

Marine Flooding on the Coast of Kaua'i during Hurricane Iniki: Hindcasting Inundation Components and Delineating Washover

C.H. Fletcher†, B.M. Richmond‡, G.M. Barnes††, and T.A. Schroeder††

†Department of Geology and
Geophysics
University of Hawai'i
2525 Correa Road
Honolulu, HI 96822, U.S.A.

‡U.S. Geological Survey
345 Middlefield Road
Branch of Pacific Marine
Geology, MS 999
Menlo Park, CA 94025, U.S.A.

††Department of Meteorology
University of Hawai'i
2525 Correa Road
Honolulu, HI 96822, U.S.A.

ABSTRACT

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The right frontal quadrant of Hurricane Iniki crossed the southeast coast of Kaua'i on the afternoon of September 11, 1992 and produced marine overwash with excursion distances of approximately 20-250 m and elevations in the range 4-9 m (mllw). Using a combination of field data, empirical relationships, and theory, we estimate that the effective maximum sustained wind velocity (V_{max}) was in the range 52.4 ± 2 m/s. We also analyze the meteorological and oceanographic components of marine flooding under the right frontal quadrant of the storm. Overwash was principally a function of eye-relative position and orientation of the coast, $\tan \theta$ (slope), the friction-controlled wave run-up, and the wave set-up. Maximum overwash was adjacent to a major bathymetric channel and a slightly embayed coastline which reduced wave-energy dissipation in the nearshore, affording greater landward translation of deep-water wave characteristics. Total combined calculated overwash on the south shore of Kaua'i at Kukuiula (~ 5.2 m mllw) is the sum of pressure set-up (0.39 m), wave set-up (1 m), wind stress set-up (0.06 m), run-up (2.9 m) and tidal stage (~ 0.8 m). Measured debris-line and still-water mark elevations there ranged from 3.91-5.90 m (mllw). To the east on the steeper Koloa Landing coast, the calculated overwash components equaled approximately 6.6 m (mllw), and measured debris-line elevations ranged from 6.84 to 9.16 m (mllw). We present and discuss maps of the Iniki debris line relative to the FEMA V-zone and 100-yr flood zone, and major transportation arteries along the shoreline at five major coastal population centers on Kaua'i.

ADDITIONAL INDEX WORDS: Hurricane Iniki, Hawai'i, Kaua'i, coastal overwash, FEMA V-zone, FIRM, debris line, hindcast analysis.

INTRODUCTION

Shortly after 3:00 PM (HST) on September 11, 1992 Hurricane Iniki, which at peak strength earlier in the day was a minimal Category 4 tropical cyclone (Saffir-Simpson scale), made landfall on the south shore of the island of Kaua'i. The eye passed the Kaua'i coast near Kaumakani (~ 5 km west of Port Allen) with devastating consequences. Sustained winds of ~ 52 m/s, gusting to ~ 64 m/s, were recorded and an uncalibrated anemometer record indicated a localized gust of ~ 99 m/s. Winds, combined with extensive coastal flooding commonly exceeding 2.5 m and as high as 9.16 m, destroyed or damaged 14,350 buildings (unless otherwise noted, all elevations are relative

to the Hawaiian datum, mean lower low water, mllw). Of these, 1421 were destroyed, and another 5152 suffered major damage (Fig. 1). Statewide, an additional 607 buildings sustained damage or were destroyed. Six deaths are attributed to the storm and over one thousand injuries reported. A year later the Property Claims Services Division of the American Insurance Services Group and the Insurance Information Institute ranked the \$1.6 billion (1990 dollars) in losses from Iniki as the fifth most costly insured catastrophe in U.S. history.

This paper describes oceanographic and meteorological factors that influenced overwash impacts in the coastal zone of Kaua'i and provides maps of the overwash pattern in and around the principal coastal population centers of Kaua'i. Primary attention is given to the south shore of the



Figure 1. An 80 unit condominium complex, lower floors destroyed by overwash, upper floors destroyed by wind. Note the overwash debris line in the background. East of Kukuiula Bay, Kaua'i.

island, in the right forward quadrant of the storm as it made landfall. It was there that overwash was most intense.

STORM HISTORY

Iniki was first identified as Tropical Depression (TD) 18-E 2700 km southwest of Baja California over the eastern Pacific near 12°N 135°W on September 5, 1992 (NWS, 1993). TD 18-E crossed 140°W and moved into the Central Pacific on the morning of September 6 heading west-northwest at 7 m/s with maximum sustained winds of 15 m/s. Initially expected to dissipate, TD 18-E did

weaken under unfavorable wind shear, but by mid-day on September 7, the system became embedded in a deep easterly flow along the southern edge of the seasonal subtropical high-pressure ridge extending from 40°N to 45°N latitude between 130°W and 170°W longitude. By 5 PM, TD 18-E was upgraded to Tropical Storm Iniki moving west at 4.5 m/s with maximum winds of 18 m/s (Fig. 2).

Iniki slowly intensified as it moved west. At 11 pm on September 8, Tropical Storm Iniki was upgraded to Hurricane Iniki at a position of 13.2°N 152.1°W, moving still west with maximum sus-

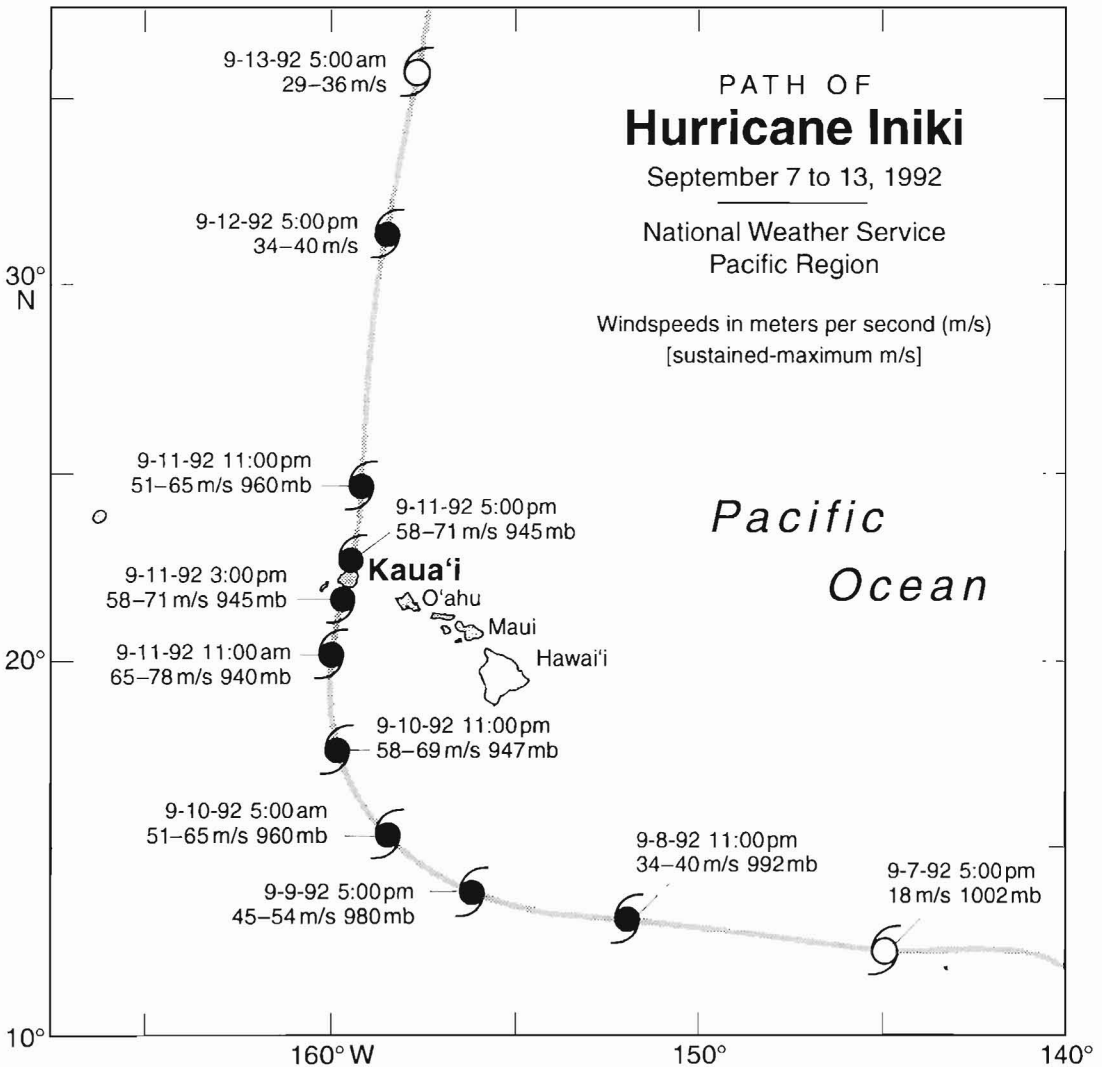


Figure 2. Path of Hurricane Iniki, and significant episodes in the evolution of the storm (NATIONAL WEATHER SERVICE, 1993).

tained winds of 34 m/s, gusting to 40 m/s. With a forward speed of 7 m/s, Iniki's central pressure slipped to 992 mb as it assumed a new heading to the west-northwest by 5 AM, September 9. At 11 AM sustained winds had strengthened to 40 m/s and gusts exceeded 49 m/s. Expected to strengthen still further, the system continued tracking west-northwest and by late afternoon was approximately 485 km south of South Point, Hawai'i. At 5 pm a high-surf advisory was issued for the south-facing shores of all Hawaiian Islands.

Early September 10, Iniki's forward motion slowed to 5 m/s 675 km south-southwest of Honolulu and by 5 PM that afternoon had turned to the northwest. Having continued to grow in intensity with top winds of 56 m/s, gusting to 69 m/s, the center was now located near 16°N and 160°W, 650 km south of the city of Lihue on Kaua'i. Surf was reported subsiding from a high of 3.5 m on the Big Island and building to 2.5 to 3.5 m elsewhere. The south shore of Kaua'i was warned of sustained, rough surf that would damage shore-

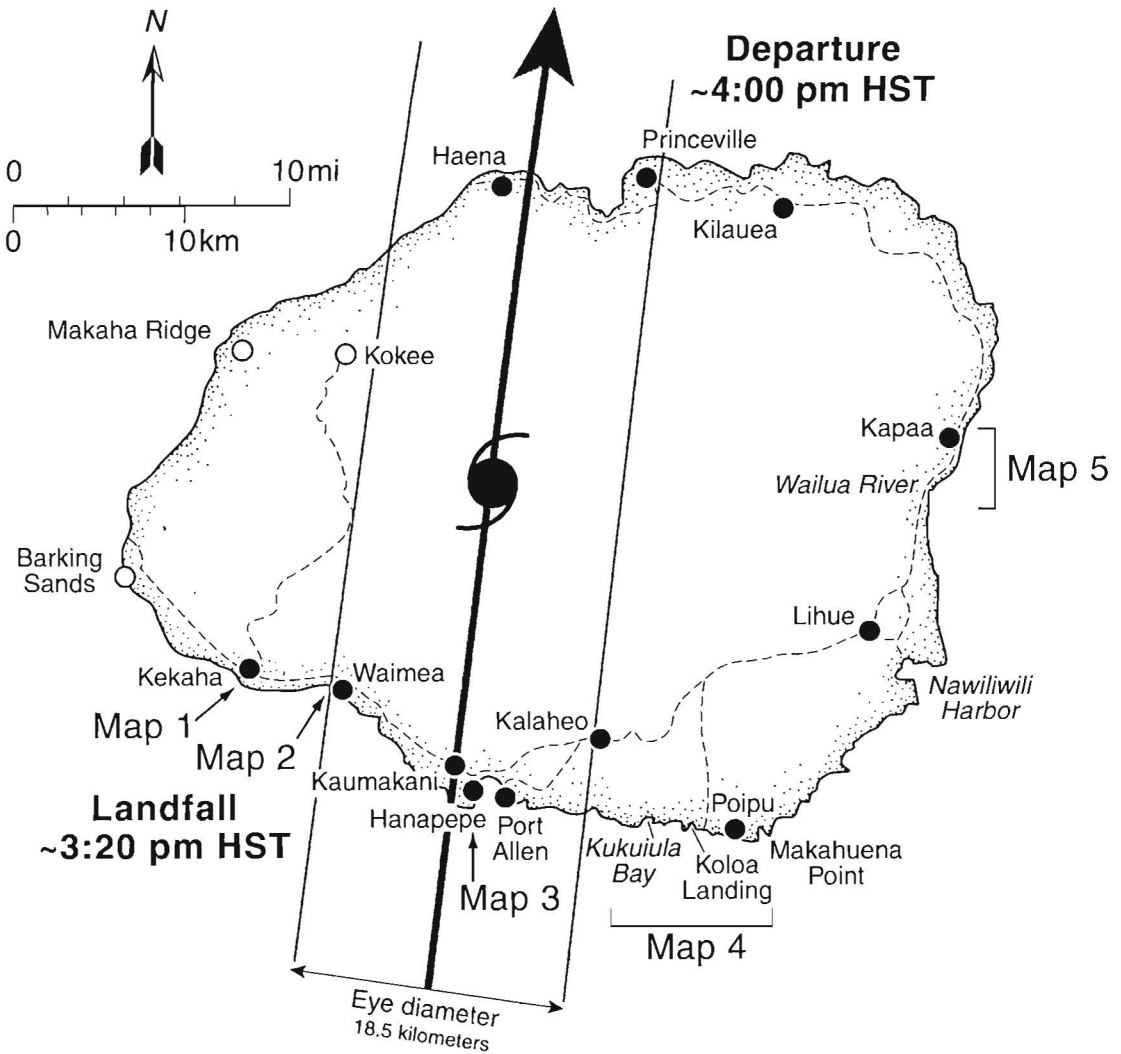


Figure 3. Map of Kauai, and path of Hurricane Iniki. Locations of separate inundation maps are shown.

line property by Friday. At 8:30 PM the alert was elevated, a Hurricane Warning was issued for Kauai and Ni'ihau, a Tropical Storm Warning for O'ahu, and a Tropical Storm Watch for Maui Co. Within two and a half hours, the alert status was elevated again. This time O'ahu was upgraded to a Hurricane Warning.

By late morning 11 AM, Iniki had reached maximum recorded strength due west of Maui and 210 km south-southwest of Lihue, capital city of Kauai. Reconnaissance aircraft recorded sustained maximum winds 65 m/s gusting to 78 m/s

and a central pressure of 938 mb, the lowest ever recorded in a Central Pacific Hurricane. The eye, with a diameter of 33 km, was a small tight center with intense energy. On Kauai, the first waves were reported crossing the coastal highway between Kekaha and Poipu and winds had built to 18-22 m/s between Kekaha and Kalaheo. O'ahu Civil Defense ordered that all persons residing within "300 ft" of all shores evacuate to higher ground.

Iniki made landfall west of Port Allen, Kauai shortly after 3 PM (Fig. 3). The eye was only 18.5

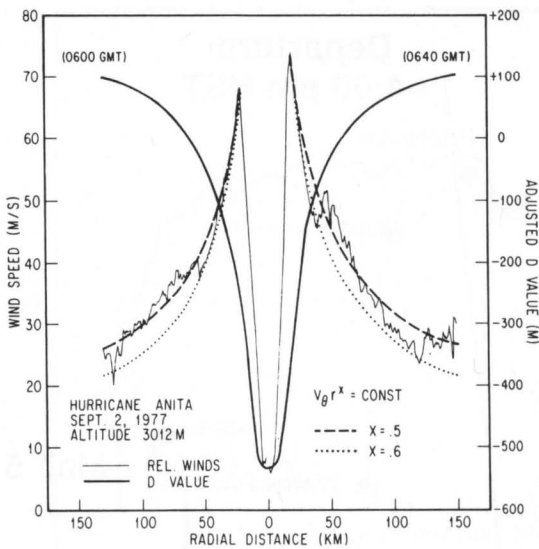


Figure 4. Radial profiles of wind speed (m/s) and pressure in Hurricane Anita. Note increased velocity to right of eye. Also shown are plots of the Modified Rankine Vortex model, $V_{\theta}r^x$ for $x=0.5$ and 0.6 (ANTHES, 1982).

km wide indicating that probable maximum sustained winds ($V_{\theta\max}$) were located near the eyewall. Unfortunately, no usable wind data are available from near the eye. The NOS tide station at Port Allen did record a low pressure of 960 mb at 3 PM, and 968 mb at 4 PM. Extrapolation of the hourly pressure record suggests a minimum pressure of about 952 mb at Port Allen (NWS, 1993). Twenty kilometers to the east, at Makahuena Pt., an anemometer recorded sustained winds at 36.3 m/s before it failed. A peak gust of 64 m/s was later extracted from the digital data recorder at Makahuena. At Lihue, 32 km east of the eye as it passed over the island, sustained winds of 43.5 m/s (3:52 PM) and a peak gust of 57.8 m/s (3:02 pm) were recorded.

By 5 PM, having left the island along a path just east of Haena, Iniki was already 80 km north of Kaua'i, and the Hurricane Warning for O'ahu was downgraded to a Tropical Storm Warning. In confusion, some officials concluded that this new warning heralded the approach of a second storm. All warnings for the State were either cancelled or downgraded by 11 pm as Iniki sped on to the north. High Surf Advisories were maintained the following day for south and west-facing shores of all islands.

MAXIMUM SUSTAINED WINDS

Hurricane Iniki had a clear eye radius of approximately 9.3 km (TRAPP, 1993). Maximum sustained winds, $V_{\theta\max}$, will be located an unknown distance beyond the eye, within the wall at the right frontal quadrant of the storm as shown in radial wind speed and pressure profiles of Hurricane Anita (Fig. 4). Our approximation of $V_{\theta\max}$ and its location, the radius of maximum winds (RMW), is based on a consideration of the cyclostrophic structure of a symmetrical vortex. The ratio of the square of maximum velocity to the radius of maximum winds ($V_{\theta\max}^2/\text{RMW}$) is estimated by the inverse of atmospheric density, ($1/1.1 \text{ kg/m}^3$) and the pressure gradient across some representative distance (Δ_p/Δ_r). Dropsonde data near Kaumakani records a central pressure of 945 mb, while 5 km away at Port Allen the extrapolated pressure record suggests a minimum of 952 mb (NWS, 1993). Based on the available pressure-field data, we assume a distance of ~ 12 km for the radius of maximum winds, and an estimate of maximum sustained wind around the vortex center is given by,

$$\frac{(V_{\theta\max})}{(\text{RMW})} = (1/\rho_{\text{atm}})(\Delta_p/\Delta_r) \quad (1)$$

$$V_{\theta\max} = \left[\left(\frac{1}{1.1} \frac{(952 - 945)(100)}{5000} \right) 12000 \right]^{0.5} = 40.98 \text{ m/s} \quad (2)$$

This is the stationary velocity. Winds in the right frontal quadrant have an additional translation speed. There is some dispute about the actual speed of Iniki as it crossed the south coast of Kaua'i. According to the Iniki Disaster Survey Report (NWS, 1993), the storm had a forward speed of "30 mph" (about 13.4 m/s). However, in its 3 PM HST news release prior to landfall, the National Weather Service citing reconnaissance aircraft data reported that "Hurricane Iniki was speeding up moving north at 21 mph" (about 9.4 m/s). Thus, for an average translation speed of 11.4 m/s, the effective maximum sustained velocity, $V_{\theta\max}$, was in the range of 50.4 m/s to 54.4 m/s (52.4 ± 2 m/s). A preliminary analysis (Fig. 5) of surface winds at landfall, using flight-level data, yields similar results (M. POWELL, pers. comm.).

Reconnaissance aircraft reported maximum sustained flight-level winds of 65.5 m/s south of

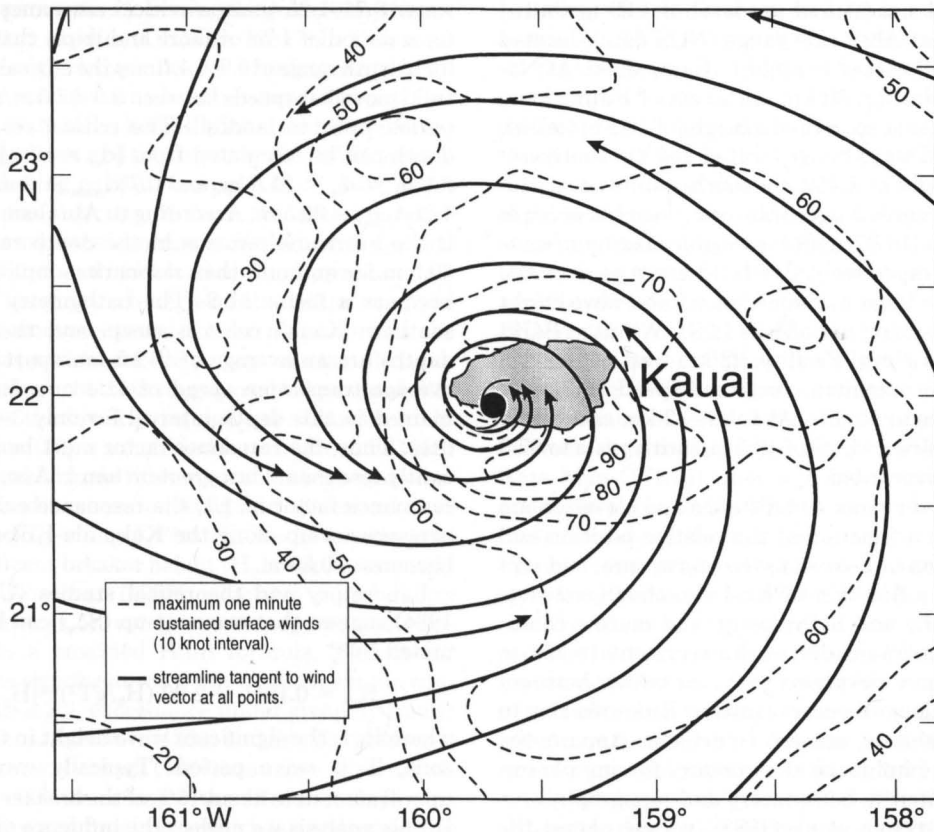


Figure 5. NOAA Hurricane Research Division open-water surface winds at landfall using empirically adjusted reconnaissance aircraft data (M. POWELL, *pers. comm.*). Island topography makes model winds invalid and they are not plotted for terrestrial locations.

Kaua'i. POWELL (1987), in an analysis of the wind structure of Hurricane Alicia (1983) at landfall, provides a conversion ratio of 0.78 for estimating surface winds from reconnaissance flight-level data, suggesting a value of 51.1 m/s for Iniki winds at or near landfall.

The Atlantic Empirical Equation relates $V_{\theta_{max}}$ to the difference of ambient and observed central pressure ($V_{\theta_{max}} = 14[1013.3 \text{ mb} - 945 \text{ mb}]^{0.5}$) based on historical observations in the North Atlantic basin. This provides a value of 59.6 m/s.

A maximum gust of 63.9 m/s was recorded at Makahuena Pt. POWELL's (1987) analysis provides a useful gust factor of 1.64, suggesting that maximum sustained winds at Makahuena Pt. were about 39 m/s. By calibrating the Modified Rankine Vortex Model (ANTHES, 1982) with $V_{\theta_{max}}$, we estimate the maximum sustained winds.

$$\begin{aligned}
 V_{\theta} r^{(0.5-0.6)} &= \text{Iniki Constant} \\
 &= (40.98)(12,000)^{0.55} \\
 &= 7179.95 \text{ m}^2/\text{s} \quad (3)
 \end{aligned}$$

$$V_{\theta} = 7179.95/r^{(0.55)} \quad (4)$$

Makahuena Pt. is a distance (r) of about 20 km from the center. Equation (4) predicts a V_{θ} of 30.9 m/s at this location, which becomes 42.3 ± 2 m/s for a translation speed of 11.4 ± 2 m/s. Thus, estimates of V_{θ} at Makahuena Pt. using Powell's gust factor (39 m/s) and the calibrated vortex model (42.3 ± 2 m/s) agree within 8%.

OVERWASH COMPONENTS

Overwash is a combination of tidal, wind, wave, and pressure effects on the sea surface. Iniki landfall was coincident with high tide. The combined

effect of storm surge components and tidal stage produced a measured sea level of 1.89 m (mllw) at the Port Allen tide gauge (NOS data), located 5 km southeast of landfall at Kaunakani. At Nawiliwili Harbor, 30 km northeast of Kaunakani, the tide gauge measured a height of 1.78 m (mllw).

Moored wave buoys located 355 km southwest of Honolulu and 452 km south-southeast of Honolulu, recorded significant wave heights of 5.5 m and 6.0 m (10.97 m most probable maximum wave height), respectively. BRETSCHNEIDER et al. (1993) determined that maximum deep water wave height was 14.6 m, and period was 12.5 s. Winds at Barking Sands Naval Facility, 22 km west of the eye, reached a maximum sustained speed of 31 m/s with gusts to 45 m/s. At Lihue 32 km east of the eye, sustained winds of 43.5 m/s with gusts to 57.8 m/s were recorded.

Washover excursion distance and elevation are primarily a function of the relative position and orientation of a coast to the storm core, and secondarily a function of local shoreline geometry, topography and bathymetry, and marine conditions. Maximum overwash excursions (>250 m inland) and elevations (~9.1 m mllw), both occurring along the coast between Kukuiula Bay to Koloa Landing, are not coincident. Apparently, this is the influence of secondary forcing parameters related to bathymetry and topography.

In FLETCHER et al. (1993), we calculated the pressure set-up (S_p) as a function of the pressure drop (D_p) from the periphery to a point within the hurricane ($D_p/\rho_{sw}g$), where ρ_{sw} is the density of seawater (1025 kg/m³). MYERS (1954) developed an empirical relation for the surface pressure distribution based on an analysis of historical data

$$p_a - p_r = [(p_a - p_c)100](1 - e^{-RMW/r}) \quad (5)$$

where p_a is the ambient pressure (assumed to be 1013.3 mb), p_r is the pressure at any distance r from the center and p_c is the central pressure of the storm (945 mb). For RMW, the radius of maximum sustained wind, we assume a value of 12 km. Thus, the set-up becomes:

$$S_p = [(p_a - p_r)(100)/(\rho_{sw}g)] \quad (6)$$

$$= [(p_a - p_c)(100)/(\rho_{sw}g)](1 - e^{-RMW/r}) \quad (7)$$

The set-up under the center of Iniki, where $p_r=945$ mb, becomes 0.68 m. On the Kukuiula-Koloa coast at a distance of 16.5 km to the east of the eye (site of maximum overwash) $S_p = 0.35$ m.

ABRAHAM (1964) suggests the long-wave surge

approaches twice this value, if a storm moves over water 0.75–1.25 times a critical resonance depth for a period of 1 hr or more and triple that value for a depth range of 0.9–1.1 times the critical depth. Iniki moved at speeds between 8.9–17.6 m/s in the period prior to landfall. The critical resonance depth can be calculated from $[d_{cr} = V^2/g]$. Thus $8.1 \text{ m} < d_{cr} < 31.6 \text{ m}$, and $0.75d_{crmin} = 6 \text{ m}$, while $1.25d_{crmax} = 39.5 \text{ m}$. According to Abraham (1964) if the hurricane remains in the depth range 6–39.5 m for an hour, then resonance amplification becomes a factor of 2. The bathymetry of the southern Kaua'i coast is steep, and these two depths are an average of 2–2.5 km apart. At an average translation speed of 11.4 m/s, Iniki remained in this depth interval for only 3–4 minutes. Thus, the resonance factor must be significantly less than 2 but greater than 1. Assuming a resonance factor of 1.1, the resonance enhanced pressure set-up along the Kukuiula-Koloa coast becomes ~0.39 m.

Laboratory and theoretical studies (USACE, 1984) suggest that wave set-up (S_{ww}) can be estimated by

$$S_{ww} = 0.19[1 - 2.82 (H_b/gT^2)^{0.5}]H_b \quad (8)$$

where H_b is the significant wave height in the surf zone, T is wave period. Typically wave set-up will amount to about 15% of the breaker height. In this analysis we neglect the influence of wave-set-down. Breaking wave heights of about 9 m (visual estimate) were reported in the region of the Kukuiula-Koloa coast at the height of the hurricane. Offshore buoy 51002, located about 280 miles south-southeast of Honolulu, recorded a deep-water significant wave height of 6 m, with a most probably maximum height of nearly 11 m (NOS buoy data). Equation (9) derives the relationship between significant breaker height (H_b) and deep-water height ($H_d = 6$ m):

$$H_b = H_d/3.3(H_d/L_d)^{0.33} \quad (9)$$

Deep-water wave length (L_d) can be calculated using ($L_d = [g \cdot 2\rho]T^2$). Assuming a wave period of 14 s (NOS buoy data), $L_d = 306$ m. Equation (9) predicts a breaking a wave height of ~6.7 m, and (8) predicts a wave set-up, S_{ww} , of about 1 m.

FLETCHER et al. (1993) calculate a combined wind stress and bottom stress set-up under $V_{\theta max} = 52.4$ m/s of 0.06 m on the Kukuiula-Koloa coast.

Although it is not possible to theoretically predict run-up because of the large number of vari-

ables, it is possible to estimate run-up from a few simple parameters following the guidelines of some laboratory studies (USACE, 1984). In this analysis we neglect the influence of infragravity band run-up motions which have been shown to increase with wave height (GUZA and THORNTON, 1982; HOLMAN and SALLENGER, 1985). We assume the following conditions apply: $H_d = 6$ m, $T = 14$ s, and the slope ($\tan\theta$) from the break point to the 6 m onshore contour at Kukuiula is approximately 0.02 and at Koloa Landing approximately 0.03. This approach neglects the influence of the water column between the break point and the shoreline and treats the run-up as a simple function of slope, bottom roughness and permeability between the break point and the excursion limit. Equation (10) is a modified form of HUNT's (1959) empirical formula relating onshore slope, breaker height and wave period to significant vertical wave run-up [$R_{uv} = T(gH_b)^{0.5}\tan\theta$]. We have estimated a significant breaker height (H_b) of approximately 6.7 m. AGRAWAL (1993) calculates a probability parameter (1.5), using wave-energy analysis applied to a modified Hunt formula. This factor converts significant wave run-up to maximum run-up, with a 2% exceedance under given hydraulic conditions. AGRAWAL (1993) and SEA ENGINEERING and BRETSCHNEIDER (1986) assume a friction value of $r = 0.85$ to estimate the effects of slope permeability and roughness which is a value used to describe grassy slopes.

$$R_{uv} = (1.5)(0.85)T[H_b g]^{0.5}\tan\theta \quad (10)$$

Thus, for Kukuiula $R_u = 2.9$ m, and for the steeper, Koloa Landing coast $R_u = 4.3$ m.

Total combined calculated overwash for the Kukuiula coast (~ 5.2 m mllw) is the sum of pressure set-up (0.39 m), wave set-up (1 m), wind stress set-up (0.06 m), run-up (2.9 m) and tidal stage (~ 0.8 m). Measured debris-line and still-water mark elevations there ranged from 3.91-5.90 m (mllw) (S. YAMAMOTO, USACE pers. comm.). On the steeper Koloa Landing coast, the calculated overwash components equaled approximately 6.6 m (mllw) and measured debris-line elevations ranged from 6.84-9.16 m (mllw).

WASHOVER PATTERNS

The Iniki overwash debris line was determined from field data, marine surveys, and aerial photographic interpretation and drafted onto GIS digital basemaps at a scale of 1:1200. The contin-

uous overwash line, extending approximately 34 km along the south coast, and 16 km along the east coast of Kaua'i, was digitized on the Universal Transmercator Zone 4 Coordinate System and archived with the State of Hawai'i, Governor's Office of State Planning Geographic Information System under the file heading INIKI.OWASH.

In the following discussion, we present maps showing the digitized Iniki overwash line, the 1986 shoreline, the FEMA Flood Hazard Zone V ("subject to inundation by the 100-year flood with the additional hazards associated with storm waves"; FEMA, 1987), and the FEMA Flood Hazard Zone A ("subject to inundation by the 100-year flood"; FEMA, 1987). These figures are State GIS products. Because of intervening shoreline movement between determination of the Flood Insurance Rate Map (FIRM) lines and the overwash line, and differences in the FEMA shoreline and the State shoreline, there is some significant positioning inaccuracy. There are instances (see Wai-*mea*, Fig. 8) where the FEMA FIRM lines wander slightly offshore. These obvious errors have been retained in the maps as an example of the inherent inaccuracies in this type of mapping technique in a dynamic environment. We estimate a positioning accuracy of ± 50 m for areas where there are no reference points, such as roads, and a greater accuracy where such points exist. Also shown are still-water mark and debris-line elevations relative to the Hawaiian datum, mean lower low water (mllw). Original elevations (msl) are supplied by the U.S. Army Corps of Engineers, Pacific Ocean Division, Ft. Shafter, Honolulu (S. YAMAMOTO, pers. comm.).

Kekaha

Ten kilometers left of the eyewall, in Kekaha, maximum debris line and still-water level heights averaged 4.0-4.3 m (mllw) (Fig. 6). Damage from marine flooding, while relatively light with respect to other areas of the island, was related to high velocity overwash at the first and second line of houses in the vicinity of Oomano Point where overwash excursion distances exceeded 200 m. The overwash line falls within the 100-year flood zone, and had all buildings been elevated to the suggested AE and/or VE elevations, the level of damage would have been significantly reduced. Shore-normal streets acted as conduits for channelizing overwash, but these flows generally remained confined to the paved roads and did not cause sig-

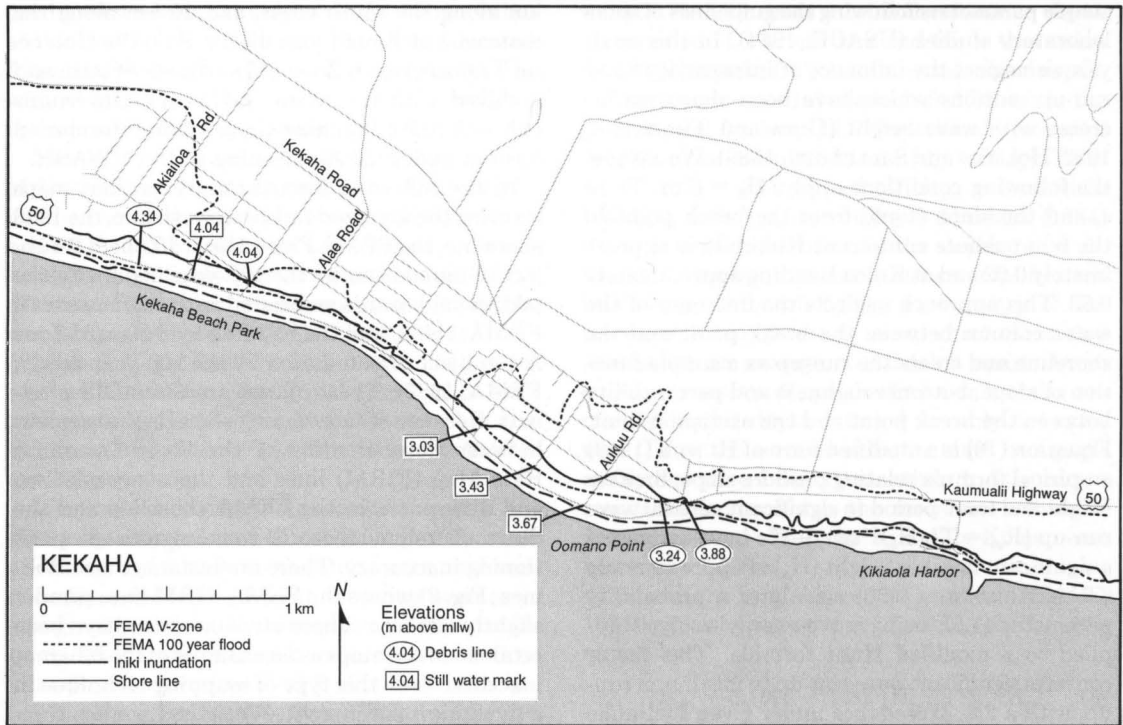


Figure 6. Overwash map of Kekaha (Map 1, in Figure 3).

nificant damage among dwellings away from the water front. Although the revetment along Kaunaulii Highway (coastal road) was overtopped by the flooding, apparently the wall was a significant factor in mitigating damage to much of Kekaha west of Oomano Point. The revetment, built to halt shoreline retreat and chronic erosion resulting from the updrift (east) construction of Kikiaola Harbor, effectively reduced both the volume and velocity of the overwash in the western and central portions of Kekaha. A history of shoreline erosion at rates of 0.15-0.6 m/yr since construction of the harbor in 1959 was an exacerbating factor in Kekaha. In many other overwash areas on Kaua'i, chronic historical erosion was a common preconditioning agent that maximized flood damage.

Waimea

In Waimea, lying along the path of the left eye wall, maximum overwash heights were in the range 2.8-3.0 m (mllw) (Fig. 7). Landward excursion of

the flooding was generally confined to the back beach and immediate areas (10-50 m from fair-weather water line). Marine flooding damaged the lower level of the first row of houses on the west bank of the Waimea River mouth where overwash excursions were greatest (~150 m). The highest measured overwash in Waimea occurred near the river, 3.09 m (mllw). Debris lines located below the top of an embankment revetment at the river mouth suggest that only minor overtopping occurred. Thus, flooding onto the low-lying coastal plain adjacent to the river was predominantly marine and did not contain any notable contribution from riverine discharge. It has been noted elsewhere that rainfall during Hurricane Iniki was generally below expected levels, and little actual river flooding occurred on Kaua'i. Precipitation at Lihue was approximately 2.3 cm and 3 cm at Princeville (TRAPP, 1993). The notable increase in marine excursion near the river was the result of the generally lower elevation around the mouth, rather than actual fluvial flooding.

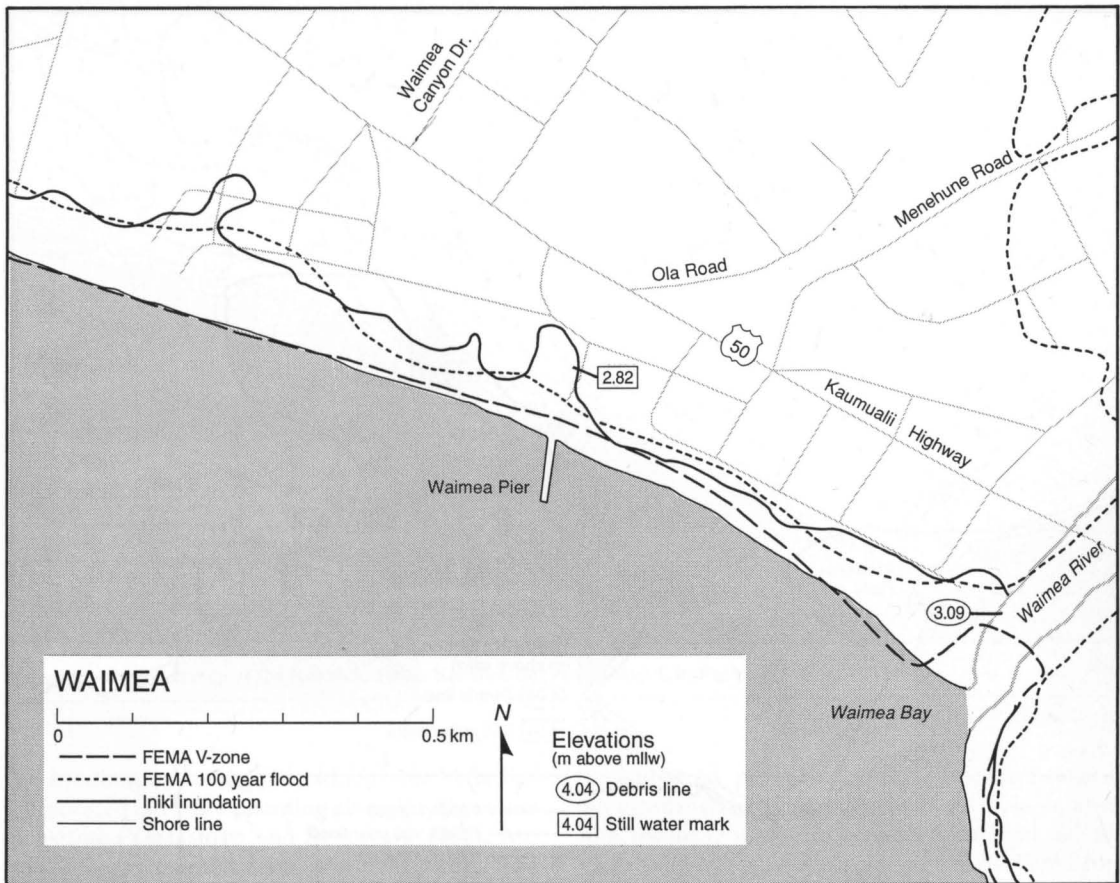


Figure 7. Overwash map of Waimea (Map 2, in Figure 3).

Hanapepe

Hanapepe, 4.5 km east of landfall at Kaunakani, experienced maximum overwash heights exceeding 2.8 m (mllw) in the city and 3.6 m (mllw) near Salt Pond to the west of the city (Fig. 8). The most extensively flooded area was on the low-lying fluvial floodplain east of the mouth of the Hanapepe River. Residents report Iniki overwash penetrated several hundred meters inland along this lowland, to the edge of the coastal highway (Rt. 50) where it crosses the river. The bridge there is a critical transportation link for communities in west Kaua'i and a determination should be made as to whether the bridge was at any point threatened by the overwash. This region falls within the FEMA 100-yr flood Zone A, but beyond the determination for the marine hazard Zone V.

Extensive damage to the coastal park in Hanapepe Bay occurred. A revetment became a source of large boulders that were carried in suspension by the overwash and destroyed park facilities including a bathing house and tennis court fencing. Soil erosion, evidenced by scarping of terrigenous deposits behind the revetment, led to high turbidity levels in the Bay and the adjacent coastal water to the west. Elevated turbidity levels remained for several weeks because of the exposure and erosion of formerly buried soil layers under beaches that experienced erosion during Iniki.

Kukuiula Bay to Keoniloa Bay

At Kukuiula, 16-17 km east of the eye at landfall, overwash debris lines and still-water marks around the Bay and in the fields to the east mea-

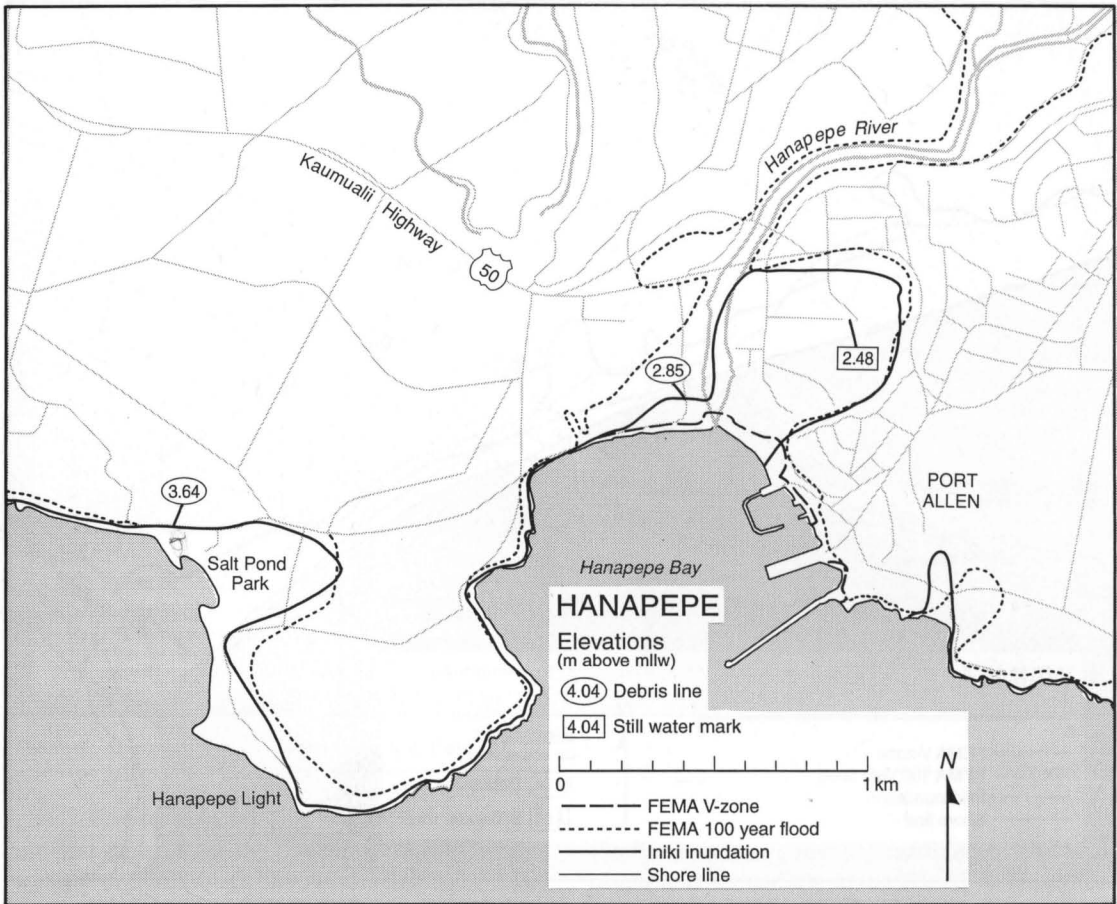


Figure 8. Overwash map of Hanapepe region (Map 3, in Figure 3).

sured 3.95-5.90 m (mllw) (Fig. 9). Because of the low relief, the gentle onshore gradient, and the absence of large offshore barriers (such as a barrier reef), this sector experienced a high degree of inland penetration by marine waters. Overwash was prevented where winds were highest (4-5 km west of Kukuiula Bay) because of extensive high coastal cliffs. Strong longshore currents directed east from RMW to the low-lying Kukuiula coast undoubtedly contributed to the overwash and maximized overwash elevation and excursion. The overwash passed through a line of coastal dwellings and seawalls, across a road and drainage ditch with a local relief of approximately 3-4 m and carried housing, agricultural, and coastal debris deep into the adjacent fields. Aerial photos of the resulting debris line, frequently more than 250 m

inland, have been widely published. These provide telling testimony to the power and destructive potential of overwash in the region (Fig. 10). The overwash slope was littered with large boulders, uprooted palms, sheets of sand, and the upper stories of wood frame houses that were swept inland after flood waters demolished lower floors (Fig. 11).

This reach of coast was devastated by Hurricane Iwa in 1982 and was the subject of numerical hindcasting under contract to the U.S. Army Corps of Engineers in 1986 (SEA ENGINEERING and BR-ETSCHNEIDER, 1986). That work reports on scenario models that accurately predict the overwash expected during an Iniki-type storm (their "worst-case scenario"). One lesson learned by this experience is the high level of reliability provided

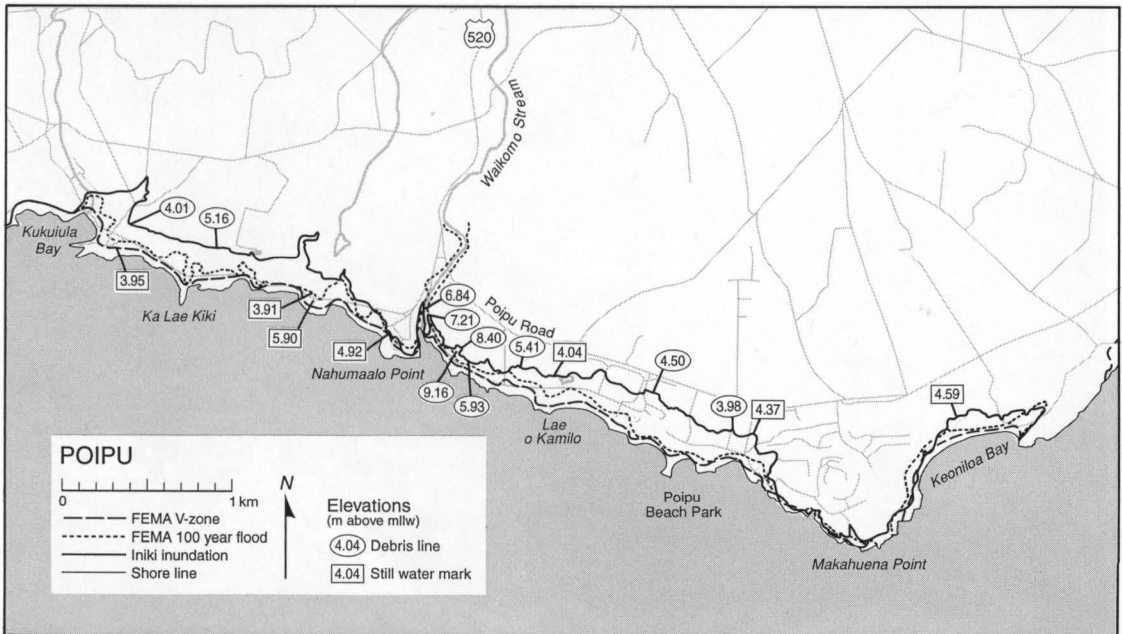


Figure 9. Overwash map of the Kukuiula-Poipu-Keoniloa Bay coast (Map 4, in Figure 3).

by hindcasting techniques which should be incorporated in future planning along the Hawaiian coastline (YAMAMOTO and SULLIVAN, 1993). Another lesson learned from overwash during Iwa and Iniki is that the coastal developments around and east of Kukuiula Bay are vulnerable to marine flooding and will sustain massive damage from hurricanes that approach from the south. Despite the obvious consequences, rebuilding activity proceeds unabated along the water's edge in this sector.

The overwash line runs well inland of coastal developments between Kukuiula Bay and Nahumaalo Point. Single family dwellings, multi-unit condominium structures, and resort hotels were all subjected to high-velocity marine flow. A double debris line in places (Fig. 12), suggests that the overwash occurred in waves and that structures were subjected to multiple episodes of flooding in a short period of time. Low-lying streambeds and other natural drainage features and depressions contained abundant overwash debris, suggesting that flooding was redirected and enhanced by local relief. Several low-lying regions, some over 100 m from the coast, contained extensive ponded sea water and were clogged with

housing and pavement debris. Pocket beaches along this coast experienced severe erosion, and the resulting exposure of underlying soil led to high levels of coastal turbidity that persisted for over a month after the hurricane. Beach accretion has been slow to rebury outcropping paleosols and many sections of beach remain in an eroded state and have not fully recovered from the effects of Iniki a year later. Subsequent minor storms and high waves enhance the erosion of these soils. The first year following Iniki has been characterized by degraded coastal water quality as a result. Although it is not possible to determine if there was pre-existing ecosystem degradation, the prolonged turbidity in the Kukuiula to Poipu coastal zone may be responsible for some shallow-water coral mortality and algal growth (FLETCHER et al., 1993).

Because of the intensity and extent of overwash in this sector a number of structures sustained massive damage from high-velocity flooding, breaking wave forces, foundation scour and undermining, and battering by suspended debris in the water column. There are field reports of hydraulic buckling of cement slab-type foundations, and examples of damage from large boulders and

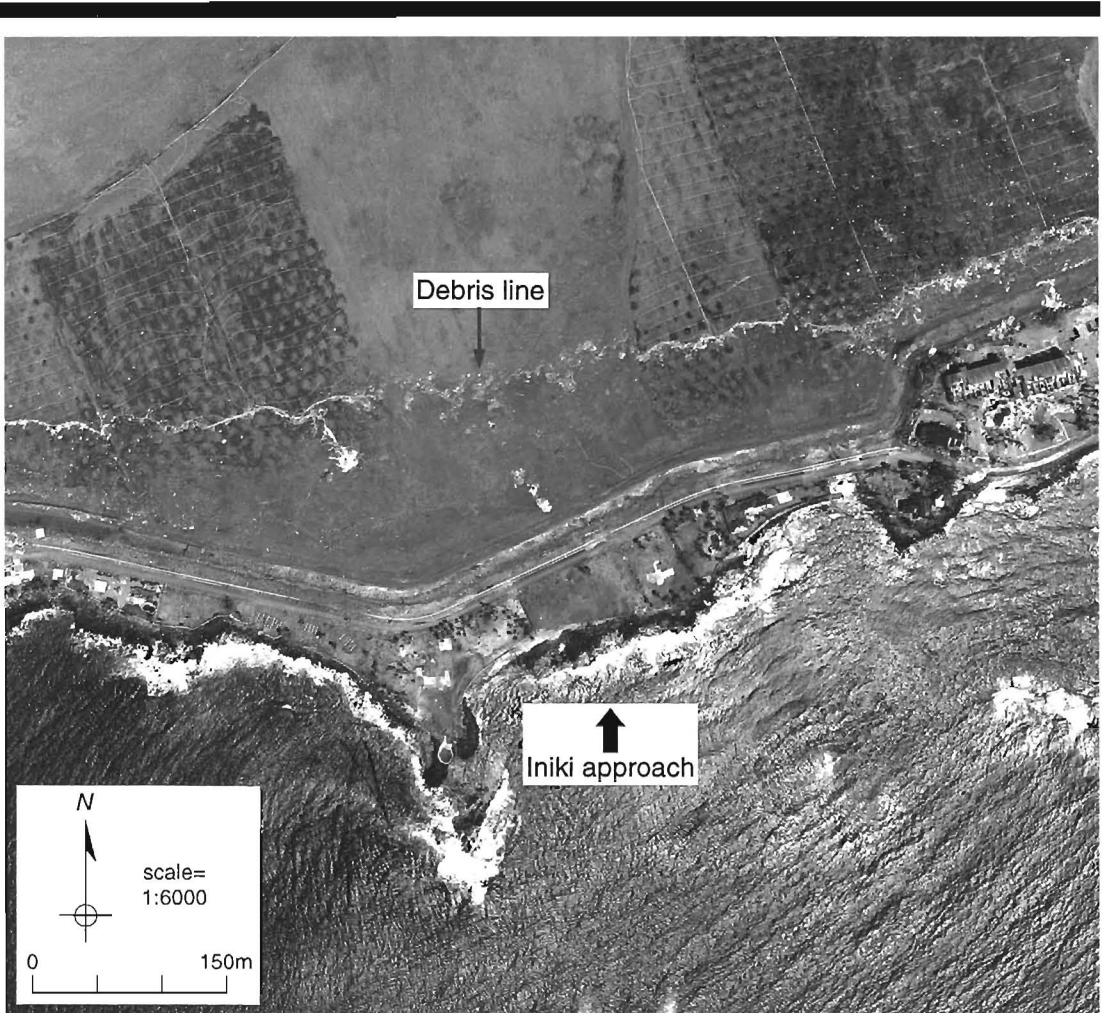


Figure 10. Overwash debris line in the agricultural fields east of Pukuiula Bay, located landward of Ka Lae Kiki Peninsula in Figure 9.

paving stone suspended in the flow literally battering down walls. At Poipu Beach Park, coconut trees bear impact scars to a height of 1.8 m above ground level. Smaller structures were frequently swept off their foundations and either floated inland, or experienced destruction of the lower floors while upper floors and roofs survived to be deposited some distance inland. Residents at Nahumaalo Point report that wave spray against the headland overtopped three-story structures, and had sufficient velocity to break windows and damage roofing materials at elevations of ~ 30 m (mllw).

The highest elevation of overwash evidence, a debris line behind a small dwelling, was discovered by surveyors from the U.S. Army Corps of Engineers (S. YAMAMOTO, pers. comm.). This was in the area immediately east of Koloa Landing. The configuration of the coast and bathymetry there apparently led to maximum run-up and breaking wave heights, and amplification of storm surge components. Debris on the road at the head of the boat ramp at Koloa measured 7.21 m (mllw). To the east, the maximum debris line was measured at 9.16 m (mllw). Nearby, at an elevation of ~ 6 m was an overwash debris line consisting



Figure 11. Overwash debris, and second and third stories of coastal dwellings located 10-50 m from their foundations. Located between Kukuilua Bay and Ka Lae Kiki Peninsula in Figure 9.

of stone blocks weighing several hundred pounds, and large household appliances.

Toward the Poipu coast the overwash line meanders inland behind townhouse and condominium developments, and the several resort hotels, staying in the elevation range between 4-4.5 m (mllw). Large ponds of brackish water mark upland areas where return flow collected in local basins. In one parking lot, two automobiles, one

a mini-van, were vertically stacked atop one another by the overwash.

On Makahuena Point, a headland with a coastal elevation exceeding 6 m, the development is sufficiently set-back, and the protection afforded by the cliffs sufficiently effective, that little overwash damage occurred. That portion of the headland composed of carbonate sandstone (aeolianite) did experience some hydraulic undermining from wave action. This was also noted across Keoniloa Bay



Figure 12. A double debris line, suggesting multiple overwash near Kukuia Harbor. Located between Kukuia Bay and Ka Lae Kiki Peninsula in Figure 9.

at Makawehi Point, another limestone headland. While no slumping was observed on basaltic coasts, there was overhang collapse and slumping along many sectors of limestone shore, demonstrating that a hazard is associated with development on these sites.

Kapaa

The highest washover debris on the east coast of Kauai, in and near the town of Kapaa, was 4.22 m (mllw), but debris lines averaged approximately 2.5-3.5 m (mllw) (Fig. 13). Because the Kapaa coast is oriented north-south, the winds of Iniki did not blow directly onshore for sustained periods, and the additional translation speed of the storm did not exacerbate the overwash. The coastal orientation was oblique to most of the surge components. Also, waves generated by Iniki had to refract around the south coast of the island before striking the Kapaa shoreline. As a result, breaking wave heights were in the range 3-5 m. Kapaa generally did not experience extreme overwash. Nonetheless, there were pockets of extensive damage in the first row of houses on coasts with a history of chronic erosion. One of these, the Waipouli neighborhood, suffered overwash damage as a result of crowded shoreline development, low-grade housing lacking the minimum elevation suggested by FEMA flood maps, and a condition of pre-existing erosion.

SUMMARY

Hurricane Iniki, the fifth most costly insured catastrophe in U.S. history and the worst storm ever recorded in Hawai'i, produced extensive marine flooding on the south coast of Kaua'i with a maximum elevation of 9.16 m (mllw). Washover debris line and still-water mark elevations were more commonly in the range ~2-5 m (mllw). An estimation analysis of wind speed suggests a stationary velocity of approximately 41 m/s at a radius of 12 km and an average translation speed of 11.4 ± 2 m/s for a maximum sustained velocity of 52.4 ± 2 m/s. Maximum overwash was located under the right frontal quadrant of the storm in the Kukuiula Bay to Keoniloa Bay region of southeast Kaua'i. Overwash was partially a result of coincident storm surge and astronomical high tide producing a combined height of 1.89 m (mllw).

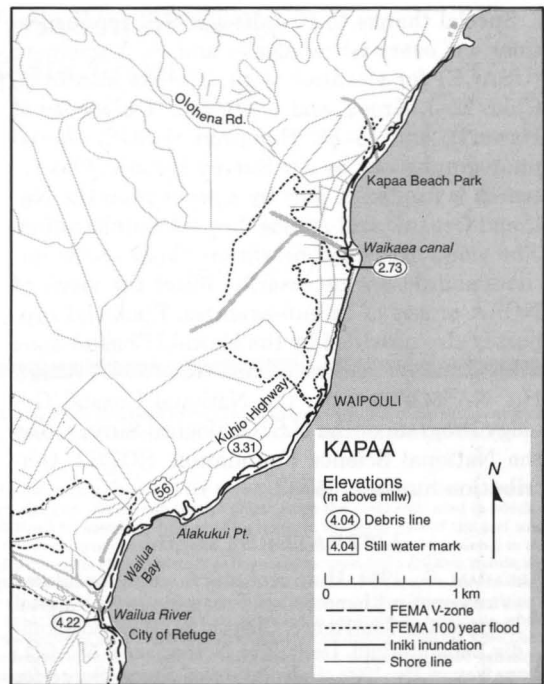


Figure 13. Overwash map of Kapaa (Map 5, in Figure 3).

Wave set-up under significant breaking wave heights of approximately 6 m equaled roughly 1 m, and run-up, dependent upon slope and permeability, varied between approximately 2.9 m and 4.3 m. Bathymetric and topographic factors apparently influenced overwash heights by controlling nearshore water movements and wave characteristics.

Overwash patterns were controlled by natural factors and anthropogenic influences. The overwash hazard is mitigated by a gentle offshore slope, natural roughness of the coastal zone, well-engineered and sufficiently large coastal armaments, and the presence of offshore topographic barriers such as a barrier reef and submerged headlands and rocky outcrops. The wave hazard is exacerbated by a steep offshore slope, a featureless bathymetry, the initial water set-up, a history of chronic erosion, poorly engineered coastal structures that may become heavy projectiles in the overwash field, and the pressure and wind stress set-up. Features that mitigate the wave environment under incident hurricane-force winds should be evaluated in coastal zone management decisions.

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