winds, and marine overwash despite the fact that the hurricane may have missed the island. Communities on the Waianae coast of Oahu suffered severe damage from hurricanes Iwa and Iniki, yet neither of these storms actually hit Oahu. Indeed, the highest wind speeds recorded during Iwa were in windward Oahu where a line of squalls spawned by Iwa on the leeward side moved over the Koolau Range and accelerated down the Pali in a waterfall effect ripping the roofs off homes in Kaneohe. Thus, storms on one side of an island may have significant impact on the other side.

It is commonly believed from recent history that Kauai lies in a more vulnerable position than the other islands. However, in his recent analysis of Hawaiian hurricanes, Dr. Tom Schroeder of the University of Hawaii, Meteorology Department, concludes that every island has been affected by hurricanes and that no island is without risk. The randomness of nature plays a key role in which islands are at highest risk during any given hurricane. In 1988, Hurricane Uleki was poised to hit Oahu or Maui but passed to the south. Hurricane Iniki in 1992, could have hit Oahu or missed the islands altogether, but instead tracked right over Kauai. Tropical depressions and storms at various times have intersected the Big Island on windward, northern, and southern coasts. In the summer of 1993, 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 might have sustained a direct hit had these storms been diverted by a shift in the large-scale atmospheric flow.

TABLE 5

Hurricanes in the Pacific that affected Hawaii since 1950

Year	Date	Name	Track	Closest island	Wind average (mph)	Wind gust (mph)	Low BP (mbar)	Rate of travel (kts)	Eye (nmi)	Rain (in)	Stream	Marine surf (ft)	Tidal surge (ft)	Max. run-up (ft)	High water (ft)	Type of damage	Damage (1998 $)	Comments
1993	8/16	Fernanda	WNW, Disintegrated 400 mi E of Oahu	Hawaii	105	125	*970	10-15		Locally heavy		10-15				Hawaii: 3 small boats broke their moorings, high waves closed roads in Hilo and Puna, 1 home damaged by water. Oahu, Windward side (Kaaawa): some coastal flooding, debris on highway. Maui, Molokai: High waves, 1 house damaged on E Molokai.		Hurricane warning issued for Hawaii.
1992	9/11	Iniki	S-N, passed just W of Port Allen, crossed over Kauai	Kauai	130	160	945			Heavy	No flooding	20-35	4.5-6.2	26.3	18.5	Kauai: 1,421 houses destroyed, 13,000 homes with minor to heavy damage, 3 people dead. Oahu: Some flood/wind damage SW shore. Hawaii: Twelve houses damaged by surf.	$500M–$5B	Strongest and most destructive hurricane to hit islands in this century. Sixth costliest hurricane in U.S. history. $1.8 billion in damage to Kauai alone.
1991		Fefa				105										Maui: SW shoreline hit by surf.		
1989	7/17-7/21	Dalilia	NW, passed 100 mi S of Hawaii	Hawaii	75		989					10-15				Hawaii, S shore: 40 kts. Wind downed trees and powerlines, rains caused minor flooding. Oahu, Kauai: Heavy rain (1.5-9 in), esp. NE shores.		
1988	8/28-8/29	Uleke	NW, passed S, threatened			120						High				Oahu: High surf along S shores. Kauai: Two people drowned.		
1988	8/2-8/9	Fabio	W, passed south of Hawaii	Hawaii		125				12-18		High				Hawaii: High surf along SE, heavy rains.		Heavy rains
1986	7/21-7/25	Estelle	W, passed S		132			20				10-20				Hawaii: 10-20 ft surf and 50 mph winds demolished 5 houses, SE shores evacuated. Oahu: Two drowned. Maui: Stretch of dirt road washed away.	$2M	Steadily weakened as she directly aimed at Hawaii.
1985	10/23-10/29	Nele	S-N, then W, passed S	Kauai								10				Kauai: 10 ft surf S shore, esp. Poipu.		
1985	9/9	Rick	N, passed to the NE	Hawaii								Minor swell						
1985	9/5-9/9	Pauline	W, turned N, passed E of Hawaii	Hawaii				10				10-15				Hawaii: 15 ft surf along Puna and Kau, debris on roads. All Islands: High surf on E shores.		Hurricane watch was issued.
1985	7/21-7/26	Ignacio	NW, passed to the S	All								10-15				Hawaii, Maui: 10-15 ft surf on SE shores, some road/structure damage.		
1983	10/14-10/20	Raymond	NW, passed over islands as Tropical Depression	Molokai	138	167	968			1-2		10-15				Maui, Molokai, Oahu: 1-2 in rain. Hawaii: 10-15 ft surf on Kalapana and Kaimu.		Posed a serious threat to Hawaii, but weakened.

[BP, barometric pressure; mph, miles per hour; mbar, millibars; kts, knots; nmi, nautical miles; in, inches; ft, feet; $, dollars; M, million; B, billion]

TABLE 5 (continued)
Hurricanes in the Pacific that affected Hawaii since 1950

Year	Date	Name	Track	Closest island	Wind average (mph)	Wind gust (mph)	Low BP (mbar)	Rate of travel (kts)	Eye (nmi)	Rain (in)	Stream	Marine surf (ft)	Tidal surge (ft)	Max. run-up (ft)	High water (ft)	Type of damage	Damage (1998 $)	Comments
1982	11/23	Iwa	NE, passed NW of Kauai	Kauai	92	126	964	18		3-6.5	No flooding	20-30	5-6	600 ft		Kauai: Flooding from Kekaha to Poipu, 67% damage. Oahu: Flooding from Makaha to Koko Head, 1 dead as ship was hit by 30 ft wave, 30% damage. 465 houses demolished, 1,712 damaged. 1 dead. No damage for Maui, Hawaii, Molokai, Lanai.	$312M	Kauai, Oahu, Ni'ihau federal disaster areas. Most destructive hurricane to date, 1,591 acres flooded in state.
1978	7/17-7/28	Fico	WNW, passed 175 mi S of South Point	Hawaii	115		955	10	30			30				Hawaii: 30 ft surf caused heavy damage. Other Islands: 8-12 ft surf, 65 ft tugboat went aground, brought 6 in rain to Oahu.		
1978	6/26-7/3	Carlotta								6								
1976	9/19-10/1	Kate	NW, passed NE of Hawaii	Hawaii								8-15				Hawaii, Maui, Oahu: 8-15 ft surf NE shores.		
1972	8/18-9/3	Fernanda	WNW, passed 150 nmi NE of Hawaii	Hawaii		115										Hawaii: Flash food in Waipio Valley, high surf damaged 3 small boats.	$2,000	
1972	8/2-8/22	Celeste	W, passed S of islands	Hawaii	138		943	6	22			High						
1972	8/8-8/20	Diana	NW, passed 300 mi E of Hawaii	Hawaii		63	982			8-10	No flooding	30	4-5			Hawaii: 30 ft surf struck Puna, 4 houses swept off, 1 flooded, overwash, road damage. Maui: 6 in rain, 20 ft surf eroded Hanoa Beach.		
1971	7/2-7/13	Denise	WNW, passed 150 mi S of South Point	Hawaii			999.5	16	30	1						Hawaii: Heavy rains blocked Kuakini Hwy.		
1966	9/7-9/17	Connie	W, passed 120 mi S of Hawaii	Hawaii				5								Hawaii, Maui: Moderate to heavy rainfall		
1959	8/4-8/7	Dot	NNW, Eye passed over Kauai, then turned west	Kauai	75	165	984	9	20-30	5						Kauai: Agricultural losses of $5.5-6M,100's houses, trees damaged, coastal areas flooded. Oahu, Hawaii: Minor wind, flood damage.	$5-6M $150,000	Eye over Kauai.
1957	11/30-11/31	Nina	NNW, passed south of Kauai	Kauai	92			8		21		35				Kauai: 20 in rain in 14 hrs, 12 homes damaged by 35 ft surf. Oahu: 3 fisherman missing, some damage. All Islands: High winds.	$1,056,000(?)	
1957	9/1-9/17	Della	NW, passed 300 mi SW of Kauai	Kauai				6	16							Kauai: 16 ft surf at Nawiliwili.		
1950	8/12-8/16	Hiki	WNW, passed 120 mi NE of Kauai	Hawaii	68	90	982.7	5	20-25	52	Waimea R flood					Kauai: 52 in rain over 4 days, flooding. Maui: 12 in rain, flooding.		

[BP, barometric pressure; mph, miles per hour; mbar, millibars; kts, knots; nmi, nautical miles; in, inches; ft, feet; $, dollars; M, million; B, billion]

TABLE 6
Tropical Storms that affected the Hawaiian Islands in historical times

Year	Date	Name	Track	Closest island	Wind average (mph)	Wind gust (mph)	Low BP (mbar)	Rate of travel (kts)	Eye (nmi)	Rain (in)	Stream	Marine surf (ft)	Tidal surge (ft)	Max. run-up (ft)	High water (ft)	Type of damage	Damage (1998 $)	Comments
1993	7/23	Eugene	W, aimed at Hawaii	Hawaii	35		*1008	25		~ 3						Hawaii: Up to 3 in rain in Hilo, Kau, Kona, some flooding. All islands: showers with isolated thundershowers.		Hurricane downgraded to tropical depression on 21st, disintegrated E of Hawaii.
1993	7/22	Dora	W, hit Hawaii	Hawaii						Heavy						Oahu: Heavy rain caused floods and power outages, especially on windward side, Polynesian Cultural Center closed, lightning over west/central Oahu, 3 in rain in 8 hrs in Nuuanu. Maui: Flooding closes Honoa-piilani Hwy, clogged drainage channel, silt in water supply, 1 family evacuated. Hawaii: Snow on Mauna Kea/Mauna Loa, some roads flooded, some damage.		Tropical storm.
1988	9/20-9/25	Wila	W, recurved NE	Hawaii	40		*1007			6-12	Wide-spread					All islands: Some heavy showers.	$50,000	Tropical storm, widespread minor floods
1988	8/8-8/9	Hector	W	Hawaii	35		*1008			6						Kauai: 6 in rain on slopes and N shore.		
1988	7/30-8/3	Gilma	NW, passed along Maui, over Oahu, just S of Kauai	Oahu	35		*1008			2-4						Oahu, Kauai: Showers, thundershowers, local stream flooding.	$500-5,000	Tropical depression.
1985	8/4-8/8	Linda	W, passed 150 mi S of South Point	Hawaii	46		*1005	17		5-10						Hawaii, Maui: 5-10 in rain on windward slopes.		Tropical storm.
1985	7/1-7/5	Enrique	SW, passed 350 mi S of Hawaii	Hawaii	29		*1010	17		Local heavy rain		10 ft				Hawaii: Local heavy showers on windward/Kona slopes. All islands: 10 ft surf on S shores, minor damage to roadways, minor injuries to surfers.	$50,000	Tropical depression.
1984	8/18-8/20	Kenna	NW, passed to the S of Hawaii	Hawaii	58		*1000			6-8 in						Hawaii: 11 ft surf on S shores, minor damge to roadways, minor injuries to surfers.		Tropical storm, downgraded to depression.
1984	7/3-7/6	Douglas	NW, dissipated 500 mi E of Honolulu	Hawaii	35		*1008			2 in						Hawaii, Maui: 2 in rain on slopes.		Tropical depression, was powerful hurricane.
1983	9/27-9/30	Narda	W, passed 150 mi S of South Point	Hawaii	52		*1003						Higher than normal			All islands: High surf on E and SE shores, high wind, rain.		
1983	8/3	Gil	NW, passed 10 nmi N of Kilauea Point	Kauai	63		1011	20		Heavy		High surf				Kauai: Heavy rains, surf, N and E shores. Oahu: High winds and surf, vessel lost.	$500-5,000	Tropical storm.
1982	7/16-7/22	Daniel	SW, curved NNE, dissipated in Alenu-ihaiha Channel	Hawaii	35		*1007				Flash floods					Hawaii: Flash floods, wind damage. Maui, E shore: flash floods, wind damage.	$1-5M crop, property	Tropical storm.
1982	7/12-7/15	Emilia	NW		55		*998	12-14		Heavy						Hawaii: Heavy rains over Hamakua, Hilo, Puna, Kau. Maui: Heavy rains island wide.	$50-500,000	Tropical storm.
1978	8/19-8/21	Iva	E	Hawaii						5-6.5						Hawaii, Maui: 5-6.5 in rain on E shores.		Vortex.

[BP, barometric pressure; mph, miles per hour; mbar, millibars; kts, knots; nmi, nautical miles; in, inches; ft, feet; $, dollars; M, million; B, billion]

TABLE 6 (continued)
Tropical Storms that affected the Hawaiian Islands in historical times

Year	Date	Name	Track	Closest island	Wind average (mph)	Wind gust (mph)	Low BP (mbar)	Rate of travel (kts)	Eye (nmi)	Rain (in)	Stream	Marine surf (ft)	Tidal surge (ft)	Max. run-up (ft)	High water (ft)	Type of damage	Damage (1998 $)	Comments
1978	8/6-8/9	#10	W, passed 300 mi SSW of Oahu		35		*1008			3-5						All islands: Heavy rains, local thunderstorms.		Tropical depression.
1978	7/3-7/11	Daniel	W							5-7						Hawaii, Maui: 5-7 in rain on windward/mountain sides. Other Islands: Spotty rainfall up to 2 in.		Ex-hurricane/vortex
1978	6/26-7/3	Carlotta	W, passed over Alenuihaha Chnl	All						6						Brought 6 in of rain, especially to Oahu.		Ex-hurricane, major weather producer of the season.
1976	8/3-8/17	Gwen	W, then WNW, passed 90 mi N of Kauai	Kauai	52		*1003			1-2						Kauai: 1-2 in of rain over entire island.		Tropical storm.
1972	9/28-10/3	Unnamed	W, then passed 150 mi S of South Point	Hawaii						up to 10.5						Hawaii: Up to 10.5 in rain on E slopes of Mauna Kea/Mauna Loa.		Tropical depression.
1971	1/8-1/18	Sarah	NW		69		987	69		3-6						Oahu: Powerlines and trees downed, 28 houses damaged, 2 injured as tree fell on car. Molokai: Five houses damaged, Lanai airport closed. Kauai: 61-66 mph winds at Kokee.	$100,000	Tropical storm, moved on to Pacific NW.
1970	8/17-8/26	Maggie	W, passed 90 mi of South Point	Hawaii	58		1003		17	25 8-14		25				Hawaii: Up to 25 in on Mauna Loa/Mauna Kea, 25 ft surf on Kapoho Beach, minor flooding landslides, crop damage. Kauai: 8-14 in rain on Mt. Waialeale, Paakea.		Tropical storm.
1967	1/1-12/31																	1967 was the year Diamond Head stayed green.
1967 8/14	8/10-	"D"	NW, passed 250 mi W of all islands					14-15		2-3						All islands: Spotty rainfall of 2-3 in.		Tropical vortex.
1967	8/2-8/11	"B"	W, passed over South Point, moved NW.	Hawaii						~12 3-4	Floods in Hilo. Kipapa, Waiawa. Hanapepe, Hanalei, Wailua					Hilo, Hawaii: 12 in rain in 36 hrs, flash flooding, landslides. Oahu: 3-4 in rain, rockslides (Pali), mudslide in Aina Haina nearly destroyed house. Kauai: 2-3 in rain, especially in Princeville, some floods.	$50,000	Tropical cyclone.
1967	7/11-7/21	Eleanor	WNW, passed 250 mi S of Oahu		63		*998			~ 9						Hawaii: Up to 9 in rain, heavy hail on Mauna Kea. Maui: 2 in rain, small hail on Haleakala, flooding between Napili and Honolua. Other Islands: 2 in rain.		Tropical storm.
1967	7/5-7/18	Denise	WNW, passed 180 mi S of South Point	Hawaii	63		*998			~ 6						Hawaii: Up to 6 in rain Other Islands: Moderate to heavy.		Tropical storm.
1967	7/4-7/8	Unnamed	W, passed S							8-10						Hawaii: 8-10 in rain in Kipa, Papaikou, Mauka, Kaumana. Other Islands: 2-3 in rain.		Tropical depression.

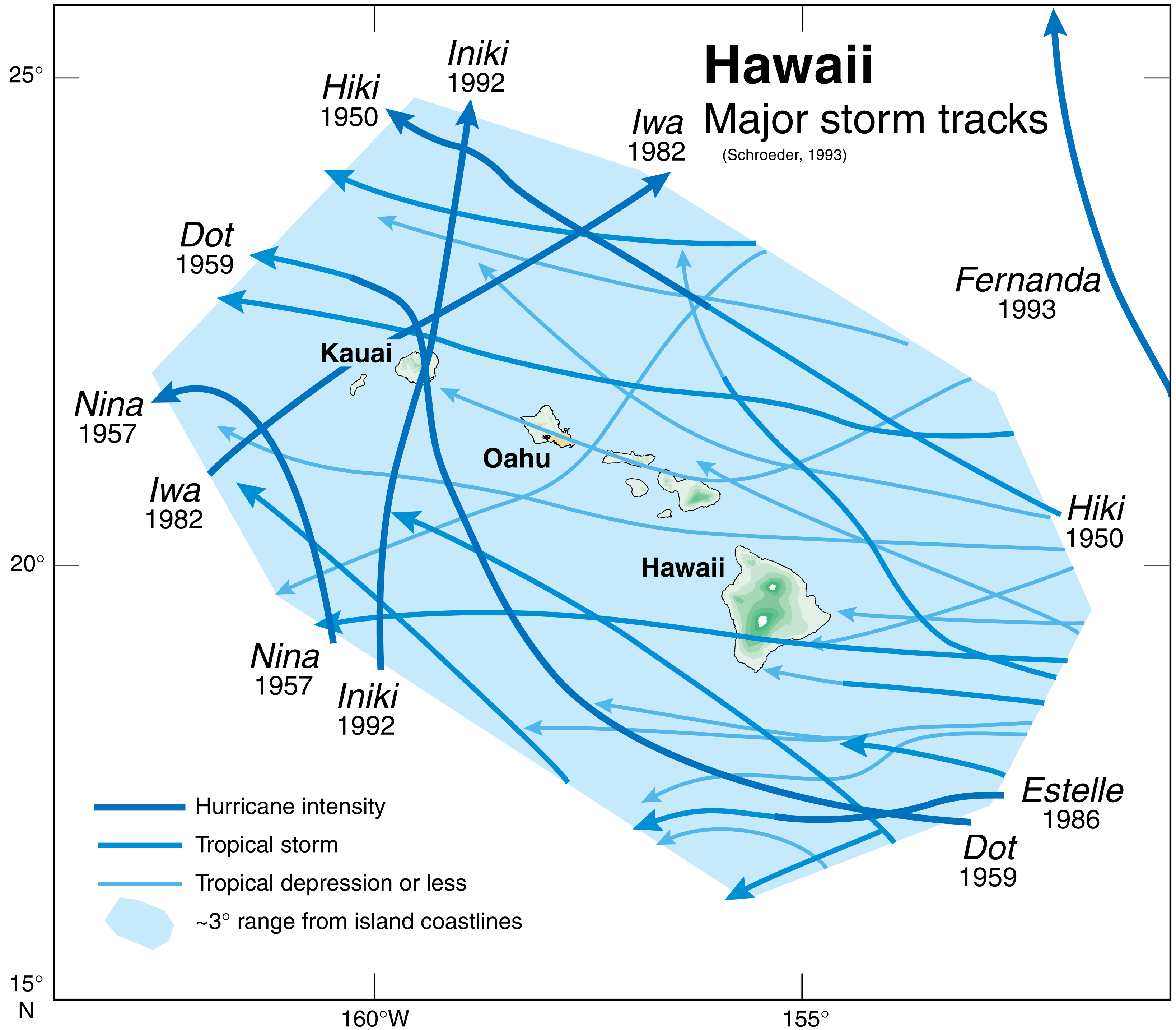
[BP, barometric pressure; mph, miles per hour; mbar, millibars; kts, knots; nmi, nautical miles; in, inches; ft, feet; $, dollars; M, million; B, billion; Chnl, Channel]

TABLE 6 (continued)
Tropical Storms that affected the Hawaiian Islands in historical times

Year	Date	Name	Track	Closest island	Wind average (mph)	Wind gust (mph)	Low BP (mbar)	Rate of travel (kts)	Eye (nmi)	Rain (in)	Stream	Marine surf (ft)	Tidal surge (ft)	Max. run-up (ft)	High water (ft)	Type of damage	Damage (1998 $)	Comments
1966	9/10-9/12	#22	W, passed 240 mi S of South Point	Hawaii						Moderate, heavy						All islands: Moderate to heavy rainfall.		Tropical depression.
1963	9/12-9/19	Irah	Center moved into Molokai channel		52		*1003									All islands: Moderate rainfall, wind 36 mph at Honolulu airport. Tropical Storm.		
1958	8/7-8/9	Unnamed	Appeared off Hilo, moved across islands	Hawaii	58	86	*1000									Hawaii: Torrential rain, houses, 3 bridges destroyed, 100's trees, powerlines down; crop damage, 1 dead in plane crash. Other Islands: Heavy rains scattered damage.	$552,000 $50,000	
1938	8/18-8/19	Mokapu Cyclone				61	1008			4						Oahu: Thunder and lightning, winds up to 61 mph. Some damage to Waimanalo plantation. Oahu, Maui: 4 in rain.		
1925	7/31-8/4	Ramage Cyclone										High				Hawaii: Honuapo and Punaluu flooded, strong winds. Oahu: Very high surf on S shore (Honolulu, Diamond Head), Fort Kam flooded		
1911	9/29	Ship Cyclone														Oahu: Rough seas capsized boat off Waikiki		
1906	10/2-10/9	Makawa Cyclone	WSW, 60 mi S of Hawaii NW to Niihau	Niihau			998.7			12.7						Maui: 12.7 in in 4.5 hrs at Makawao, low BP.		
1874	11/17-11/20	Die Deutsche Seewarte III						1002.4			20					Oahu: 20 in in Honolulu in 2 days. Molokai: 23 houses destroyed, 50 destroyed at Kalaupapa.		
1871	8/9	Kohala Cyclone		Hawaii							Heavy					Hawaii: 150 houses, and fields destroyed in Waimea, Kohala, 27 houses at Waipio. Maui: Heavy rains, stream flooding, gale winds, rain squalls.	$10,000	(1871 dollars)
1870	9/21-9/24	Die Deutsche Seewarte II	WNW, passed 50 mi S of South Point	Hawaii														

[BP, barometric pressure; mph, miles per hour; mbar, millibars; kts, knots; nmi, nautical miles; in, inches; ft, feet; $, dollars; M, million; B, billion]

*Values are calculated from Po = 1013 - $v^2/14^2$, where Po = minimum pressure (mbar), and v = maximum sustained winds (kts). This empirical relationship relating minimum pressure to maximum wind speed was determined by the National Hurricane Center.



Tracks of the major storms that have affected the main Hawaiian Islands.

Our rankings are based on levels of windspeed, historical structural damage, and overwash elevation. In the absence of any meteorological theory or process to the contrary, we have assumed that all Hawaiian coasts are equally vulnerable to hurricane impacts and that the only mitigating variables are local in nature (that is, slope, elevation, geology, offshore barriers). The highest intensity ranking (no. 4) is based on overwash exceeding 10 ft (~3 m above low tide) in elevation, which is sufficient on most Hawaiian beaches and low-lying coastlines to flood the area landward of the beach, often including the lower level of the first row of structures behind a beach. This was the case on Kauai during both Iwa and Iniki. We have also included a wind gust value of ~75 mph 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 again related to an overwash above 10 ft in elevation and a sustained windspeed sufficient to cause localized damage to individual dwellings, estimated to be ~40 mph. Note that sustained winds of 39 to 73 mph are used by meteorologists to classify tropical storms, while hurricanes have sustained wind speeds of 74 to 149 mph.

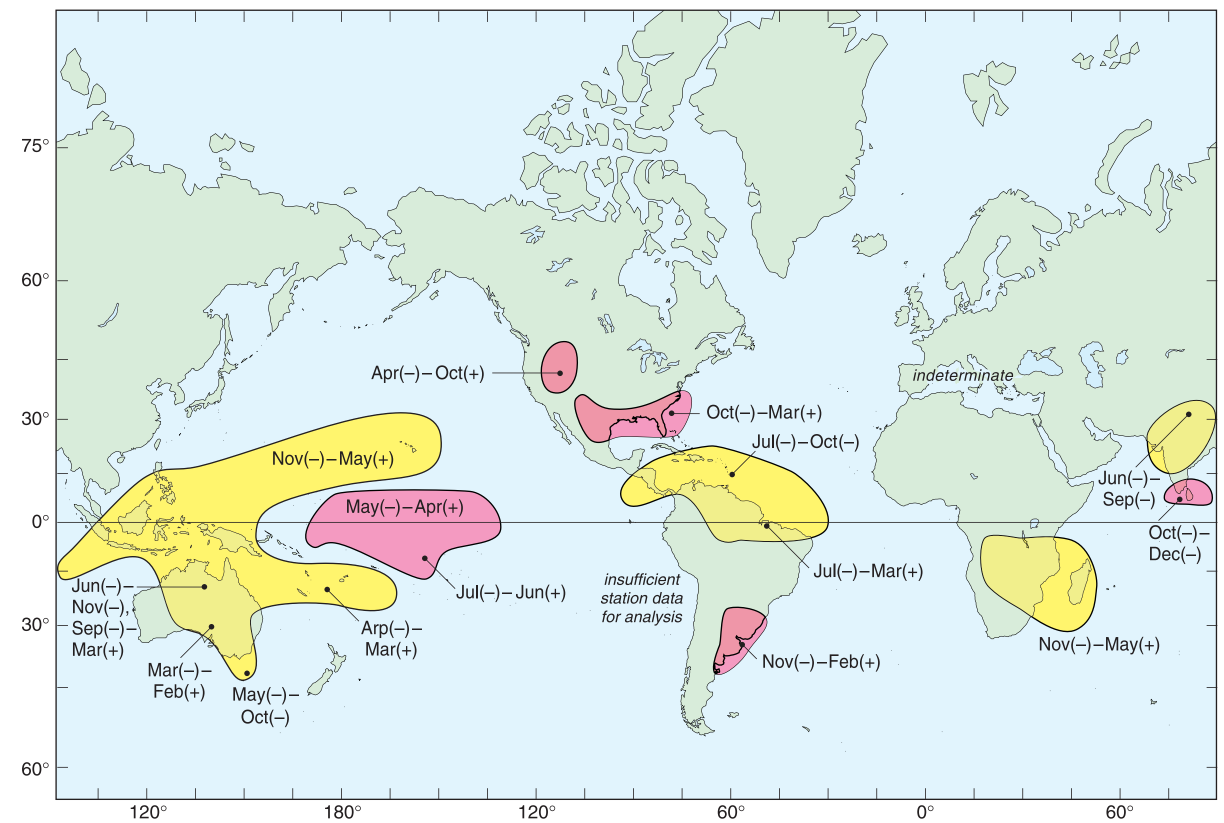
In studying the aftermath of Hurricane Iniki it was discovered by researchers at the Army Corps of Engineers and the University of Hawaii (Fletcher and others, 1994) that the greatest threat related to hurricane overwash in the Hawaiian Islands is due to water-level rise from wave forces rather than wind forces. This differs from the mainland where the wind in a hurricane is known to drive water against the coast and cause flooding, called wind set-up. During Iniki, the strongest component of the overwash was the result of large waves, called wave set-up. Wind set-up appeared to be relatively less important. Other factors leading to coastal overwash are the low atmospheric pressure, the tide stage, coastal topography, and the location relative to the eye of the hurricane. Unfortunately few of these can be predicted before a hurricane is in the neighborhood and thus overwash mitigation must be enacted prior to the event. This would include adequate building setbacks so that development does not occur in high hazard areas of the coastal zone, elevation of existing structures to recommended levels, break-away ground floors that permit overwash flooding without compromising an entire structure, and other construction techniques designed to reduce flood damage.

EL Niño

A large-scale meteorological pattern governs temperature and precipitation trends in the Pacific Ocean. This pattern is called the Southern Oscillation and it is related to the pressure difference between a body of dry air (a high pressure system) located in the southeast Pacific over Easter Island and a body of wet air (a low pressure system) located over Indonesia in the southwest Pacific. Under normal conditions, air flows from the high pressure to the low pressure and creates the trade winds. These blow east to west across the surface of the equatorial Pacific and drive a warm surface current into the western Pacific. This water is replaced in the east by deep cold ocean water (a process called upwelling) that is rich in nutrients fueling an important fishing industry off the coast of South America.

On occasion, the pressure difference between the two centers decreases and the trade winds die. This is known as El Niño. As a result, the warm water of the west Pacific surges to the east and heats up the ocean surface in the central and eastern Pacific. Precipitation in the east increases because the warmer water evaporates more readily. Upwelling temporarily comes to an end. Torrential rains and damaging floods across the southern U.S. have resulted, and the Peruvian fishing industry falters, leading to nationwide economic hardship in that country.

During an El Niño the Hawaiian Islands usually experience a decrease in rainfall. In fact, the ten driest years on record are all associated with El Niño years. Rainfall decreases because of a southerly shift in the atmospheric circulation system of the north Pacific, a feature called the Hadley Cell. The Hadley Cell is a large continuous belt of air that rises, moisture-laden, from the warm waters north of the equator at about 8° latitude, and moves north across the subtropics where the Hawaiian Islands are located. During its journey the air cools, losing its ability to hold moisture, and produces abundant rainfall. Eventually it descends back to Earth's surface as a column of dry, cool air and creates a pressure system known as the Pacific High. Under normal conditions the Hawaiian Islands experience a wet climate, while to the north and northeast, the Pacific High creates a dry climate. However, during El Niño the surface waters at the equator become significantly warmer and the rising motion of the Hadley Cell shifts to the south. This brings the Pacific High south as well, and the Hawaiian Islands experience a decrease in rainfall.



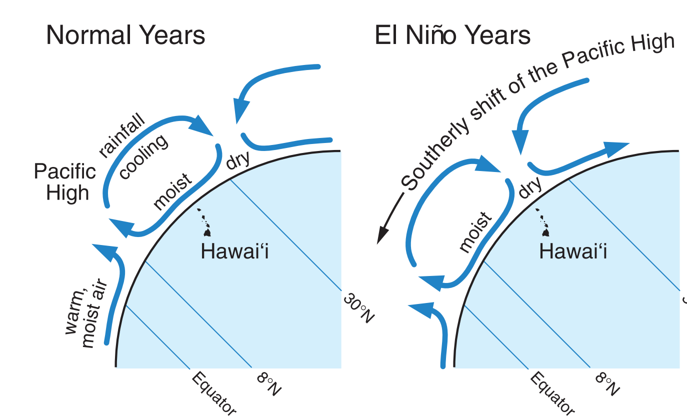
During El Niño, precipitation is enhanced in some (pink) areas and diminished in other (yellow) regions. The months indicate when these regions are affected, typically coinciding with local rainy seasons. The year that unusually high sea-surface temperatures first appear is indicated by (-); (+) refers to the following year. (Source: Philander, 1992).

As reported by T. Schroeder (1993) nearly all major statewide droughts have coincided with El Niño events (Table 7).

TABLE 7
The ten driest years in Hawaii

Percentile Rank	Year	El Niño Event
1	1897	1896-1897
2	1926	1925-1926
3	1919	1918-1919
4	1953	1953
5	1912	1911-1912
6	1941	1941
7	1903	1902-1903
8	1905	1905
9	1977	1976-1977
10	1925	1925-1926

Latitudinal location of Hadley Cells for normal (left) and El Niño years (right).

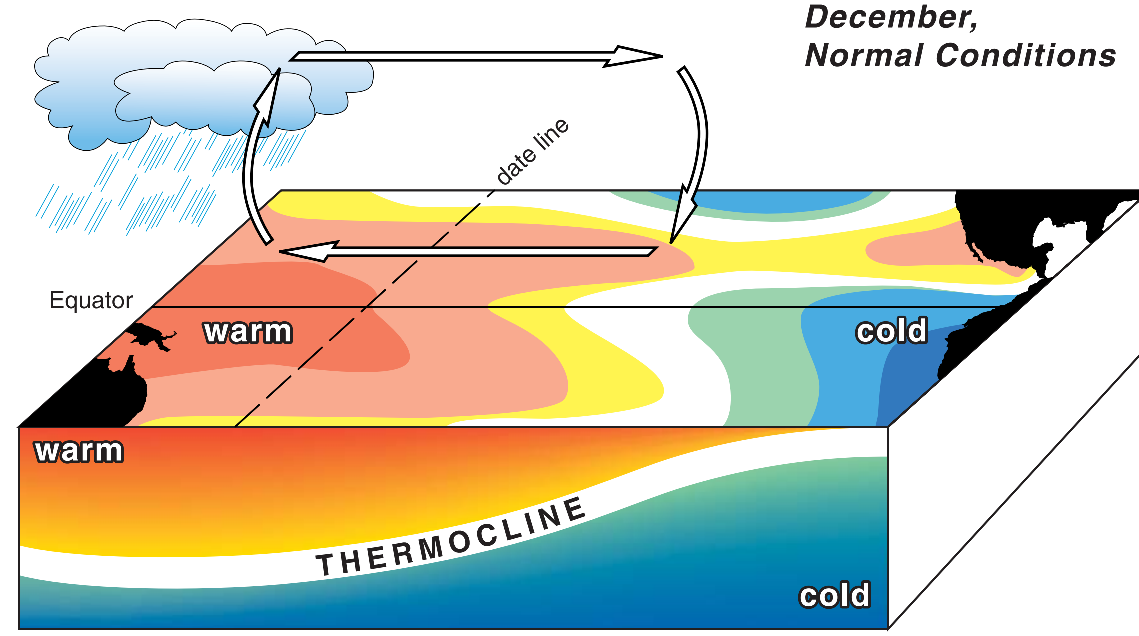


El Niño, in addition to controlling Hawaiian episodes of major drought, plays an important role in the location of hurricane genesis in the Pacific. The primary source of central Pacific hurricanes are cyclonic disturbances that form in the eastern Pacific and move west, steered by the winds in their surrounding environment (Schroeder, 1993). During the onset year of an El Niño, changes in the equatorial wind pattern of the central Pacific create a shear zone between equatorial west-flowing winds and subtropical east-flowing winds. This shear zone may cause cyclonic disturbances that can grow into hurricanes. Under normal conditions, waters of the central Pacific are warm enough to permit hurricane genesis but lack the necessary initial atmospheric disturbance. During the onset of an El Niño, tropical storms gradually form farther eastward as the shear zone migrates from the west Pacific into the central Pacific.

The impacts of El Niño on specific coastal segments by its influence on storms, waves, and sea-level changes are not entirely predictable, and as a result, El Niño does not directly enter our hazard rankings. We offer the previous discussion to illustrate that El Niño is a vital and recurring climatic event which influences the magnitude and frequency of coastal hazards.

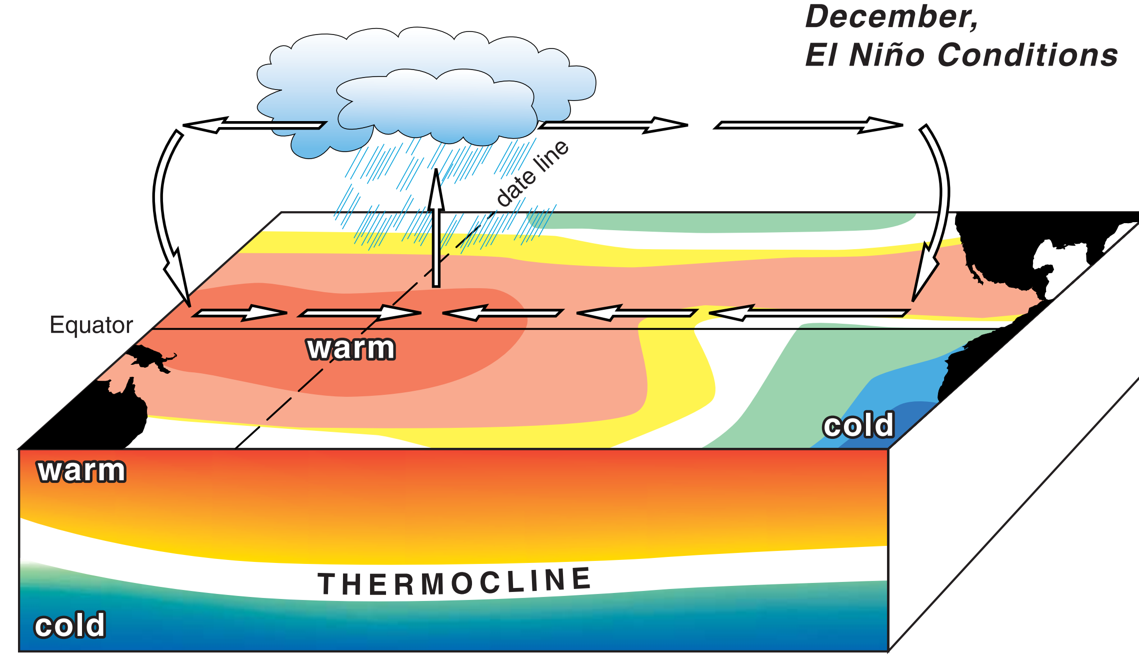
Schroeder reports (Table 4) that El Niño warm phases in the Southern Oscillation have corresponded to some of the largest annual storm counts in the central Pacific. However, the relationship is not unique because 1972, 1982, and 1992 were warm phase years and major storm years. 1978 was not an El Niño year, yet it still had as many storms as the warm phase years. 1977 was a warm phase year and the central Pacific storm count was zero.

December,
Normal Conditions



In a normal year, intense westward winds (white arrows) drive equatorial currents that push warm Pacific surface waters steadily to the west and expose colder waters from the deeper water column, to the surface in the east. (Source: Philander, 1992)

December,
El Niño Conditions



In an El Niño year, the trade winds relax, allowing a surge of warm water eastward across the Pacific and changing the characteristics of waters in the eastern part of the ocean basin. (Source: Philander, 1992)

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 0.5 to 1 ft/yr (15 to 30 cm/yr) (Hwang, 1981; Sea Engineering, Inc., 1988; Makai Ocean Engineering, Inc. and Sea Engineering, Inc., 1991). Recent studies on Oahu (Table 8; Fletcher and others, 1997; Coyne and others, 1996) have shown that nearly 24%, or 17.1 mi of an original 71.6 mi of sandy shoreline (1940's) has been either significantly narrowed (10.7 mi) or lost (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, beach loss has been identified on the other islands as well, with nearly 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 (such as 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 and others, 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 (when 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.

TABLE 8
Beach Narrowing and Loss on Oahu

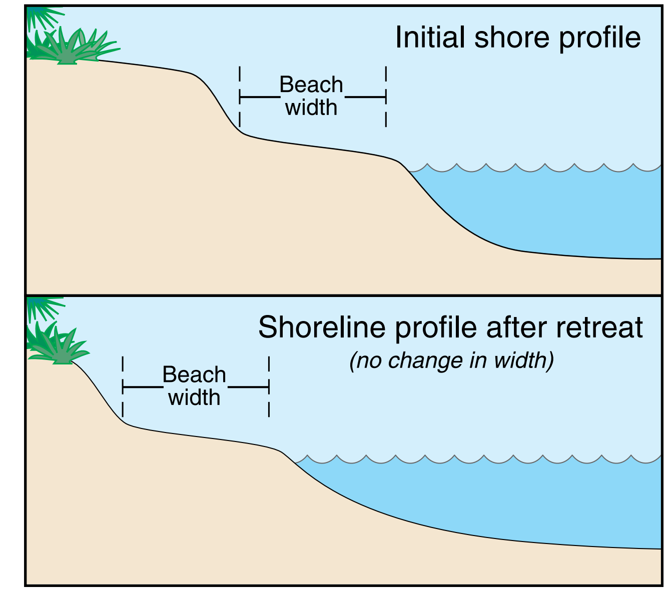
	Mokuleia	Kaaawa	Kailua-Waimanalo	Maili-Makaha	Island-wide
A. Originally sandy (km)	12.2±1.0	7.5±0.6	15.5±1.3	6.0±0.5	115.6±9.8
B. Narrowed beach (km)	2.1±0.2	3.2±0.3	0.9±0.1	1.3±0.1	17.3±1.5
C. Lost beach (km)	0.2±0	0.8±0.1	1.6±0.1	0.2±0	10.4±0.9
D. Degraded beach	18.7%	53.6%	16.3%	24.9%	23.9%
E. Short-term, 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	not calculated
F. 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	not calculated
G. Non-armored mean sandy beach width	26.8 m	13.2 m	22.4 m	43.7 m	not calculated
H. Armored mean sandy beach width	12.8 m	8.9 m	7.1 m	24.5 m	not calculated
I. Mean long-term shoreline change rate for armored sites (m/yr)	-0.2	-0.3	-0.6	-0.5	not calculated
J. 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	not calculated

• 97.4 per cent of armored beaches experienced chronic erosion prior to the period of narrowing.
• 92.1 per cent of armored beaches experienced long-term (>12 yr) chronic erosion prior to narrowing.
• Island-wide, all narrowed beaches are on armored shorelines.

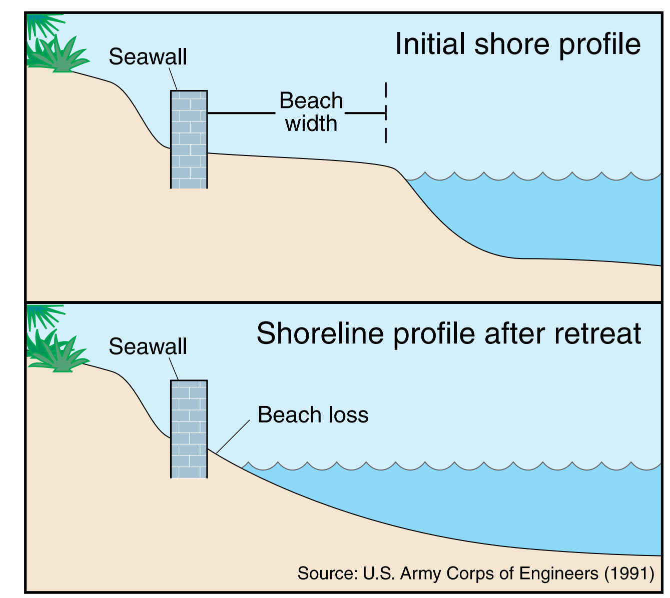
Most beach sand in Hawaii is composed of bioclastic carbonate grains derived from the skeletons of corals, mollusks, algae, and other reef-dwelling, carbonate-producing organisms. Studies indicate relatively low modern sand production on Hawaiian reefs compared to 2000 to 4000 years ago when sea level was higher and our reef systems made larger volumes of sand. The formation of beachrock, storage of sand in coastal dunes, and irretrievable sand loss to deeper water beyond the reef crest all contribute to a relatively low volumes of sand available to the beach system. On many Hawaiian beaches the available sand ends beyond the toe of the beach in a water depth of 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 yards) 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: a) reduced sediment supply; b) large storms; and, c) 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.



A beach undergoing net longterm retreat will maintain its natural width.



Beach loss eventually occurs in front of a seawall on a beach experiencing net longterm retreat.

Sea Level

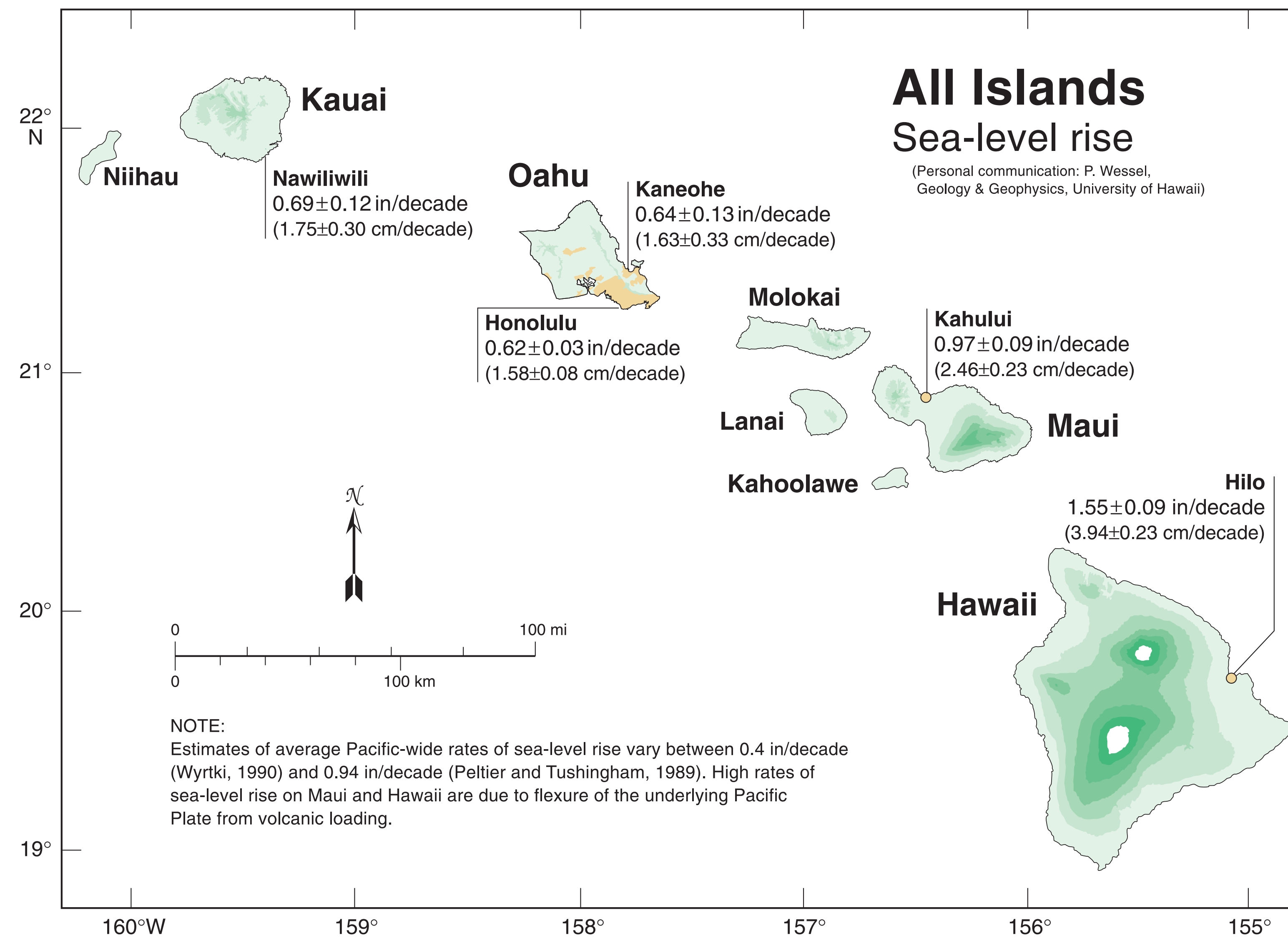
Hawaii has a system of tide gauges, maintained and operated by the federal National Ocean Service, located on the islands of Kauai, Oahu, Maui, and Hawaii that record fluctuations in sea-level. Analysis of these records provides scientists with rates of long-term sea-level rise around the state. A fascinating outcome of this has been the realization that each island has its own rate of rising sea level. This is not because of ocean behavior, it is due to island behavior. The Big Island, because of the heavy load of geologically young volcanic rocks, is flexing the underlying lithosphere causing the island to subside. This creates a relatively rapid rate of sea-level rise, on the order of 1.5 in/decade. Because it lies near the Big Island and is also geologically youthful, Maui is affected by the flexure process and is experiencing rapid sea-level rise, nearly 1 in/decade. Oahu and Kauai lie outside the area of subsidence and have lesser rates of rise, approximately 0.6 in/decade.

Sea-level rise is not presently a cause for alarm. Questions regarding future rates of rise resulting from an enhanced greenhouse effect have been discussed by scientists, planners, and policymakers throughout the 1980's and 1990's. At present, sea level is projected to rise 2 ft over the 21st century. This is more than twice the rate of rise of the 1900's. The impact of rising sea level in the Hawaiian Islands will be severe unless planners and resource managers incorporate sea-level rise scenarios into their coastal management efforts. As sea-level rise accelerates in the future, low-lying, low relief, readily erodeable, and low slope coasts will be the most vulnerable to sea-level hazards. These locations can be readily determined using our data on slope zone ranking and coastal geology. A more complete discussion of future sea levels and impacts is available in Fletcher, 1992.

Present rates of sea-level rise play a role in coastal retreat. The engineers' "Bruun Rule" (relating sea-level rise to beach retreat (Bruun, 1962)) predicts a retreat of 4-5 ft/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.

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. We have used a rate of 0.12 in/yr as a ranking variable, in conjunction with coastal slope. Where the rate is high 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.

Many examples of natural beaches (right of groin) exist in stark contrast to narrow stretches of lost beach (left of groin) owing to shoreline harding (Kualoa, Oahu).



Seismicity and Volcanism

The Hawaiian Islands are located in a more complex and hazardous seismic setting than is generally realized. Volcanism is the source of energy for approximately 95% of the earthquakes on the Big Island. However, in the central region, defined by Furumoto and others (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 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.

According to Heliker (1991) the Island of Hawaii experiences thousands of earthquakes each year. Although most are too small to be noticed, one or more quakes are felt in the state annually, and minor damage resulting from a stronger shock is not an infrequent occurrence. The majority of Big Island seismicity is related to the movement of magma within Kilauea or Mauna Loa. A few quakes are related to movements along fault zones located at the base of the volcanoes or deeper within the crust due to the gravitational adjustment of the volcanic edifice. Seismic tremors on the Big Island have caused ground cracks, landslides, ground settlement, damaging tsunami, and mudflows. Buildings, bridges, and water tanks have been destroyed or damaged, and utility, sewer, and water lines have been disrupted.

Strong earthquakes of magnitude 5 or higher, based on the Richter Scale, can cause property damage and endanger lives. Because much of the Big Island is rural and sparsely developed, the majority of significant damage is usually caused by larger earthquakes. Table 9 lists damaging Big Island earthquakes of magnitude 6 or greater.

Furumoto and others (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 to 12 years. The research of Wyss and Koyanagi (1988) identified two regions, the East Kona Block and the South Kona Block, as not having seismically ruptured in the last one hundred years. Such areas are called seismic gaps, and the potential of large earthquakes occurring in these regions is high.

Two damaging earthquakes on the Big Island are especially notable, the Great Kau Earthquake of 1868 and the Kalapana Earthquake of 1975. These were the most destructive earthquakes in recorded Hawaiian history.

Six days of foreshocks preceded the Great Kau quake before the main shock hit at 3:40 pm on April 2, 1868. Every stone wall in the District of Kau, on the southeast flank of Mauna Loa, was knocked down, and nearly every wooden house was moved off its foundation. Stone walls were knocked down along the coast from Hamakua to Hilo, and pendulum clocks stopped in Honolulu. The tremors were felt as far away as Kauai. Fissures opened in the streets of Hilo. In the Kau District the earthquake triggered a mudflow that killed 31 people. A tsunami that accompanied the main shock washed away 180 houses on the Kau-Puna coast on the Big Island and drowned 46 people. The port town of Keauhou, near Halape on the Big Island was completely destroyed, and is no longer found on maps of the region.

The Kalapana Earthquake of 1975, with a magnitude of 7.2, occurred on November 29 at 4:48 am in the District of Puna. Damage was relatively small because of the sparse population of the region. Losses amounted to 2.7 million dollars, and 23 houses were damaged. Unfortunately a deadly tsunami was generated when the Kalapana coast subsided as much as 11 ft. Two campers were killed by the wave at the Halape Campgrounds in Kau, boats and piers were damaged in Hilo, houses were destroyed on the Punaluu coast, and fishing boats were sunk in Keahou Harbor south of Kona. Because of the extensive history of seismicity on the Big Island related to both volcanism and gravitational adjustment of the growing volcanic edifice, the Big Island has upgraded their Uniform Building Code (UBC) seismic zone factor to 4. The UBC seismic zone factor is used in calculations of shear and impact to structures due to ground motion relating to seismic activity. The value prescribed for this factor in Hawaii ranges between 0.2 (for a seismic zone factor of 2) and 0.4 (for a seismic zone factor of 4) depending on a number of ground characteristics (rock type, consolidation of sediment). In certain instances, subtle divisions within this ranking scheme are designated with alphabetic suffixes (2A, 2B).

Studies of the seismic history of the central region over the last two decades have concluded that the seismic risk to the islands of Maui, Molokai, Lanai, Kahoolawe, and Oahu is greater than generally perceived by the public. The region has experienced three damaging earthquakes within historical times. Building codes and earthquake mitigation measures, although continually upgraded, have been characterized as inadequate for the potential seismic risk. In 1994, Maui County upgraded their UBC seismic hazard ranking for Maui Island from 2 to 2B and for Molokai, Lanai, and Kahoolawe Islands from 1 to 2B. Oahu and Kauai Counties raised their UBC seismic hazard rankings to 2A and 1, respectively.

TABLE 9
Damaging earthquakes of magnitude 6 or greater since 1868 on the Big Island of Hawaii

Year	Date	Location	Magnitude
1868	Mar. 28	Mauna Loa south flank	6.5-7.0*
1868	Apr. 2	Mauna Loa south flank	7.5-8.1*
1929	Oct. 5	Hualalai	6.5*
1941	Sept. 25	Kaoiki between Kilauea and Mauna Loa	6.0*
1950	May 29	Mauna Loa SW rift zone	6.2
1951	Apr. 22	Kilauea	6.3
1951	Aug. 21	Kona	6.9
1952	May 23	Kona	6.0
1954	Mar. 30	Kilauea south flank	6.5
1962	Jun. 27	Kaoiki	6.1
1973	Apr. 26	Honomu	6.2
1975	Nov. 29	Kilauea south flank	7.2
1983	Nov. 16	Kaoiki	6.6
1989	Jun. 25	Kilauea south flank	6.1

Source: Heliker, 1991; *estimated from eyewitness accounts

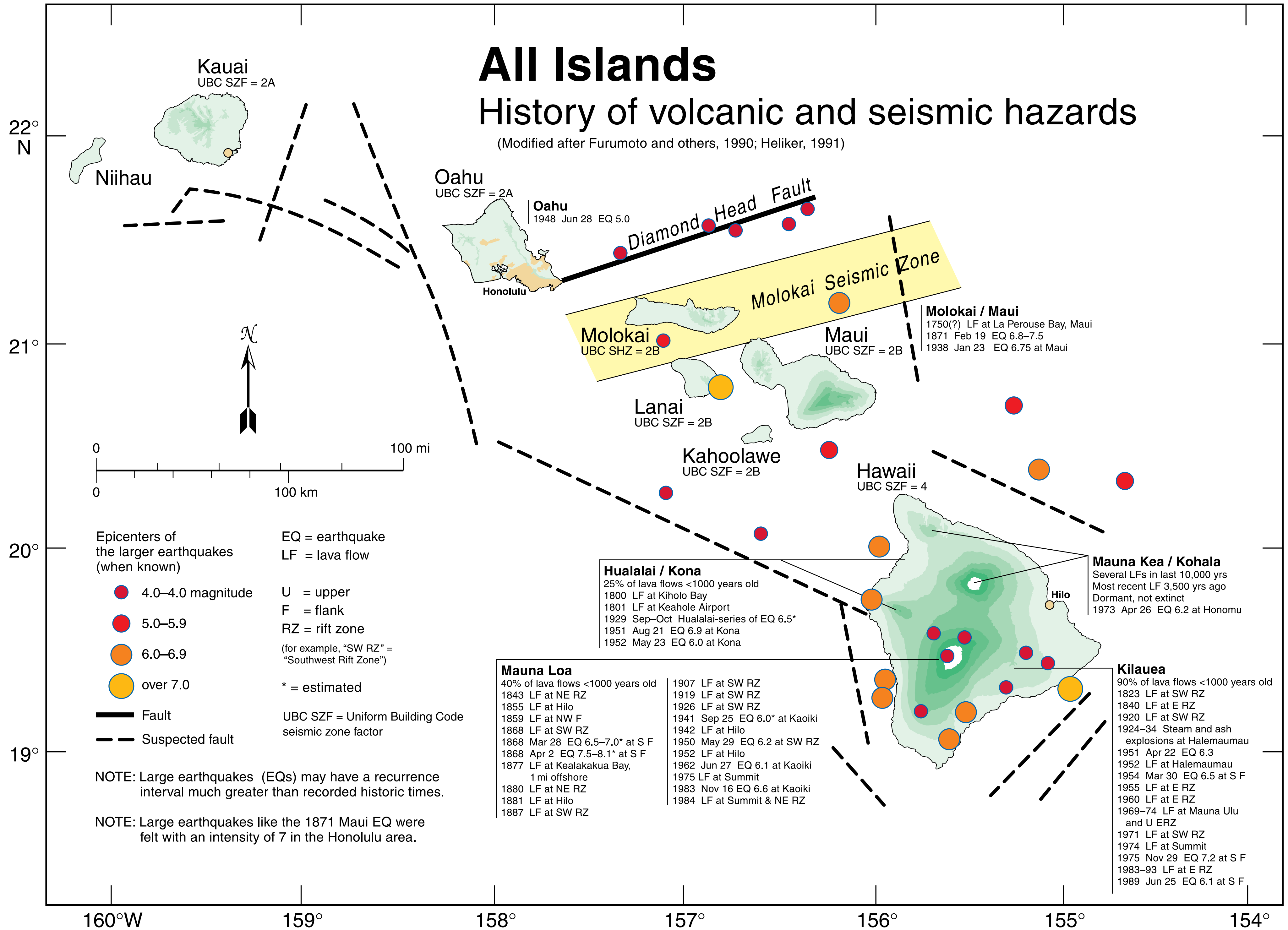
Of special concern is the nature of the sedimentary layer under the commercial sector of Honolulu, which will tend to experience heightened ground motion relative to adjacent regions where the bedrock is less prone to seismic acceleration. We have incorporated these recommendations in our ranking of the combined volcanic/seismic risk and assigned a ranking of 3 to the southern half of Oahu from Makaha around Diamond Head and Makapuu Head to Kaneohe Bay. The remainder of the island is ranked a 2 with respect to the volcanic/seismic hazard.

Tectonic activity capable of generating hazardous earthquakes in the central region is related to seafloor fractures and suspected 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 larger.

The Oahu Earthquake of 1948, which occurred along the Diamond Head Fault, resulted in broken store windows, plaster cracks, fissures and ruptures to building walls, and a broken underground water main. Cox (1986) assigned a magnitude of 4.8 to this earthquake, while Furumoto (1980) estimated a magnitude of approximately 5.0. Landslides generated by the quake-blocked roads in Kipapa Gulch were quickly cleared. The Diamond Head Fault also passes through Koko Crater and extends along the seafloor northeast of Oahu. Several earthquakes of 4.0 to 5.0 magnitude have been detected along this fault.

The Molokai Fracture Zone is an extension of a transform fault from the East Pacific Rise that reaches from Molokai to the Gulf of California. Because this fracture is tectonic in origin, and thus associated with seismically active seafloor spreading processes, it is suspected to contribute to central region seismicity. Two known earthquakes (1871 and 1938) have occurred along the fracture, leading Furumoto (1980) to designate this the Molokai Seismic Zone.

The Lanai Earthquake of 1871 had a magnitude of 7 or greater with vibrations that have been described as lasting 55 seconds in a northeast to southwest rocking motion. Walls were severely cracked and damaged and two houses were reported to have split open on Oahu. At Punahou School (Oahu) chimneys were thrown down, and in Ewa (Oahu) the belfry tower of the Catholic Church collapsed. Ground fractures and land slippage



occurred in Waianae (Oahu) and Lahaina (Maui). Massive rockfalls and cliff collapse occurred on Lanai, and houses and churches were flattened on the islands of Maui and Molokai. Damage was also reported from the Big Island.

The 1938 Maui Earthquake was assigned a magnitude of 6.7-6.9 with an epicenter located only 6 miles north of the island of Maui, in the Molokai Seismic Zone. Numerous landslides closed the road to Hana, and long sections of the Hana highway collapsed into the sea. Waterpipes and a reservoir were severely damaged and ground cracks opened on Maui, Molokai, and Lanai. Damage on Oahu was reported to be slight, confined mainly to broken objects shaken from shelves and local landslides.

In a major report in 1986, Cox compiled statistics on Hawaiian seismicity and listed 113 felt earthquakes on the island of Oahu between 1859 and 1983. An earthquake is felt on Oahu nearly annually. Recurrence probabilities of a major earthquake (magnitude 7 or greater) in the central region were estimated in Furumoto and others (1990). The probability for a major earthquake occurring from 1989 to 1998 is estimated at 6%. If no quake occurs by 1998, a 78% probability is estimated for a major quake for 1999-2008. A probability greater than 99% is estimated for 2009-2018 if no major earthquake occurs by 2008.

Klein and others (2001) have 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 give the 10% and 2% probability of peak ground acceleration exceeding predicted values in 50 years, which correspond to return times of about 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, should be considered minimal. While 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 decreases exponentially toward the northwest. Peak horizontal ground acceleration is predicted to be 50% in Hilo and 13% in Honolulu relative to the southeast coast of the island of Hawaii (100%).

Our volcanic/seismic hazard intensity rankings attempt to account for the variability in (1) geology, (2) UBC seismic zone factor rankings for each island, (3) history of volcanic and seismic activity, and (4) recent scientific predictions of the probability distribution of seismic hazards among the main Hawaiian Islands. The volcanic/seismic hazard ranking generally increases uniformly from Kauai toward the Big Island, because of the increase in volcanic and seismic activity found along the southeast coast of the Big Island.

Volcanic hazards are, of course, greatest on the south shore of the Big Island where the volcanoes are active. But active seismicity on Haleakala Volcano, Maui, and Mauna Loa Volcano on the Big Island, apparently dormant volcanoes, indicate that these volcanoes should continue to be perceived as potentially hazardous. Indeed, because we base our hazard intensities on the historical record, the eruption on the southwest flank of Haleakala in the late 1700's elevates that region to a high ranking for volcanism and seismicity.

The U.S. Geological Survey has completed an extensive mapping program to determine the history and severity of the volcanic hazard on the Island of Hawaii. Hawaiian volcanoes erupt either at their summits where lava collects, and may overflow from craters called calderas, or along their flanks where lava issues through fractures 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.

The lava flow hazard zone map divides the island of Hawaii into nine zones that are ranked 1 to 9 based on the occurrence probability of lava flows (Table 10). Although the other volcanic hazards are not ranked, these hazards also tend to be greatest in the areas where lava flows are ranked at highest probabilities.

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 consequences of lava movement. At the coastal zone, flowing lava tends to slow and spread laterally, because of the diminished slope, causing damage along the shoreline.

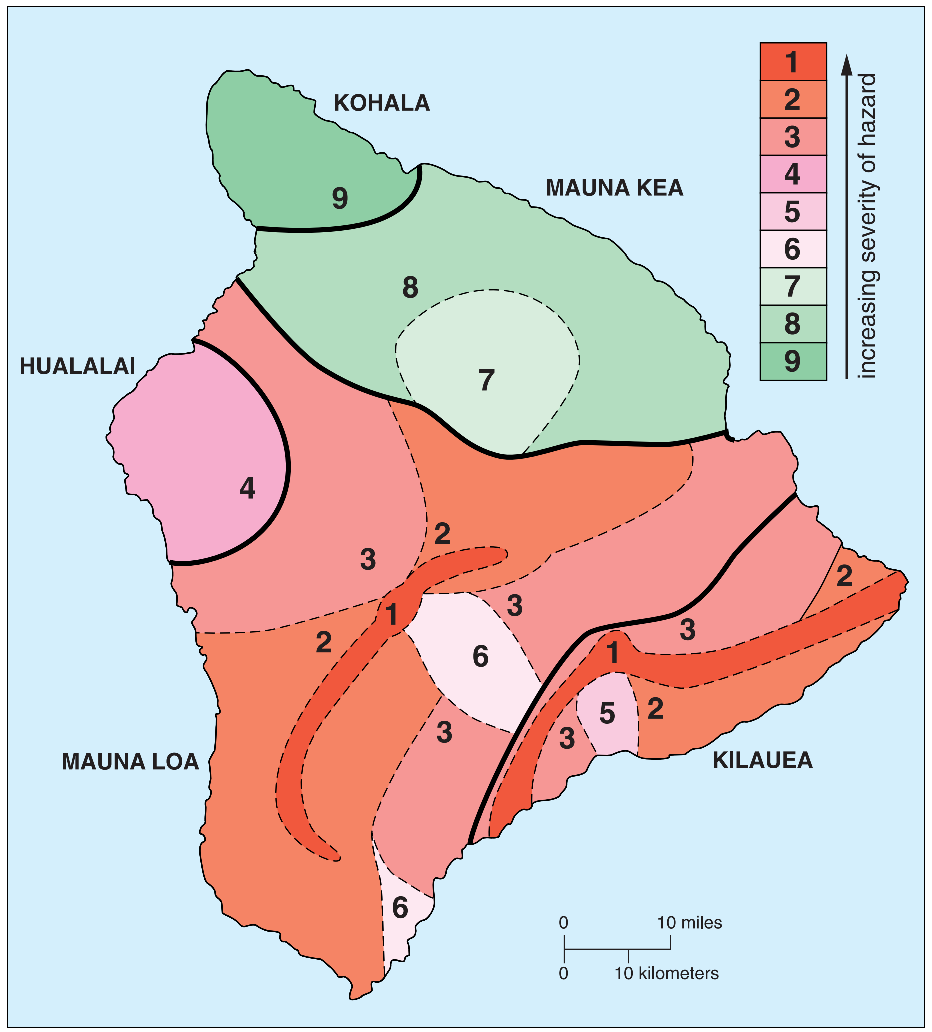
TABLE 10
Hazard zones for lava flows

Zone	Percent of area covered by lava: since 1800	Percent of area covered by lava: in last 750 yrs	Explanation
Zone 1	> 25%	> 65%	Includes the summits and rift zones of Kilauea and Mauna Loa where vents have been active in historic time.
Zone 2	15–25%	25–75%	Areas adjacent to and downslope of active rift zones.
Zone 3	5%	15–75%	Areas gradually less hazardous than Zone 2 because of greater distance from recently active vents and/or because topography makes it less likely that flows will cover these areas.
Zone 4	1-5%	<15%	Includes all of Hualalai, where the frequency of eruptions is lower than on Kilauea and Mauna Loa. Flows typically cover large areas.
Zone 5	none	about 50%	Areas currently protected from lava flows by the topography of the volcano.
Zone 6	none	very little	Same as Zone 5.
Zone 7	none	none	20% of this area covered by lava 3,000–5,000 years ago.
Zone 8	none	none	Only a few percent of this area covered in the last 10,000 years.
Zone 9	none	none	No eruption in this area for the past 60,000 years.

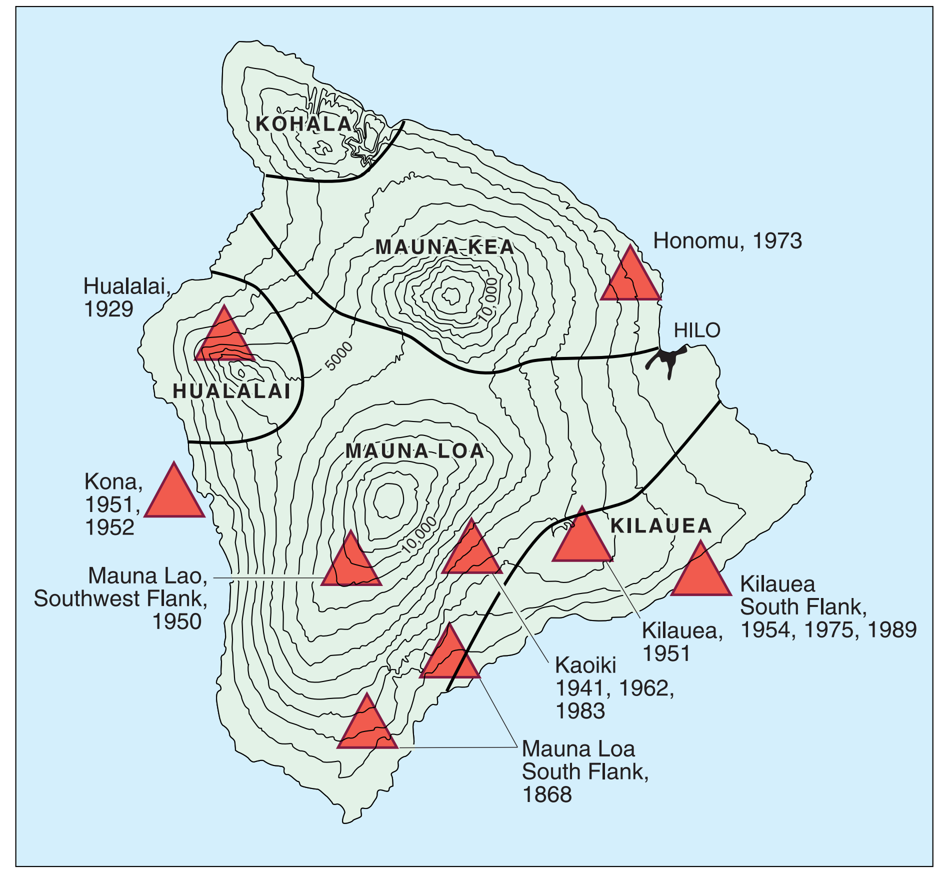
Airborne ash, cinders, and other lava fragments are usually only hazardous in the immediate vicinity of an eruption. Volcanic gases generated by the present eruptions at Kilauea are composed mostly of water vapor, with lesser amounts of sulfur dioxide, carbon dioxide, and hydrogen. Small quantities of carbon monoxide, hydrogen sulfide, and hydrogen fluoride have been measured, but not in health-threatening concentrations. These gases, particularly sulfur dioxide, can mix with rainwater 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 lead-based metals such as roof flashing, lead-headed nails, and pipe solder that can be leached into solution by high-acidity water. Widespread testing in 1988 found that many water-catchment systems on the island of Hawaii, especially those down-wind of the main eruption center, contained elevated concentrations of lead.

Explosive eruptions are not common at Kilauea but they have occurred within historical times. The interaction of ground water and hot magma can lead to a violent explosion, and the resulting magnitude of the event can be catastrophic in the wrong circumstances. In 1790 turbulent avalanches of hot gases and rock fragments, called pyroclastic surges, flowed several miles to the southwest from the summit of Kilauea. These can move at speeds approaching 200 miles per hour and kill any living thing in its path. A band of approximately 80 Hawaiian warriors traveling from Hilo to the Kau 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 widespread surges have occurred in the recent past.

Although volcanism and seismicity pose a significant risk in the Hawaiian Islands, the hazard level can be reduced and, in places, mitigated. Programs of public education can teach the citizens of the state about the proper behavior around volcanically active regions and of life-saving steps to take during an earthquake. Proper building codes and frequent re-evaluation of the appropriate level of construction techniques are a key component in public safety. Land-use zoning that restricts development on or near steep slopes that may fail during earthquakes and away from areas characterized by sedimentary and/or saturated materials that are likely to amplify ground motions during an earthquake are important steps to reducing hazard levels. Loss of life and damage to communities can be reduced by proactive management and public awareness.



Lava flow hazard zone map for the five volcanoes on the Island of Hawaii.



Historical earthquake epicenters on the Island of Hawaii.

Concluding Notes

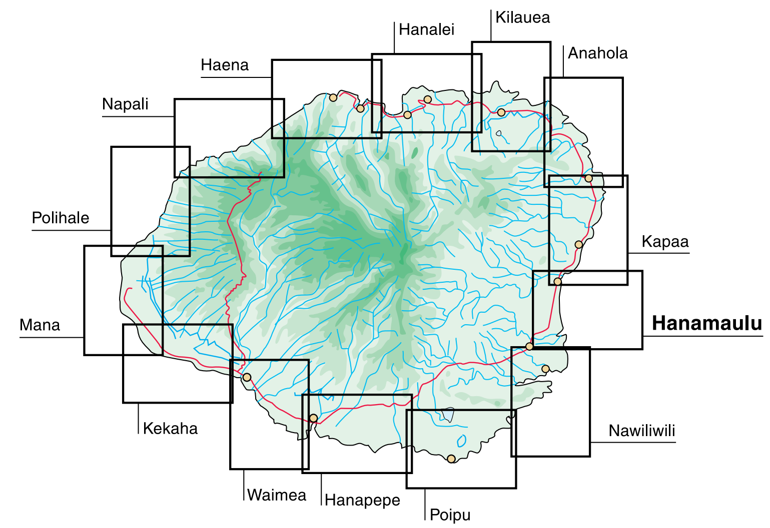
A few minor concluding notes are in order at this point before we move on to an analysis and assessment of the natural hazards in the Hawaiian coastal zone.

Part of our 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 19th to 20th centuries, and only the era of satellite technology (1960 to present) allows controlled coverage of meteorological hazards. For instance, volcanic and seismic hazards probably 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. Our understanding of storm intensity and frequency is therefore skewed towards this dataset, and a broader understanding of hazard history in Hawaii is not possible.

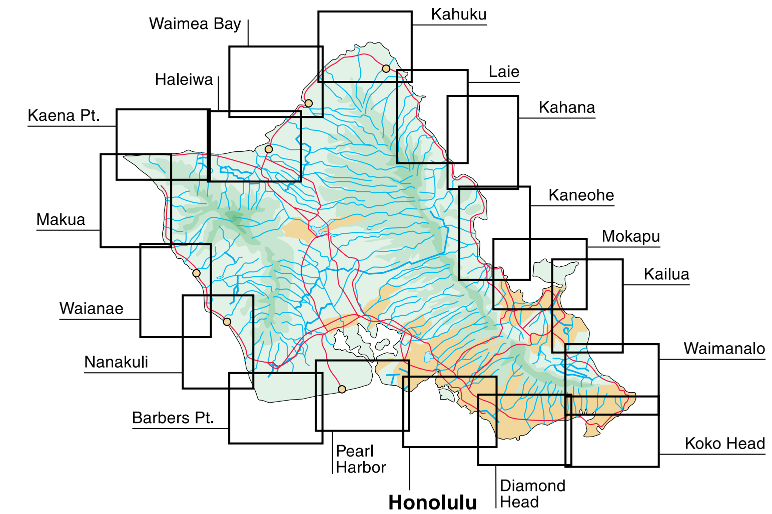
Damage in areas hit by natural hazards during early years (prior to 1960) was generally only recorded in populated regions, thus a significant (and unknown) hazard history may exist for areas that are only recently populated. Because of this, newly populated areas may have been assigned a lower severity ranking than may be appropriate.

Index to Technical Maps

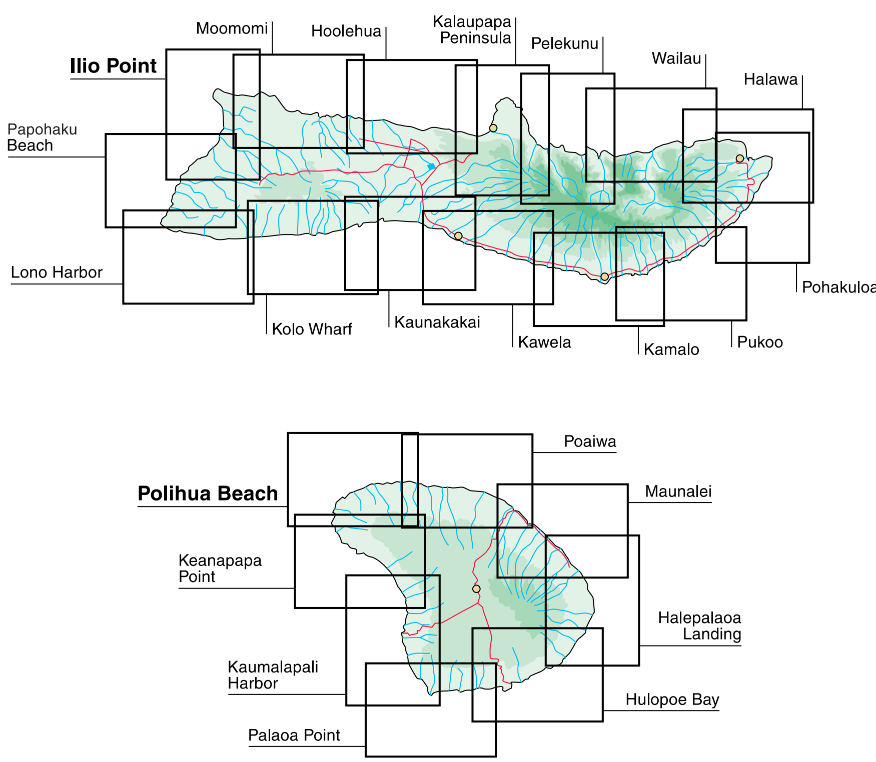
Kauai



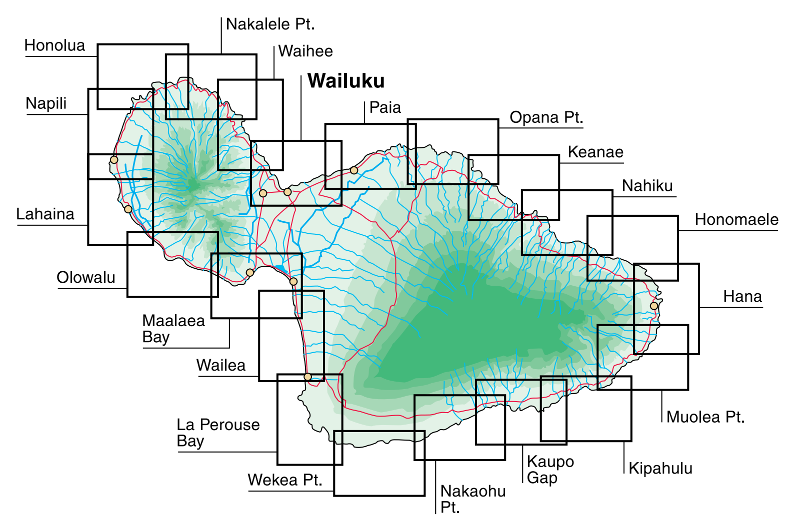
Oahu



Molokai and Lanai



Maui



Hawaii