# A Modern Coastal Erosion Investigation: Kapa‘a Beach, Kaua‘i

## Hawaiian Islands

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***Abstract*—Sea Engineering, Inc. conducted a detailed 14-month study to investigate sand transport processes and beach erosion at Kapa‘a Beach and develop beach improvement alternatives. The study consisted of the following key components: evaluation of sand transport mechanisms and processes acting along the shoreline at Kapa‘a; identification of potential beach material borrow sites and available volumes through a geophysical investigation of offshore sand deposits; development of computational wave and circulation models for nearshore Kapa‘a Beach using advanced numerical modeling and visualization software; and, development of coastal engineering improvement concepts for mitigation of beach loss and shoreline retreat at Kapa‘a Beach.**

***Keywords - erosion; Hawaii; nearshore circulation; Kapaa; shore protection***

## I. Introduction

Kapa‘a is located on the windward shore of Kaua‘i Island, State of Hawai‘i (Fig. 1). The Kapa’a Beach shoreline has a history of beach erosion and shoreline retreat. Portions of the shoreline have required hardening with protective structures such as seawalls and revetments in order to preserve backshore properties. The most noticeable feature is a grouted rock seawall which was built along roughly 700 feet of shoreline to stabilize the eroding embankment fronting the Pono Kai Resort on the portion of Kapa‘a Beach just north of Waika‘ea Canal (see Fig. 2). The existing seawall was constructed in 1993, following erosion and damage by Hurricane Iniki of the pre-existing original wall. A smaller, non-engineered riprap revetment about 150 feet long has been built along the shoreline about 300 feet south of Mo‘ikeha Canal. At higher tides, no dry beach exists in front of either of these structures. Additionally, north of Mo‘ikeha Canal (top of Fig. 2), a 900-foot long revetment was constructed in 1964 in response to severe erosion. This beach loss was likely due to the dredging of a nearshore borrow pit directly offshore of this location, and which is now observed to be partially filled with sand.

Sea Engineering was tasked by the County of Kaua‘i to conduct a beach coastal processes study and erosion evaluation along the Kapa‘a Beach Park shoreline.

### A. Project Location

Kapa‘a Beach Park is located on the windward shore of Kaua‘i, where the shoreline consists of a calcareous sand beach approximately 1,830 m (6,000-feet) long, interrupted by the hardened entrances of Waika‘ea and Mo‘ikeha Canals. The project area was specifically defined as the portion of Kapa‘a Beach Park bounded by the two canals (see Fig. 2).

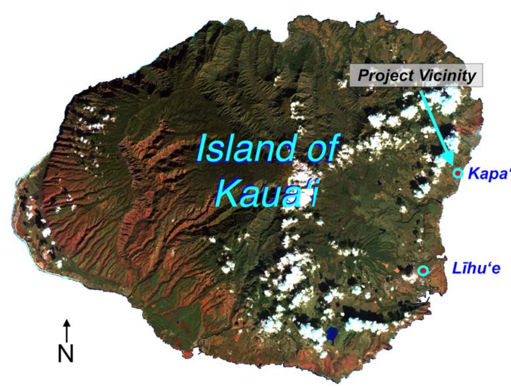


*Figure 1.* Project Vicinity Map for Kapa’a Beach.

### B. Project Objectives

The focus of this study is beach erosion and sand transport processes within the portion of Kapa‘a beach bounded by Waika‘ea Canal to the south and Mo‘ikeha Canal to the north. Data collection and analysis were extended beyond these bounds, as required, to adequately characterize coastal processes which affect conditions within. Specific objectives of the study included the following items:

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1. Evaluation of sand transport mechanisms and processes along the shoreline within the study area,
2. Identification of possible beach material borrow sites through a geophysical investigation of offshore sand deposits, and estimation of quantities of sand sources for use as beach nourishment at the project site,
3. Development of a wave and circulation model for Kapaʻa Beach using modern oceanographic modeling software which adequately predicts nearshore current patterns,
4. Development of coastal engineering improvement alternatives for mitigation of beach loss and shoreline retreat at Kapaʻa Beach.

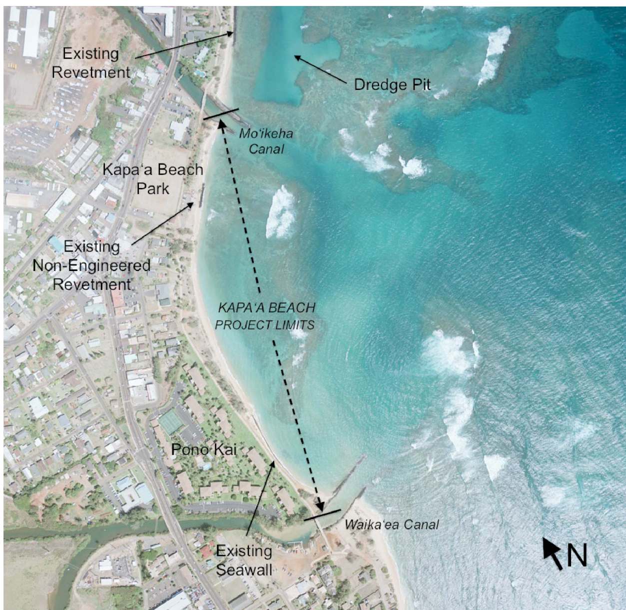


*Figure 2.* Project Site Map for Kapaʻa.

## II. Background

The primary forces driving shoreline change and sand transport along most Hawaiian beaches, including Kapaʻa Beach, are waves and wave induced currents. In the US Mainland, where beaches are typified by uninterrupted reaches where bottom topography is gradual and fairly constant across the beach, longshore currents are the dominant transport mechanism. In contrast, areas where the seafloor is primarily hard bottom, such as Hawaiʻi, the nearshore bathymetry typically dictates the path of the currents. Here, current flow from wave setup is channeled and steered by the terrain as it returns seaward through channels in the reef, rocky troughs and around shoals.

Tidal ranges in Hawaiʻi are a little over 3 feet, producing relatively minor nearshore effects. Waves are known to be the dominant force influencing nearshore currents, circulation, and beach processes in Hawaiʻi, and so this study concentrated on the measurement and characterization of local wave processes including wave induced currents, and physical measurement of beach response to wave conditions along the shoreline.

Primary tasks of this study included the following elements: (1) Recurring beach profiles along 18 established transects over a one year duration; (2) Measurement of waves and currents through *in situ* instrument deployments; (3) Offshore geophysical surveys along with diver jet probing at selected locations; (4) Numerical wave modeling of wave driven currents developed over the complex reef structure; and, (5) Development of appropriate shoreline protection improvement alternatives.

## III. Methodology & Procedures

### *A. Beach Surveys*

Survey work included 18 beach profiles along Kapaʻa Beach, spaced roughly 100 m (330 ft) apart. These profiles were re-surveyed approximately every two months for the project duration. A total of six beach profile surveys of the 18 transects were conducted over the project duration.

Beach profile surveying was completed using real time kinematic (RTK) GPS survey equipment. Profiles were measured to record any breaks in slope, berms, beach toe, and any other significant beach features encountered in the field. In addition to beach profiles, sand samples were obtained at each transect location just above the swash zone.

### *B. Wave and Current Measurements*

The wave and current measurement program for Kapaʻa was separated into two basic elements, an offshore monitoring location to measure conditions continuously over one year, and a series of nearshore monitoring stations used to observe the seasonal responses during three-month deployments in the winter and summer seasons. The following sections discuss the details for each component.

#### *1) Offshore Monitoring Station*

The offshore monitoring station was located approximately 1.16 km (0.72 mi) offshore from Kapaʻa Beach at a water depth of 12.2 m (40 ft), as shown in Fig. 3. This location allowed measurement of transitional depth waves as they begin to be transformed by shallow water, as well as regional tidal currents, and local wave driven currents. The offshore monitoring station, identified as 'Offshore ADCP', was occupied with a 600 kHz Teledyne RD Instruments acoustic Doppler current profiler (ADCP) with directional wave measurement capability.

The deep water ADCP measured three-dimensional current profiles using a 50 cm (1.6 ft) cell size (vertical bin size) at 20 minute intervals, and directional wave energy spectra at an hourly interval. The ADCP was attached to a deployable base mount and weighted to the bottom with lead and further secured with rock bolts.


*Figure 3.* Oceanographic Monitoring Station Locations

*2) Inshore and Nearshore Monitoring Stations*

The inshore and nearshore station locations were chosen to best characterize nearshore circulation patterns and current response to incident wave conditions recorded at the offshore gage. These instruments were deployed for three month intervals during the winter and summer. Their specific locations are shown in Fig. 3. The instrumentation consisted of a 2000 kHz Nortek Aquadop ADCP with directional wave measurement capabilities, and two single-point 640 kHz Greyline ultrasonic acoustic Doppler current meters. The ADCP was deployed in the channel just offshore of the inner fringing reef at Kapa‘a, and identified as ‘Inshore ADCP’. The ADCP deployment site was roughly 200 m (660 ft) from the shoreline in approximately 10 m (33 ft) of water. The single-point current meters were deployed at locations roughly 50 m (164 ft) from the shoreline in approximately 1 m (3 ft) of water on the broad reef shelf complexes to the north and south of Kapa‘a Beach Park. The gages were rock-bolted into hard substrate for stability. Locations for these gages are shown as ‘North Current Meter’ and ‘South Current Meter’ in Fig. 3.

*3) Drogues*

In order to track nearshore current patterns over the shallow reef, shore break, and swash zone areas at Kapa‘a Beach, custom fabricated GPS-based current drogues were employed. Drogues were released nearshore and monitored for movement; if movement was too rapid and they were in danger of becoming swept out to sea in the strong channel current, they were recovered and redeployed inside the reef.

*C. Offshore Sand Deposit Mapping*

A detailed effort was conducted to map and characterize possible submerged sand deposits offshore of Kapa‘a Beach, utilizing geophysical marine survey technologies for seafloor mapping, along with divers used for manual sampling of targeted sand deposits. The task was subdivided into the following: side scan sonar survey, sub-bottom profile survey, and diver jet-probing and sand sample collection.

*1) Side Scan Sonar Survey*

The side scan sonar survey was completed utilizing a C-Max CM2 towfish, with dual frequencies (325/780 kHz), and positioning was accomplished with a Trimble SPS 461 differential GPS receiver and KVH heading sensor. All data were collected in ‘high-resolution’ mode utilizing the 780 kHz frequency for the best possible image of the seafloor. The swath data produced by the side scan sonar were logged using the C-max MaxView software. Multiple survey lines were completed to collect the swath data in several directions, in order to acoustically ‘illuminate’ the seafloor features from various angles. The side scan sonar survey was conducted at Kapa‘a on 22 February 2011, on the 74 ft survey vessel *Huki Pono*.

*2) Sub-Bottom Profile Survey*

For this survey, an EdgeTech 0512i “chirp” sub-bottom profiler was used with an EdgeTech 3200XS processing system. The EdgeTech 0512i system is in fact a specialty system designed for use in coarse coralline sand environments. Different sonar pulses are available with the system for use in different bottom types. After on-site system deployment, trial survey lines were conducted using various pulse configurations. The optimal pulse for the seafloor substrate around Kapa‘a was found to be a 20 millisecond pulse with a frequency range of 0.5 kHz to 7 kHz. This is a relatively low frequency range, but necessary for penetration into the coralline limestone sands and gravels found in Hawai‘i. The sub-bottom survey was conducted at Kapa‘a on 21 February 2011, on the 74 ft survey vessel *Huki Pono*.

*3) Diver Jet-Probing and Sampling*

Potential nearshore sand deposits identified during the geophysical surveys were used to target areas for diver investigation by jet probing. Jet probing was conducted along four separate transects at Kapa‘a, all within the nearshore basin formed by the confluence of Mo‘ikeha and Waika‘ea Canals. Probes were conducted at 15 m (50 ft) intervals along the transects, which were located utilizing differential GPS navigation. A 2.4 m (8 ft) stainless steel air-jet probe with portable air supply was used for the investigation. Fig. 4 is a photograph of an SEI diver jet-probing at the inshore basin at Kapa‘a.

Sand samples were collected along each profile from approximately one-third to one-half meter below the bed surface. The samples were then sent for laboratory analysis of grain size distribution. Additionally, divers excavated small pits up to 1 m (3.3 ft) deep along each profile to assess visual signs of organic material content (seen as dark cloudy plume if present) or significant fraction of fines (seen as light-colored plume if present). This step was important, because in Hawai'i, submerged sands in certain environments, typically low energy environments, tend to accrue a dark layer of anoxic organic material just inches below the surface, tainting these sands with an unpleasing odor and discolored appearance, essentially rendering them unusable as beach nourishment material.

*Figure 4.* Diver Jet-probing at Kapa'a.

### *D. Numerical Wave and Circulation Modeling*

As open ocean waves approach and propagate over the fringing reefs of Hawai'i, they are extensively transformed due to various factors. To best characterize this complex transformation at Kapa'a, and the wave generated currents nearshore, a numerical modeling analysis was conducted. The models selected for this analysis were developed by the Coastal and Hydraulics Laboratory of the U.S. Army Corps of Engineers (USACE) and packaged for commercial use through Aquaveo's Surface Water Modeling System (SMS 11.0), and included BOUSS-2D for wave modeling, and CMS Wave and CMS Flow for wave driven current modeling.

#### *1) Wave Model: BOUSS-2D*

BOUSS-2D simulates the propagation and transformation of waves in coastal regions and harbors based on a time-domain solution of Boussinesq-type equations. The governing equations are uniformly valid from deep to shallow water and can simulate most of the phenomena of interest in the nearshore zone, including shoaling and refraction over variable bathymetry, reflection and diffraction near structures or land formations, energy dissipation due to wave breaking and bottom friction, cross-spectral energy transfer due to nonlinear wave-wave interactions, and wave interaction with porous structures such as riprap jetties or revetments.

The phase-resolving BOUSS-2D model was appropriate for this study due to its capability of realistically modeling complicated wave transformation patterns over complicated submerged obstacles such as coral reefs. The model simulations were forced with wave conditions measured at station "Offshore ADCP".

#### *2) Circulation Model: CMS-Flow and CMS-Wave*

The hydrodynamic circulation model CMS-Flow is a component of the Coastal Modeling System developed by the US Army Corps of Engineers Coastal and Hydraulics Laboratory. CMS-Flow is a two-dimensional, finite-difference numerical approximation of the depth-integrated continuity and momentum equations. The model simulates currents, water level, sediment transport, and morphology in the coastal zone. CMS-Wave, also a component of the Coastal Modeling System, is a two-dimensional, phase-averaged, wave spectral transformation model that employs a forward-marching, finite-difference method to solve the wave action conservation equation.

Because wave conditions affect currents, the currents produced can then affect the waves themselves. The strength of the CMS models for this project is their capability for coupling results from one model to the other, sometimes known as 'steering'. This interaction means that for every time step in the simulation, the wave model can pass calculated wave height and other parameters to the flow model for its calculations, which in turn can pass back wave-induced current data to the wave model, enabling a direct solution for a seemingly difficult iterative process. The simulations for Kapa'a were driven with wave parameters measured at station "Offshore ADCP", and validated with current data from all the current meters. Cases were modeled for the most common conditions observed as well as the most common maximum condition.

## IV. Results

### *A. Beach Surveys*

#### *1) Beach Profile Results*

Beach profiles were conducted at 18 individual transects along Kapa'a Beach from September 2010 through September 2011. Example profile results are presented in Fig. 5. In general, the collection of plots indicate that beach shape is fairly consistent throughout the year at each of the locations. Beach slope ranged from (1V:14H) to (1V:5H) for the survey area, however the slope was consistently 1:5 between Waika'ea and Mo'ikeha Canals except for profiles which were adjacent to or over the seawall fronting Pono Kai Condominiums. The relative steepness of the beach here indicates that this region is exposed to increased wave energy compared to the rest of the survey area. These findings suggest a reasonably energetic wave environment for this section of beach.

Typically, beaches that are exposed to open ocean swells have a seasonal response to wave energy, with beach material migrating southward in the winter and then reversing to the north in the summer. Profile results indicate that this is not the case at Kapa‘a, and further suggest that the broad fringing reef complex effectively shelters the shoreline from most wave energy, and filters essentially all wave directions to shore-normal by the time they reach the beach.

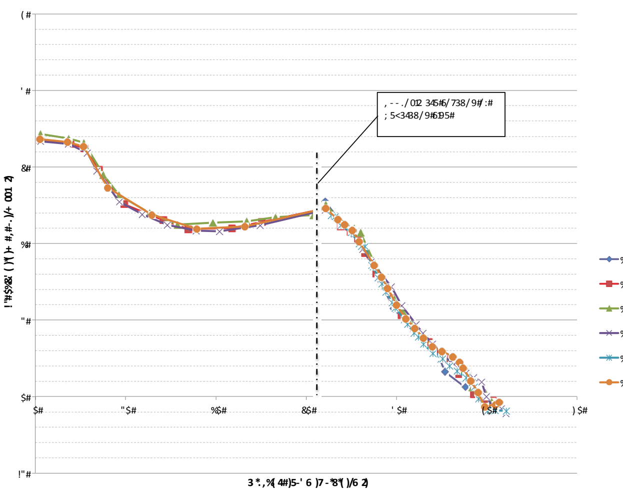

*Figure 5.* An Example Beach Profile, at Station K-2.

Beach profile data were used to calculate estimated cross section volumes for all surveys. Results revealed a net average erosion rate of 1 $m^3$ per meter length of beach between September 2010 and November 2010, a net average accretion of 0.65 $m^3/m$ between November 2010 and January 2011, a net average accretion of 0.33 $m^3/m$ between January 2011 and March 2011, a net average accretion of 0.05 $m^3/m$ between March 2011 and June 2011, and a net average erosion of 2.59 $m^3/m$ between June 2011 and October 2011. Overall, the volume changes show a relatively mild degree of beach change during the course of this study, with no evidence of seasonal fluctuations. The profile plot in Fig. 5 is representative of most locations, where the beach profile is consistent throughout the year.

An exception to the beach’s general stability are those areas adjacent to hardened structures, where volume changes were occasionally two to three times greater than other profiles and as much as ten times greater in the case of the profile on the north side of Waika‘ea Canal. This profile is adjacent to both the north jetty at Waika‘ea Canal as well as the south end of the seawall at Pono Kai. The location is of particular interest because the beach profile was very consistent here until the October 2011 survey, when a dramatic amount of beach loss was observed. Since no significant accretion was recorded elsewhere along the beach, it must be assumed that the sand was lost offshore.

Collectively, the profile data suggest that erosion along Kapa‘a Beach is both episodic (significant amount occurring in a discrete event), as well as a slow and steady loss which may not be discernable over a year but compounds over many years or even decades. Importantly, it also implies that the existing hardened shoreline structures may be having a negative effect on beach stability at Kapa‘a.

*2) Beach Grain Size Distribution Data*

Results from the laboratory sieve tests indicated that the sand from Kapa‘a Beach was generally a well-sorted sand (grain size is fairly consistent), with an average 40/60 mix of medium to fine grade sands. A combined plot of grain size distributions for all profiles is presented in Fig. 6, along with the USCS (Unified Soil Classification System) classifications labeled for reference. No significant fraction of fines (silts or clays) were present in any samples.

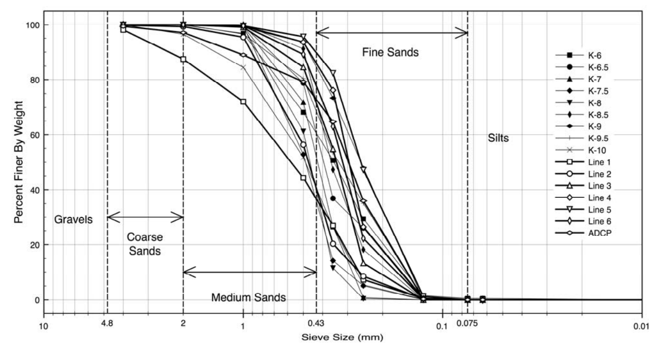


*Figure 6.* Grain Size Distribution for Kapa’a Beach & Offshore Profiles.

## *B. Wave and Current Measurements*

*1) Offshore ADCP Station*

*a) Waves*

Significant wave height ($H_s$), peak direction ($D_p$), and peak period ($T_p$) were measured at the offshore Kapa‘a ADCP station at hourly intervals for one year. The data indicate that a large majority of deepwater wave energy is either filtered or refracted to a nearly shore-normal direction by the time it has reached the station location at a water depth of 12 m (40 ft), with 75% of waves in the 40° wide band between 60° and 100° north. Comparison with deep water buoy data indicate that waves from the northwest that typify the energetic winter wave climate in Hawai‘i are absent at Kapa‘a. The most common wave condition at this location was a significant wave height of 1.2 m (4 ft) with a peak period of 10 seconds from 80° north. The average ‘episodic’ wave condition, defined here as the average of the maximum significant wave heights from the ten largest swell events recorded, was a wave height of 2.5 m (8.2 ft) with a period of 12 seconds from 80° north. The maximum observed condition was a significant wave height of 3.27 m (10.7 ft) with a period of 9.4 seconds from 77° north which occurred on 03 December, 2010. An example wave rose plot is provided in Fig. 7.

In addition to the wave rose plots, a wave parameter time series plot was constructed for the Offshore ADCP Station, which illustrates the relationship between incoming deep water wave conditions (recorded at CDIP Buoys 098 and 106), with the project site wave conditions offshore of Kapaʻa. In these plots, the significant wave height at Kapaʻa is represented by a heavy blue line with grey fill, and significant wave height at Waimea (106) in magenta and Mokapu (098) in brown. Wave direction at Kapaʻa is shown in green and wave period in grey.

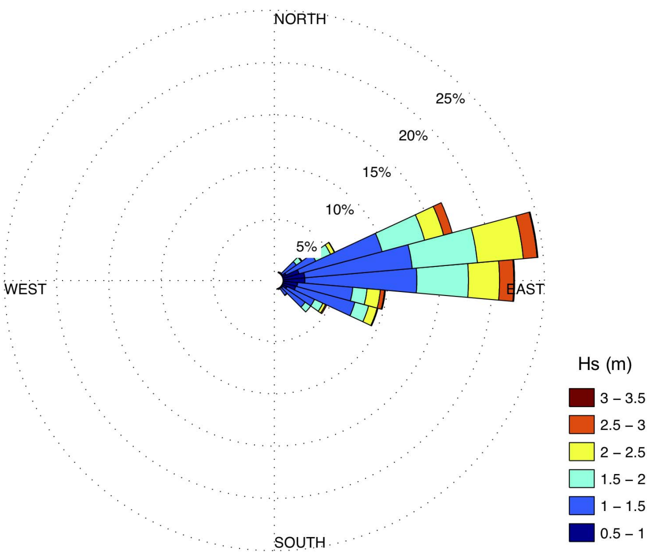


*Figure 7.* Wave Height Rose Plot for Offshore ADCP.

The relationship between deep water wave conditions and the resulting conditions offshore of Kapaʻa is typified in Fig. 8 which shows that the largest wave episodes experienced at Kapaʻa are from the east (090°) and are short period at 8 to 12 seconds, and that large northwest swells (25 Sept., 20 Oct., 02 Nov., 21 Dec. 2010) typically resulted in no increase at Kapaʻa. The large north swell events are highlighted for the reader by red dashed lines on the plot.

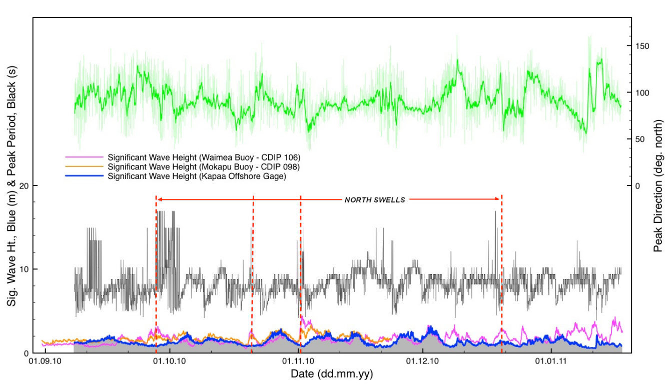


*Figure 8.* Offshore Wave Height Comparison.

The relationship displayed in this plot implies that tradewind generated wind swell is the primary source of wave energy at this location, with minimal wrapping of energy from typical winter north swells.

*b) Currents*

Current direction and magnitude were measured at the offshore Kapaʻa ADCP station at 20-minute intervals for one year, using 50 cm (1.6 ft) depth cells for a total of 20 cells in the profile. The overall average current speed for all deployments (14 months) was 0.15 m/s (0.49 ft/s), and the maximum observed velocity was 0.958 m/s (3.14 ft/s).

Results indicate that the bottom two-thirds of the water column is dominated by a reciprocating north-south flow driven by tidal forces, averaging approximately 0.20 m/s (0.66 ft/s) and typically 0.5 m/s (1.64 ft/s) at the upper limit. This finding is in agreement with research compiled by the School of Ocean and Earth Sciences and Technology (SOEST) at the University of Hawaii, which found that tidal currents on the east shore of Kauaʻi were typically between 0.25 and 0.40 m/s[1] (0.82 to 1.31 ft/s) in the N-S direction. The upper third (surface layer) of the water column experiences the tidal N-S flow, plus a well defined flow west to east. The eastward flow includes the highest observed velocities in the dataset ranging up to 0.958 m/s (3.14 ft/s), which is likely due to wave generated rip currents flowing out to sea through the Kapaʻa Channel. The phenomenon is illustrated in Fig. 9, where directions are given as ʻcoming fromʼ. The mid-depth layer shows traces of this eastward flow, while the near bottom layer has no evidence of it.

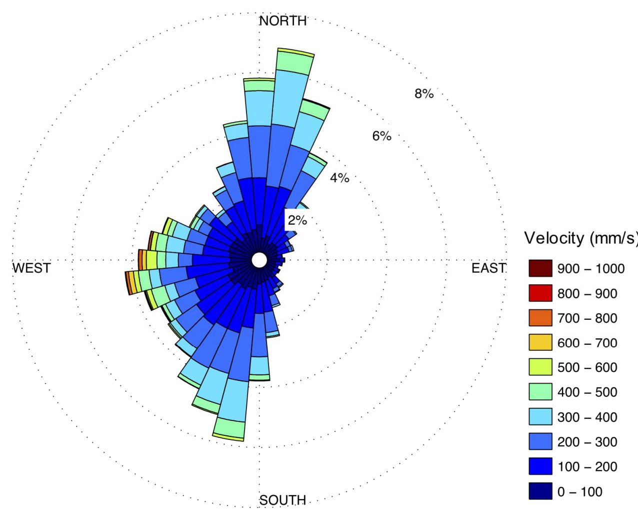


*Figure 9.* Offshore Surface Current Rose Plot.

### 2) *Inshore ADCP Station*

*a) Waves*

Wave parameters were measured at the inshore Kapaʻa ADCP station at an hourly interval for one year. The

[1] *Information excerpted from the UH Manoa website at http://www.soest.hawaii.edu/hioos/oceanatlas/tides.htm.*

instrument was deployed in the inner channel basin in approximately 10 m (33 ft) of water, directly offshore of the inner fringing reef that rises sharply landward to depths less that 1 m (3 ft). The wave data indicate that all incoming wave energy is refracted to shore normal orientation by the time it propagates to this location, with $H_s$ typically 33% smaller when compared with the Offshore gage.

*b) Currents*

Current direction and magnitude were measured at the inshore Kapaʻa ADCP station at 20-minute intervals for two deployments of approximately three months each, using 50 cm (1.6 ft) depth cells with 15 cells in the profile. The data clearly indicate a unidirectional flow regime, where currents are always flowing from north to south. Current velocities averaged from 0.16 to 0.22 m/s (0.52 to 0.72 ft/s) near the bottom and 0.3 m/s (0.98 ft/s) near the surface. The maximum measured velocity was 1.05 m/s (3.44 ft/s), recorded in the surface layer on 19 May 2011.

The unidirectionality and comparatively high current magnitudes at this location are the result of wave setup on the broad, shallow reef complex to the north. This condition forces a rip current to flow from north to south into the main Kapaʻa Channel and then out to sea. The tradewinds, which are responsible for generating the vast majority of wave energy observed at Kapaʻa, are persistent throughout much of the year, as are the rip currents flowing out the channel. The relation between waves and currents at this location is clearly illustrated in Fig. 10 which indicates that current velocity is directly dependent on wave height. No tidal influence was observed.

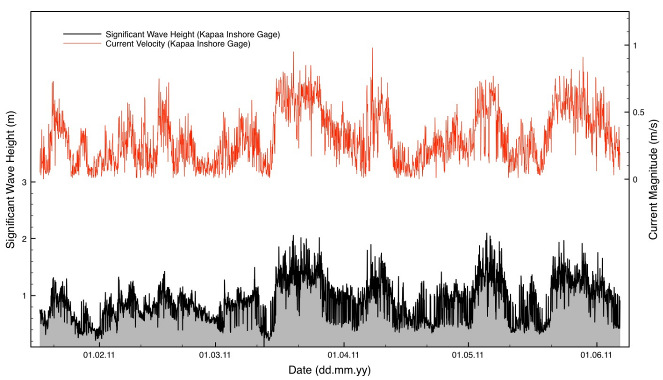


*Figure 10.* Inshore Surface Current with $H_s$.

*3) Nearshore Current Meters*

One dimensional, single-point current meters were deployed north of Moʻikeha Canal and south of Waikaʻea Canal. The meters were configured to record current velocity along a shore-parallel axis (bounded by the shoreline), with southward flow being positive and northward negative at the North Current Meter station, and reversed for the South Current Meter station. The north current meter recorded currents from 19 January to 22 February, 2011, while the south current meter was unrecoverable.

Results from the north current meter indicated no reversal of flow direction during the entire period of observation. Average velocity for the dataset was 0.25 m/s (0.82 ft/s), and the maximum observed current velocity at this location was 1.29 m/s (4.23 ft/s), which was recorded 06 February, 2011. Statistical analysis shows that the 'micro-longshore' current is between 0.10 and 0.40 m/s (0.33 – 1.3 ft/s) for approximately 90% of the time, and greater than 0.50 m/s (1.64 ft/s) approximately 5% of the time. Micro-longshore currents exceed 1.25 m/s (4.1 ft/s) 1% of the time.

*C. Offshore Sand Deposit Mapping*

The side scan sonar survey at Kapa'a covered an area of approximately 5.7 $km^2$ (2.21 $mi^2$), centered on the Kapaʻa Channel. The survey area contained depths ranging from over 70 m (230 ft) offshore to less than 3 m (10 ft) inshore. Shallow area coverage was limited by safe navigability of the survey vessel. The prominent feature in the survey area is a broad sand channel which cuts through the reef (see Fig. 11 through 13). The sand channel is likely a fossilized ancient stream bed, formed by the confluence of the Moʻikeha and Waikaʻea Streams during the Holocene Epoch, a period when sea levels were hundreds of feet lower. A continuous escarpment is also visible in the side scan sonar image along the 35 to 38 m depth contour. This escarpment may represent a relic shoreline, formed during the same period as the stream channel.

Sub-bottom profiling was conducted over the same areas as the side scan. Sub-bottom acoustic imagery revealed sharply sloping channel walls (Fig. 11), which could be seen descending into the sediment to beyond 55 m (180 ft) in depth, resulting in a large sediment layer of 25 m (80 ft) or more. However, it is likely that a significant fraction of this volume is composed of rocky gravel or silts, which would be unusable as beach nourishment. Upper layers would likely have the best potential as beach quality sand.

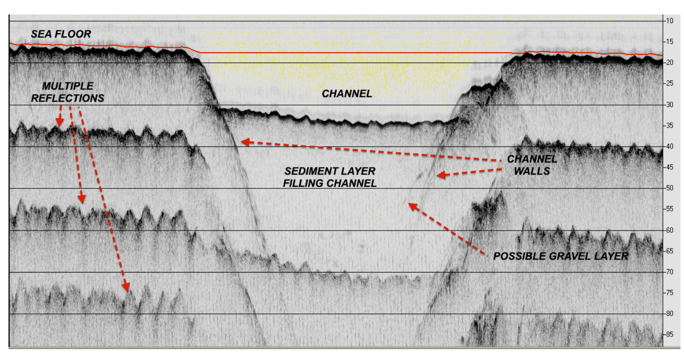


*Figure 11.* Sub-bottom Profile Across Kapaʻa Channel.

In general, the data show that sand deposits essentially fill the channel complex (Fig. 13), ranging from less than 1 m thick along the channel edges, and up to 60 m (197 ft) thick in places. Particularly promising sand deposits were found in the vicinity of our Offshore ADCP deployment, and the inner basin. Sub-bottom data indicate that these deposits may be up to 30 m (98 ft) thick. Initial calculations yield an estimated 790,00 $m^3$ (1 million $yd^3$) of available material. All sampled offshore deposits showed similar grain size distributions to that of the beach (refer to Fig. 6).

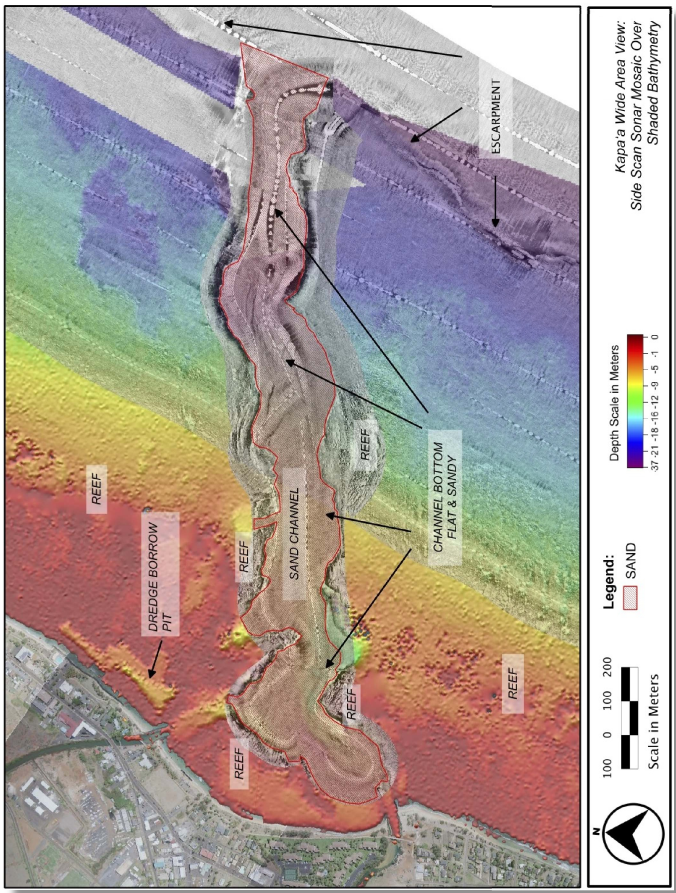


*Figure 12.* Side Scan Sonar Mosaic.

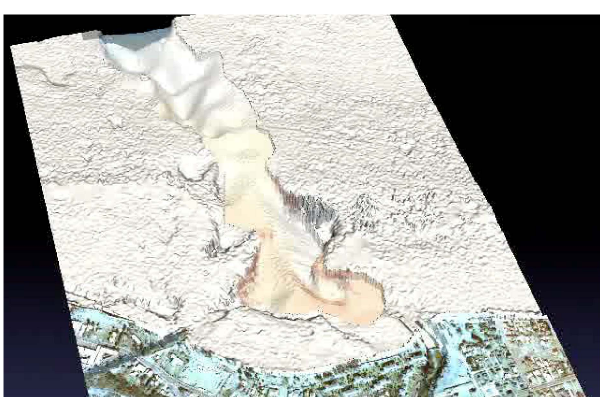

*Figure 13.* DEM Model of Sub-Bottom Isopach.

*D. Numerical Modeling*

To better understand coastal processes at Kapaʻa, a numerical modeling analysis was completed using a phase-resolving nonlinear wave model called Bouss-2D, and the coupled CMS Wave and CMS Flow models. The wave and current data collected during the field investigation portion of this effort were used to drive all models, utilizing a range of values to bracket expected conditions at the site. Model results produced very complex diffraction patterns for all cases, with extreme examples of wave bending and reflection due to the complex and pronounced bottom relief at Kapaʻa. Interestingly, all wave angle cases resulted in essentially the same shore-aligned or nearly shore-aligned wave crests at the beach. This suggests that the fringing reef is very effective at filtering wave direction and reducing wave height at the shoreline (Fig. 14).

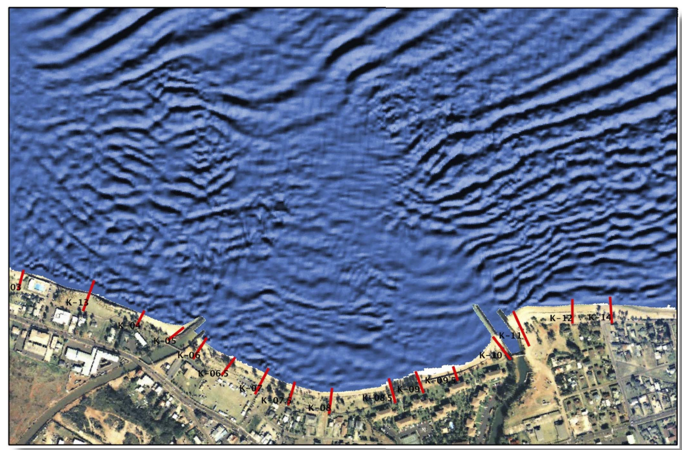

*Figure 14.* Example Bouss2D Results for North Swell.

Circulation model results produced similar current patterns for all cases. In general, the current pattern results show that nearshore currents always flow from the northern and southern reef flats and converge into the main, central channel of Kapaʻa, where they combine and intensify as they flow directly offshore, guided by the main channel (Fig. 15), where increasing red indicates increasing flow velocity. Flow is initiated by breaking waves on the outer reef which drive water shoreward onto the reef flat, where it is eventually deflected by the shoreline boundary, flowing relatively slowly at 0.1 to 0.15 m/s alongshore towards the Kapaʻa channel. As the currents drain off of the reef tops and into the channel from the north and south, typical velocities are in the 0.3 to 0.5 m/s range. The channel flow provides deep water and a path back to sea. Further offshore, flow accelerates to (0.6 to 0.9 m/s) due to the convergence of flow from the north and south reef platforms.

Model results compared well with the current meter data at the Inshore ADCP station. The model case representing typical tradewind conditions with a 1.2 m (4 ft) east wind swell from 090° produced a 0.426 m/s flowing from the north, and the current data for the summer deployment, which best represents the typical condition at Kapa‘a, averaged 0.417 m/s flowing from the north. Similarly, at the Offshore ADCP station, the model calculates a current velocity of 0.230 m/s flowing from the west, and the average surface velocity from the summer current data is 0.214 m/s flowing from the west.

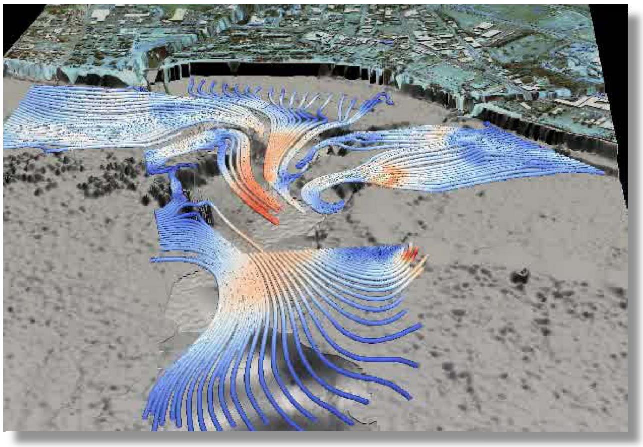

*Figure 15.* Circulation Model; Current Streamlines for N. Swell.

## V. Summary

The shoreline survey work, current and wave measurements, and numerical modeling completed for this project have focused on determining the important coastal processes affecting Kapa‘a Beach, so that effective beach improvement alternatives can be designed and implemented. The illustration in Fig. 16 schematically summarizes these findings, displaying wave direction, currents, sand transport paths and areas of sand loss. In the figure, white arrows represent the driving force of tradewind wave action, where breaking waves initiate water flow onto the shallow reef platforms; light blue arrows represent major currents comprising the general circulation pattern; beige arrows represent the main pathways of sediment movement; and, red-dashed lines indicate areas where sand is permanently lost from the littoral system, from which it cannot return by natural forces. These areas are sometimes referred to as sand sinks.

Wave data indicated that fringing reefs offshore, and island shadowing around Kaua‘i, combine to filter out all but easterly wave components at this site. The wave exposure window at Kapa‘a was found to be between northeast and southeast, with the bulk of wave energy coming from due east. Numerical wave modeling indicated that the shallow reef complex and deeper channels produced very complex wave patterns, however by the time waves propagate to the shoreline, they were similarly aligned parallel to the shoreline for all incident wave directions. In response, the beach shape was largely consistent throughout the year.

Tradewind waves breaking on the fringing reef drive a continual and persistent circulation pattern that is dictated by the submerged reef complex. Water flows steadily across the broad reef flats to the north of Mo‘ikeha Canal and to the south of Waika‘ea Canal, then flows to the south and north respectively toward the Kapa‘a Channel, where they converge, flowing eastward out to sea through the Kapa‘a Channel. Between the Mo‘ikeha and Waika‘ea Canals, flow is to the south along the shoreline and then eastward out the channel in the vicinity of the Waika‘ea Canal, with the exception of approximately 140 m (450 ft) of shoreline immediately south of Mo‘ikeha Canal. Here, currents flow to the north, and then eastward out the channel in the vicinity of Mo‘ikeha Canal.

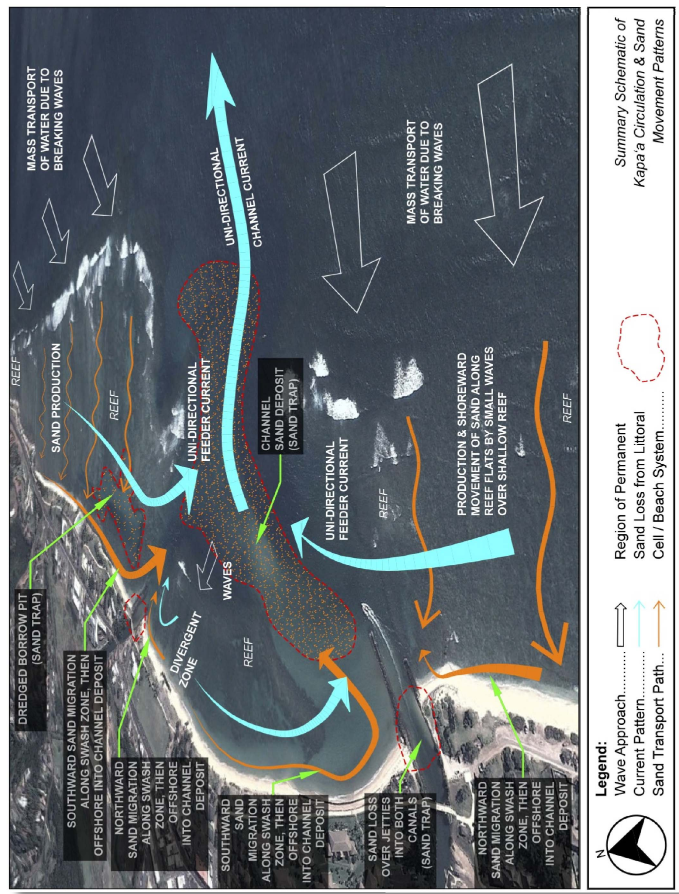


*Figure 16.* Summary Schematic of Coastal Processes at Kapa‘a.

Sand transport paths follow the general circulation pattern described above, where sand is transported along the shoreline, and then out into Kapa‘a Channel. A key finding of this study is that this appears to be the primary mechanism of beach sand loss. Consistent with this finding, geophysical and diver surveys found an extensive deposit of beach quality sand close to shore in the Kapa‘a Channel. The constancy of the tradewind wave-driven circulation and the steep sides of the deep channel prevent possible return back to the beach by natural processes of sand deposited there. This suggests that future steady erosion of the beach is likely.

Other sources of beach sand attrition include sand wash over the jetty crests into both Mo‘ikeha and Waika‘ea Canals, and deposition into the dredged borrow pit on the reef platform north of Mo‘ikeha Canal.

## VI. Recommended Improvement Alternatives

Significant beach nourishment is proposed to restore the entire beach between the canals to the 1950 shoreline, as determined by historical aerial photographs. Beach nourishment is recommended at Kapa‘a because the existing jetties would act to stabilize the fill, the fringing reef effectively limits wave energy reaching the beach, and the availability of a large deposit of beach quality sand located directly offshore. Furthermore, the field measurements and numerical modeling completed by this study indicated that the sand in this deposit is permanently lost to the beach and littoral system due to the persistent, strong seaward flow out the Kapa‘a Channel. Nourishing a smaller segment of the beach is not advisable because this small scale fill would represent a perturbation to the existing beach’s equilibrium shape, and the sand would likely be rapidly dispersed along the entire beach length, minimizing the intended effectiveness.

Nourishment of the entire beach would involve placing an estimated 74,000 cubic yards of sand on the beach to extend it seaward approximately 20 m (65 ft) along the southern half, and approximately 8 m (26 ft) on the northern half. Using the erosion rates presented in Section III.A, this nourishment would be expected to last between 25 and 50 years. Accelerating sea level rise, however, could significantly increase erosion rates and diminish the duration of the nourishment. The offshore sand deposit at Kapa‘a appears to contain sufficient volume for numerous nourishment projects. In addition, the work conducted during this project indicates that the sand eroded from the beach will be transported and re-deposited in the channel, from where it could be used again to re-nourish the beach.

Additional measures include jetty spurs and jetty cap walls. Spurs are relatively short appendages to a jetty, forming an “L” shape. The principle behind a spur is to cut off and deflect the boundary currents which develop along the up-current sides of jetties, and which have the potential to carry significant volumes of suspended sediment. A jetty spur would reduce the amount of sand carried out of the littoral system by deflecting and possibly reducing the boundary currents that develop alongside the jetties. A jetty spur would also serve to reduce wave energy along the shoreline in the lee of the spur. Reduced wave energy would encourage accretion of sand along the shoreline, and would help retain additional sand placed along the shoreline.

Construction of a jetty spur could be implemented as a stand-alone project designed to improve the beach and protect the shoreline at the existing erosion hotspots immediately north of Waika‘ea Canal and south of Mo‘ikeha Canal, and reduce the rate of sand loss into the Kapa‘a Channel, or it could be implemented as part of the beach nourishment to mitigate sand attrition and improve the longevity of the nourished beach. An example is shown in Fig. 17.

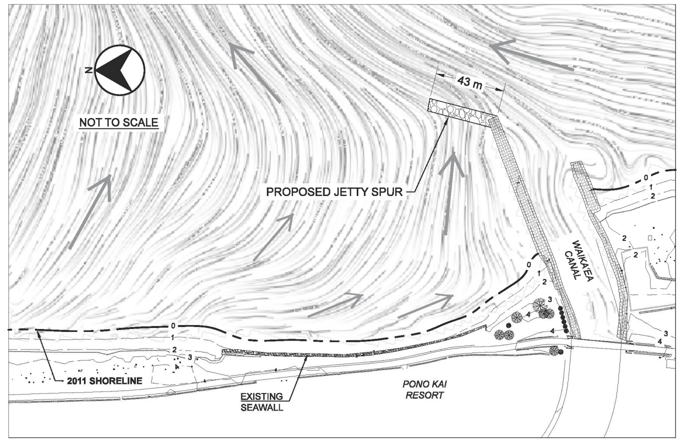


*Figure 17.* Jetty Spur Example, Overlain With Flow Model Results.

Currently, the beach berm height is typically as high or higher than the jetty crest heights at Waika‘ea and Mo‘ikeha Canals, and sand is regularly washed over the jetties and into the canals. Once it migrates into the canals, it is lost from the beach and littoral system, and may be flushed out during terrestrial floods and deposited offshore in Kapa‘a Channel. To prevent the steady loss of sand over the jetties, a grouted cap wall is proposed to elevate the landward jetty crest height for the north jetty at Waika‘ea Canal, and south jetty at Mo‘ikeha Canal.

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