

**SOUTHEAST OAHU
REGIONAL SEDIMENT MANAGEMENT
DEMONSTRATION PROJECT**

REGIONAL SEDIMENT MANAGEMENT PLAN

Prepared for:

**U.S. Army Corps of Engineers
Honolulu District**

and

**State of Hawaii
Department of Land and Natural Resources
Office of Conservation and Coastal Lands**

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EXECUTIVE SUMMARY

The U.S. Army Corps of Engineers (USACE) began a National Regional Sediment Management (RSM) Demonstration Program in 1999. RSM refers to the effective use of littoral, estuarine, and riverine sediment resources in an environmentally effective and economical manner. Several U.S. Army Engineer Districts are conducting RSM programs in cooperation with state or local partners.

The Honolulu District of the U.S. Army Corps of Engineers (POH) has performed an RSM Demonstration Project on the southeast shores of Oahu. The project was co-sponsored by the State of Hawaii Department of Land and Natural Resources (DLNR) Office of Conservation and Coastal Lands (OCCL).

The overall objective of a Regional Sediment Management Plan was to provide guidance on solving sediment problems in the region using a systems approach that considers the entire region from the mountains to the sea. A series of objectives have been identified and are discussed in this report.

The Southeast Oahu Regional Sediment Management (SEO/RSM) demonstration project's tasks were to: (1) document long-term trends in wave climate for the windward side of Oahu, Hawaii, (2) model nearshore circulation, (3) develop a regional sediment budget, (4) develop a geographic information system (GIS) along the southeast Oahu coast, (5) map shoreline change for the region, and (6) identify suitable sand sources.

Wave climate and circulation modeling were completed by the Coastal and Hydraulics Laboratory using STWAVE and ADCIRC. Development of a bottom friction capability in the wave model was completed for application to the extensive reefs in the SEO study area. It was shown that bottom friction is extremely important and has a pronounced effect on modeling transformation over reefs, reducing the wave height at the inshore location by 64-93% based on the range of published JONSWAP bottom friction value for coral reefs. Similarly, Manning coefficient values of 0.15 to 0.25 were applied, reducing wave heights on average by 60 to 80%. The range of response indicates the importance of selecting the appropriate bottom friction value to represent the reefs in the study area. Validation of the model was accomplished by applying a variable bottom friction field and comparing the results with measured nearshore wave heights. Friction factors were adjusted to achieve best comparison with the measured wave heights.

A sediment budget was developed for each part of the SEO/RSM study area: Kailua Beach, Lanikai Beach, Bellows Air Force Station, and Kaiona and Kaupo Beaches. The budgets are based on shoreline change rate maps produced by the University of Hawaii. The USACE's Geotechnical and Structures Laboratory made geotechnical investigations on coral sand from the region.

A web-based GIS platform was deployed for the SEO Region. The GIS contains geo-referenced maps, attributes, and metadata corresponding to SEO/RSM requirements. Aerial photography, digital elevation models, geotechnical information, survey data,

wave parameters and other pertinent georeferenced information have been automated via the GIS.

Historical shoreline change analysis for the SEO region was conducted by the University of Hawaii Department of Geology and Geophysics. The analysis consisted of determining the rate of shoreline change at 20-m intervals over the period from the early 1900s to 2005. UH also identified, mapped, and estimated volumes for reef-top sediment bodies in the study area.

To involve the public in the project, four workshops were held to inform community stakeholders and coastal experts on the goals, progress, and results of the demonstration project and to solicit feedback from attendees.

Four potential demonstration projects (PDPs) were selected and discussed by participants in the workshops: Kaelepulu Stream, Lanikai Beach, Bellows Beach, and Kaupo and Kaiona beaches. The Kaelepulu Stream mouth PDP focused on better use of sediments periodically removed from the mouth. Discussions are underway between the State of Hawaii Department of Health and the City and County Department of Parks and Recreation to reach an agreement on the relocation of sand from the Kaelepulu Stream mouth and stream banks to the eroding area on the north side of the boat ramp.

The PDP for Lanikai Beach presented two conceptual designs for shoreline restoration—beach nourishment with and without structures—as methods of producing a useable beach along a shoreline armored by seawalls. The nourishment without structures conceptual design produced a dry beach width of 30 feet and requires 182,000 cubic yards of sand for the initial nourishment at an estimated cost of \$33,000,000. Additional nourishment of the beach was projected to be necessary every 8.4 years, resulting in an estimated total cost over 50 years of \$109,000,000. The nourishment with structures conceptual design included construction of 12 groins with arc-shaped beaches between. This concept also produced a minimum dry beach width of 30 feet and required 146,000 cubic yards of sand for an estimated initial cost of \$33,400,000 and a total cost of \$41,600,000 over 50 years.

The PDP at Bellows Air Force Station beach presented three conceptual designs along a shoreline where a series of revetments protect recreation cottages, but also trap sand that otherwise might go into the littoral system. The first two conceptual designs involved nourishing the beach. The first concept included nourishment from Wailea Point to the Waimanalo Stream jetties, requiring 247,400 cubic yards of sand to produce a minimum 30-foot wide beach crest. The first conceptual design would have an estimated initial cost of \$43,000,000. The beach is projected to require re-nourishment every 7.5 years, resulting in a total cost over 50 years of \$95,000,000. The second concept reduces the nourishment coverage to the revetted shoreline only and would initially require 106,000 cubic yards of sand for a cost of \$18,500,000. Re-nourishment every 7.5 years would result in a total cost over 50 years of \$55,000,000.

The third conceptual design involved removing the revetments and predicting the response of the shoreline. This would release sand impounded by the revetments to

the littoral system. The short-term equilibrium shoreline position was estimated to be as much as 52 feet inland of the present revetment location. This shoreline recession would impact at least five cabins near the shoreline and three other buildings near Wailea Point. The sediment deficit caused by the revetments was also calculated.

The beach nourishment costs presented for Lanikai and Bellows assume that there is a suitable source available. A cost of \$150 per cubic yard was developed based on cost estimates for offshore sand recovery at other locations in Hawaii. The project costs described above are considered to be very approximate estimates only. Final design would require a detailed estimate from a dredging contractor, which could result in a different unit cost.

Kaupo and Kaiona beaches at the south end of the region suffer from shoreline and embankment erosion and are evaluated in the fourth PDP. The State of Hawaii Department of Transportation stabilized Kalanianaʻole Highway along a 200-foot stretch of Kaupo Beach Park in 2006. The project included relocating a stretch of the road 20 feet mauka and driving pilings to reinforce the roadway. Stretches of Kalanianaʻole Highway along Kaiona Beach Park are presently in danger of being undermined and include seawalls and revetments as shore protection.

The Regional Sediment Management Plan presented herein presents the program's objectives, completed work, and results of the four potential demonstration projects (PDP).

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LIST OF ACRONYMS

AEHR	Annual Erosion Hazard Rate
ADCIRC	ADvanced CIRCulation long-wave hydrodynamic model
CGG	Coastal Geology Group
CHL	Coastal and Hydraulics Laboratory
DLNR	Department of Land and Natural Resources
DPP	Department of Planning and Permitting
ERDC	U.S. Army Engineer Research and Development Center
GIS	Geographic Information System
GSL	Geotechnical and Structures Laboratory
OCCL	Office of Conservation and Coastal Lands
PDP	Potential Demonstration Project
POH	Honolulu District U.S. Army Corps of Engineers
RSM	Regional Sediment Management
RSMP	Regional Sediment Management Plan
SEO	Southeast Oahu
STWAVE	STeady-state spectral WAVE model
UH	University of Hawaii
USACE	U.S. Army Corps of Engineers

I. INTRODUCTION

The islands of Hawaii are the most remote islands in the world. Located in the vast expanses of the Pacific Ocean, the island of Oahu is home to a division and district office of the U.S. Army Corps of Engineers. The Honolulu District (POH) has performed a Regional Sediment Management (RSM) Demonstration Project on the southeast shore of Oahu. The project was co-sponsored by the State of Hawaii Department of Land and Natural Resources (DLNR) Office of Conservation and Coastal Lands (OCCL). In the future, additional demonstration projects could take place on the other Hawaiian Islands.

The project consisted of a series of studies to characterize the coastal processes as described below. The Regional Sediment Management Plan presented herein contains the program's objectives, completed work, and results of the four potential demonstration projects (PDP).

The project is a combined effort of POH, the Coastal Hydraulics Laboratory, the Geotechnical and Structures Laboratory, the University of Hawaii Department of Geology and Geophysics, Oceanit Laboratories, Inc, Sea Engineering, Inc., and Group 70 International. OCCL provided advisory assistance.

The original RSM report was prepared by Oceanit Laboratories and submitted in December 2006. The report has been updated by Sea Engineering and AECOM Technical Services to include work completed since the original report. Completed work since the original report includes analysis of wave transformation and bottom roughness, revised regional sediment budget calculations and figures, updated shoreline change maps, sediment trend analysis, and findings of the four PDPs.

II. REGIONAL SEDIMENT MANAGEMENT PROGRAM

The U.S. Army Corps of Engineers began a National RSM Demonstration Program in 1999. RSM refers to the effective use of littoral, estuarine, and riverine sediment resources in an environmentally effective and economical manner. RSM strives to maintain or enhance the natural exchange of sediment within the boundaries of the physical system.

Managing sediment to benefit a region potentially saves money, allows use of natural processes to solve engineering problems, and improves the environment. As a management method, RSM

- Includes the entire environment, from the mountains to the sea
- Accounts for the effect of human activities on sediment movement as well as its transport in streams, lakes, bays, and oceans
- Protects and enhances the nation's natural resources while balancing economic needs

The U.S. Army Corps of Engineers (USACE) holds in trust and manages lands and waterways across the U.S. Using regional sediment management concepts will significantly improve the USACE's mission accomplishment. The USACE's engineers and scientists develop new technologies through research to make management decisions more accurate and efficient. Simultaneously, they evaluate RSM concepts through demonstration projects that highlight and improve sediment management activities.

Regional sediment management encompasses the following characteristics:

- RSM is a “system-based approach” that seeks to solve sediment-related problems by designing solutions that fit within the context of a regional strategy.
- RSM is the integrated management of littoral, estuarine, and riverine sediments to achieve balanced and sustainable solutions to sediment-related needs. This approach provides opportunities to achieve greater effectiveness and efficiency.
- RSM involves making local project decisions in the context of the sediment system and forecasting the long-range implications of management actions.
- RSM recognizes sediment as a resource – sand and sediment processes are important components of coastal and riverine systems that are integral to economic and environmental vitality.
- RSM engages many stakeholders. Many federal and non-federal sediment management activities may potentially have system-wide effects.
- RSM recognizes that sediment management actions have potential economic and ecological implications beyond a given site, beyond originally intended effects, and over long time scales (decades or more).
- RSM is a Corps-wide approach that is being implemented through coordinated activities using several Corps authorities.
- RSM is implemented by establishing an RSM team, seeking management support, engaging and involving other agencies that have a stake in managing sediment, and informing and engaging other key stakeholders, including the public (US Army Corps of Engineers, 2004).

III. SOUTHEAST OAHU REGIONAL SEDIMENT MANAGEMENT DEMONSTRATION PROJECT

The Southeast Oahu Regional Sediment Management (SEO/RSM) demonstration project's purpose is to: (1) document long-term trends in wave climate for the windward side of Oahu, Hawaii, (2) model nearshore circulation, (3) develop a regional sediment budget, (4) develop a geographic information system (GIS) along the southeast Oahu coast, (5) identify suitable sand sources, and (6) map shoreline change for the region.

The SEO region is located on the southeast shoreline of the island of Oahu, Hawaii (see Figure 1 and Figure 2). It extends along approximately 12 miles of shoreline from Mokapu Point in the north to Makapu`u at the south end. There are three littoral cells, Kailua in the north, Lanikai in the middle, and Waimanalo in the south part of the study area. Both sub-aerial and offshore geologic controls affect sediment transports within these cells. The offshore region is a 2,000 foot long sloping reef along which waves break. Wave heights are limited by the 4-foot reef depth as they approach the shoreline.

Long-term (decadal or more) shifts in wind, wave direction, and wave period may shift sediment transport patterns and magnitudes. As a result, sediment transport processes of these beaches are difficult to understand. The final products from this study are wave and current model results, a sand source inventory, web-enabled GIS platform, a sediment budget, regional shoreline change maps, PDP results, and this regional sediment management plan for the study area. The SEO/RSM Regional Sediment Management Plan (RSMP) documents all of the activities that have been conducted since the beginning of the SEO/RSM investigations in fiscal year 2005. Work performed by the Honolulu District, Coastal & Hydraulics Laboratory, Geotechnical and Structures Laboratory, the University of Hawaii (UH), and Sea Engineering is summarized herein along with the results of the study workshops. Some of the completed tasks are provided as appendices to this document. Many of the SEO/RSM products can be found online at the following web site.

<http://gis.poh.usace.army.mil/rsm/pages/>



Figure 1 Southeast Oahu Region

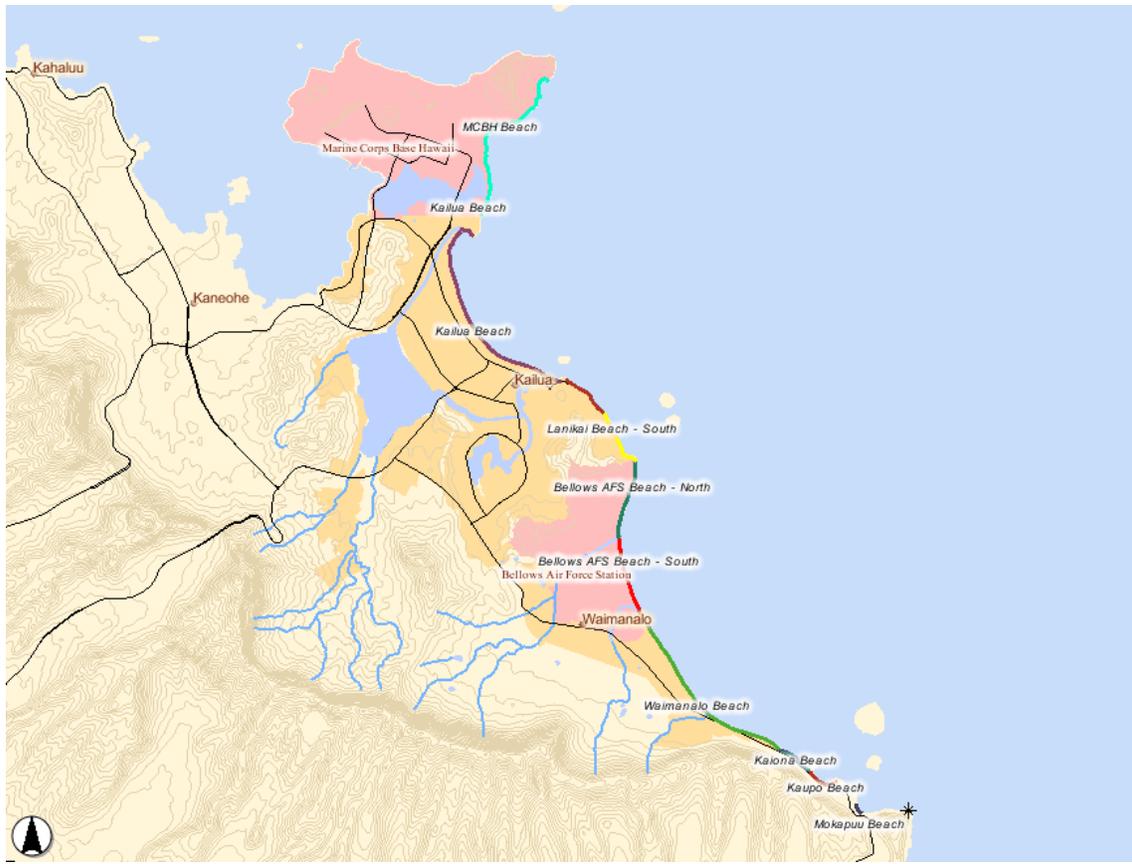


Figure 2 Southeast Oahu RSM Map

IV. COASTAL ECOSYSTEM

The primary focus of the project is on the physical factors that influence regional sediment processes. Much of the sediment is biologically derived, e.g., calcium carbonate sand is produced by coral and algae, and the study seeks to understand the best tools, either physical or environmental, to manage the sediment.

The typical coastal ecosystem in southeast Oahu consists of coral sand beaches sometimes backed by coastal dunes; a nearshore flat shallow area of sand, rubble, and hard substrate; and a fringing coral reef that drops off into deeper water.

The beach is dynamic; it changes continually with waves, currents, tides, and wind. Seasonal changes are normal. A beach may change quickly in response to storms and high waves. When a beach is eroding, upland areas, such as houses or highways, can be threatened and damaged.

Dunes are typically built by wind-blown sand and serve as a reserve sand source that replaces sand lost to storm waves. A stable dune will often have vegetation, which tends to collect and hold the blown sand.

The fringing reef and reef flat are sources for beach sand. They are also the habitat for much of the marine life found in Hawaii. A healthy reef helps maintain a healthy beach. Reefs are sensitive to water quality that often depends on inland conditions. Rainfall runoff can carry silt and other pollutants that will damage or kill a coral reef. Nutrients in runoff will encourage the growth of algae that will displace live coral polyps and take over a coral area.

V. COASTAL EROSION, BEACH LOSS AND CORAL REEF DEGRADATION

The primary cause of coastal erosion is waves; however, there are a number of other factors that affect the work of the waves. These include sea level rise, variability in sediment supply, storms, deflation by wind, longshore and offshore sediment transport, reduction of sediment supply, removal of sediment by man, interruption of material in transport, and change in natural protection by man or nature.

Erosion is a natural response to the water and wind processes at the shore, but erosion is only a problem when human development is at risk. Sometimes, man-made alterations to the littoral system, including modifications to sediment sources or sinks, may contribute to the eroded condition (Coastal Engineering Manual, Section 1-2-4).

Much of the beach sand in Hawaii is carbonate based. It is made by coral and algae growing on nearshore reefs. If reef growth is slowed by poor water quality, sediment from runoff, or if the reef is otherwise unhealthy, sand production is reduced and erosion may remove sand faster than it can be replaced. Since the beach size depends on sand supply, a beach can shrink in response to reef degradation.

VI. OBJECTIVES

The overall objective of a Regional Sediment Management Plan is to provide guidance on solving sediment problems in the region using a systems approach that considers the entire region from the mountains to the sea. A series of objectives are identified and discussed in the paragraphs below.

A. Identification of Erosion Hotspots and Erosion Watchspots

Erosion hotspots are areas where coastal erosion has threatened shoreline development or infrastructure. They are existing management challenges. In most cases, the shoreline has been armored to protect property and development, and there has been a noticeable environmental impact and/or a decrease in recreational use. Erosion hotspots can be restored, but restoration will require substantial economic resources. **Erosion watchspots** are areas where the coastal environment will soon be threatened if shoreline erosion trends continue. (Mullane and Suzuki, 1997)

Shorelines where erosion exists or threatens to be a problem must be thoroughly evaluated before deciding on shoreline use. Planning includes identifying eroding shorelines in the SEO Region.

B. Guidelines for Shore Protection Measures

A plan objective is to identify shore protection methods appropriate for erosion control in the region. These methods include both soft methods such as beach nourishment and hard methods such as seawalls. The choice must be based on engineering, economic, environmental, and regulatory considerations. A set of selection guidelines should be developed based on the SEO/RSM study results.

C. Beach Nourishment

1. Sand Sources for Beach Nourishment

For beach nourishment to be a viable form of shore protection, sand sources must be identified and mapped. Sources need not be in the region, but the cost of hauling sand from long distances is a major factor in deciding to use nourishment. Nearby offshore sources might be easier and more economical to use. The University of Hawaii, as part of the SEO/RSM project, has produced a report titled, "Reef Top Sediment Bodies in Windward Oahu," which is attached in Appendix F. This report will be the primary reference for locating potential offshore beach nourishment sand sources in the study area.

2. Pilot Beach Nourishment Project

Pilot beach nourishment projects are recommended as two of the potential demonstration projects discussed later in the plan.

D. Dune Preservation and Restoration

An objective is to preserve and restore beach dunes, since they are one of the primary natural shore protection systems. Sections of the regional shoreline such as Lanikai and Kailua have dune systems that can be stabilized or enhanced for better protection. Some dune areas, such as Lanikai and Kailua Beaches, have been identified during the SEO/RSM studies. Dune evaluation is recommended as an objective for the PDPs discussed later in this plan.

E. Coral Reef Ecosystems, Water Quality, and Upland Activities

The primary source for coral sand is Hawaii's reefs. If reefs suffer in a coastal region because of runoff or pollutants entering nearshore waters, they will produce less sand. Environmental control and clean water are therefore necessary for healthy reefs and consequently healthy beaches. This objective includes keeping the reef healthy by controlling water quality and upland activities that could pollute nearshore waters.

These upland activities are as diverse as construction, agricultural and urban runoff, streams, sewage production, and industrial pollution. Water activities including recreation such as boating, fishing, snorkeling, or SCUBA can also affect reef ecosystems.

F. Shoreline Setbacks and Coastal Erosion Hazard Data

The City and County of Honolulu (County) regulates shoreline setbacks and has started a program to study coastal erosion rates and quantify erosion hazards. The program is being performed by the University of Hawaii Department of Geology and Geophysics under contract with the County. Shoreline setbacks are already established in the county, but variable setbacks based on local or regional erosion rates could be used to regulate coastal development.

G. Proactive Development of Coastal Lands

Development of coastal lands, especially along shorelines with beaches, requires advanced planning by owners, developers, and regulatory agencies. Many, if not most, landowners, developers, and real estate agents do not understand coastal dynamics and the potential problems they might encounter.

The “Beach Management Plan for Maui” states the following:

Proactive management occurs in the planning stages of new developments or redevelopments along the shoreline, well before project layout is finalized. This type of planning is beneficial to coastal landowners and developers who are not always aware of shoreline processes, coastal hazards, and the potential impacts of development on the beach and other nearshore areas. The permitting agency should apprise the applicant of the recommendations listed below during project layout. Incorporating the advice of the Planning Department would streamline the permitting process and decrease the risk of coastal hazards.

Developers and landowners should be encouraged to pre-consult with various experts and governmental agencies familiar with coastal erosion in order to get appropriate recommendations on project design. Developers and landowners should also acknowledge that developments along the shoreline are subject to the risk of coastal erosion and high wave events and that any request to protect structures and property with shoreline armoring is currently discretionary based on grounds of hardship and impacts on the environment.

These ideas can be applied to the County Department of Planning and Permitting (DPP) on Oahu as well as to various state regulatory agencies.

H. Inter-Agency Coordination

An objective of the RSMP is to use inter-agency coordination and cooperation whenever possible to make sediment management projects simpler and faster with minimal regulatory processing.

The “Beach Management Plan for Maui” states the following:

Much of the coastline of Maui consists of parks, highways, and other public works projects, which are threatened or will soon be threatened by erosion and other coastal hazards. Inter-agency communication and education is necessary to more effectively plan for or mitigate coastal hazards and implement more environmentally sound projects. Better inter-agency coordination would also reduce delays, duplications, paperwork, and resource demands in permit processing, resulting in cost-savings to both permit applicants and governmental agencies.

In Hawaii, the state has responsibility for regulating coastal development seaward from the certified shoreline. The county has responsibility for areas landward from the certified shoreline. The Corps of Engineers, representing the federal government, regulates development in “waters of the United States,” which include all waters subject to the ebb and flow of the tide and inland waters such as streams, lakes, and wetlands. These three areas of governmental jurisdiction may overlap, and permits from more than one agency are sometimes necessary when coastal development is planned.

An example of inter-agency coordination is the Small-Scale Beach Nourishment (SSBN) Project permit. The State Department of Land and Natural Resources processes this permit that includes the state Conservation District Use Permit, the Department of the Army Permit, the State Programmatic General Permit, the State of Hawaii Department of Health Section 401 Water Quality Certification, and the Hawaii Coastal Zone Management Federal Consistency Review.

However, the City and County of Honolulu Department of Planning and Permitting does not fully participate in the SSBN permit process. Currently, if a land owner plans to place beach nourishment and the placement extends above the certified shoreline, the County requires a permit and an environmental assessment for placing the sand and for any temporary sandbag retaining or protection structures. This objective includes convincing DPP to cooperate more fully with the State DLNR’s SSBN Permit processing and to not require a separate permit.

I. Structures and Activities within the Shoreline Area

1. Minor Structures

For the County, minor structures are defined in the Department of Planning and Permitting Rules, Part 2, Rules Relating to Shoreline Setbacks and Special

Management Areas, Chapter 15, Minor Structures and Activities. Typically, minor structures are those that have little or no effect on shoreline processes. This objective supports continued use of a simplified process for approving minor structures.

2. Major Structures

For major structures, the objective is to convince Honolulu to cooperate more fully with the State DLNR's SSBN Permit processing. Currently, if a land owner plans to place beach nourishment and the placement extends above the certified shoreline, the County requires a permit for placing the sand and for any temporary sandbag retaining or protection structures.

J. Beach Management Districts

The SEO/RSM project does not include beach management districts as a primary task; however, this is a secondary objective for longer-term consideration. Maui County lists beach management districts as one of their objectives (Mullane and Suzuki, 1997). The SEO Regional Sediment Management Demonstration Project area is probably somewhat larger than Maui's beach management districts but contains shoreline areas such as Lanikai or Kailua that would qualify as management districts. A summary of Maui's objectives is as follows:

***Beach management districts** should be established on a neighborhood scale to help maintain or restore nearby beaches and other shoreline areas. A beach management district (BMD) is a special designation for a group of neighboring coastal properties that provides a mechanism for implementing erosion mitigation projects at multi-property scales. BMDs streamline the permitting requirements for beach preservation and restoration projects and facilitate cost sharing between the group of neighborhood owners and county, state, and federal agencies. Further details about establishing beach management districts and the advantages and challenges of establishing them are thoroughly discussed in a 1992 report entitled *Beach Management Plan with Beach Management Districts* by Hwang and Fletcher. Certain beach management projects (e.g., large beach restorations) affect several beachfront properties. The formation of a beach management district allows a group of adjacent landowners to address shoreline issues as a unit rather than as individual property holders (Hwang and Fletcher, 1992). As a beach management district, the group can pool its resources and streamline the permitting process for such projects. Often, county, state, and federal agencies will participate in cost sharing for a particular project, if it benefits the public. Some condominium associations and neighborhood boards already act as de facto beach management districts.*

Although beach management districts have been recommended for Maui County, they have not yet been defined for Oahu. However, DPP has considered neighborhood beach areas when evaluating neighborhood problems.

Oahu has a Development/Sustainable Community Plan for the shoreline area of Ko`olaupoko on the windward side along the same area as the SEO/RSMP (Department of Planning and Permitting, July 2000). Excerpts from the plan are given below. If implemented on Oahu, beach management plans would be the next lower level of planning. The Ko`olaupoko plan states the following:

Land Use Policies, Principles, and Guidelines

3.1.3.2 Shoreline Areas

Ko`olaupoko's shoreline characteristics are quite varied, from the rocky headlands of Makapu`u at the south end of the district, to wide sandy beaches fronting Waimanalo Bay and Kailua Bay, to mud flats along Kaneohe Bay. The shoreline provides residents and visitors with significant active and passive recreational value. Thus, public access, both mauka-makai and lateral, should be maintained and improved. In addition, Ko`olaupoko's shoreline areas offer spectacular scenery. As such, views from public roads to the shoreline should be maintained or created. Particular segments of the shoreline are discussed below.

Mokapu Peninsula. *Sandy beach dunes facing the ocean are situated between large remnants of volcanic craters. On one side of Nuupia Ponds, at the neck of the peninsula, is a narrow, sandy beach facing Kailua Bay, and on the other side is a siltier beach fronting Kaneohe Bay. Except at certain times for special events, the general public is denied physical access to the peninsula, which is under military jurisdiction.*

Kailua Bay, from Kapoho Point to Alala Point. *Kailua Beach is wide and sandy, but dynamic and subject to significant erosion and accretion cycles. It is famed for its high quality as a recreation area. Kailua Bay is attractive for a variety of ocean recreation activities, notably swimming, body surfing, windsurfing, kayaking and canoe racing. Public access to the beach and coastal waters is provided primarily at Kailua Beach Park, on either side of the Ka`elepulu Stream outlet, and at the smaller Kalama Beach Park. At both locations, vehicular parking spaces are in great demand on weekends and holidays. There are five public rights-of-way for pedestrians at dispersed points along Kalaheo Avenue, the street that runs parallel to the beach, but no off-street parking, public restrooms or showers are available at these locations. Visual access to the shoreline from the adjacent street is available only at Alala Point and the Ka`elepulu Stream crossing.*

Kailua Bay, from Alala Point to Wailea Point (Lanikai). *Severe erosion is occurring at either end of Lanikai Beach, where adjacent residential property owners have built seawalls and revetments along most of the shoreline. The remaining sandy beach in the central portion is popular for recreation. Public access for pedestrians is provided at eleven points along the parallel public street, Mokulua Drive, but no offstreet vehicular parking, public restrooms or*

showers are available for beach-goers. Visual access to the shoreline from the street is very limited.

Waimanalo Bay, from Wailea Point to Makapu`u Point. Wide sandy beaches front almost the entire length of Waimanalo Bay. There is a narrower beach and emerging reef rock in the vicinity of Pahonu Pond in the mid-section of the Bay shoreline. While Kalaniana`ole Highway is relatively distant from the shoreline at the northern portion of the beach, physical access is readily available during peak recreation periods at Bellows Air Force Station and Waimanalo Bay State Recreation Area. In the beachfront residential area of Waimanalo, there are three pedestrian rights-of-way to the shoreline along Laumilo Street. Further south, at Waimanalo Beach Park and Kaiona Beach Park, the highway is close enough to the shoreline to afford both visual and physical access. In the southernmost stretch, along Kaupo Beach Park and Makapu`u Beach Park, visual and physical access to the shoreline is virtually unimpeded. The highway offers dramatic vistas of coastal headlands and cliffs, ocean waters and off-shore islands, and a direct link to the proposed 354-acre scenic shoreline area extending from Makapu`u Point to Koko Head in East Honolulu.

Guidelines pertaining to shoreline areas are listed below:

Maintain existing makai view channels along Kalaniana`ole Highway between Makapu`u Point and Waimanalo Beach Park; along Kawailoa Road and North Kalaheo Avenue in Kailua; along Lilipuna Road in Kaneohe; and along Kamehameha Highway north of Kaneohe. Avoid visual obstructions, such as walls and dense landscaping.

Create and maintain new makai view channels along Kamehameha Highway and Kahekili Highway north of Kaneohe through selective clearing of dense vegetation and the removal of structures. Such view channels should be created by public acquisition of shoreline properties along the highway or by obtaining easements and maintenance agreements with private landowners. Priority should be given to the areas where clearing would open up vistas of perennial streams, wetlands, fishponds and off-shore islands.

Place high priority on maintaining the untamed landscape quality of the Makapu`u view shed. Any modification to this shoreline area should be done in a manner that continues the landscape character of the proposed scenic shoreline corridor on the East Honolulu side of Makapu`u Point.

Consideration should be given to the establishment of buffer zones for the protection of rare coastal resources and recognition that such resources should be defined and identified.

Increase opportunities for physical access to the shoreline areas of Kaneohe and Kailua by acquiring additional shorefront areas. The top priority for such

acquisition is in Kaneohe. In Kaneohe, access is being designed at the site of the Kaneohe Wastewater Pre-Treatment Facility, to be named Waikalua Bayside Park. The park is adjacent to Kaneohe Stream, which will be dredged to a depth of nine feet. Future expansion may be possible by either acquiring the adjacent Kokokahi YWCA facility or entering into a cooperative agreement with this organization for the joint use of both properties. Other sites in Kaneohe are at King Intermediate School and at a spot north of Heeia Kea Landing. The latter may require realignment of a portion of Kamehameha Highway to create adequate land area makai of the roadway. In Kailua, an additional park site should be sought in either the Oneawa Beach area, near the surf spot known as "Castles" or in the frontage along Kalaheo Avenue between Kailua Beach Park and Kalama Beach Park. The latter beach park could also be expanded if there is an opportunity to acquire an adjoining property.

Existing pedestrian rights-of-way to the shoreline should be improved by providing onstreet or off-street parking nearby; secured bicycle racks where the access point adjoins an existing or planned bikeway, such as along Mokulua Drive in Lanikai and Kaneohe Bay Drive in Kaneohe; and provisions for emergency vehicle access and lateral access along the shoreline.

To maintain lateral access along popular beaches that are subject to long-term and seasonal erosion, particularly at Lanikai and Kualoa, beach management plans should be developed and implemented, with an emphasis on non-structural approaches and prevention of adverse effects on adjacent coral reef ecosystems. Greater shoreline setbacks should be established for new structures along these and other unstable shoreline areas, using criteria developed in various shoreline studies.² Plans and activities should be consistent with the objectives and policies of the State Coastal Zone Management Program.

The placement and design of exterior lighting in areas adjacent to the shoreline may contribute to disorientation, injury or death of seabirds. Therefore, lighting should be designed and constructed to avoid such effects, using DLNR guidelines.

The Alala Point to Wailea shoreline should be designated as an erosion-prone area and a beach management plan prepared and implemented. Periodic beach restoration activities should also focus on the Bellows Air Force Station beach and Kaupo beach.

The shoreline along Kamehameha highway adjacent to Kualoa Ranch to Kualoa Point should be designated as an erosion-prone area and be subject to a beach management plan.

To preserve public ownership and use of shoreline resources, legislation should be pursued to render all shoreline accretion as public (State) property in perpetuity.

Discourage the use of shore armoring structures.

² See *City and County of Honolulu Department of Land Utilization, Oahu Shoreline Study, Parts 1 and 2, (prepared by Sea Engineering, Inc.), 1988 and 1989.*

K. Public Awareness and Education

The SEO Regional Sediment Management Demonstration Project has hosted four public workshops that are discussed further in Section XIII.

VII. GEOMORPHOLOGY

Historical shoreline position, beach profile, aerial photography, bathymetric, and geologic information for the study area were evaluated to identify (a) long-term trends in shoreline position; (b) long-term trends in bathymetric change; (c) locations with possible sources of beach nourishment material, and (d) geologic controls on littoral processes. Historical shoreline position data were available from the University of Hawaii. Sand samples were taken both onshore and offshore, and jet probes were conducted and analyzed to identify possible offshore sources of beach quality material. Because of the low hardness value of the sediment, it is possible that abrasion or mechanical disintegration is a significant process in shoreline retreat. The abrasive characteristics of beach sediments were quantified. This task provided data for development of the regional sediment budget.

VIII. COASTAL PROCESS MODELING

A. Modeling Tasks

The SEO Regional Sediment Management demonstration project includes tasks for modeling coastal processes. The scopes of these tasks are summarized in the following paragraphs.

B. Wave Climate

From observations of shoreline position on the northeast side of Oahu, it appears that there is a long-term trend (15 or more years) of alternating episodes of erosion and accretion. These cycles of beach change may be caused by shifts in wave climate, including multi-decadal shifts in storm activity associated with the Pacific Decadal Oscillation. The long-term wave climate was developed by using the updated Wave Information Study hindcast for the project area. Directional wave buoy data were also available for the years 2000-2006, and non-direction wave buoy data were available for more than 20 years. The directional wave data was obtained from National Data Buoy

Center station 51201, shown in Figure 3, which is located approximately five miles northwest of Waimea Bay in a water depth of about 650 feet. Data is collected at 30-minute intervals. This task provided a regional wave climate for regional shoreline change analysis.

The STWAVE model was adapted for the SEO/RSM and validated using field data. STWAVE is a spectral wave transformation model that incorporates many of the factors that change wave characteristics as they proceed toward the shoreline. The model was applied using 1,274 selected nearshore conditions that were saved at 10 points (Figure 4) to create nearshore time series lookup tables. The report on the model study, "Southeast Oahu Coastal Hydrodynamic Modeling with ADCIRC and STWAVE," is included as Appendix C.

- Current status:
operational
- Most recent location:
**21° 40.36 N 158° 6.95 W
(21.6727° -158.1158°)**
- Instrument description:
Datawell directional buoy
- Most recent water depth (MLLW):
200 m (656 ft, 109 fm)
- Measured parameters:
**wave energy, wave
direction, sea temperature**
- NDBC identifier:
51201

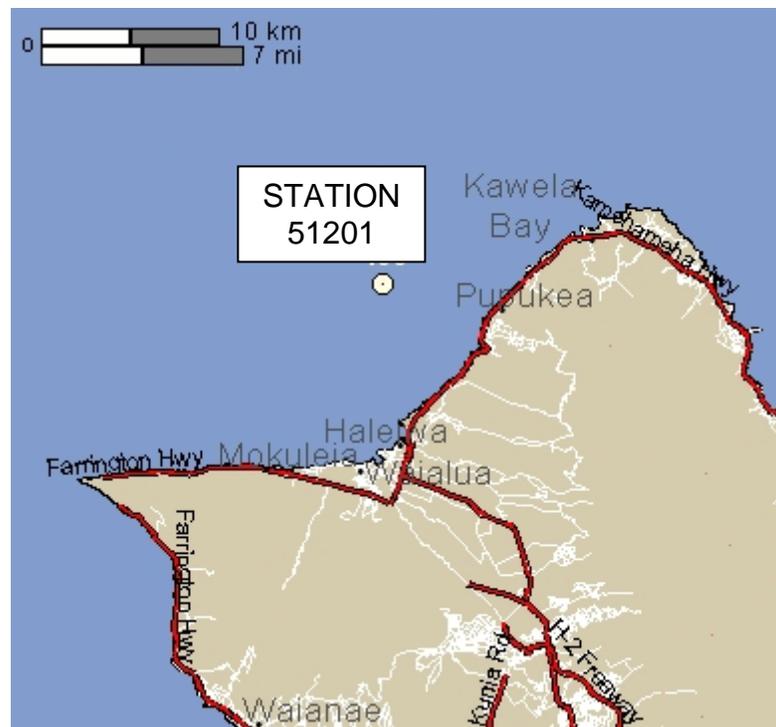


Figure 3 Station 51201 Map
(located approximately 5 miles NW of Waimea Bay)

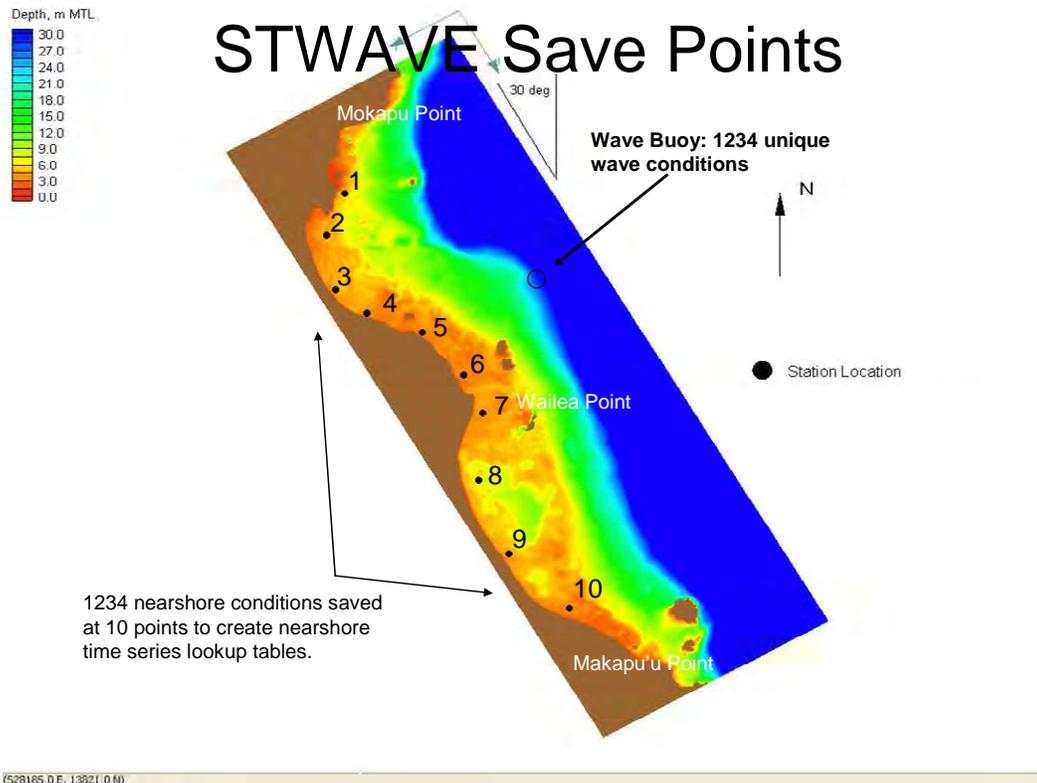


Figure 4 Location of the STWAVE nearshore save point locations

C. Wave Transformation and Bottom Roughness

Development of a bottom friction capability in STWAVE was completed for application to the extensive reefs in the SEO study area. Based on existing literature, values of the JONSWAP bottom friction applied for coral reefs range from 0.04 to 0.12 m/sec; the corresponding Manning coefficient range would be 0.10 to 0.25. A single friction value can be applied to the entire STWAVE domain, or a range of friction values can be applied on a spatially-varying basis. As an example, the 134 wave conditions simulated in the initial climate development were repeated with the revised STWAVE, applying a JONSWAP bottom friction coefficient typical for reefs of 0.05 m/sec. With the inclusion of bottom friction, wave height at the nearshore location ranged from 18–38% of the previous results without bottom friction. On average, the wave height is 26% of the frictionless value at the selected location. The total wave spectrum refracts less with the inclusion of bottom friction, likely due to the dissipation of low-frequency energy. As another example, for each of the 1,274 selected wave conditions simulated for the revised wave climate, wave transformation *including bottom friction* was simulated by applying STWAVE over the project domain for each of the 1,274 wave spectra. The constant 0.05 m/sec value of bottom friction reduced nearshore wave heights by approximately 73% compared to wave heights without bottom friction.

The extended domain STWAVE grid was applied in the model validation process for the August 2005 model validation time period. Initially, a constant bottom friction value was

applied to each cell of the STWAVE domain. Several simulations with different constant JONSWAP bottom friction values ranging from 0.04 to 0.12 m/sec were made to examine the range of response (wave height) at the gauge locations. Bottom friction reduced the wave height at the ADV1 location by 64% for a bottom friction value of 0.04 (wave height is 36% of the offshore wave height), by 71–76% for a bottom friction value of 0.05 (wave height is 24–29% of the offshore wave height), and by 93% for a bottom friction value of 0.12 (wave height is 7% of the offshore wave height). Similarly, Manning coefficient values of 0.15 to 0.25 were applied, reducing wave heights on average by 60 to 80%.

The range of response indicates the importance of selecting the appropriate bottom friction value to represent the reefs in the study area. Validation of the model was accomplished by applying a variable bottom friction field and comparing the results with measured nearshore wave heights. Friction factors were adjusted to achieve best comparison with the measured wave heights.

D. Water Circulation

Because waves are depth-limited as they approach the study area, it is believed that nearshore circulation (wave-, tide- and wind-induced) may be a significant process controlling sediment transport. This task involved setting up and running the Advanced Circulation model, ADCIRC, for the study area. The modeling effort was a cooperative effort of the Pacific Ocean Division, Honolulu District of the U.S. Army Corps of Engineers, and the Coastal Hydraulics Laboratory. There were no nearshore circulation data available for model validation/calibration; thus, wave, current, and drogoue studies were conducted for a one-month period in August 2005. This information is also included in the report “Southeast Oahu Coastal Hydrodynamic Modeling with ADCIRC and STWAVE,” found in Appendix C.

E. Regional Sediment Budget

A sediment budget was developed for each part of the SEO/RSM study area: Kailua Beach, Lanikai Beach, Bellows AFS, and Kaiona and Kaupo Beaches. The budgets are based on shoreline change rates in each project area. The most recent historical shorelines (typically 1996 and 2005) as determined from aerial photograph analysis performed by the University of Hawaii were used in the calculation of the sediment budget to best approximate present conditions.

Volumetric change for historical and present-day time periods was developed for the active littoral region. These data, together with knowledge of the long-term wave and wind climate and regional shoreline change analysis were used to develop sediment budgets for the region. Sediment sources and sinks were identified and quantified. A regional sediment budget was developed, including an assessment of whether long-term sand sharing between littoral cells occurs. The regional sediment budget was used to develop this RSM Plan.

The following steps were conducted in the development of a regional sediment budget for Southeast Oahu (Mokapu Point to Makapu'u Point). As described elsewhere in this report, the University of Hawaii determined historical shorelines for the SEO/RSM study area based on historical aerial photography, USGS T-sheets, and other available map/survey products. The low water mark (LWM) for each historical shoreline was the shoreline reference feature. The position of the LWM relative to a base point was measured at 20-m (66-foot) transects. The difference in these positions produced the shoreline change rate at each transect.

The volumetric change rate was determined by first examining beach profiles measured by the USGS (Gibbs et. al., 2001) in the project area. The typical elevation between the beach toe and the beach crest was found to be approximately 6.6 feet (2 meters). The volumetric change related to one foot of shoreline change is a function of the beach elevation, regardless of the foreshore slope. One foot of shoreline change, therefore, corresponds to a volumetric change of 0.24 cubic yards per linear foot of shoreline. The volumetric rate at each transect was determined as the product of the transect spacing, the shoreline change, and the elevation difference between the toe and crest, divided by the time interval between historical shorelines.

Littoral cells were then identified by contiguous reaches of accretion and erosion. Net transport was inferred at each cell boundary. Figure 5 through Figure 9 display shoreline change rates, littoral transport cells, net sediment transport rates, and cell boundary sediment transport vectors by sub-region of the study area.

The Kailua Bay sediment budget is presented in Figure 5. The analysis shows that the shoreline experienced accretion in the north central reach, opposite the Kailua sand channel. The figure also shows the erosion occurring in the southern portion of the bay near the boat ramp and some of the sand is lost from the system into Kaelepulu Stream mouth.

The sediment budget for the Lanikai shoreline is shown in Figure 6. The shoreline has two hardened areas; between those two areas, the sand is moving from the central reach of the shoreline toward the north, where it is accreting.

The shoreline from Wailea Point through Kaiona Beach Park is a continuous littoral cell and is shown in two figures simply for the sake of presentation. The southern shoreline of Bellows AFS and the northern portion of Waimanalo, shown in Figure 7 are accreting; however, this is directly attributed to the erosion and northward sediment transport from the southern portion of the Waimanalo shoreline shown in Figure 8.

Further south, the sediment budget for Kaupo Beach (Figure 9) shows alternating patterns of accretion and erosion on a complex shoreline. The figure also shows Makapuu Beach, which is quite cyclical. The figure shows considerable erosion; however, this appears to be an artifact of the analysis procedure, which compares two shorelines over a 30-year interval.

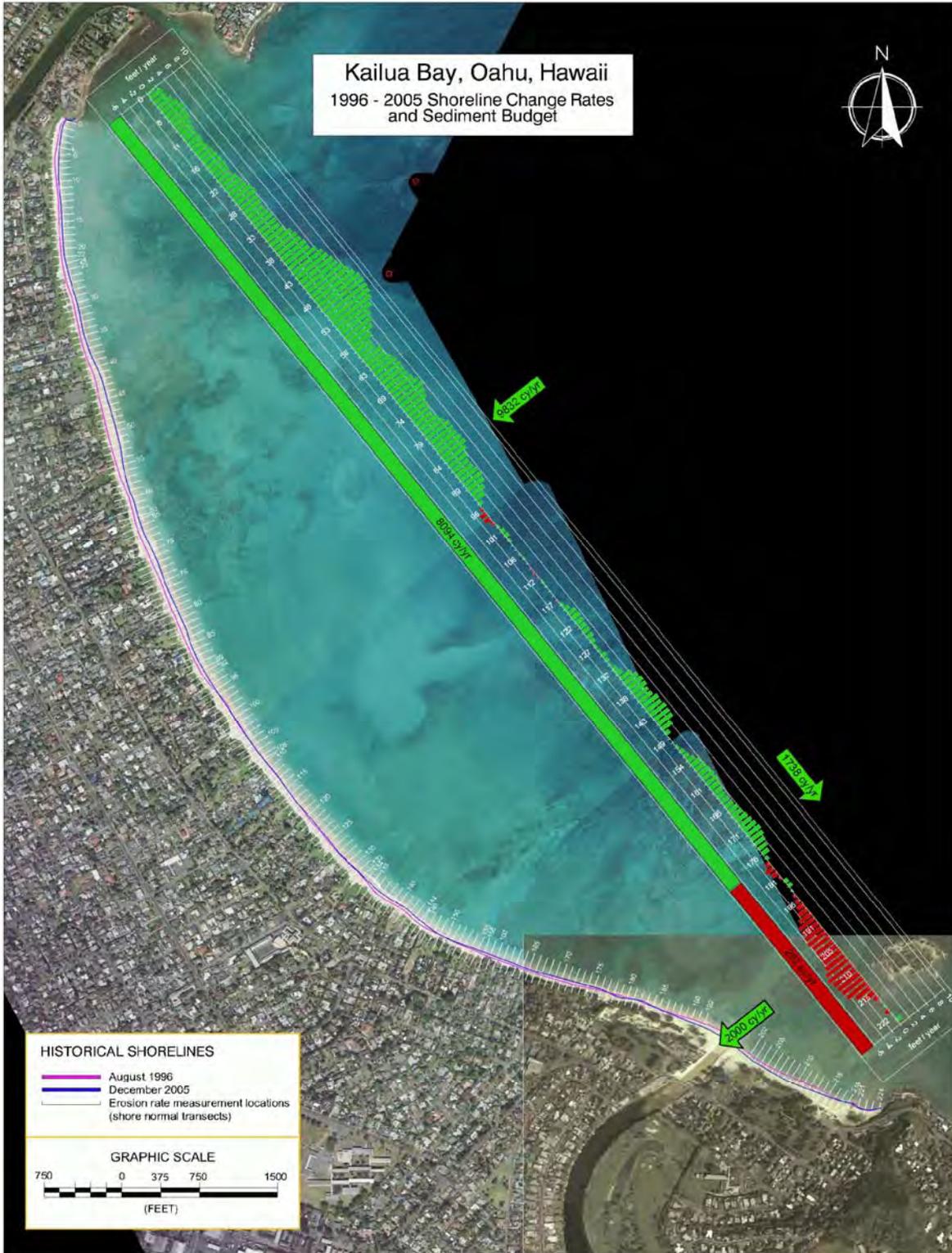


Figure 5 Kailua Bay shoreline change rates, littoral transport cells, net sediment transport rates and cell boundary sediment transport vectors.

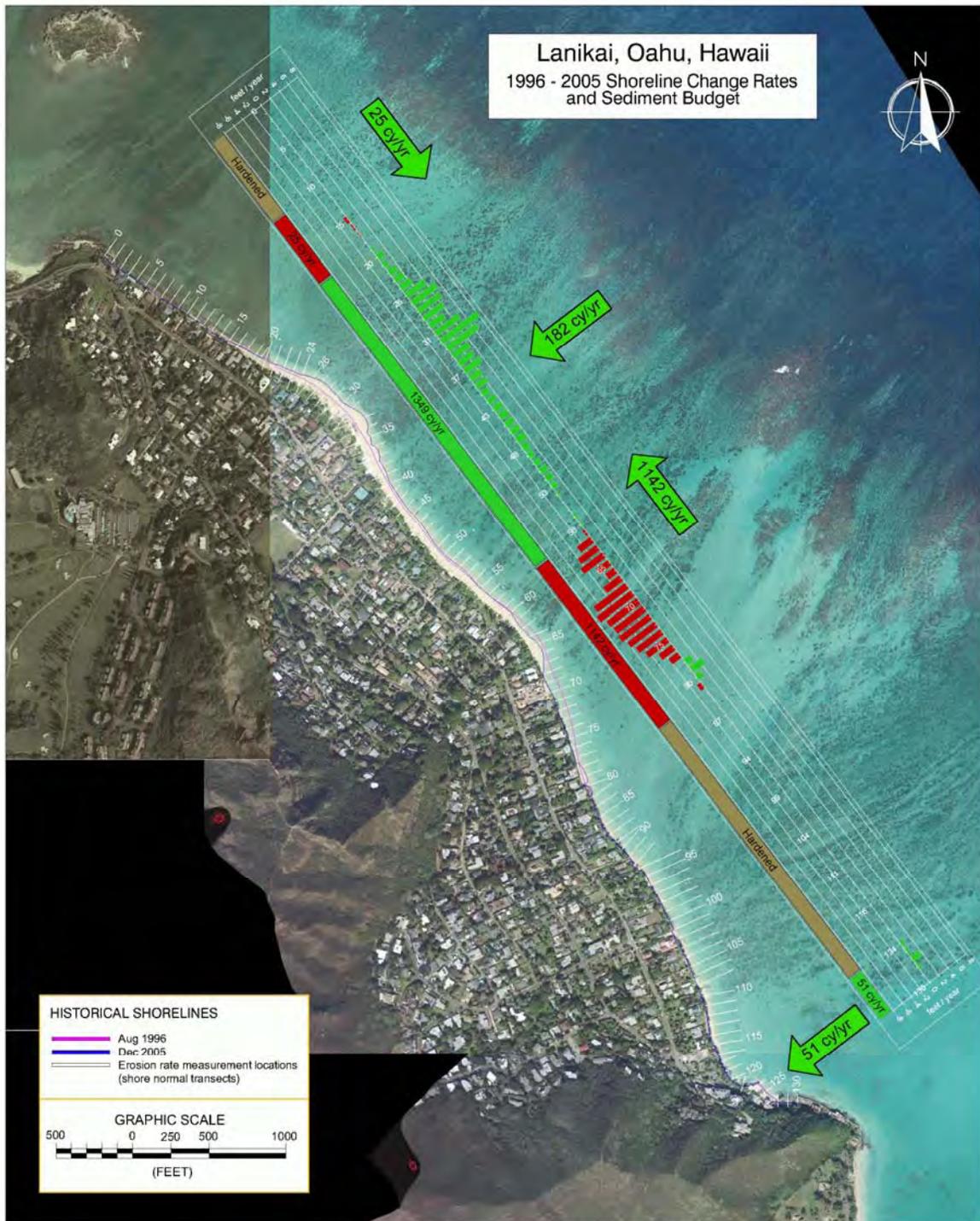


Figure 6 Lanikai shoreline change rates, littoral transport cells, net sediment transport rates and cell boundary sediment transport vectors.

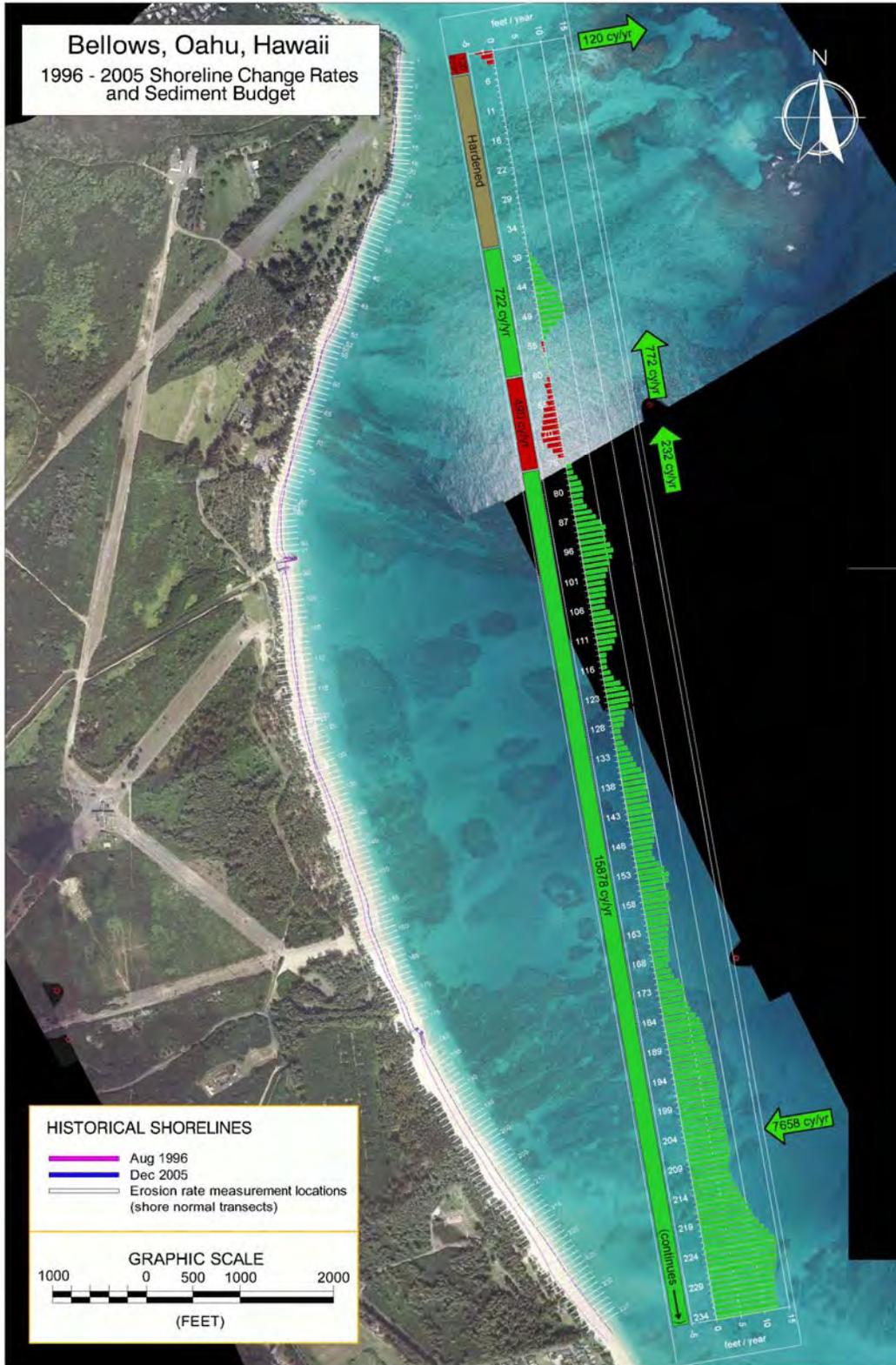


Figure 7 Bellows Air Force Station shoreline change rates, littoral transport cells, net sediment transport rates and cell boundary sediment transport vectors

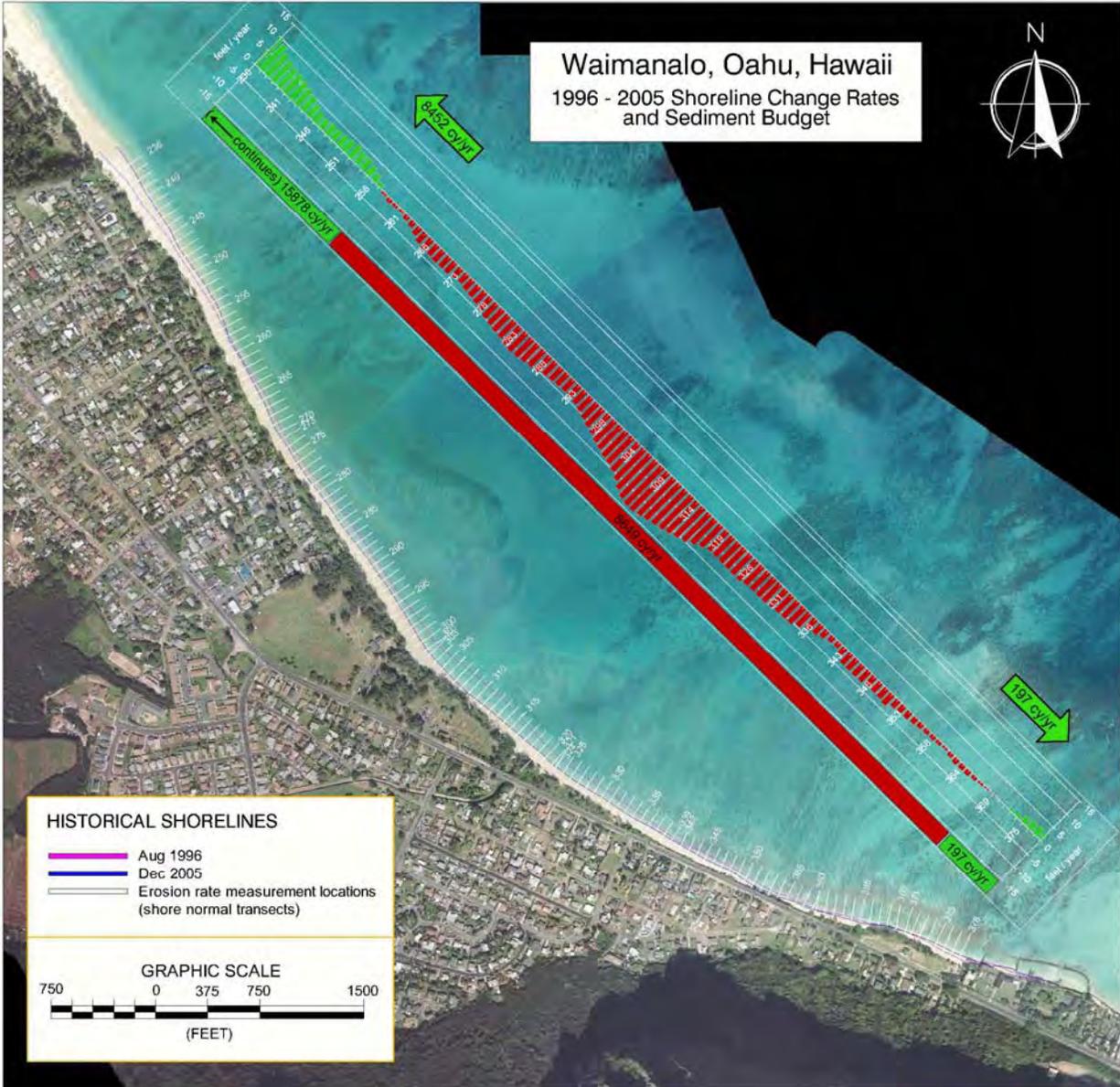


Figure 8 Waimanalo Bay shoreline change rates, littoral transport cells, net sediment transport rates and cell boundary sediment transport vectors

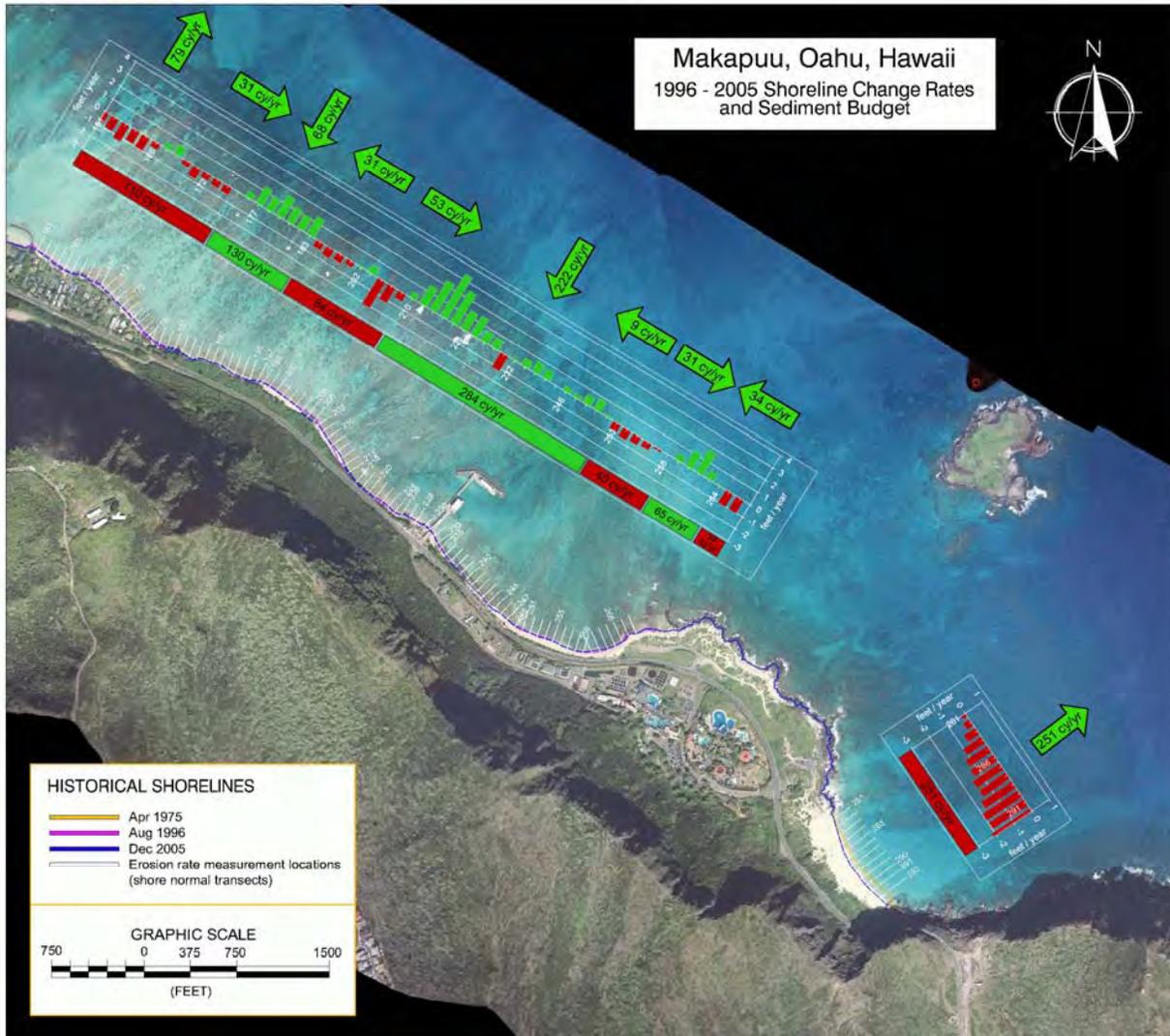


Figure 9 Makapuu’s shoreline change rates, littoral transport cells, net sediment transport rates and cell boundary sediment transport vectors

IX. SHORELINE CHANGE

The University of Hawaii (UH) Department of Geology and Geophysics conducted a historical shoreline analysis for the SEO region. The analysis consisted of determining the rate of shoreline change at 20-m intervals over the period from the early 1900s to 2005. NOAA “T” sheets dating from the early 20th century were orthorectified using modern GPS ground controls and were used in comparison with four to eight orthorectified aerial photographs from the post WWII era to determine a long-term rate of shoreline change. The initial analysis technique used a re-weighted least median of squares linear regression technique to determine the long-term trend of historical shoreline change. This technique eliminates outlier points from the linear regression and combines measurement and positional uncertainties with regression uncertainties in calculating the standard deviation of the trend (Fletcher et al, 2003; Genz et al, in

review). The technique was later modified to include a polynomial fit of the data points, as discussed in the journal article “Historical Shoreline Change, Southeast Oahu, Hawaii; Applying Polynomial Models to Calculate Shoreline Change Rates” (Romine, et. al., 2009), included in Appendix F.

New aerial photographs ca. 2005 at a scale of 1:8400 digitally scanned at 10 microns were acquired for the study. These cover a coastal strip approximately 800 to 1000-m wide centered on the shoreline. Stereo photogrammetry using orthorectified pairs of photos, with GPS ground control, were used to create coastal DEMs. These were digitally combined with offshore SHOALS Lidar data (where such data exist) to create a seamless topographic/bathymetric DEM for the study area.

Historical photography and “T” sheets were orthorectified using the 2005 DEM so that all derived shoreline data are based on orthorectified positions, thus minimizing positional errors. RMS positional error of final orthorectified photos is typically ~1-2 m. Using topographic field profiles to measure beach and dune volume shoreline change rates can be converted to rates of sand volume change over time. The UH study is in progress and the shoreline change maps have been updated to reflect the newest techniques for calculating the shoreline change.



Figure 10 Kailua Beach Shoreline Change

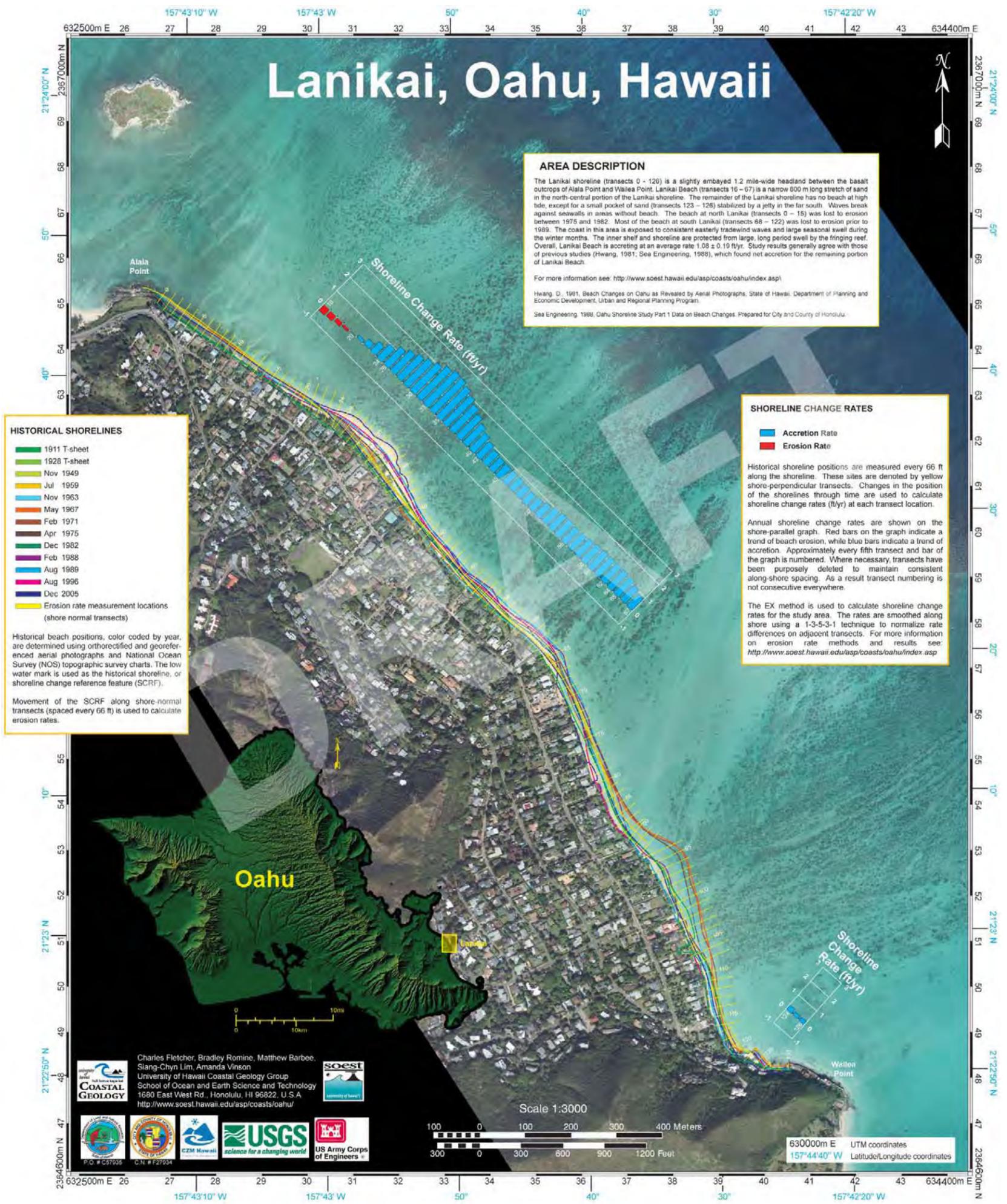


Figure 11 Lanikai Beach Shoreline Change

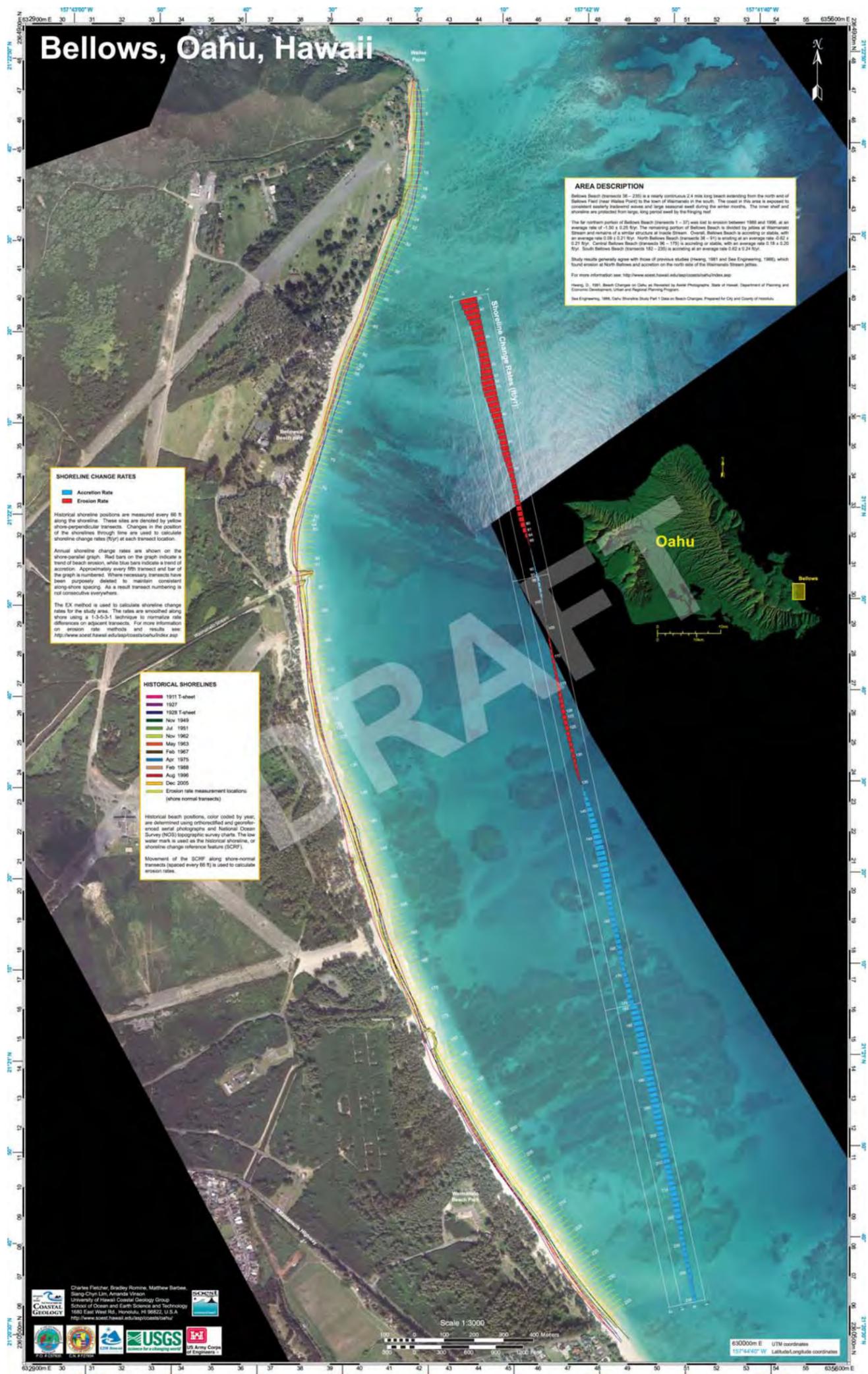


Figure 12 Bellows Beach Shoreline Change

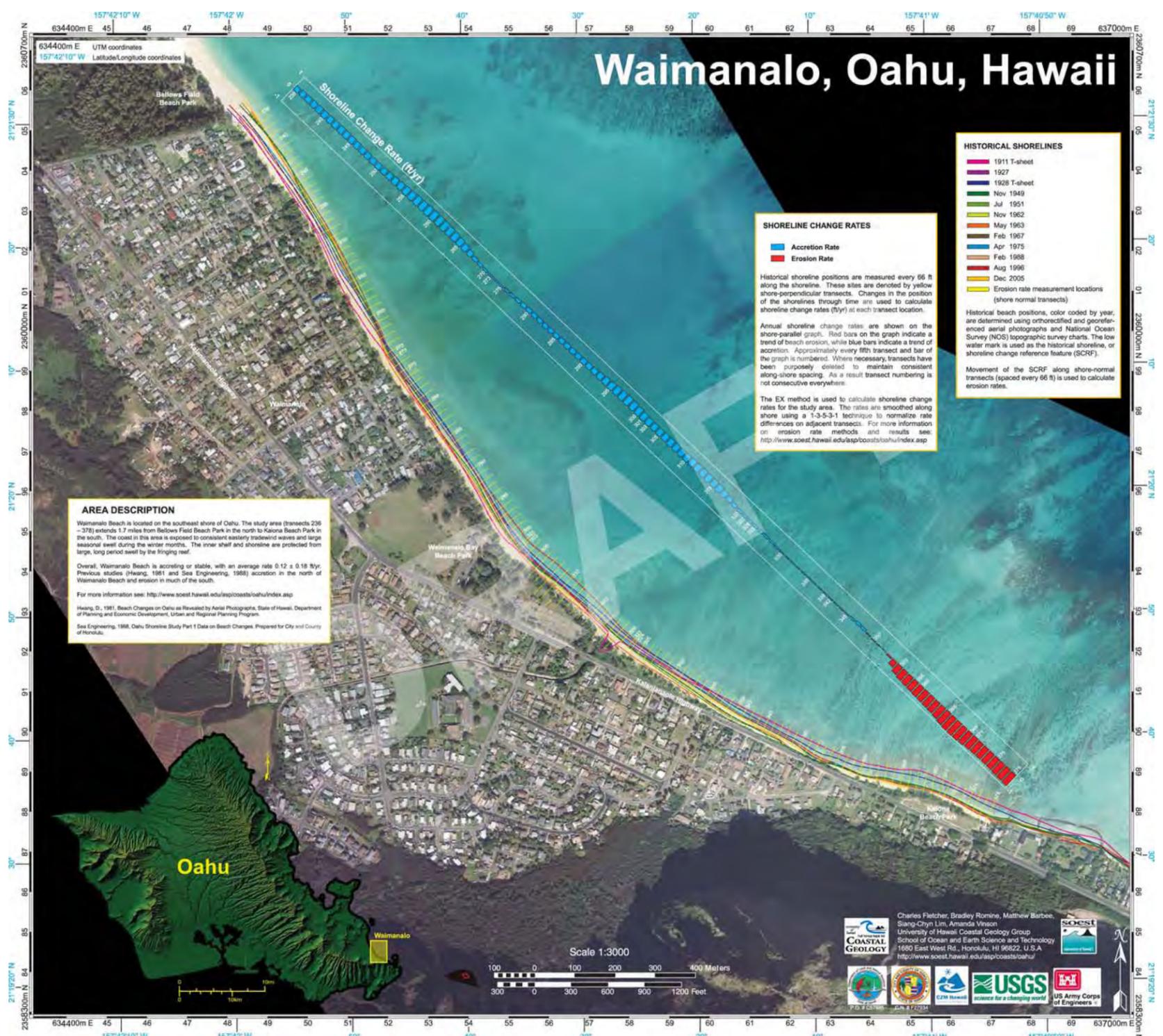


Figure 13 Waimanalo Shoreline Change

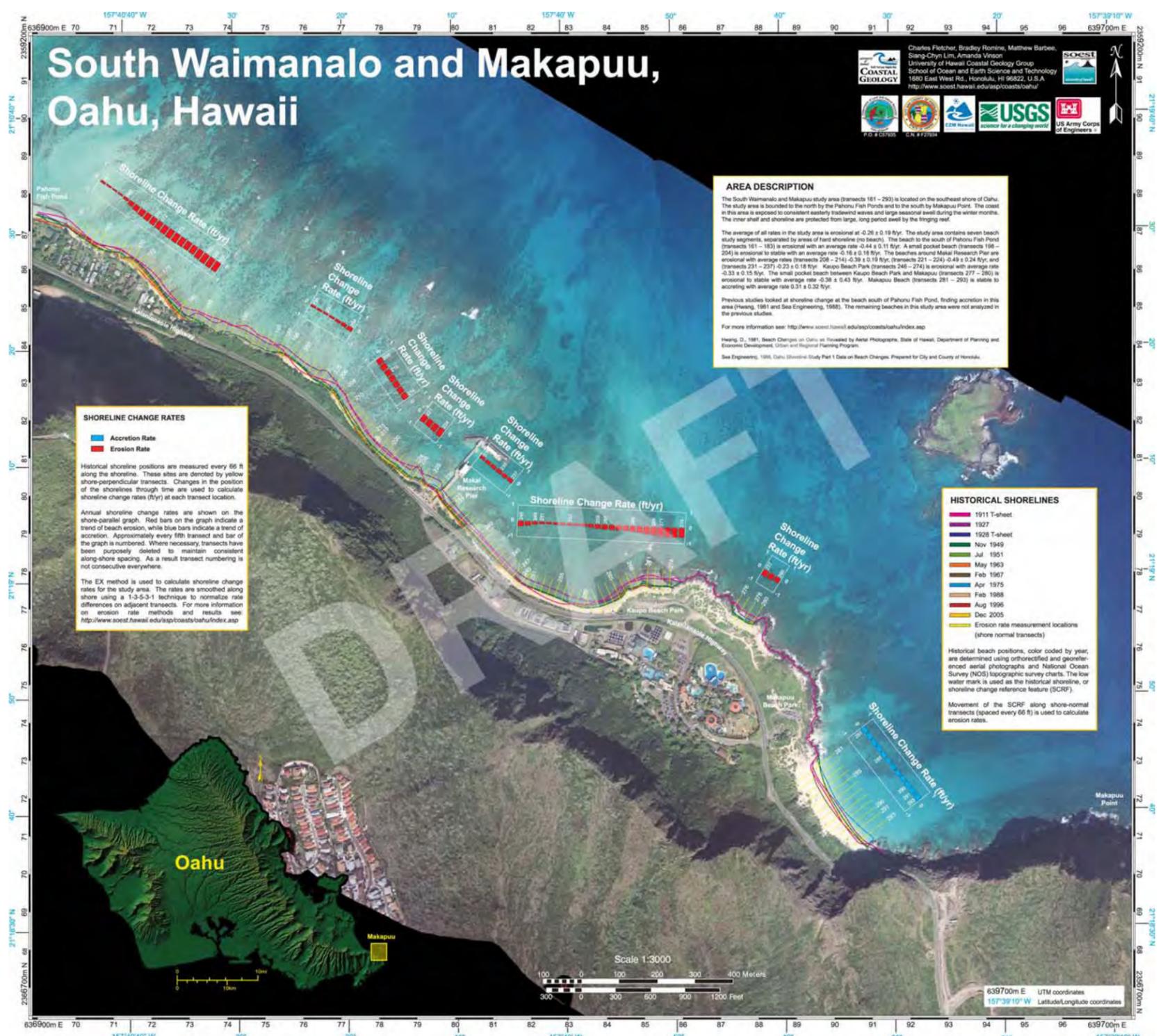


Figure 14 Makapu'u Shoreline Change

X. SEDIMENT TREND ANALYSIS

The University of Hawaii tested the hypothesis that littoral sediment transport occurring between Bellows and Lanikai beaches controls historical shoreline change at Lanikai. They examined the direction of this exchange and assessed factors that have potentially altered sand transport over time. Following is a summary of the findings; the full report can be found in Appendix F.

Grain-size trend analyses (GSTA) were integrated into the hydrodynamical modeling package Delft 3D. GSTA is a method of determining sediment transport direction based on the sediment grain-size distribution of successive samples. In this study, 214 samples were collected and sieved. This study applied two separate methods put forth by Gao and Collins (1992) and Le Roux (1994) to the dataset collected offshore of Lanikai and Bellows beaches. These two methodologies use significantly different mathematical approaches for locating trends in the data, yet have been shown to detect sediment transport at similar spatial scales. This study utilizes two methods to confirm that similar conclusions can be reached through two different means and to provide a comprehensive view of the regional transport processes.

Transport pathways can be identified if a series of sediment samples follows one of the trends listed below (using \emptyset units after Folk and Ward, 1957):

- Trend 1: finer, better sorted, and more negatively skewed
- Trend 2: coarser, better sorted, and more positively skewed
- Trend 3: coarser, better sorted, and more negatively skewed
- Trend 4: finer, better sorted, and more positively skewed

The method put forth in Gao and Collins (1992) determines sediment transport direction by comparing grain-size parameters among a group of sampling sites. Parameters at each site are compared with those of neighboring sites within a predefined characteristic distance. In every case where either Trend 1 or Trend 2 is identified, component vectors with the unit length (i.e., equal to 1) are drawn in the direction of the neighboring site. Summing all component vectors at each site produces a single vector referred to as a transport vector. Component vectors are relevant only in terms of direction. Their lengths do not reflect differences in grain-size parameters or distance between points. Details of the steps and calculations are included in the full text in Appendix F.

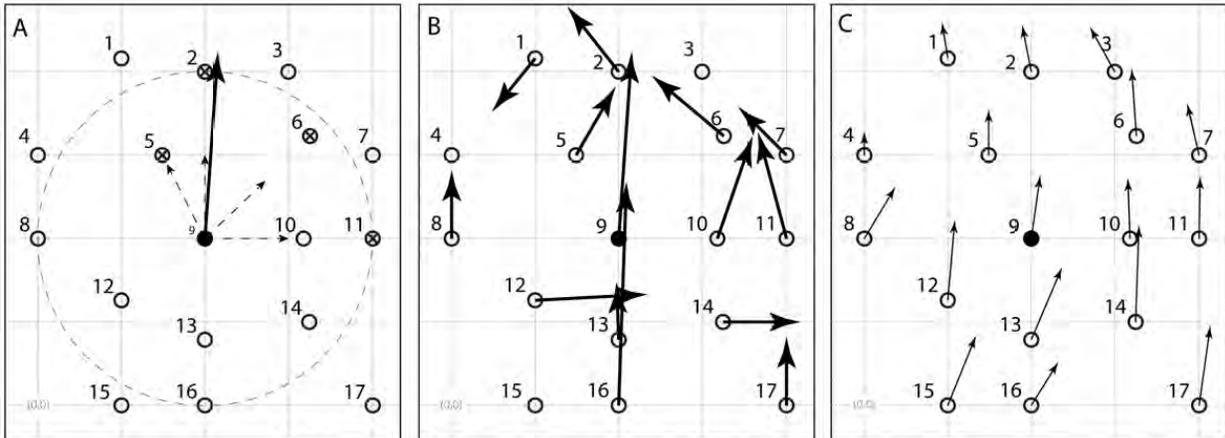


Figure 15 Gao-Collins method for determining sediment transport.

Note: See full report for data and calculations used in the figure. **A)** Illustration of transport determination at site 9 with characteristic distance equal to 2 (dashed circle). Circles represent sampling sites; those containing “x” show either a trend 1 or trend 2 relationship in grain size parameter with site 9. Dashed arrows indicate component unit vectors (length = 1) drawn in the direction of each trend positive site, while the bold arrow is the summation of the component vectors. **B)** The process is repeated at each site producing a transport vector field, which is filtered **(C)** by averaging adjacent vectors.

The method of Le Roux (1994b) functions by comparing grain-size parameters of a central site with the closest four neighboring sites in all cardinal directions (i.e., one site is selected from the North, East, South, and West quadrants). The Le Roux method searches for all four trend types individually, producing a vector field of transport for each trend. Transport values are defined for every site and then the value of the central site is subtracted from each adjacent site and the relative difference between sites is used to define the length of component vectors, which are summed to produce a final transport vector. This process is repeated at every site to produce a field of transport vectors for each trend type.

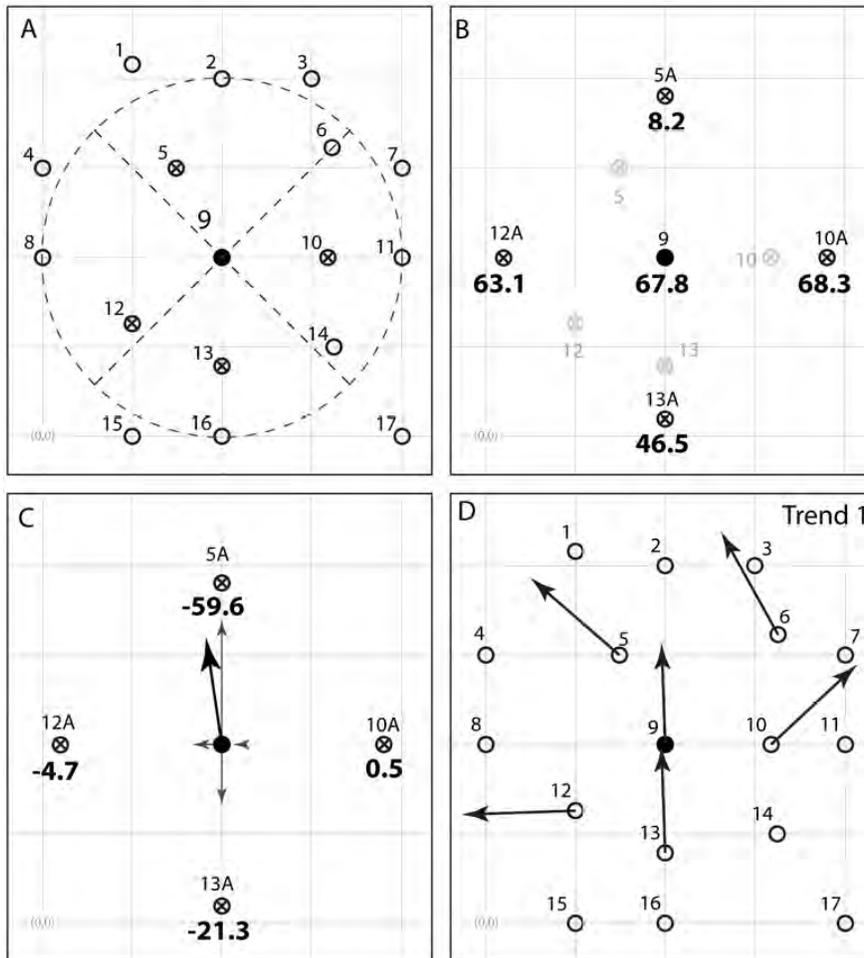


Figure 16 Le Roux method for determining sediment transport

Grain size parameters are identical to those of Figure 15. This method considers each trend type separately, only Trend 1 is considered in this example. A) The closest site in the Northern, Eastern, Southern, and Western quadrants is selected for use; dotted lines illustrate quadrants and “x” on a site indicates selection. B) All sites are transformed to lie at an equal distance from the central site on the cardinal radials; site 5 is at the position of site 5A, 10 is moved to 10A, etc. Grain size parameters are modified to reflect the new positions and summed using the appropriate form of equation (1) for the trend type being investigated. C) The value of the central site is subtracted from all sites. The resulting values indicate transport magnitude in each direction, with negative values indicating transport away from the central site and positive values towards the central point. Summation of component vectors determines the final transport vector. D) The process is repeated at every site with available adjacent sites to produce a vector field for that trend type.

Analysis of shoreline change in this study draws from a portion of data collected in a separate study of the entire southern coastline of Oahu by Romine et al. (2009), presented in Appendix F. Historical shoreline positions were hand digitized from survey quality aerial photos and T-sheets of the study area acquired during the period 1911 through 2005. The position of MLLW and observations of seawall construction were used to create a timeline of shoreline change and armoring activity for the study area.

In the case of a hardened shoreline where no beach currently exists, the vegetation and MLLW lines are the same.

Figure 17 shows an interpolated grid created from all available shoreline position data for the study area over time. Grid cell color indicates the rate of change (gradient in meters-per-year) in the shoreline during that time period (horizontal axis) and for a particular length of beach (vertical axis). The Lanikai-Bellows shoreline has been subject to considerable accretion and erosion. Viewing shoreline position data as a running average of accretion or erosion rates allows these trends to be more readily apparent. For ease of discussion, the historical data is divided into eight time periods (I through VIII) that show common trends of localized accretions and erosion. Littoral sub-cell boundaries and the associated longshore transport patterns can both be inferred from this presentation of the data. Vertical and horizontal arrows indicate the direction of longshore transport over a time period as it is implied by shoreline change. This timeline of inferred littoral transport trends forms empirical control that the results of hydrodynamic modeling and sediment grain-size trends can be compared to. Figure 18 overlays the time periods defined in Figure 17 on the record of wind direction.

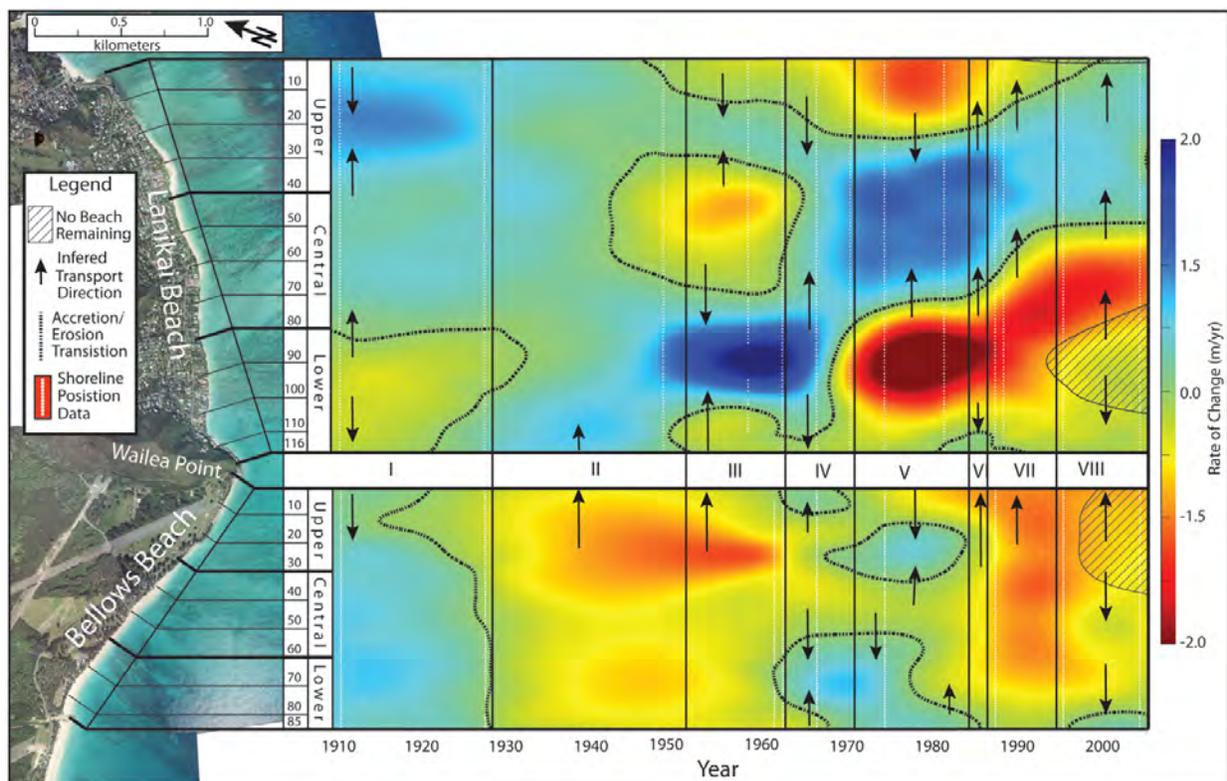


Figure 17 Historical Shoreline record for the Lanikai-Bellows shoreline. Red indicates erosion rate, blue indicates accretion rate

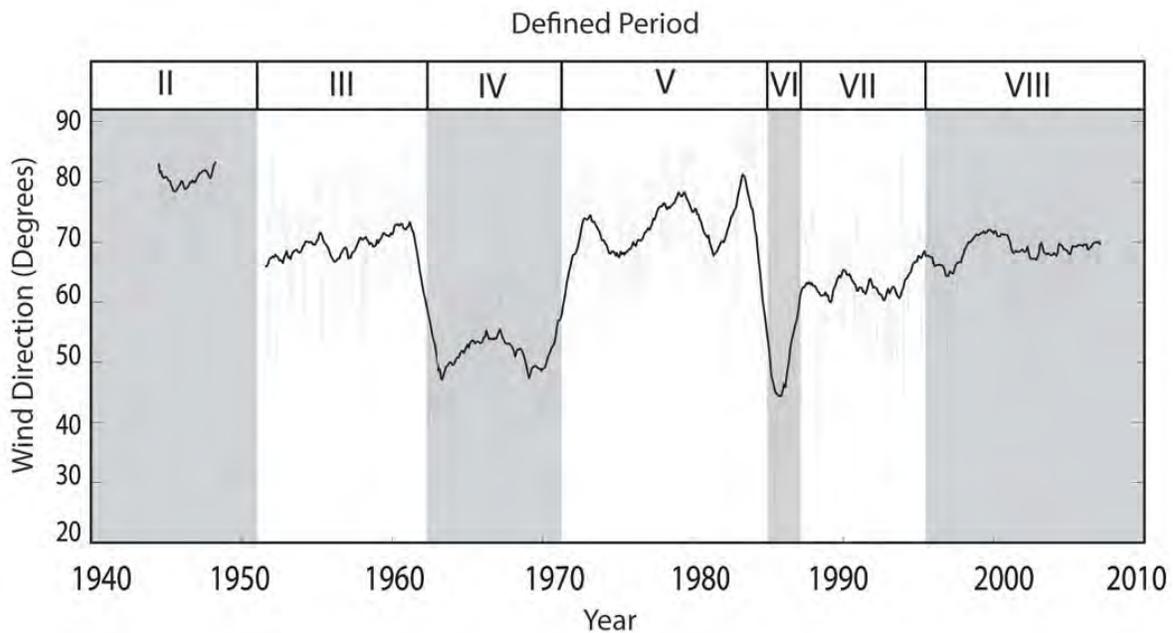


Figure 18 The wind record showing divisions used to separate period of like sediment transport

The combined results of the historical shoreline and hydrodynamic modeling provide both an empirical record of change and process information. The GSTA results further support the transport pathways established by these other two methods. Figure 19 shows a combined interpretation of both GSTA methods. The points of divergence or convergence on Figure 19 are approximately transects 10 and 30 in Bellows and transects 110, 90, 70 in, transect 90 in Lanikai. It is important to note many of these points of littoral transport divergence and convergence are similar between all three datasets.

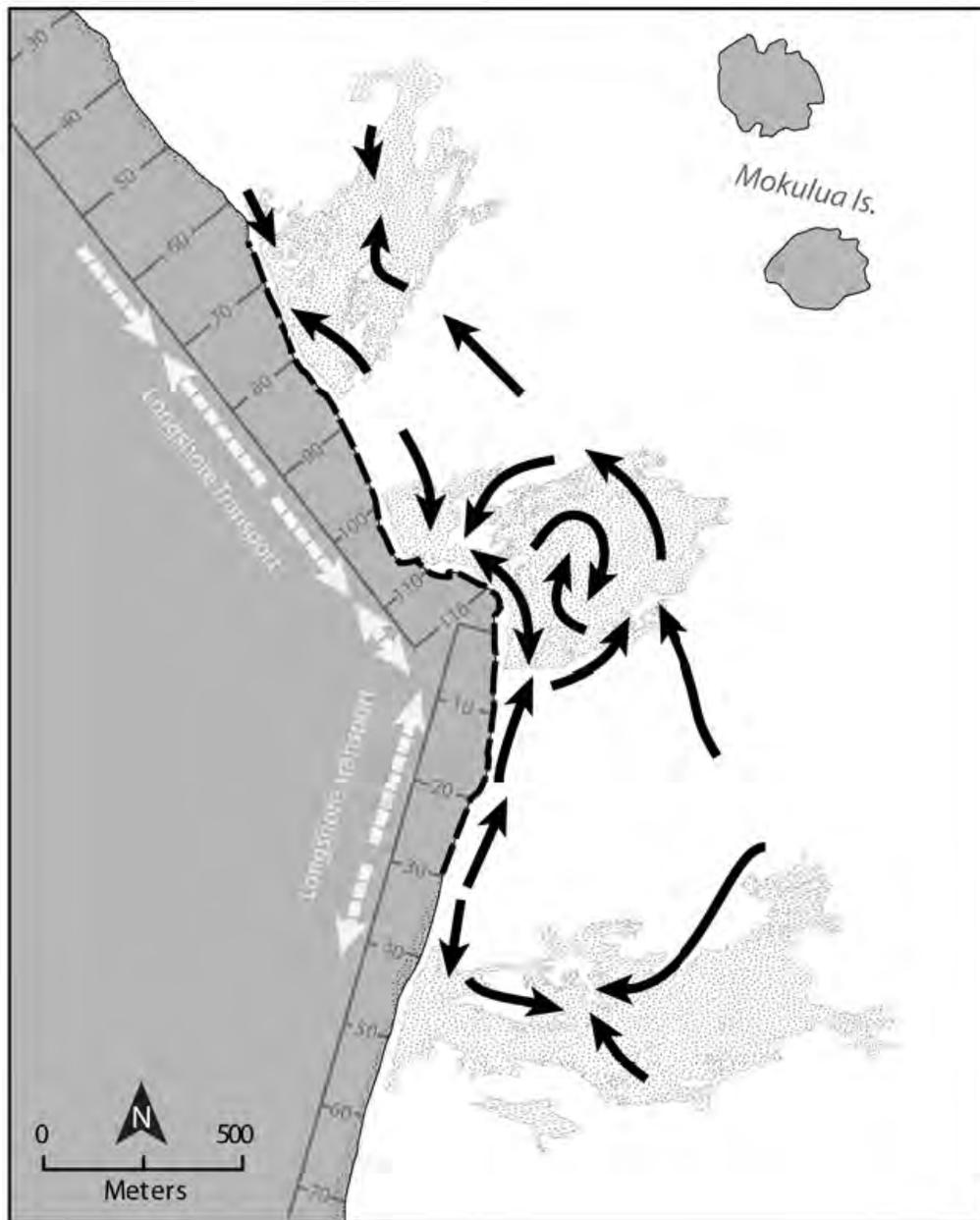


Figure 19 Combined interpretation of results from Le Roux and Gao-Collins methods

XI. SAND SOURCE INVESTIGATIONS

Sand bodies have been mapped by UH in areas offshore from the region. The maps are given in the report, "Reef Top Sediment Bodies in Windward Oahu, Hawaii," which can be found in Appendix F. Research and development of sand manufacturing techniques has been done by the Corps' Geotechnical Structures Laboratory. The final report is not yet received, but a briefing is contained in the Appendix D.

XII. WEB-BASED GIS

A web-based GIS platform was deployed for the SEO Region. The GIS contains georeferenced maps, attributes, and metadata corresponding to SEO/RSM requirements. Aerial photography, digital elevation models, geotechnical information, survey data, wave parameters and other pertinent georeferenced information have been automated via the GIS. The GIS uses state-of-the-art web enabling software to provide real-time access of products to the public through the internet. Examples of the website capabilities are shown in Appendix E. The GIS site can be accessed at: <http://gis.poh.usace.army.mil/rsm/pages/index.htm> .

XIII. WORKSHOPS

Four workshops were held to inform community stakeholders and coastal experts on the goals, progress, and results of the demonstration project and to solicit feedback from attendees. Summaries of the workshops are found in the following web site. <http://gis.poh.usace.army.mil/rsm/pages/workshops.htm>

1. Workshop #1
 - a. June 2004 at Waimanalo Library
 - b. Twenty-five attendees
 - c. Breakout session identified data needs, environmental concerns, environmental permits, potential funding sources, and potential demonstration projects
2. Workshop #2
 - a. June 2005 at Ko`olau Golf club
 - b. Twenty-four attendees
 - c. Breakout sessions on Potential Demonstration Projects identified problems specific to each site, opportunities/issues at each location, alternatives possible in each PDP area, and potential funding sources
3. Workshop #3
 - a. August 2006 as a field trip to PDP sites
 - b. Twenty-six attendees
 - c. Included an overview of Southeast Oahu RSM, update of SEO/RSM activities, site visits, and a summary on follow up discussions
4. Workshop #4
 - a. August 2008 at Ko`olau Golf club
 - b. Thirty-two attendees
 - c. Included presentations and poster sessions of the findings from the PDPs and discussion of the condition of Kailua Beach Park
 - d. Minutes and attendee list presented in Appendix J.

XIV. POTENTIAL DEMONSTRATION PROJECT DESCRIPTION

Four PDPs were selected by participants in Workshop #1 and discussed further in Workshop #2. A PDP was subsequently developed for each site. A summary of the discussion on each PDP with suggested alternative solutions and the selected demonstration project follows.

A. Ka`elepulu Stream

Proposed Demonstration Project Location:

The proposed demonstration project is located at the mouth of Ka`elepulu Stream in Kailua Bay. Beach sand from either side of the stream along with terrestrial sediments deposits at the mouth of the stream and impedes navigation, stops flow, and degrades water quality. To the south, the beach narrows at the boat ramp and terminates at the adjacent headland (Alala Point). North of the stream, the beach is relatively wide and advancing seaward as evidenced by the vegetated backshore and by historical shoreline mapping (Figure 10).

Problem Statement:

Sand is removed from the Ka`elepulu Stream mouth during stream maintenance and is then stockpiled on the stream banks. Some sand is blown inland by trade winds and lost to the system. Some returns to the beach. The scope of the stream management project is limited by permits. A better plan would consider the sand budget on all of Kailua Beach and put the sand where it is most needed. Kailua Beach remains a natural beach system. One problem raised is that the sand removed from the stream mouth acts as a natural filter for upland water quality. Removing the sand allows unfiltered water to enter the ocean.

Opportunities Identified:

The University of Hawaii performed a shoreline erosion study for Kailua in 2000 and has recently updating it. The SEO/RSM study takes advantage of the updated information in calculating the sediment budget.

Since Kailua Beach is natural, study of the beach provides an opportunity to see if what is learned can be applied to other areas. It would be beneficial to learn why Kailua Beach and its dunes remain stable and if there is any interaction between Kailua and Lanikai Beaches.

A workshop participant suggested that the Corps of Engineers might be a source of funding for problems resulting from Kawainui Marsh. If there is a surplus of sand at the stream mouth, it might be used as a sand source for beach nourishment activities. About 10,000 to 12,000 cy of sand was bypassed to Lanikai in 2000. No effect on

Kailua Beach Park was seen. A temporary beach 500-600 feet long lasted for 6 months.

The State Department of Health is doing a TMDL water quality study for the watershed. The data that applies to Ka`elepulu Stream should be obtained.

Issues:

The primary issue raised was on water quality from Ka`elepulu Stream. Storm events can cause the sand berm to be removed resulting in dirty water flowing into the ocean. Should a sand buffer be left in the mouth? There can be a difference between natural and urban river systems. Is Ka`elepulu natural or urban and should it be dirty after heavy rainfall? Enchanted Lakes, located upstream, has not been dredged because there is contamination in the lakes. How is beach management at the stream mouth related to the watershed study and management of Ka`elepulu?

Alternatives:

There are several alternatives to handling the sand removed from Ka`elepulu Stream. A start is to develop and implement a Dune Management Plan. Part of the plan could be to backpass material to updrift locations such as the boat ramp or Lanikai, or to put it back into the north transport channel during the right conditions. Another alternative is to stockpile the sand and use it for individual erosion events as needed.

Alternatives related to the stream include restoring the natural stream flows so that the channel flushes itself, restoring the Kawainui Marsh natural drainage patterns and developing and implementing a watershed study.

B. Lanikai Beach

Proposed Demonstration Project Location:

The proposed demonstration project is located along the entire shoreline of the Lanikai community.

Problem Statement:

Shoreline erosion has resulted in the loss of dry beach along the southern portions of the Lanikai shoreline. To the north, the beach tends to widen thereby providing a buffer to wave-induced impacts to upland development. Almost the entire length of the Lanikai shoreline has been hardened through construction of various types of coastal structure.

During the workshops, participants raised many questions on what should be done at Lanikai. Participants discussed goals for restoration; loss of recreation; seawalls; characteristics, trends, and patterns of erosion; and sediment budgets and beach stability.

Opportunities:

Some of the opportunities listed include developing a sediment budget, mapping biological zones and structures, modeling waves and currents, and developing a Special Management Area Plan. Other potential opportunities were conducting an economic study, use as a fisheries management area, and planning for recreational use.

Issues:

There are many issues that might potentially affect finding a solution for Lanikai's erosion problems. The causes are complex and more than one type of solution will probably be necessary. Use of beach nourishment could damage marine life including coral, algae, and fish. Nourishment will affect water quality. Since shore-front homes extend the entire length of Lanikai Beach and most of these homes are protected by seawalls or revetments, new shore protection schemes will have to use the area seaward of the walls. It will be difficult to receive approval to add additional shore protection structures, because both the community and the regulatory agencies may object.

Other issues discussed at the workshops include the need for a historical study of the shoreline, the possibility of considering the sand dune areas of the beach as ecosystems rather than just recreational areas, and the need to protect lateral access.

Alternatives:

Alternatives suggested by workshop attendees included using a combination of beach fill and hardened structures, creating designs that would replace existing seawalls, and considering the beach as an ecosystem. To get sufficient knowledge to design any new solution, attendees listed developing a master plan and focusing on science such as sediment budget analysis.

C. Bellows Air Force Station

Proposed Demonstration Project Location:

The proposed demonstration project is located at the northern end of Bellows Air Force Station in front of recreational beach cottages. The project extends approximately 3,000 linear feet along the shoreline.

Problem Statement:

Erosion is threatening the recreational beach cottages. To stop the erosion, a rock revetment has been constructed along the shoreline. This revetment is seen by some in the community as tying up the sand supply for down-drift beaches in Lanikai. The

beach to the south is used for amphibious training by the Marines and must also be preserved. The training beach will likely be affected if beach dynamics change by the cottages. Marine training is going to be an important factor in the solution for Bellows. Another important factor is that Bellows is a rest and recreation area for military members and their families.

Opportunities:

There is an opportunity to build partnerships with the Marine Corps Base, Air Force Station, City & County of Honolulu, and others that would facilitate solving coastal problems in overlapping areas of interest. Another opportunity is to receive information from the AFS pier dump site “installation restoration study” and coincidentally for the RSM team to help educate the Air Force staff.

There are other opportunities to coordinate with the EPA/DOH on priority pollutant cleanup of the Ko`olaupoko watershed, perform pilot projects on selected areas of Bellows Beach, and to model the original coastal system.

Issues:

Workshop attendees presented a number of issues that should be considered during the search for solutions to Bellows’ erosion. These are the need to protect lateral access, the need to add reefs into the models, and the need to consider endangered species such as sea turtles in proposed studies.

A participant asked what effect the revetment has on other shorelines nearby. Another asked about conflicts with military training.

Alternatives:

A number of alternatives were suggested at the SEO/RSM workshops. These include moving cottages back, removing the revetment and allow a natural shoreline, moving the revetment inland, removing the jetty at Waimanalo Stream to release trapped sand, recycle or back-pass sand in front of the revetment, and investigate sand that might be trapped in the streams. The solution will likely include more than one method.

D. Kaupo and Kaiona Beaches

Proposed Demonstration Project Location:

Kaupo Beach is located south of the Makai Research pier. The length of the potential demonstration project area is approximately 1,500 feet. Kaiona Beach is located north of the pier and the problem area is also approximately 1,500 feet in length. These two narrow beaches front Kalanianaʻole Highway and provide only minimal protection against wave induced impacts to the road and adjacent upland development. To the south of Kaupo Beach, a rocky headland extends out into Waimanalo Bay and provides

coastal storm damage protection to the highway. North of Kaiona Beach, the highway turns mauka of the shoreline. Between the two problem areas, the shoreline is sheltered from wave energy by Manana Island and a wide shallow reef system.

Problem Statement:

Erosion is threatening approximately 500 to 800 feet of Kalanianaʻole Highway. The Beaches are narrow and unstable and offer little protection to the highway. The embankment is steep. Erosion is undermining the highway and the state Department of Transportation is placing pilings to stabilize the embankment.

There are a number of issues that reduce the options for a solution to the problem. The area sees high recreational use for surfing, wind surfing, and fishing. The nearby beaches are heavily used. Sea Life Park is very close to the damaged road. The road provides the sole access around Makapuʻu Point from Waimanalo to Hawaii Kai. There is not sufficient space to move the road inland because of the cliffs or because of Hawaiian homelands between the road and the cliffs. Also rock fall hazard is high beneath the cliffs. Drainage under the road might contribute to the erosion.

Makai Pier and its breakwater are located just offshore near the highway erosion area. These structures plus nearshore bathymetry will affect coastal waves, currents, and consequently beach erosion. Manana Island and Kaohikaipu Island are located offshore from the site and do have an effect on coastal processes.

Opportunities:

Workshop attendees listed several opportunities presented by the problem.

The State of Hawaii Department of Transportation has a plan for coastal work along windward Oahu highways that was completed by Ed Noda & Associates. The report has good background information and contained a plan to widen the road. Coordination with DOT is advisable since the problem is erosion below the highway.

Detailed wave models can be used to determine changes in wave patterns with different versions of structural solutions.

There is an opportunity to develop a site-specific sediment budget.

The State Department of Health (DOH) designated this area for priority pollution control. There is an opportunity to work with DOH prior to selecting a solution.

Alternatives:

A number of alternative solutions were listed during the SEO/RSM project workshops. These include a groin, an offshore breakwater, bank stabilization, beach nourishment, elevating the road on pilings over the beach, and moving or abandoning the road.

XV. POTENTIAL DEMONSTRATION PROJECT CONCEPTUAL ALTERNATIVES

A. Ka`elepulu Stream Mouth

The south end of Kailua Beach and the Ka`elepulu Stream mouth are shown in Figure 20. Based on POH research, the recommended alternative for Ka`elepulu Stream is straightforward. The sand removed from the stream mouth should be placed at other locations on Kailua Beach where it is most needed (see Figure 21). Kailua Beach is accreting except at the south end between Alala Point and the stream.

Based on informal communications with City and County of Honolulu maintenance personnel, approximately 3,000 cubic yards of sand is removed from the stream mouth monthly (36,000 cubic yards per year). The material is currently being pushed up onto the banks of the stream and spread north and/or south of the stream mouth as deemed appropriate. The portion of sand relegated to the stream bank can be considered as lost to the littoral zone unless physically reintroduced back into the active beach profile.

Alternatives for effective utilization of the beach quality sand that is periodically extracted from the Ka`elepulu stream mouth include bypassing and back passing the material to various reaches along Kailua Beach. Construction of rubble mound groins on either side of the stream, designed to intercept the material before it enters the stream mouth, is another sediment management option. As the holding capacity of the groin fillets begin to reach capacity, the sand would be redistributed along appropriate reaches of Kailua Beach. Redistribution of the sand currently locked up along the banks of the stream, back into the littoral zone, should also be considered in the development of best management practices for Ka`elepulu stream mouth clearing activities.

Kailua Beach is currently accreting except at its southern end between Alala Point and the Ka`elepulu stream. As previously discussed, sand removed from the stream mouth should be placed along reaches of Kailua Beach where it is most needed (Figure 21). The City and County of Honolulu has a Department of the Army (DA) permit that allows placement of the sand excavated from the stream along designated reaches of shoreline. The DA permit should be reviewed and revised if necessary to allow sand placement anywhere within the entire Kailua Bay littoral cell.

Low flows through Ka`elepulu stream may be the cause of excess sedimentation at its seaward extent. Historically, the stream may have had sufficient flow velocities to periodically flush sediment from its mouth and into the receiving waters of Kailua Bay. Impacts of the Kawainui Marsh Federal flood control project on the flows through Ka`elepulu Stream may be responsible for the lack of sediment flushing at the mouth of the stream. Section 1135 of the 1986 Water Resource and Development Act provides authority for the U.S. Army Corps of Engineers to restore degraded ecosystems through modifications and operations of Federal structures. The maximum Federal cost for project development and construction of any one project is \$5,000,000 and each project must be economically justified, environmentally sound, and technically feasible. At the

request of an appropriate non-Federal sponsor, a Section 1135 study might be initiated to investigate the impacts of the Kawainui Marsh flood control project on the Ka`elepulu stream ecosystem.



Figure 20 Ka`elepulu Stream and Kailua Beach (UH photo)

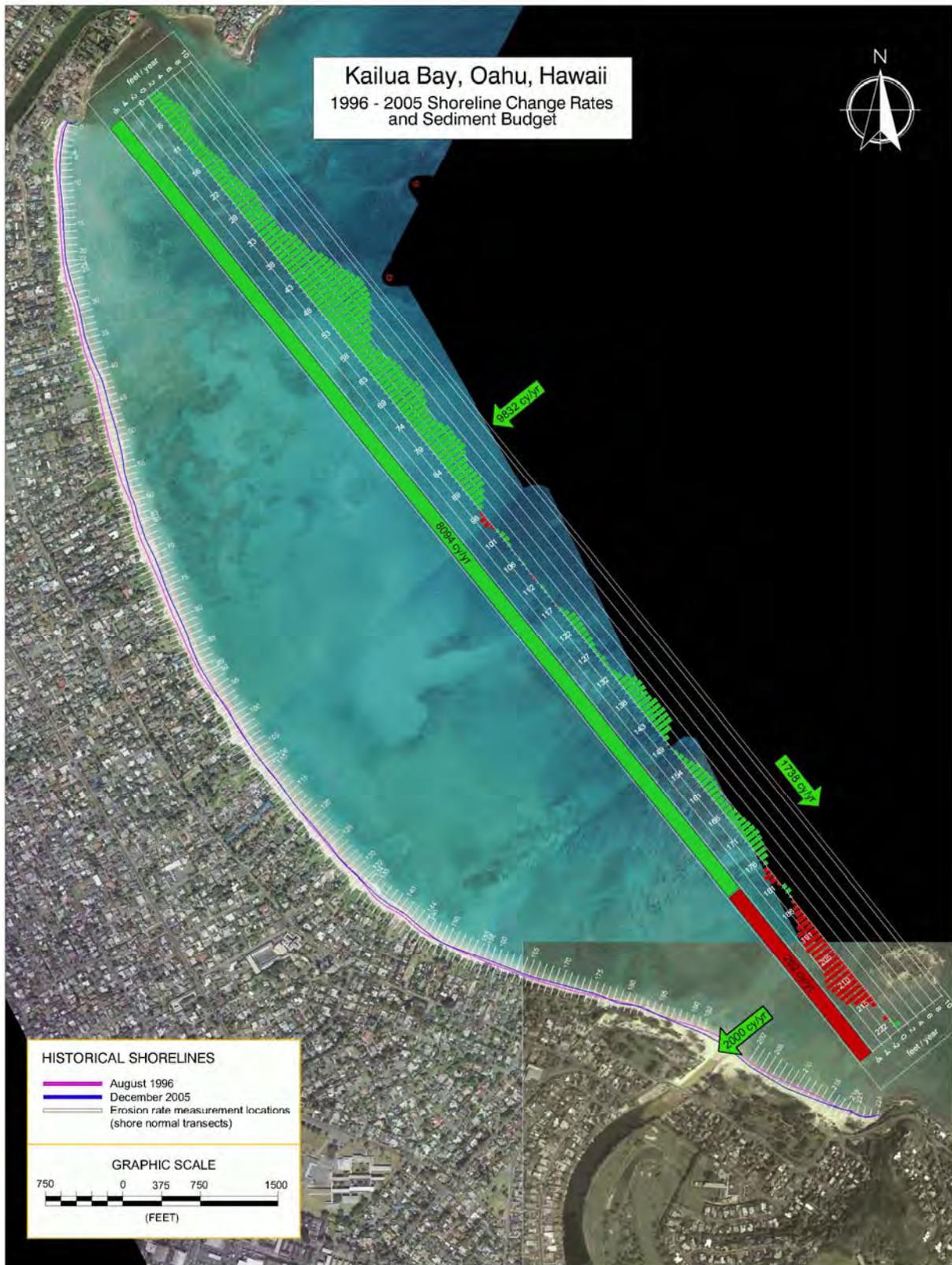


Figure 21 Kailua Sand Budget

A result of RSM workshop #4 was for development of a focus group to discuss management of the stream mouth and sand. Discussions are underway between the State of Hawaii Department of Health and the City and County Department of Parks and Recreation to reach an agreement on relocating sand from the Kaelepulu Stream mouth and stream banks to the eroding area to the north of the boat ramp.

A meeting was held on September 18, 2008, to discuss the erosion problem at Kailua Beach. Attendees included representatives from the U.S. Army Corps of Engineers, State of Hawaii, City and County of Honolulu, University of Hawaii, and the Hawaii and U.S. legislatures. Discussion focused on the effects of backpassing sand from the Kaelepulu Stream mouth to the eroded area adjacent to the boat ramp. The group agreed to draft a Memorandum of Understanding to outline issues of placing sand at the boat ramp and to ensure that all parties have agreed beforehand on procedures in the event that a complaint is registered. Meeting minutes are included in Appendix I.

B. Lanikai Beach

The proposed demonstration project is located along the entire shoreline of the Lanikai community (Figure 22). Shoreline erosion has resulted in the loss of dry beach along the southern portions of the Lanikai shoreline and at the north end near Alala Point. To the north, the beach tends to widen. Almost the entire length of the Lanikai shoreline has been hardened through construction of various types of coastal structures.

The erosion has been studied, but the process and causes are not completely understood. There is a reef offshore from Lanikai where most waves break. The area between the reef and the shoreline is complex and not easily characterized. The bottom is a mix of sand, hard substrate, and coral heads. The nearshore area has changed in the lifetime of some residents.

The calculated sand budget for Lanikai is shown in Figure 23. The graph shows that the southern half of Lanikai Beach and the north end approaching Alala Point are eroding. The north central portion is accreting, due to longshore transport mainly from the south. Offshore sand body locations as determined by UH are shown in Figure 24.

The following is a hypothesis of what could be happening in Lanikai. More data are necessary to prove, disprove, or refine the hypothesis. The nearshore configuration at Lanikai appears to influence the erosion and accretion at the beach. At the north end offshore from Alala Point, there appears to be a gap or deeper area in the reef south of Flat Island. More wave energy can reach the beach than at locations farther south. Waves passing through the gap are diffracted resulting in a dispersion area or node at the beach. That is, sand is pushed in both directions leaving a narrow beach.

In the north-central section of Lanikai, the beach becomes wider, and photos show waves breaking on the outer reef thereby reducing their energy. Also, the bottom inside the reef looks to have more reef material, rocks, or hard bottom that may also reduce

wave energy. It appears possible that the sand is pushed into an area of lower energy and remains there to form the wider beach.

The southern part of the beach, noted for erosion problems, has two large sand patches reaching from the shoreline to the outer reef. The lack of breaking waves suggests deeper water again. The Mokulua Islands are located just outside the reef break. The islands block and diffract waves causing mixed wave patterns as they propagate to the beach. The beach will typically conform to these mixed patterns.

The shoreline change map (Figure 11) shows that the southern part of Lanikai Beach went through an accretion/erosion cycle that may have started in the 1940s or 1950s reached maximum accretion between 1967 and 1971, and returned to its starting point by about 1989. The cycle appears to have been more than 40 years. Of interest is that the center section of the beach that has recently been accreting was much narrower in 1967 when the southern part was widest. If the reason for the cycle can be determined, then solutions for current erosion might be more apparent.

There is probably no single solution for erosion at Lanikai. Community and regulatory agency restrictions may limit the use of more coastal structures for shore protection. Moving homes inland is not likely to be acceptable to property owners and there is no inland space. Beach nourishment is probably acceptable to both residents and regulatory agencies, but available and economic sand sources will have to be identified.

At the north end of Lanikai, the sediment budget (Figure 23) shows that sand moves into the accreting area south of Alala Point. The north central portion of the beach is accreting and probably needs no protection now. However, it appears to be accreting with sand carried from the eroding southern half of the beach. The southern part of the beach could benefit from beach nourishment to replace the eroded volume. UH studies (Appendix F) have located nearby offshore sand deposits, particularly off Wailea Point. These deposits may have sufficient sand to nourish Lanikai Beach; however, the deposits may not be thick enough to dredge efficiently, as many sand areas are less than one meter thick. Beach nourishment, then, would require additional sand from other sources either offshore or land-based.



Figure 22 Lanikai Aerial Photo

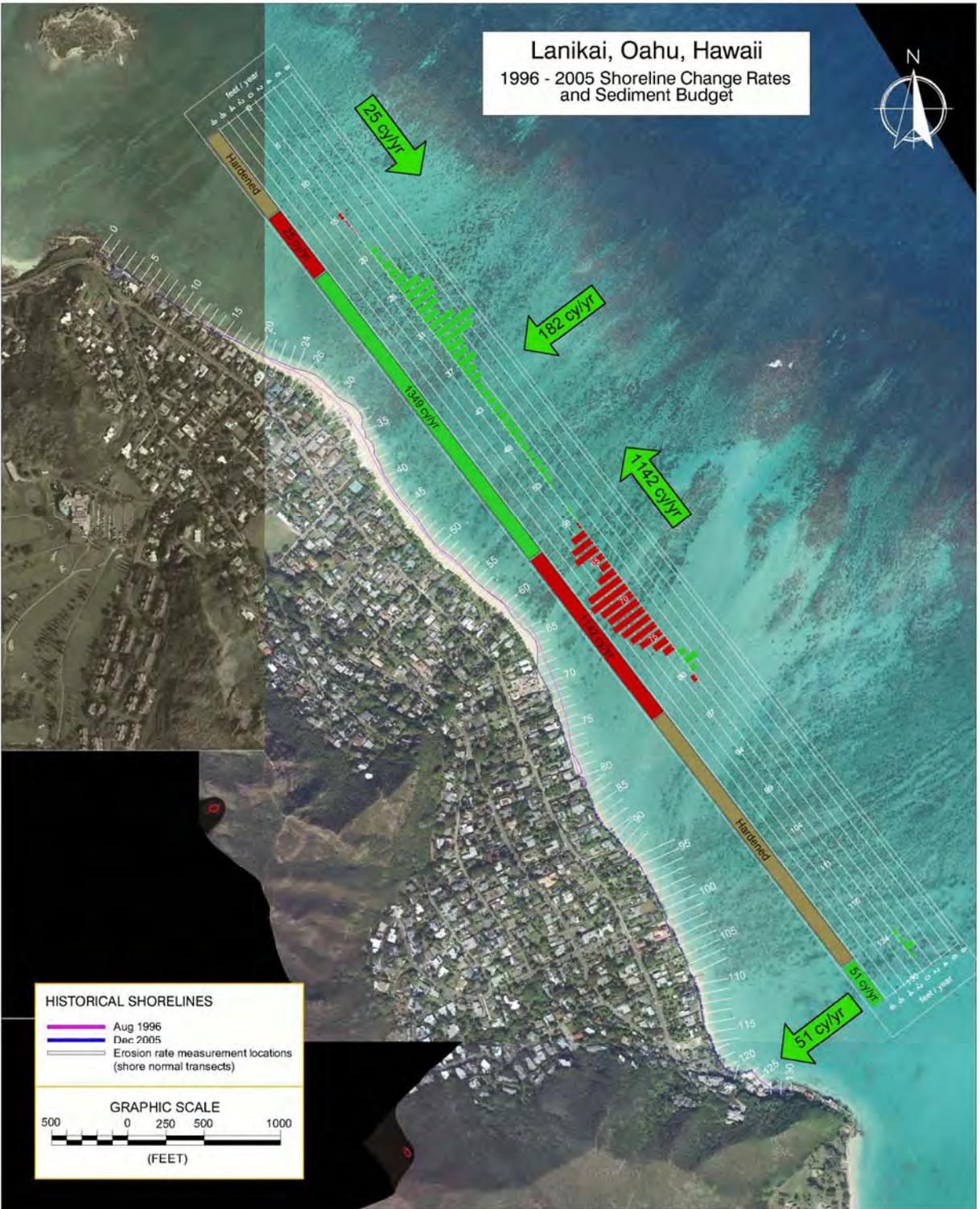


Figure 23 Lanikai Sediment Budget

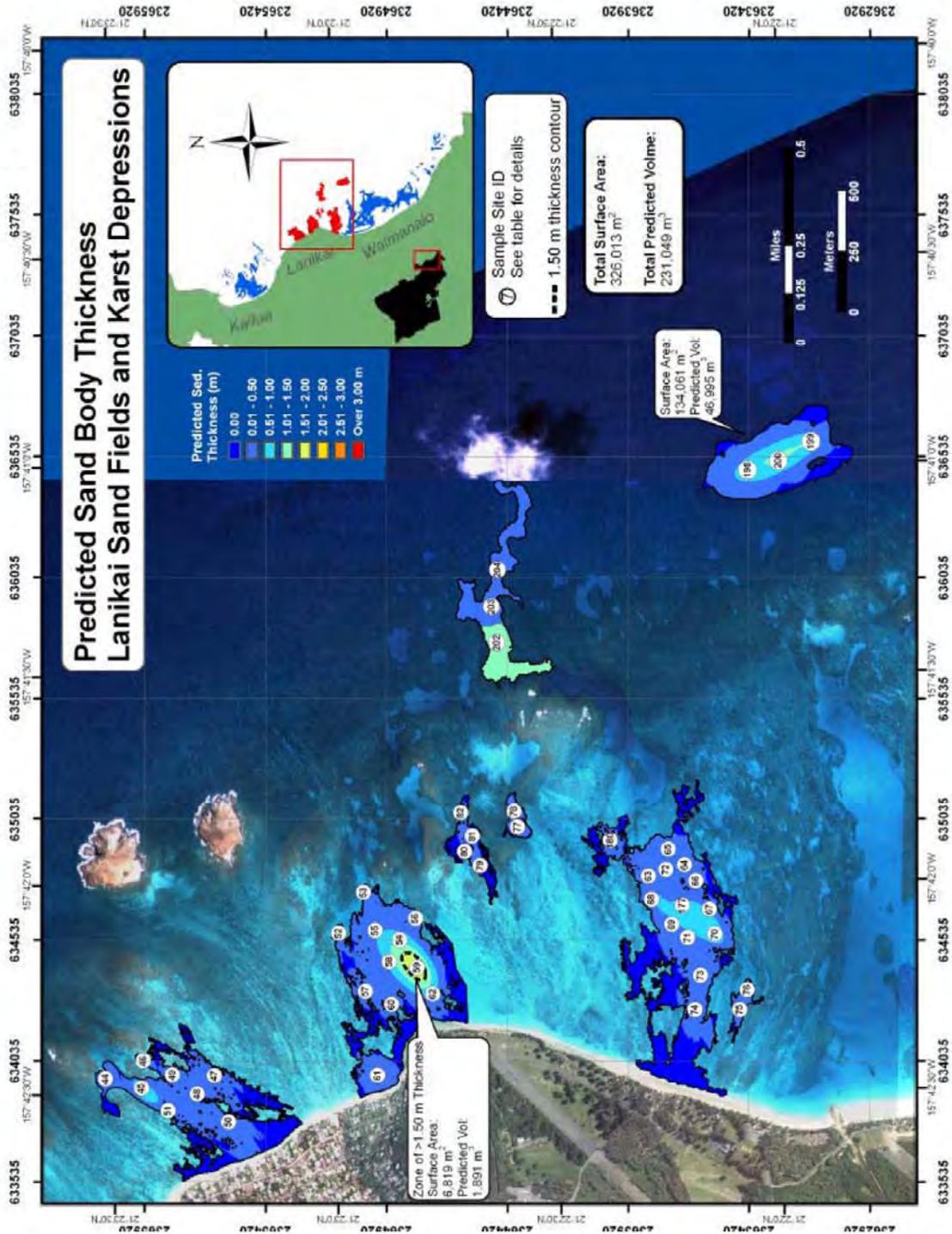


Figure 24 Lanikai Sand Bodies (University of Hawaii)

The selected demonstration project for Lanikai Beach included two conceptual designs for shoreline restoration—beach nourishment with and without structures—as methods of controlling erosion along a shoreline armored by seawalls. Oceanographic design parameters were developed for the site; an east-northeast wave with height 6 feet and period 8 seconds was determined to be the prevailing condition. Numerical modeling using REF/DIF-1 and BOUSS2D was performed for the four wave conditions presented in Table 1. An overview of the study area and a view of the wave orientations for the prevailing wave condition are shown in Figure 25.

Table 1 Selected typical deepwater wave conditions for the Lanikai study based on WIS Station 99 and CDIP Mokapu Buoy data

Wave Direction	Wave Period (seconds)	Wave Height (feet)
N	14	6.0
NE	8	6.0
ENE	8	6.0
E	9	8.0

The nourishment without structures conceptual design produced a minimum dry beach width of 30 feet over two shoreline reaches totaling more than 6,000 feet. Figure 26 shows the planform view of this configuration. The existing dry beach between the two conceptual nourished reaches shown in Figure 26 presently is greater than 30-feet wide and does not need nourishing. The cost of mining offshore sand deposits has been estimated to be \$150 per cubic yard. This conceptual design requires 182,000 cubic yards of sand for the initial nourishment at an estimated cost of \$33,000,000. Additional nourishment of the beach was projected to be necessary every 8.4 years based on historical shoreline change rates presented by the University of Hawaii Coastal Geology Group (CGG). Total cost of this conceptual design over 50 years is estimated to be \$109,000,000.

The nourishment with structures conceptual design included construction of 12 tuned T-head groins with nourishment between the groins producing arc-shaped beaches. The groin heads were positioned to orient the gap between the groins to the incident wave crests. Structure size and spacing determine the location of the Mean Low Water line of the beach, based on empirical data for natural headland beaches. Figure 27 shows a generalized schematic of a tuned T-head groin system.

Two conceptual groin fields were designed for Lanikai Beach. The north field consists of three groins between Alala Point and the accreted area of shoreline. The southern field consists of nine groins, with the southernmost groin located adjacent to Wailea Point. A planform view of this layout is shown in Figure 28. The groins head and gap orientations were determined from numerical modeling of prevailing conditions. The conceptual groins are designed to be rubblemound structures. Figure 29 shows typical

groin and beach cross sections. Experience has shown that these projects require annual maintenance costing approximately 0.5% of the initial project cost.

This conceptual design produced a minimum dry beach width of 30 feet in each beach cell. This conceptual design requires 146,000 cubic yards of sand at an estimated cost of \$150 per cubic yard. Construction costs, including sand, rock, and labor, are estimated to be \$33,400,000 for the initial construction, with a total cost of \$41,600,000 over 50 years.

The costs presented for beach nourishment assume that there is a suitable source available. The University of Hawaii has identified and quantified two offshore sand sources near Lanikai. A cost of \$150 per cubic yard was developed based on cost estimates for offshore sand recovery at other locations in Hawaii. Final design would require a detailed estimate from a dredging contractor, which could result in a different unit cost.

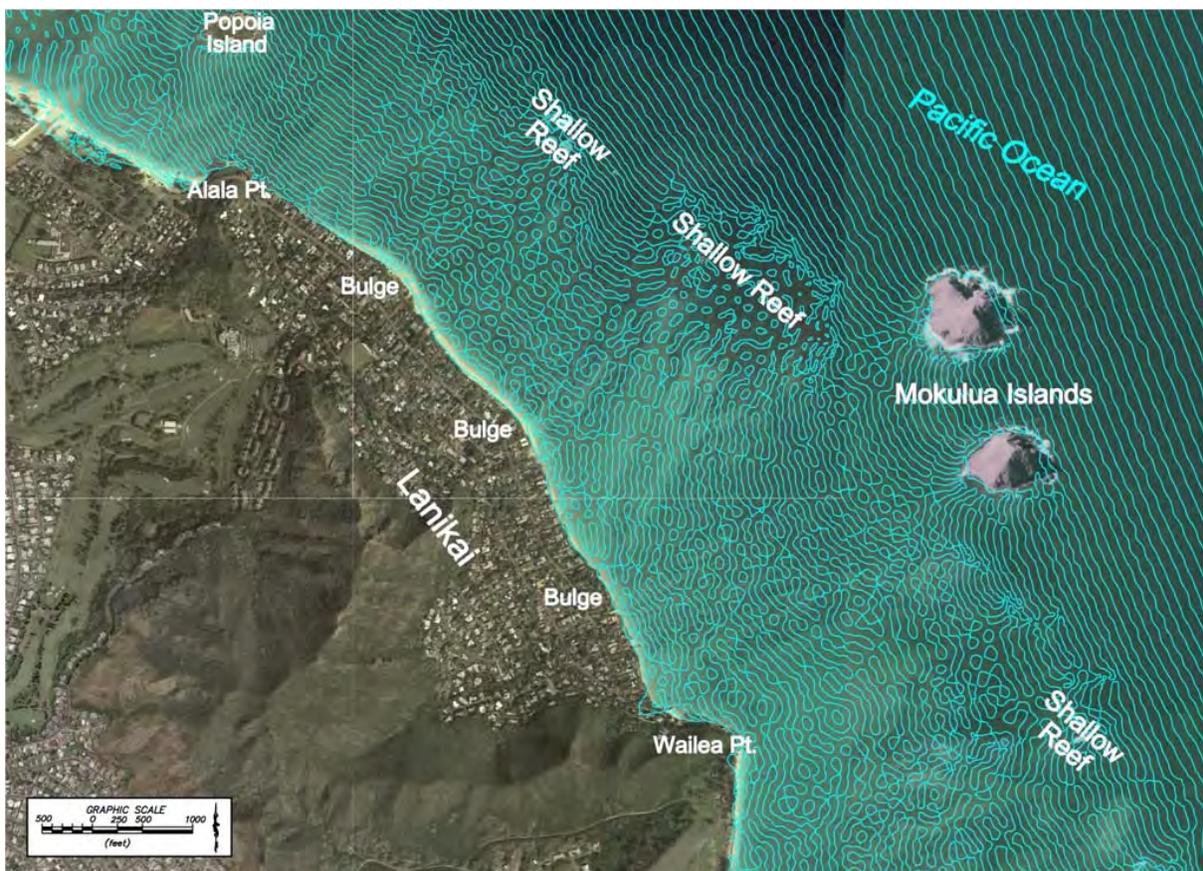


Figure 25 BOUSS2D wave crest orientation, $Dir = ENE$, $H = 6$ feet, $T = 8$ seconds

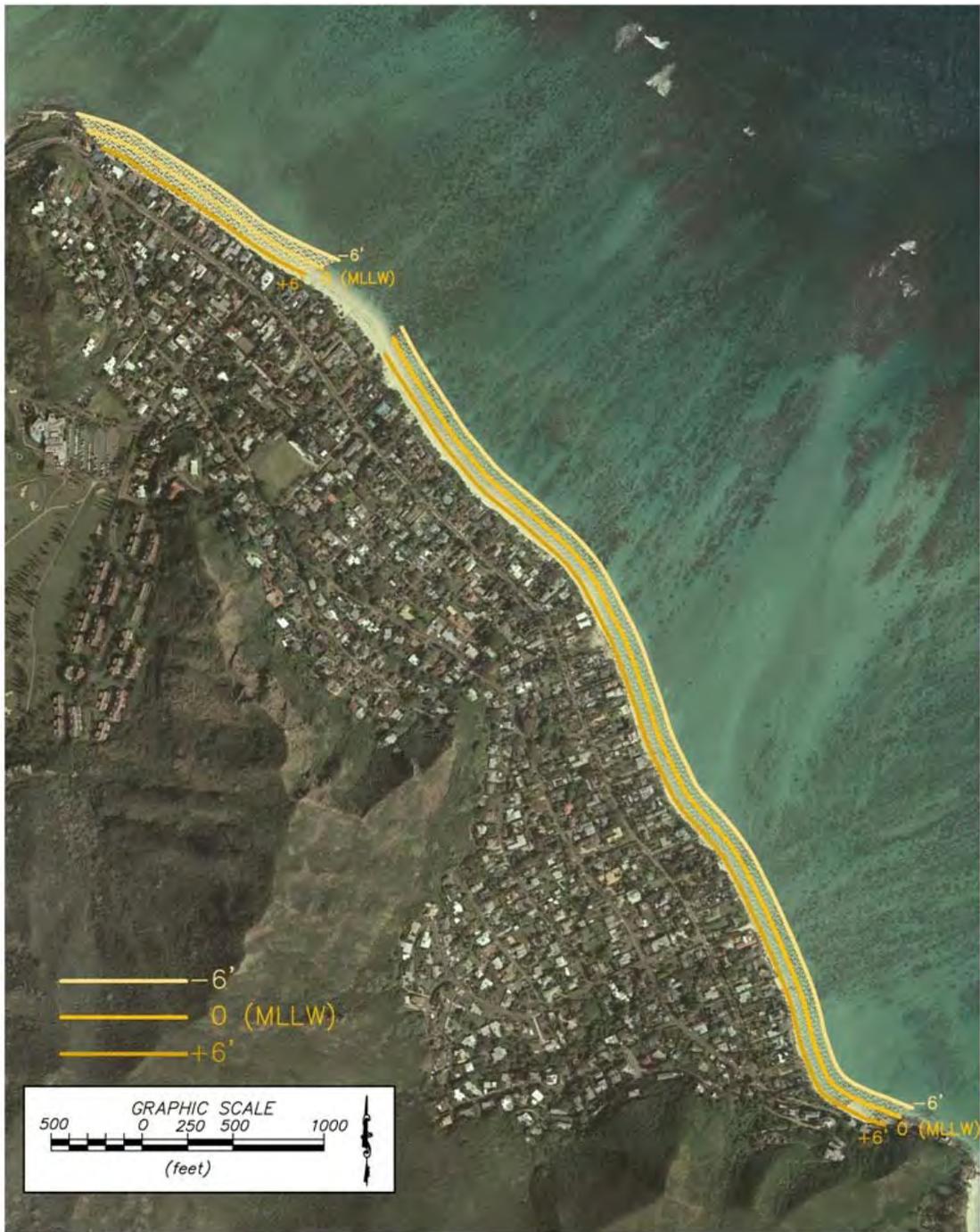


Figure 26 Beach nourishment without structures conceptual design--Lanikai

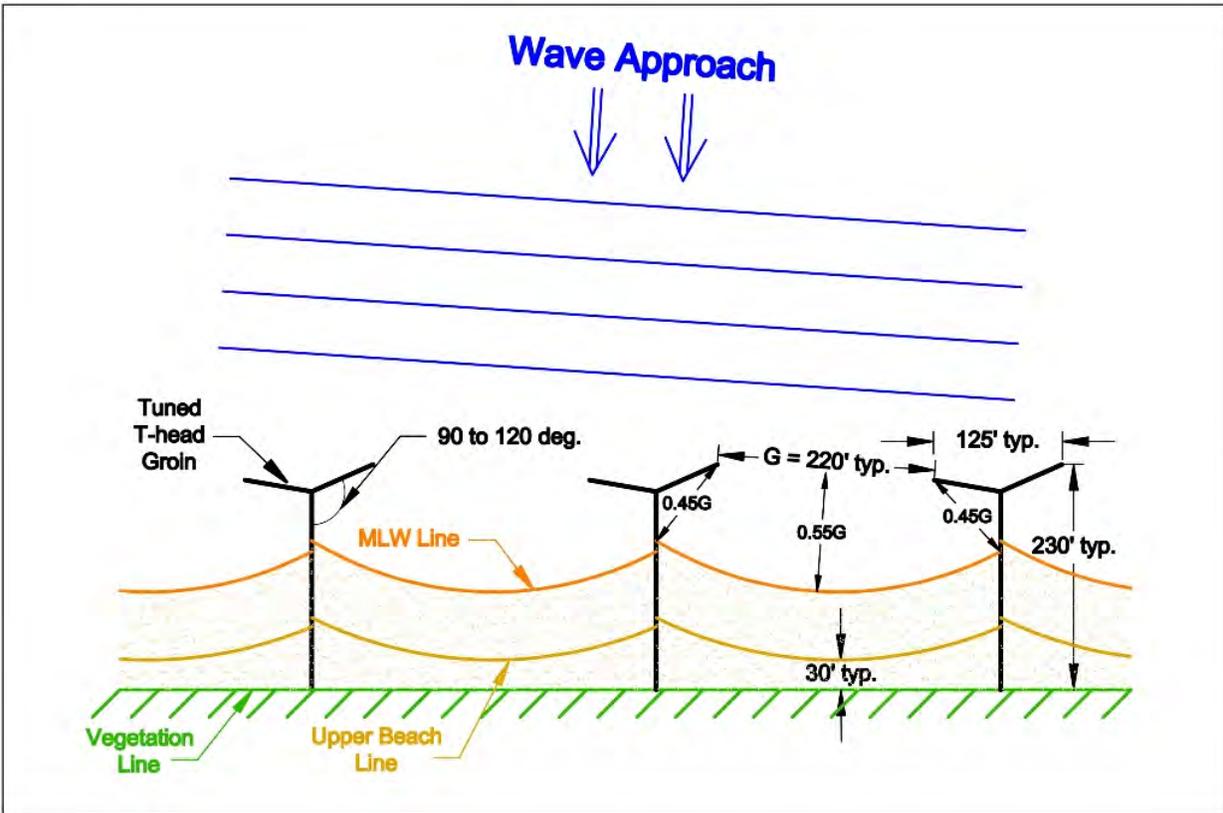


Figure 27 Tuned T-head groin schematic



Figure 28 Beach nourishment with structures conceptual design--Lanikai

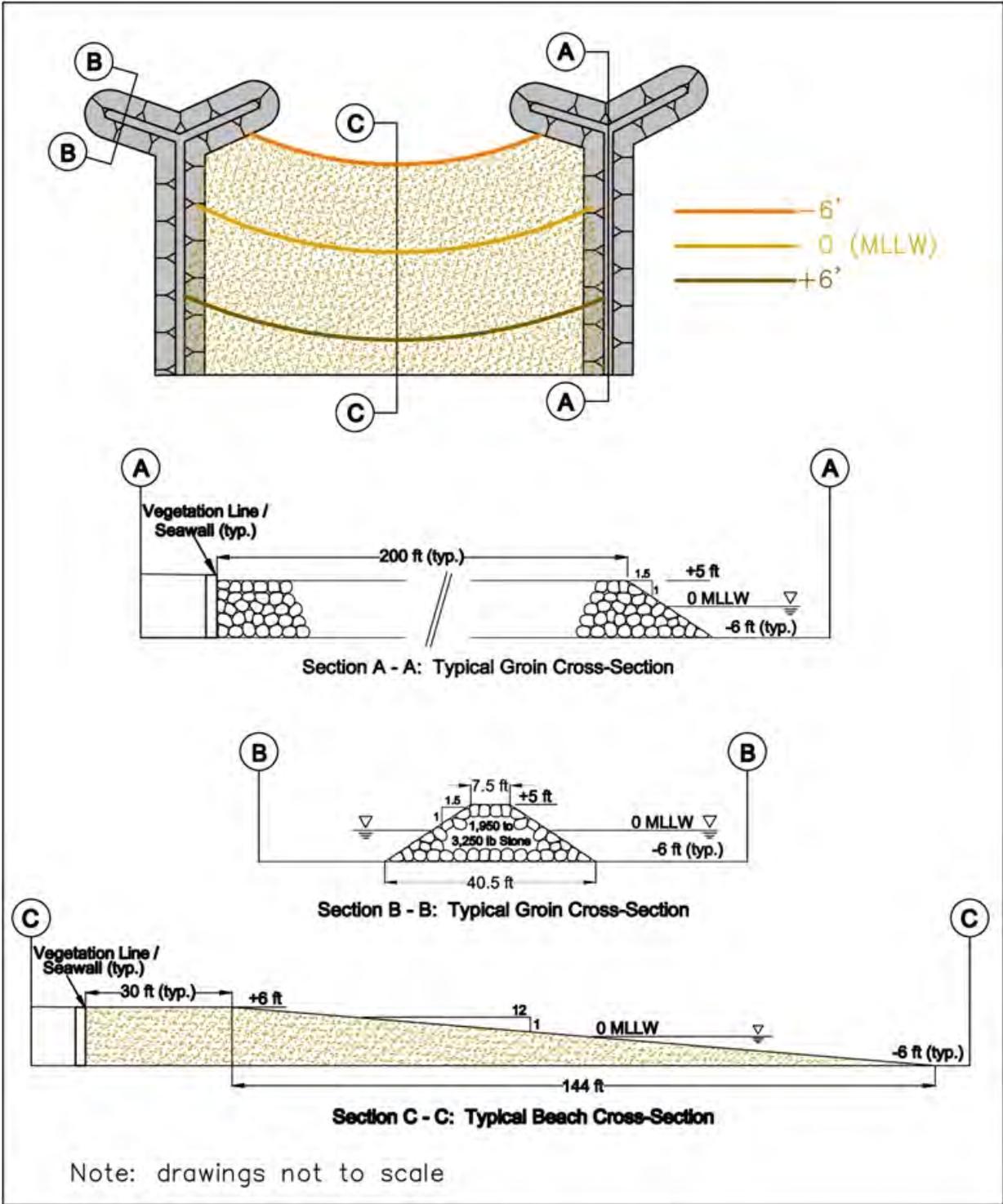


Figure 29 Typical groin and beach cross sections

C. Bellows Air Force Station

Bellows Air Force Station has approximately two miles of shoreline. The northern portion of the shoreline has experienced severe erosion and has been stabilized with rock revetments. There is presently no dry beach fronting the 2,300 feet of revetments that extend southward from Wailea Point. The southern portion of the shoreline consists of wide sandy beach. Aerial photos of Bellows are shown in Figure 30 through Figure 32.

There are several factors that restrict the solutions that might be applied to Bellows. This is a military recreation area where families come to enjoy the beach. Sacrificing any of the beach or backshore area would be counter to the intended use. The beach is also used for amphibious training by the Marines, so any solution that interfered with that training would likely face opposition. It is obviously critical to receive support and cooperation from the Air Force and Marine Corps to make any proposed solution work. If Bellows removes the revetment, the resulting erosion will take valuable land and eventually make the cottages unusable. A solution that helps Lanikai at the expense of Bellows is highly unlikely to be acceptable. With that in mind, it does not appear likely that the Air Force would readily agree to remove the revetment.

An obvious partial solution is to move the threatened cottages inland. Many are built close enough to the water that, even without erosion, they could be subject to storm wave damage, especially if the revetment were to fail.

Based on SEO/RSM study data and the beach and nearshore configuration shown in aerial photographs, the north beach needs a continuing supply of sand. Sand budget calculations show that the south end is accreting, while the north end is unable to naturally hold a beach (Figure 33). Therefore, beach nourishment should be considered a partial solution. UH studies show that there are offshore sand bodies along Bellows Beach. These are typically thin layers with only small areas being over 1.5 m thick. University of Hawaii field investigations indicate sufficient quantities in the bodies to make up the annual loss. Upland sand might be an additional source at Bellows. The base is located on a sandy plain, but the availability of inland sand must be studied before a decision can be made on its use.

To slow down nourished sand movement out of the local system, groins or offshore breakwaters might be necessary. State and county agencies typically discourage the use of shore protection structures, so groins and breakwaters will probably be opposed.

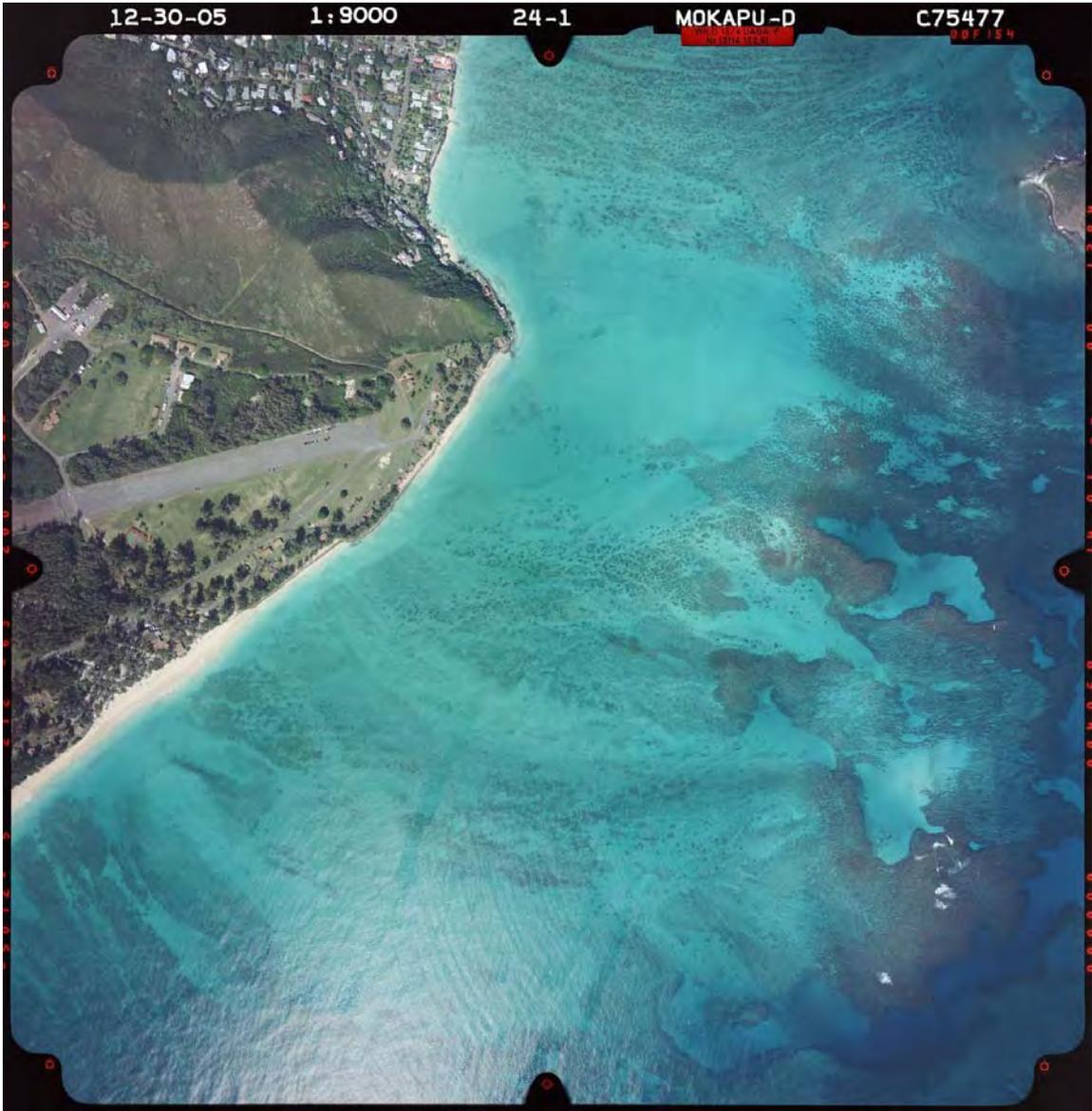


Figure 30 Bellows North End



Figure 31 Bellows Central



Figure 32 Bellows South

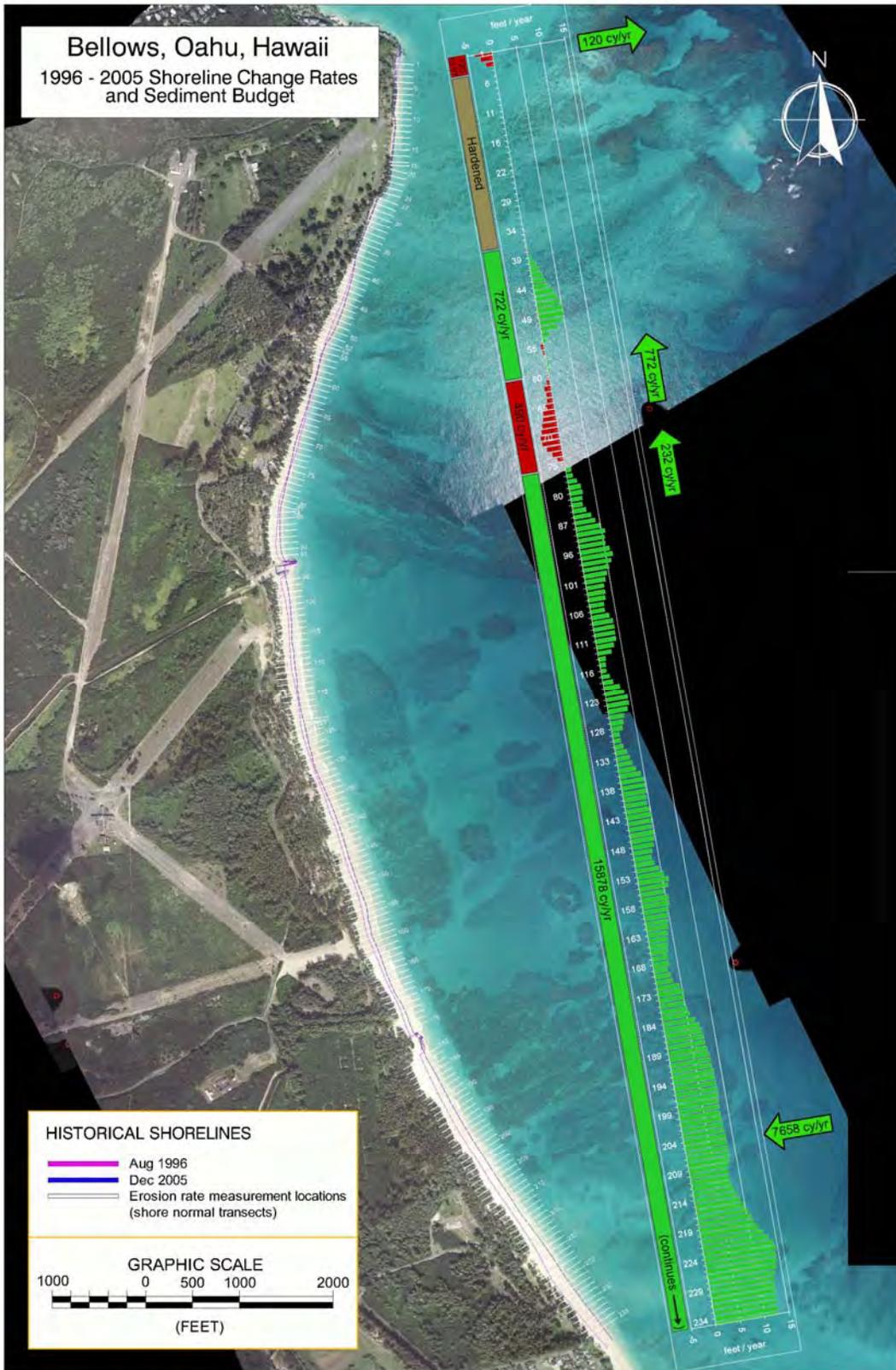


Figure 33 Bellows Sand Budget

The demonstration project at Bellows Air Force Station beach presented three conceptual designs along a shoreline where a series of revetments protect recreation cottages, but also trap sand that otherwise might go into the littoral system. The first two conceptual designs involved nourishing the beach, while the third investigates the effect of removing the revetments.

The first conceptual design included nourishment from Wailea Point to the Waimanalo Stream jetties to produce a minimum 30-foot wide beach crest. Figure 34 shows the overall layout of this conceptual design. The nourished shoreline location was based on the 1988 shoreline, which was the last continuous sandy shoreline recorded in historical aerial photographs. This conceptual design requires 247,400 cubic yards of sand and would have an initial cost of \$43,000,000. The beach is projected to require re-nourishment every 7.5 years, based on historical shoreline change rates presented by the University of Hawaii Coastal Geology Group. The cost of mining offshore sand deposits has been estimated to be \$150 per cubic yard. The estimated total cost over 50 years is \$95,000,000.

The second conceptual design reduces the nourishment coverage to the revetted shoreline only, producing 30 feet of dry beach along that reach, as shown in Figure 35. The nourished shoreline would smoothly join the present shoreline approximately 200 feet south of the end of the revetment. This conceptual design would produce a minimum 30-foot dry beach width; however, the shoreline would not necessarily be stable, particularly where the shoreline bulges near the center of the nourished reach. This conceptual design would initially require 106,000 cubic yards of sand for a cost of \$18,500,000. Re-nourishment every 7.5 years would result in a total cost over 50 years of \$55,000,000.

The costs presented for beach nourishment assume that there is a suitable source available. The University of Hawaii has identified and quantified two offshore sand sources near Bellows and Waimanalo. A cost of \$150 per cubic yard was developed based on cost estimates for offshore sand recovery at other locations in Hawaii. Final design would require a detailed estimate from a dredging contractor, which could result in a different unit cost.

The third conceptual design involves removing the revetments and predicting the response of the shoreline. The short-term equilibrium shoreline position is shown in Figure 36 and was found to be as much as 52 feet inland of the present revetment location, endangering as many as eight structures. Where possible, the buildings could be relocated further inland to mitigate the potential damage.

Construction of seawalls or revetments may impound sand, thus interrupting the natural movement of sand along the shoreline. In addition to sand that might be impounded by the revetments, wave-structure interaction causes sand loss in form of profile deflation, where the foreshore face slope flattens and lowers. An estimate is made presently to quantify the sediment deficit caused by the revetments at Bellows AFS.

The unrevetted vegetation line shown in Figure 36 is an estimate of the location of the present-day vegetation line if the shoreline had not been stabilized. The average shoreline recession is 25.6 feet and LiDAR data shows the backshore elevation to be +7 feet MLLW. The beach foreshore is expected to have a 1:12 slope starting at the projected vegetation line. Representative existing and unrevetted cross-shore profiles were determined and are shown in Figure 37. Zero on the horizontal axis refers to the 2005 vegetation line and -25.6 is the unrevetted vegetation line.

Comparison of the existing profile with the projected unrevetted profile shows that the revetments have resulted in significant loss of sand, an estimated 506 cubic feet per linear foot of shoreline, due to deflation of the profile. In addition, the figure shows that the revetments have resulted in impoundment of an average of 34 cubic feet of sand per linear foot of shoreline. Over the revetted shoreline, this translates into a sediment deficit of 46,000 cubic yards.



Figure 34 Beach nourishment conceptual design 1—Bellows AFS



Figure 35 Beach nourishment conceptual design 2—Bellows AFS



Figure 36 Shoreline response to removed revetments—Bellows AFS
(The red Xs mark cottages and other buildings that may be threatened by the shoreline recession)

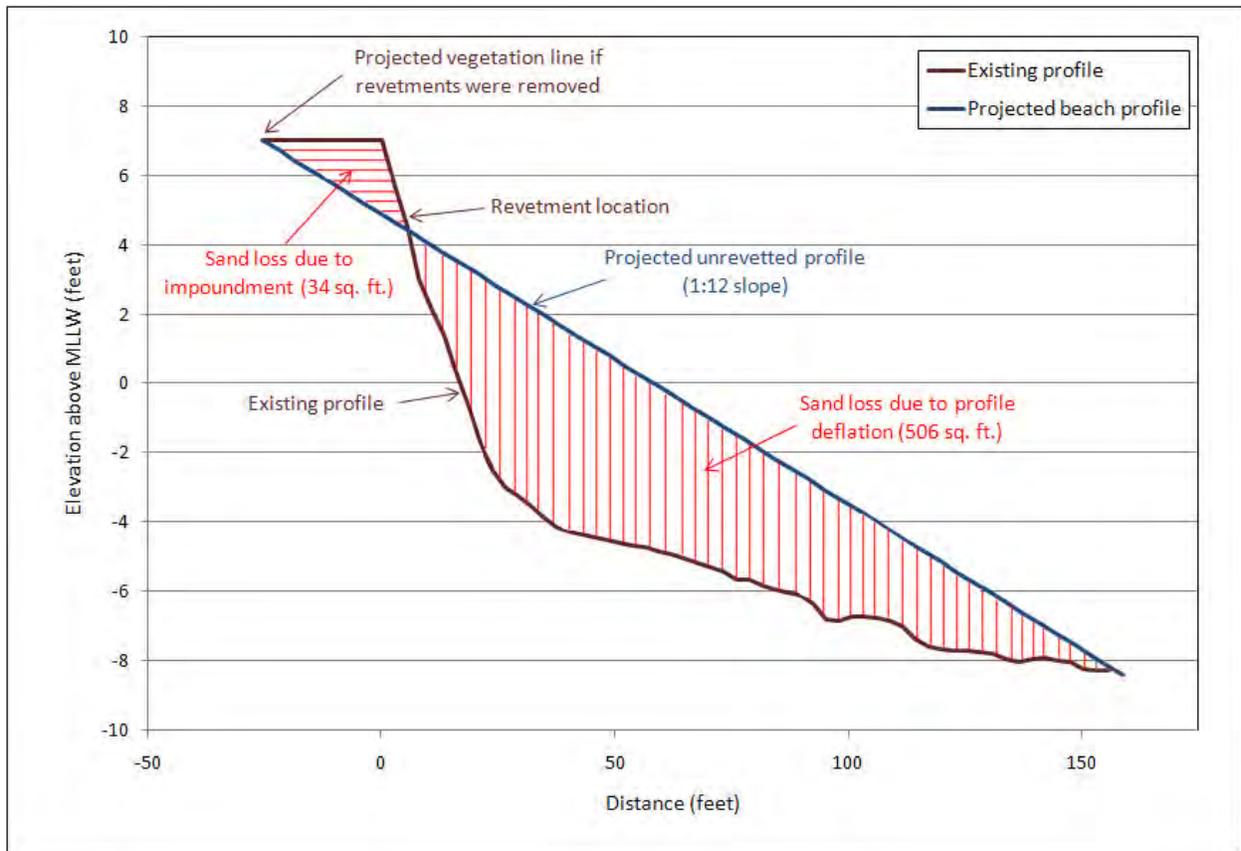


Figure 37 Typical existing profile and projected unrevetted profile

D. Kaupo and Kaiona Beaches

Kaiona Beach suffers from net erosion that threatens the highway and private homes. Sediment transport is primarily longshore at Kaiona Beach (Figure 41). The eroded sand appears to move both north toward Waimanalo and with a small amount moving south toward Makapu`u. Parts of the eroded area near the highway are protected by seawalls or revetments. Just to the south are two shore-connected breakwaters that probably affect sediment transport.

Beach nourishment, groins, and offshore breakwaters are all possible solutions for the Kaiona erosion. There are sand deposits off Waimanalo Beach Park to the north that could possibly be used for beach nourishment. Waimanalo Beach is accreting, so any proposed solution must consider the effect of shore protection on this beach.

Kaupo Beach and the road embankment south of Makai Pier are eroding. The erosion appears to be a combination of beach erosion caused by waves and currents and embankment erosion caused by rainfall runoff from the highway and upland areas. The state Department of Transportation (DOT) has protected the road embankment with piles.

Based on the historical shoreline studies, the beach north of Makai Pier shows patterns of accretion and erosion over small reaches of shoreline (Figure 14). Stretches of the eroding shoreline are armored. Aerial photographs of Kaupo Beach (Figure 38) show a beach at the eroded shoreline below the road damage. They also show what appear to be large sand patches in nearshore area. The University of Hawaii has mapped sand bodies seaward from the pier and breakwater (Figure 39).

A sand channel (Pukakukui Channel) is located on the south side of Makai Pier offshore from the eroding area (Figure 40). This channel was periodically dredged years ago when an underwater habitat and submersibles were deployed from Makai Pier. Water is deeper in the channel than in the surrounding area. It is probable that, under some conditions, waves pass over the channel without breaking before they hit the eroding shoreline. The unbroken waves carry more energy to the beach. The photos show waves breaking over the reef to the north but none breaking over the channel. The two conditions, the offshore sand deposits and the fact that higher wave energy might reach the eroding beach, suggest that beach nourishment and offshore breakwaters should be considered as possible solutions. The breakwaters would reduce wave energy reaching the eroded area. Nourishment would replace some of the lost sand. However, the source of nourishment sand must be carefully considered since dredging in the wrong location could make the erosion worse.

According to sediment budget calculations, alternating stretches of accretion and erosion dominate along Kaupo Beach (Figure 42). It is presently unclear if a groin or a series of groins would help stabilize the beach. With the data available from the SEO/RSM studies, an offshore breakwater system can be modeled to determine shoreline response. Sufficient sand can be added to the design to minimize several years' erosion. These actions should move the shoreline seaward.

That still leaves the problem of an unstable embankment under the highway. The DOT has stabilized the road with piles, but stabilizing the bank between the road and the beach probably should be a joint project between DOT and DLNR. There are various bank-stabilization best management practice (BMP) methods that should be considered including terraces, gabions, redirection of runoff flow, and vegetation.

The sediment budget for Makapu'u Beach was calculated with the 1988 and 2005 shorelines, as an aerial photograph of the 1996 shoreline was not available. Makapu'u Beach is bordered by rocky headlands and is therefore considered closed to longshore transport; all sediment transport is onshore-offshore. The beach width is cyclical and varies greatly with season and wave climate. The use of the aerial photographic analyses to produce a sediment budget for such a cyclical beach may produce misleading transport rates.



**Figure 38 Aerial Photo Kaupo Beach and Makai Pier
(University of Hawaii)**

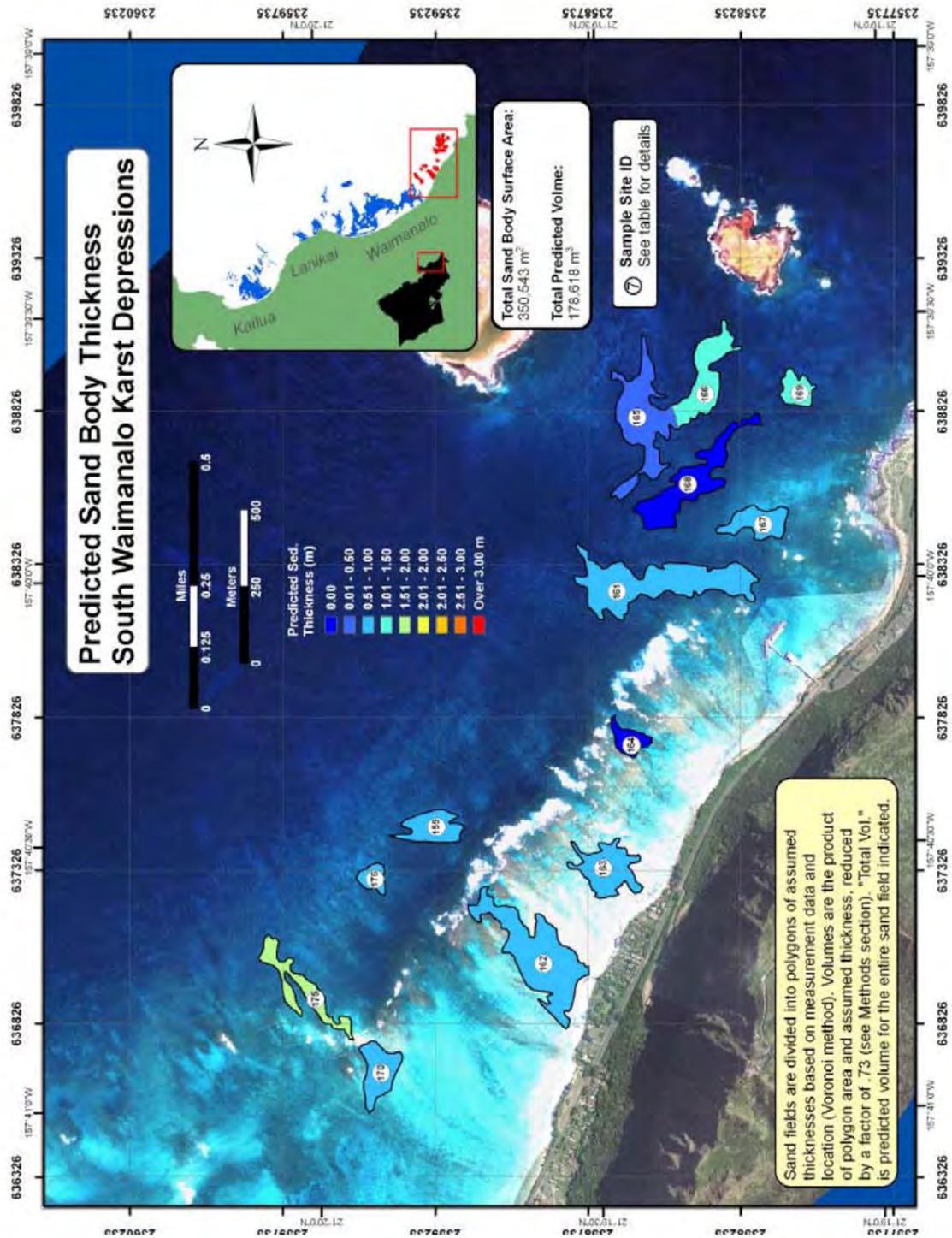


Figure 39 South Waimanalo Sand Bodies (University of Hawaii)



Figure 40 Oblique Aerial Photo Showing Channel Area and Breaking Waves (University of Hawaii Photo)

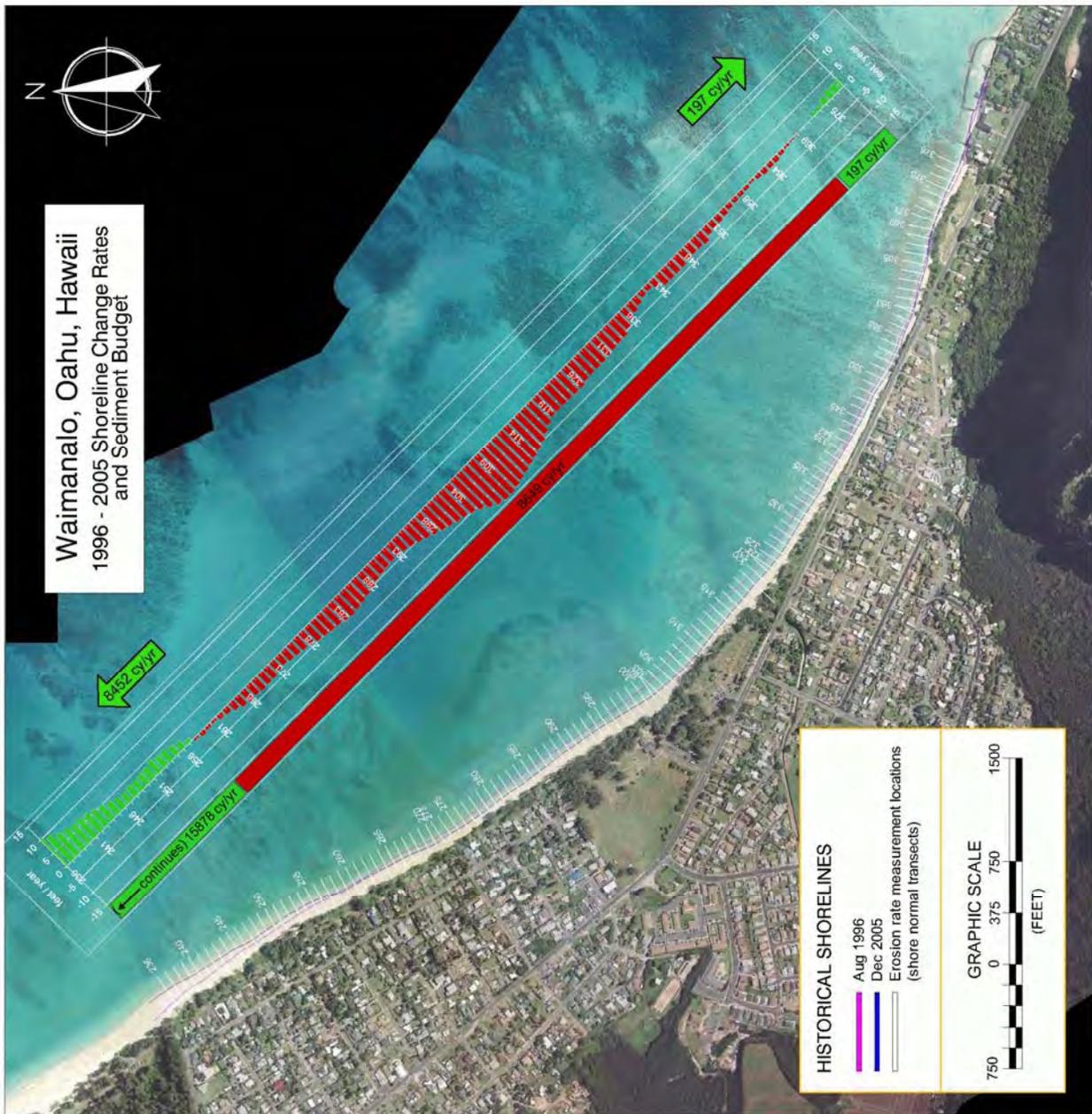


Figure 41 Kaiona Beach Sand Budget

XVI. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

The SEO/RSM project shoreline consists primarily of calcareous sand beaches, some of which are eroding, causing damage to private and public property. Several studies conducted by the U.S. Army Corps of Engineers and the University of Hawaii have helped characterize the littoral processes and nearshore configuration of the study area. The results of these studies provide a basis for designing solutions to regional erosion problems. This RSM Plan provides guidance for additional planning and research necessary to further develop alternative concepts for the four PDPs. Active sediment management will result in less shoreline erosion, lower threat to private and public property, and more available recreational space.

Beach nourishment was found to be a common element in the PDP evaluations; however, more sand sources must be identified. The problems associated with sediment management at the Ka'elepulu stream mouth could be addressed by the multi-agency team focused on optimizing the beneficial use of the sand resource. The erosion at Lanikai might be mitigated by beach nourishment and use of groins or offshore breakwaters. At Bellows Air Force Station, threatened cottages could be moved inland and inland sand sources might be used for beach nourishment. Kaiona Beach would probably benefit from nourishment controlled by structures. The eroding embankment at Kaupo Beach could use shoreline stabilization with sand and drainage best management practice methods.

B. Recommendations

Ka'elepulu Stream: The Department of the Army permit for steam cleaning and the Department of Health permit for sand placement should be reviewed and revised if appropriate to allow for additional maintenance material disposal options. Currently, material removed from the stream mouth is placed along the banks of the stream and/or along the shorelines adjacent to the stream. Optimally, the material should be placed wherever it is needed at the time of stream cleaning within the limits of Kailua Beach.

Lanikai: State and local interests should utilize the information provided in this RSM Plan to develop a long-term strategy to manage shoreline recession in this portion of the SEO region. Beach nourishment (possibly in conjunction with properly designed coastal structures) could be implemented to stabilize the Lanikai shoreline. A pilot restoration project could be developed to demonstrate the effectiveness of beach nourishment with structures. Offshore sand bodies have been preliminarily identified for use as a source of beach quality material. Suitable beach fill material may also be available within the upland limits of Bellow Air Force Station.

Bellows Air Force Station (AFS): RSM options for Bellow AFS station include removal of the existing rock revetment and Waimanalo Stream groins to restore the natural

sediment transport regime along this portion of shoreline. Given the case where these structures are left in place, the Air Force should consider placement of an equivalent volume of sand to offset the sediment budget deficit that the structures have caused since their construction.

Kaiona and Kaupo Beaches: Since Kaiona Beach has been partially armored and it would be unrealistic to try to maintain a beach along its reach, no action is recommended for that portion of shoreline at this time. On the other hand, bank stabilization, storm water runoff control, and beach nourishment in combination would stabilize the Kaupo Beach shoreline and provide needed protection to Kalaniana'ole Highway.

The Southeast Oahu Regional Sediment Management demonstration project has produced a regional sediment budget for use in the development of sediment management strategies within the region. Coastal processes modeling and geotechnical investigations have been conducted as part of the SEO/RSM effort to facilitate future beach nourishment and other shore protection alternative investigations. This Regional Sediment Management Plan provides documentation on the tasks undertaken and the products resulting from the SEO/RSM demonstration project. Additional products and information can be found at <http://gis.poh.usace.army.mil/rsm/index.htm>.

REGIONAL SEDIMENT MANAGEMENT PLAN

APPENDICES

APPENDIX A
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APPENDIX B

**SOUTHEAST OAHU REGIONAL SEDIMENT MANAGEMENT
DEMONSTRATION PROJECT
SCOPE OF WORK**

SOUTHEAST OAHU REGIONAL SEDIMENT MANAGEMENT DEMONSTRATION PROJECT

Regional Beach Management Plan Scope of Work August 7, 2006

BACKGROUND: The Southeast Oahu Regional Sediment Management (SEO/RSM) demonstration project is being conducted to (1) document long-term trends in wave climate for the windward side of Oahu, Hawaii, (2) develop a regional sediment budget and a geographic information system (GIS) for three littoral cells along the southeast Oahu coast, (3) identify suitable sand sources, and (4) develop/calibrate a sediment transport model for the region. The SEO region is located on the southeast shoreline of the island of Oahu, Hawaii. There are three littoral cells, Kailua in the north, Lanikai in the middle, and Waimanalo in the south part of the study area. There are geologic controls (both sub-aerial and offshore) affecting sediment transports within these cells. The offshore region is a sloping reef along which waves break on its outer edge. Waves are depth-limited by the reef as they approach the shoreline. SEO/RSM investigations are being conducted to determine if there is sediment transport between the cells. Long-term (decadal or more) shifts in wind, wave direction, and wave period may shift sediment transport patterns and magnitudes. As a result, sediment transport processes of these beaches are difficult to understand, and RSM solutions are not readily apparent. The final products from this study will be a sand source inventory, web-enabled GIS platform and regional beach management plan for the SEO region.

REGIONAL BEACH MANAGEMENT PLAN: The work to be performed under this task order is the preparation of the SEO/RSM Regional Beach Management Plan (RBMP) report. The RBMP report will document all of the activities that have been conducted since the beginning of the SEO/RSM investigations in fiscal year 2005 (see attached SEO/RSM scope of work). Work that has been performed by the Honolulu District, Coastal & Hydraulics Laboratory, Geotechnical and Structures Laboratory and the University of Hawaii (UH) will be documented in the RBMP report along with the results of the study workshops (the next workshop is to be held on August 23, 2006). Descriptions of the various tasks that have been completed are provided as attachments to this document. Reference is also made to the "Beach Management Plan for Maui" dated December 1997 as prepared for the County of Maui Planning Department by UH Sea Grant Extension Service. Many of the SEO/RSM products can be found online at the following web site.

<http://gis.poh.usace.army.mil/rsm/pages/index.htm>

RBMP Report: The RBMP report will consist at a minimum of the follow sections that compile the study results to date:

Executive Summary

Introduction

Regional Sediment Management

Southeast Oahu Regional Sediment Management Demonstration Project

Coastal Ecosystem

Coastal Erosion, Beach Loss and Coral Reef Degredation

Objectives

 Identification of Erosion Hotspots and Erosion Watchspots

 Guidelines for Shoreline Protection Measures

 Beach Nourishment

 Sand Sources for Beach Nourishment

 Pilot Beach Nourishment Project

 Dune Preservation and Restoration

 Coral Reef Ecosystems, Water Quality, and Upland Activities

 Shoreline Setbacks and Coastal Erosion Hazard Data

 Proactive Development of Coastal Lands

 Inter-agency Coordination

 Structures and Activities within the Shoreline Area

 Minor Structures

 Major Structures

 Beach Management Districts

 Public Awareness and Education

Coastal Processes Modeling

 Wave Climate

 Water Circulation

 Littoral Sediment Transport

 Regional Sediment Budget

Geomorphology

Shoreline Change

Sediment Trend Analysis

Sand Source Investigations

Workshops

Web-based GIS

Literature Search/Inventory

Potential Demonstration Projects (PDP)

PDP Alternatives (to be developed as part of this report)

Appendices (to include documentation of all study products covered in the attachments to this SOW and the SEO/RSM web site).

SPECIFICATIONS: The report is to be prepared in Microsoft Office Word as a “doc” file. All products generated in the process of report preparation will be provided to the Government upon completion of the task order work. Arial 12 font will be used for the text portion of the report.

MEETINGS: The A/E firm will meet individually with Oahu representatives having input into the various study products (such as employees of the Honolulu District, Hawaii Department of Land and Natural Resources (DLNR) and the University of Hawaii) to attain an in depth perspective on SEO/RSM related activities. The A/E will also make telephone contact with mainland contributors to the study. The A/E will arrange at least four progress meetings with SEO/RSM project delivery team (PDT members include Honolulu District, DLNR and UH personnel) to discuss progress on the report and issues to be resolved. The A/E will prepare draft minutes from each meeting and provide them to the PDT for review and comment. The A/E will prepare final meeting minutes based on comments received from the PDT.

DELIVERABLES: Deliverables will consist of meeting minutes as well as preliminary, draft and final RBMP reports. All products generated in the preparation of the final RBMP report will be provided to the Government prior to issuance of final payment.

SCHEDULE:

TASK	DATE
Preliminary FBMP Report	September 28, 2006
Draft FBMP Report	October 27, 2006
Final FBMP Report	November 30, 2006
Associated Products	November 30, 2006
Final Meeting Minutes	10 days after meetings

ATTACHMENT 1:

Regional Sediment Management Southeast Oahu Hawaii

Purpose: This study will (1) document long-term trends in wave climate for the windward side of Oahu, Hawaii, (2) develop a regional sediment budget and a geographic information system (GIS) for three interconnected littoral cells along the southeast Oahu coast, (3) identify suitable sand sources, and (4) develop/calibrate a sediment transport model for the region. The final products from this study will be a sand source inventory, regional sediment management (RSM) plan and web-enabled GIS platform for the South East Oahu (SEO) Region.

Problem: The SEO Region is located on the southeast shoreline of the island of Oahu, Hawaii. There are three littoral cells, Kailua in the north, Lanikai in the middle, and Waimanalo in the south part of the study area (Figure 1). There are geologic controls (both subaerial and offshore) affecting sediment transport within these cells. The offshore region is a sloping reef along which waves break on its outer edge. Waves are depth-limited by the reef as they approach the shoreline. The cells are not believed to share sediment with each other. The long-term average rate of shoreline retreat is nominally 2 feet/year. Long-term (decadal or more) shifts in wind, wave direction, and wave period may shift sediment transport patterns and magnitudes. As a result, sediment transport processes of these beaches are difficult to understand, and RSM solutions are not readily apparent. In addition, sand sources for this region have not been identified.

Proposal: A description of the tasks is presented below. Figure 2 shows a timeline of the various tasks.

Total duration: 4 years.

Task 1: Develop long-term wave climate.

Time: 12 mos.

From observations of shoreline position on the northeast side of Oahu, it appears that there is a long-term trend (20 or more years) of erosion and accretion. These cycles of beach change may be caused by shifts in wave climate, including multi-decadal shifts in storm activity associated with the Pacific Decadal Oscillation. Task 1 will utilize or generate updated Wave Information Study hindcast for the project area. Directional wave buoy data are available for the years 2000-2002, and non-direction wave buoy data are available for more than 20 years. These data will be used for validation of the hindcast. This task will provide a regional wave climate for Task 5, regional shoreline modeling.

Task 2: Nearshore circulation.**Time: 8 mos.**

Because waves are depth-limited as they approach the study area, it is believed that nearshore circulation (wave- and wind-induced) may be a significant process controlling sediment transport. This task will setup and run the Advanced Circulation model for the study area. There are no current data available for validation; thus, three separate drogoue studies are planned under a range of wave and wind conditions.

Task 3: Geomorphic analysis of study area.**Time: 10 mos.**

Historical shoreline position, beach profile, aerial photography, bathymetric, and geologic information for the study area will be evaluated to identify (a) long-term trends in shoreline position; (b) long-term trends in bathymetric change; (c) locations with possible sources of beach nourishment material, and (d) geologic controls on littoral processes. Historical shoreline position data are available from the University of Hawaii. Sand samples will be taken for each littoral cell, and sediment cores will be collected and analyzed for possible offshore sources of material. Because of the low hardness value of the sediment, it is possible that abrasion or mechanical disintegration is a significant process in shoreline retreat. The abrasive characteristics of beach sediments will be quantified. This task will provide data for Task 4, development of the regional sediment budget, and the calibration and verification data set for Task 5, regional shoreline modeling.

Task 4A: Develop a regional sediment budget.**Time: 10 mos.**

Volumetric change for historical and present-day time periods will be developed for the active littoral region. These data, together with knowledge of the long-term wave and wind climate (Task 1) and regional shoreline modeling (Task 5), will be used to develop sediment budgets for each littoral cell. Sediment sources and sinks will be defined and quantified. A regional budget will be developed, including an assessment of whether long-term sand sharing between littoral cells occurs. The regional sediment budget will be used to develop a RSM plan, and a with-project regional sediment budget will be forecasted.

Task 4B: Develop a web-enabled GIS platform.**Time: 10 mos.**

A web-based GIS platform will be developed for the SEO Region. The GIS will contain georeferenced maps, attributes and metadata corresponding to SEO Region RSM requirements. Aerial photography, digital elevation models, geotechnical information, survey data, wave parameters and other pertinent georeferenced information will be automated via the GIS. The GIS will utilize state-of-the-art web enabling software to provide real-time access of products through the internet. The GIS will reside at the Mobile District.

Task 5: Regional shoreline change modeling.

Time: 12 mos.

The regional shoreline change model presently in developmental testing, Cascade, will be calibrated and verified for the study region. The wave climate produced in Task 1 will drive the model, and shoreline positions, geologic controls, and bathymetric contours defined in Task 3 will be used for calibration and verification. The regional modeling will work hand-in-hand with development of the regional sediment budget (Task 4A). A RSM plan will be developed using results from each task. This RSM plan will document long-term trends in beach change, and identify possible sources of sand, to management of sediment within the region. Travel funding for trips to/from the mainland for various team members is also included in the estimate.

Task 6B: Sand source investigations.

Time: 4 years

Sand sources will be identified in areas offshore and upland of the region. Research and development of sand manufacturing techniques will also be carried out under the task.

Schedule and Funding: As indicated in Figure 2, the RSM demonstration project for the SEO Region will take four years to complete.



Figure 1. Project study area

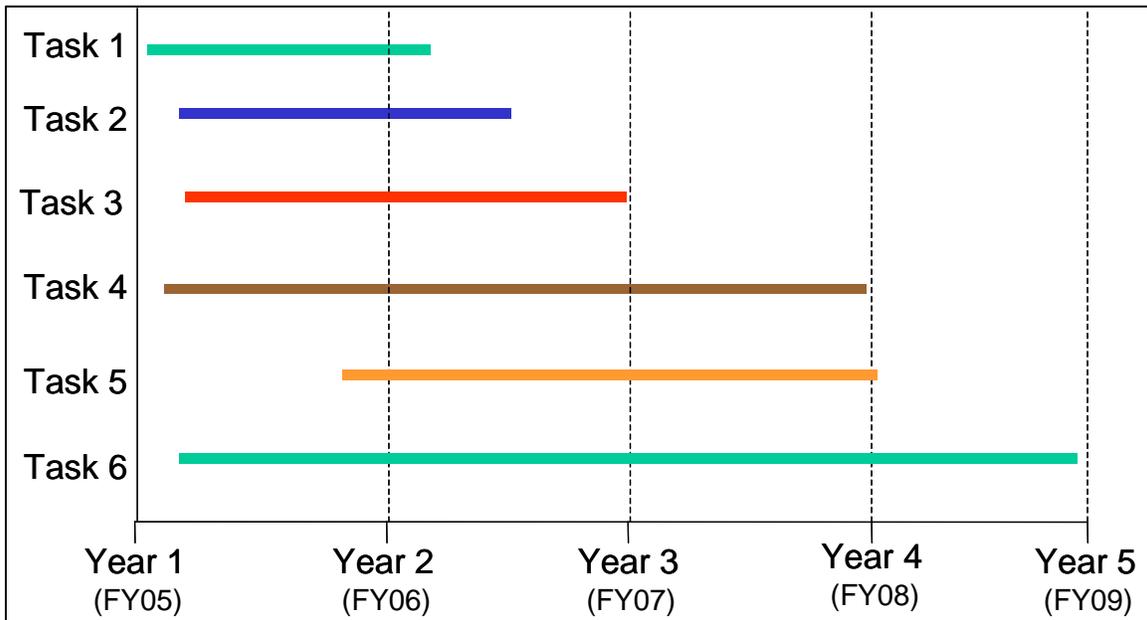


Figure 2. FY schedule and funding levels for the Southeast Oahu RSM demonstration project.

ATTACHEMENT 5

DRAFT Scope of Work CHL Nearshore Circulation Modeling for Southeast Oahu, Hawaii

The proposed work includes six technical tasks: data collection/assessment, finite element and finite difference grid development, development of model forcing conditions, model calibration, model simulations, and simulation analysis. The tasks are linked and sequential, however, the first three tasks may be accomplished in parallel. The final product from these tasks is a calibrated hydrodynamic model for the project site. The models applied will be as follows:

a) Long-Wave Hydrodynamic Model – ADCIRC. The ADCIRC long-wave hydrodynamic model simulates the circulation and water levels associated with both tides and storms. A two-dimensional (depth-averaged) version of ADCIRC will be applied. ADCIRC has been extensively applied in the Atlantic and Pacific Oceans (and world wide) to simulate tidal circulation and associated storm surge and currents. The hydrodynamic modeling component will require the following tasks:

1. Grid development to include recent bathymetry and shoreline data.
2. Calibration and verification of the bathymetric grid to known tidal constituents. This phase of the investigation will provide circulation patterns for determining placement of water elevation and current measurement gages.
3. Re-verify model by comparison to measurements made for this study.
4. Development/selection of alternative forcing conditions.

b) Short-Wave Modeling – STWAVE. *STWAVE is a spectral wave transformation model, which is capable of representing wave-current interaction (wave-action equation, current-induced breaking, and wave blocking by a current). The ADCIRC and STWAVE models will be coupled to allow the interchange of radiation stresses from STWAVE to ADCIRC, and tide-, wind-, and wave-generated currents from ADCIRC to STWAVE. Application of STWAVE will require the following:*

1. Development of computational grid to simulate wave propagation.
2. Verification of calculated waves by comparison to measurements.
3. Generation of wave climate.

Study Phases

An approach toward development of a “turn-key” hydrodynamic modeling system should be pursued in a phased process. Activities including identifying and assembling data, grid development, tidal and wind-driven current and water level calibration, and nearshore wave transformation will be accomplished via a cooperative effort between POH and CHL personnel with in the field assistance provided by CHL.

Phase 1:

POH and CHL will jointly develop the geographic, bathymetric, hydrodynamic (waves and circulation), and meteorological data necessary to develop and calibrate the modeling system. An assessment of the quality of available data will aid in the specification of necessary additional field measurements. In addition, a decision will be reached as to what computer platform will be utilized to exercise the modeling system. CHL and POH will develop and calibrate the ADCIRC model for tidal constituent forcing, including in the field assistance if desired. Development of the finite element grid for the overall project will focus on a coarse resolution at the seaward, deep-water boundaries and detailed resolution in the nearshore regions of interest. Any recently collected bathymetric data will be evaluated and incorporated into the model grid and bathymetric databases will be used to supplement bathymetry for the grid domain.

Phase 2:

CHL will establish the range of atmospheric forcing required for accurate simulations. CHL and POH will develop and calibrate the STWAVE grid and perform an additional ADCIRC calibration including atmospheric forcing and coupling with STWAVE. This effort will include in the field assistance by CHL. These calibration simulations will utilize the POH current field measurement effort. Tidal forcing conditions will be developed for the ocean boundary condition using the LeProvost or OSU Pacific constituent database. Offshore wind and pressure fields generated by a combination of NCEP/NCAR winds and pressures adjusted for local observations will also be used as forcing conditions for the hydrodynamic model.

Phase 3:

CHL will assist POH in developing recommendations for alternative simulations, will document the methodologies and procedures, and will provide consultation in executing simulations and analyzing simulation results. The transfer of the completed modeling system to POH will be accomplished within the SMS framework.

ATTACHMENT 6:

Project: Southeast Oahu Regional Sediment Management Demonstration Project – Identification of Beach Quality Sand Sources and Investigation of Sand Manufacturing Techniques

Scope and Purpose: Carbonate sand is needed for the repair and restoration of beaches in Southeast Oahu, Hawaii. This project is directed to:

- 1) Locating sources of coral-based carbonate rock or gravel that can be ground to provide a clean carbonate sand.
- 2) Developing protocols for manufacturing carbonate sand by crushing and grinding coral-derived rock or gravel. Specifically this would involve the development of techniques for processing the carbonate to produce sand that will not re-cement when placed above the tidal zone on a beach.
- 3) Locating any alternate sand sources both onshore and offshore that could be used in beach construction. The goal of this project is to locate coral-reef derived carbonate material for the beach construction in sufficient quality to allow the development of a plan for the reconstruction effort and to determine the methods, equipment and material requirements needed for the production of a non-cementing carbonate beach sand. Additionally the project will complete a survey of the general availability of beach construction materials both on-shore and offshore. The time constraints and the level of funding for this phase of the work do not allow for dredging to obtain any new underwater carbonate samples.

Approach: A preliminary investigation of the carbonate supply problem will be undertaken to determine the availability of carbonate deposits using data developed in the investigations that have been undertaken by researchers from the U.S. Geological Survey, the University of Hawaii, and contractors. Archived sediment samples will be requested from past investigations. A preliminary assessment will be followed up with the collection of additional data and archived or stockpiled samples of the most promising deposits that occur within distances from the project area that make transport realistic economically.

Re-cementation of carbonate sand that is above sea level and subjected to leaching in fresh water is a significant problem. In Florida and Bermuda, natural carbonate beaches rarely have re-cementation problems that impact beach usage. The lack of dissolution of calcium carbonate and recrystallization of carbonate as cement is thought to be related to the presence of natural organic coatings on the carbonate sands. Extraction and analysis of organics from natural organic sands

shows that the surface of the grains has a coating of calcium salts of naturally occurring fatty acids (calcium stearate or calcium laurate). The coatings prevent the surface of the calcium carbonate from wetting effectively and disrupt any epitaxial growth of carbonate cements. In manufactured calcium carbonate sand, the freshly crushed material has clean surfaces that can act as templates for the formation of more crystalline calcium carbonate that can cement adjacent surfaces together. Additionally the presence of fine-grained material and sand-sized material with sharp edges and corners can contribute to the dissolution and reprecipitation that make beach rock out of beach sand.

The investigation of methods of manufacturing non-cementing beach sand will concentrate on the usefulness of using a well-sorted sand-sized particles that are tumbled to produce rounded grains and on the effects of adding coatings calcium salts of fatty acids. Phosphates in small quantities retard carbonate crystal formation and many fatty acids occur in nature with phosphate groups attached. As a coating material these compounds could be very effective crystal growth (cement) inhibitors. The systems proposed for investigation are all natural processes that are being reintroduced into a manufactured sand to reproduce the non-cementing phenomenon occurring on normal carbonate beaches.

To support the development of a sand manufacturing protocol, a lab bench scale test will be set up to evaluate the importance of grain size and shape and the usefulness of coating materials. A test matrix will be developed with a variety of control samples to allow the evaluation of the separate properties of the sand treatments.

An overall assessment of aggregates (carbonate and non-carbonate and on-shore and off-shore) will also be included in this investigation. This survey of availability to assure that the most economical sources of material are located from the project and no useful resource that could make the project more effective or economical is overlooked. This phase of the investigation will allow the beach repair planners to optimize the use of resources and justify their selection of specific materials and specific sources. The program will include characterization of selected materials and estimates of amounts available and transport to the construction site.

APPENDIX C

**TR-08-9: SOUTHEAST OAHU COASTAL HYDRODYNAMIC MODELING
WITH ADCIRC AND STWAVE**

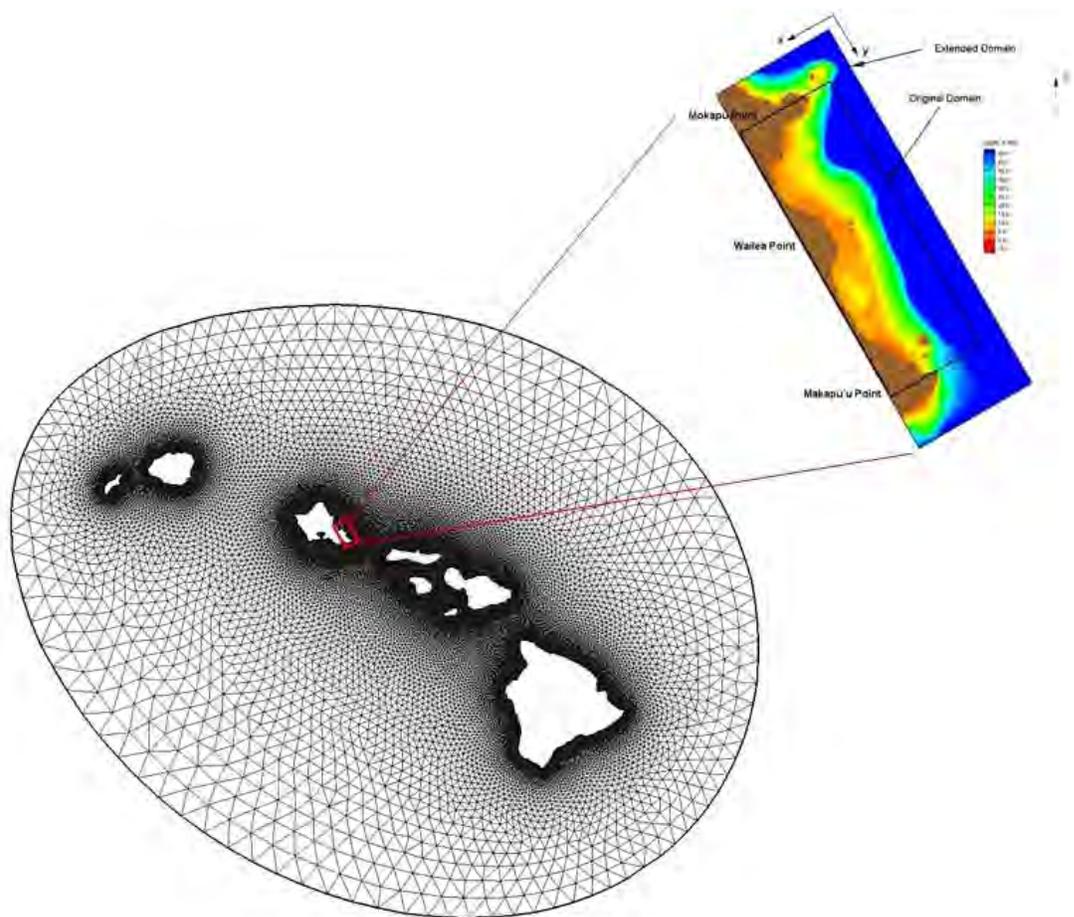


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Southeast Oahu Coastal Hydrodynamic Modeling with ADCIRC and STWAVE

Mary A. Cialone, Mitchell E. Brown, Jane M. Smith,
and Kent K. Hathaway

July 2008



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Final report

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Abstract: This study provides the Honolulu District (POH) with numerical modeling tools for understanding nearshore circulation and sediment transport for Southeast Oahu (SEO). Circulation and wave models are developed and validated for this region and can be applied to assess sediment transport potential for various forcing conditions and to determine the likelihood of accretional and erosional areas within the model domain.

Application of a wave model includes the generation of a wave climate. In the wave climate development technique, nearshore conditions are extracted from the wave model results for each simulation. A transformation correlation between the offshore and nearshore condition is then determined for each simulation. By applying the appropriate transfer function to each wave condition in the offshore time series, a long-term nearshore time series is generated. The nearshore time series demonstrates that there is a reduction in wave height from the offshore location to the nearshore location, landward of the extensive reef system as expected. The technique of developing a nearshore wave climate by applying the wave model for a range of offshore wave conditions provides a permanent “look up” table of nearshore wave conditions at any location in the computational domain and can be applied to any time period for which offshore data are available, provided that bathymetric conditions within the model domain remain similar. POH is applying the database-generated time series to develop sediment transport potential estimates in the project area.

Development of a bottom friction capability in the wave model was completed for application to the extensive reefs in the SEO study area. It is shown that bottom friction is extremely important and has a pronounced effect on modeling transformation over reefs, decreasing wave heights from the without-friction condition by 71-76% for a constant JONSWAP bottom friction value of 0.05.

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Preface

This technical report describes a hydrodynamic modeling study for Southeast Oahu, Hawaii. The purpose of the nearshore circulation modeling study for the Southeast Oahu Regional Sediment Management (SEO/RSM) demonstration project was for the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL) to provide the U.S. Army Engineer District, Honolulu, with a tool for understanding nearshore circulation and sediment transport in the study area. RSM supported field data collection and initial modeling and the Surge and Wave Island Modeling Studies Project supported refinement of STeady-state spectral WAVE model (STWAVE) friction capability and publication of this report. The study was conducted during the period April 2005 through September 2006.

The numerical modeling investigation was conducted by Mary A. Cialone, Coastal Processes Branch (CBP), CHL; and Mitchell E. Brown, Senior Scientist Group, CHL; with technical assistance from Jane M. Smith, CBP, CHL; and data reduction from Dr. Lihwa Lin, Coastal Engineering Branch, CHL. The field data collection was conducted by Kent K. Hathaway, Field Research Facility, CHL; and Raymond Chapman, CBP, CHL; with local assistance from Thomas Smith, Jessica Hays, and Stan Boc, Honolulu District; Chip Fletcher, University of Hawaii at Manoa; and Oliver Vetter, University of Hawaii at Manoa, now of the National Oceanic and Atmospheric Administration.

This project was conducted under the direct supervision of Ty Wamsley, Chief, CPB. General supervision was provided by Dr. William D. Martin, Deputy Director, CHL; and Thomas W. Richardson, Director, CHL.

COL Richard B. Jenkins was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

1 Introduction

The project area for the hydrodynamic modeling study described in this report is located along the southeast shoreline of the island of Oahu, Hawaii from Mokapu Point to Makapu'u Point (Figure 1). This stretch of coast is considered part of the “windward” side of the island, that is, where the predominant wind travels from the sea to land. Tradewinds and North Pacific waves affect the island’s windward side. Tradewind waves occur throughout the year, but are most persistent in the summer, ranging between 1 and 3 m high with periods of 6 to 10 sec. The direction of approach, like the tradewinds themselves, varies between north-northeast and east-southeast and is centered on the east-northeast direction.

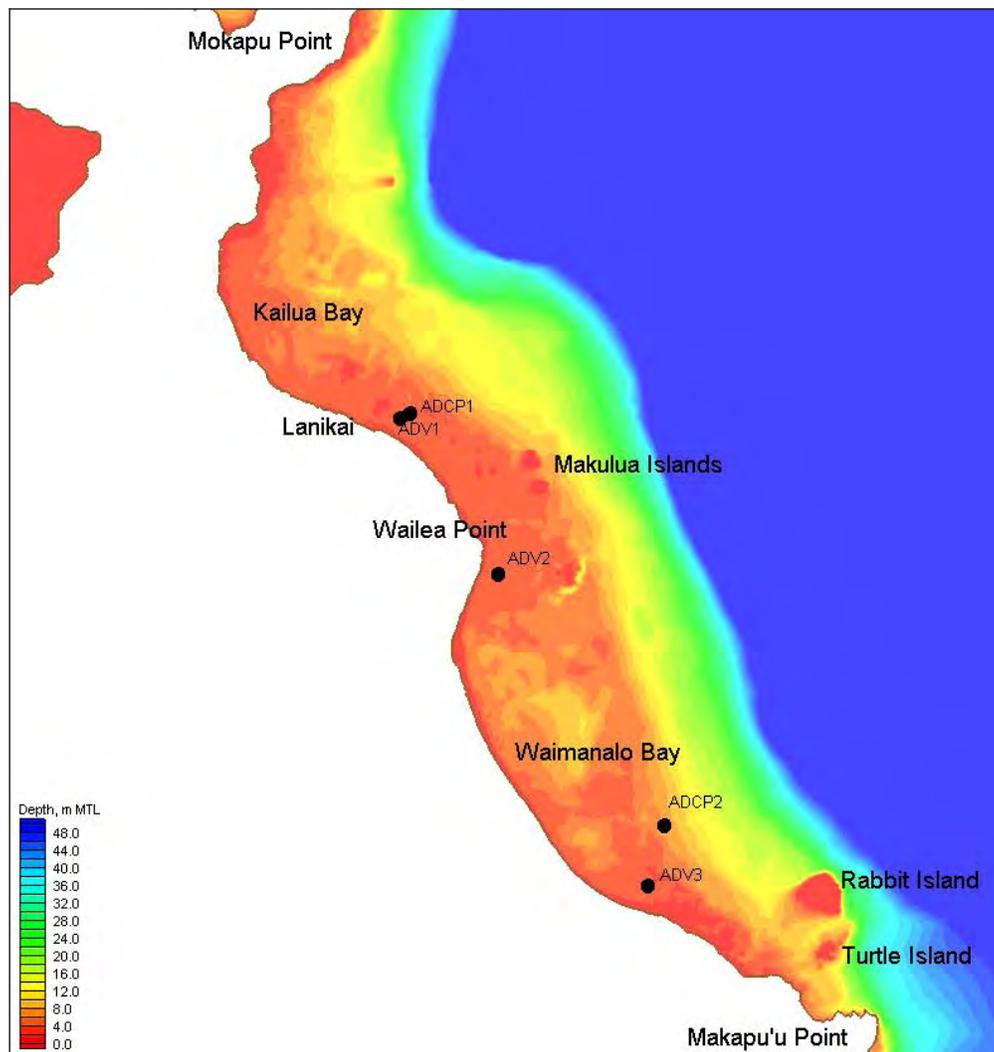


Figure 1. Project area location map and instrument locations.

During the winter months, storms generate large North Pacific swells that range in direction from west-northwest to northeast and arrive at the northern Hawaiian shores with little attenuation of wave energy. Deep-water wave heights often reach 5 m and, in extreme cases, can reach 9 m with periods of 12 to 20 sec. In the study area, offshore waves are generally from the east-northeast and range in height from 0.5 to 6.0 m. Peak wave periods are generally 6 to 16 sec (Sea Engineering 2008).

The ultimate goal for the Honolulu District (POH) was to understand sediment transport potential in the region and determine the likelihood of accretional and erosional areas within the model domain. There are three littoral cells along the project reach: Kailua in the north, Lanikai in the central portion, and Waimanalo in the southern part of the study area in which geologic controls (both subaerial and offshore) affect sediment transport. The offshore region is a sloping reef along which depth-limited waves break. Long-term (decadal or longer) shifts in wind, wave direction, and wave period have the potential to shift sediment transport patterns and magnitudes, therefore making sediment transport processes for this region difficult to understand. The focus of the work presented in this report, however, is the nearshore circulation study project, which included six technical tasks:

1. data collection/assessment,
2. finite-element and finite-difference grid development,
3. development of model forcing conditions,
4. model validation,
5. model simulations, and
6. simulation analysis.

The final product from these tasks was validated hydrodynamic and wave models for the Southeast Oahu (SEO) region. The Honolulu District could then apply the models with various forcing conditions to achieve their goal in better understanding the nearshore circulation and sediment transport potential in the region and determining the likelihood of accretional and erosional areas within the model domain.

Circulation (ADCIRC) and wave (STWAVE) models were applied in this study. The ADvanced CIRCulation (ADCIRC) long-wave hydrodynamic model simulates the circulation and water levels associated with both tides and atmospheric conditions (Luettich et al. 1992).

The two-dimensional, depth-averaged version of ADCIRC was applied in this study. ADCIRC has been extensively applied in the Atlantic and Pacific Oceans (and world wide) to simulate tidal circulation and associated storm surge and currents (U.S. Army Corps of Engineers (USACE) 2006; USACE, Mobile District, 2008; Kraus and Arden 2003; Kraus 2006). The hydrodynamic modeling component for this study required:

1. grid development to include recent bathymetry and shoreline data,
2. validation of the bathymetric grid to known tidal constituents and wind forcing, and
3. comparison of the ADCIRC simulation model results for the bathymetric grid forced with known tidal constituents, wind, and waves to measurements for the field data collection time period.

The application and validation of ADCIRC for the SEO study provides POH with the capability of simulating circulation in the study area for any required time period.

The STeady-state spectral WAVE model (STWAVE) is a spectral wave transformation model, which is capable of representing depth-induced wave refraction and shoaling, current-induced refraction and shoaling, depth- and steepness-induced wave breaking, diffraction, wind-wave growth, wave-wave interaction and whitecapping (Resio 1988; Smith et al. 2001). The purpose of applying nearshore wave transformation models such as STWAVE is to describe quantitatively the change in wave parameters between the offshore and the nearshore. Offshore time-series wave data are typically available; however, nearshore wave information is required for the design of almost all coastal engineering projects. STWAVE has previously been applied to numerous sites with a gently sloping seafloor or small areas of hardbottom. Due to the wide and relatively shallow reef fronting the shoreline of the SEO region, this application of STWAVE required the added feature of simulating wave transformation over a reef. Development of a bottom friction capability in STWAVE was completed to address this unique bathymetry specific to the island environment. Application of STWAVE for this project required development of a computational grid to simulate wave propagation, verification of calculated waves by comparison to measurements, and generation of a wave climate. The ADCIRC and STWAVE models were then coupled to allow the STWAVE radiation stresses to force circulation within ADCIRC.

The approach toward development of a “turn-key” hydrodynamic modeling system for this region was pursued in a phased process. In the first phase, the Honolulu District and the Coastal and Hydraulics Laboratory (CHL) jointly developed the geographic, bathymetric, hydrodynamic (waves and circulation), and meteorological data necessary to develop and validate the modeling system. An assessment of the quality of available data aided in the specification of additional field measurements that were to be collected for this project. CHL developed and validated the ADCIRC model for tidal constituent forcing at the ocean boundary condition using the Oregon State University (OSU) Pacific constituent database. Development of the finite-element grid for the overall project focused on a coarse resolution at the seaward, deepwater boundaries and detailed resolution in the nearshore region of interest. All recently collected bathymetric data, including SHOALS (Wozencraft and Irish 2000) data collected in 2000, were evaluated and incorporated into the model grid, and bathymetric databases were used to supplement bathymetry for the grid domain.

In Phase 2 development, CHL established the range of atmospheric forcing required for accurate simulations. CHL developed the STWAVE grid, validated the STWAVE model, and performed an additional ADCIRC validation including atmospheric forcing and coupling with STWAVE. These validation simulations utilized the field measurement effort for comparison to model results. Tidal forcing conditions were developed for the ocean boundary condition with the LeProvost tidal constituent database, which provided a stable solution for the linked model validation time period (LeProvost et al. 1994). Offshore wind and pressure fields generated by a combination of wind fields and pressures adjusted for local observations were used as forcing conditions for the hydrodynamic model. These fields are discussed in detail in Chapter 3, section on “Wind sources.” Wave conditions from a Coastal Data Information Program (CDIP) buoy near the study site were used to generate boundary forcing conditions for the wave model. STWAVE was validated by comparing model-predicted and field measurements of wave conditions at the field data collection locations. The bottom friction was calibrated in the model to represent the reef and non-reef areas until a close comparison was achieved. ADCIRC was validated by comparing model-predicted and field measurements of water level and velocity at the field data collection locations. A hybrid friction formulation in ADCIRC and a range of wave radiation stress gradients from STWAVE were applied to achieve the best comparison.

In Phase 3, CHL assisted POH in developing recommendations for alternative simulations, documented the methodologies and procedures, and provided consultation in executing simulations and analyzing simulation results. The completed modeling system has been transferred to the Honolulu District within the Surface Water Modeling System (SMS) framework and training has been provided to the Honolulu District for future applications.

2 Field Data Collection

Wave and current data were collected for this project from 9 August to 14 September 2005 with two RD Instruments Workhorse Acoustic Doppler Current Profilers (ADCPs) and three Sontek Hydra Acoustic Doppler Velocimeters (ADV). The field data collection deployment period was dominated by tradewind weather (typically occurring from April through September in Hawaii) as characterized by consistent winds from the northeast and occasional swells from the southeast and southwest. Large wave events affecting the windward coast are not typical during this season. Waves along the windward coast during these months are typically generated from local winds, and this is evident in the relatively small wave heights and northeasterly incident direction of the waves recorded during the deployment period. Instrument locations and additional information are shown in Figure 1 and Table 1. All recording gauges were referenced to coordinated universal time (UTC).

Table 1. Instrument identification and location (Hawaii RSM gauge locations, August–September 2005).

Gauge		Latitude deg min	Longitude deg min	Recording Time Period	Nominal Depth, m
Type	Name				
ADCP	ADCP1	21 23.905	157 42.994	9 August–14 September	3.3
ADCP	ADCP2	21 20.318	157 40.786	10 August–4 September	6.6
ADV	ADV1	21 23.861	157.43.079	9 August–14 September	2.5
ADV	ADV2	21 22.509	157 42.233	9 August–14 September	2.7
ADV	ADV3	21 19.795	157 40.930	9 August–14 September	2.5

ADCP gauges

For this study, two RD Instruments 1200 kHz Workhorse ADCP gauges were deployed for approximately 1 month. The ADCPs were bottom mounted, facing upward with the sensor head approximately 0.4 m off the bottom. The water depth at ADCP1 was approximately 3.3 m and the water depth at ADCP2 was approximately 6.6 m, located near the seaward edge of the reef flat. These gauges have four acoustic transducers for measuring currents and a pressure sensor, from which horizontal and vertical current profiles were computed at 0.2 m vertical spacing. Waves were calculated from the decay in orbital velocities. These instruments sampled at 2 Hz for

directional wave measurements. Each hourly wave burst was approximately 34 min long, starting at the top of each hour, and consisted of 4096 points. The instruments have a 0.44-m blanking distance from the transducer head, and a 0.2-m bin width makes the first sample 0.72 m above the transducer. The profiles, therefore, span from 1.12 m off the ocean bed to the moving free surface position. Current profiles were collected every 10 min from a 200 point average.

The ADCP deployments were on 9 August 2005 and retrieval was on 14 September 2005. ADCP2 was reprogrammed on 10 August so data collection started a day later than the other instruments, and the batteries were depleted on 4 September, about 10 days before retrieval of all gauges. The ADCP2 data record was, therefore, 11 days shorter than the other gauge records.

ADV gauges

In addition to the two ADCPs, three ADV gauges were deployed for the same 1-month time period. ADV deployments were on 9 August 2005 and retrieval was on 14 September 2005. The three ADV gauges were Sontek's Hydra model that samples a single-point current velocity (U, V, and W) and contains an external pressure sensor. With these instruments, wave height, period, and direction are determined from PUV analysis (pressure and orbital velocities) (Guza and Thornton 1980). The sample volume for the current measurement is approximately 1–2 cm in size and about 0.17 m above the center transducer. This instrument uses three beams to determine the three current components. Both the ADCP and ADV instruments and their mounts are shown in Figure 2. Figure 3 shows wave height, peak period, and mean direction for the three ADV gauges. Figure 4 depicts wave roses (peak direction) for the two ADCP gauges.

Current drogues

Four current drogues (drifters) were designed and built at the CHL Field Research Facility (FRF) in Duck, NC, for deployment at the beginning (10 August 2005) and end (13 September 2005) of the ADCP/ADV deployment period. The approximately 1-m by 1-m drogues were constructed with polyvinyl chloride (PVC) pipe, vertical risers, rubber unions (connectors), hose clamps, and sails. They used Global Positioning System (GPS) receivers for tracking and radio telemetry for positioning (Figure 5).

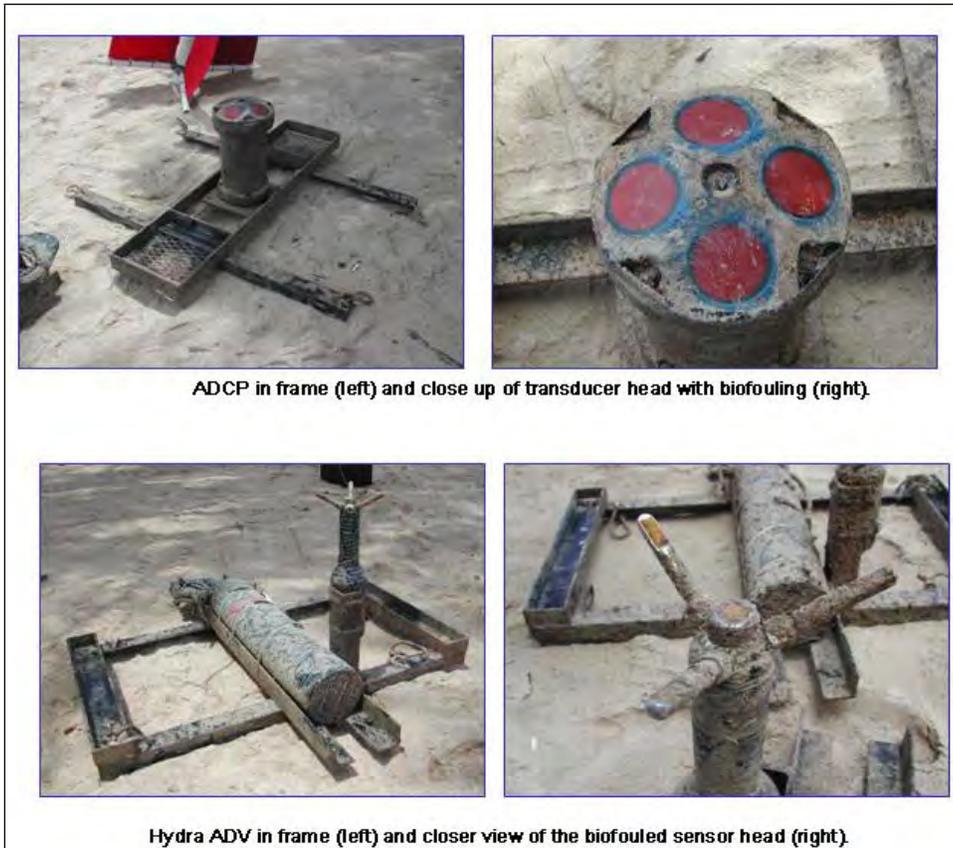


Figure 2. Images of gauges and mounts.

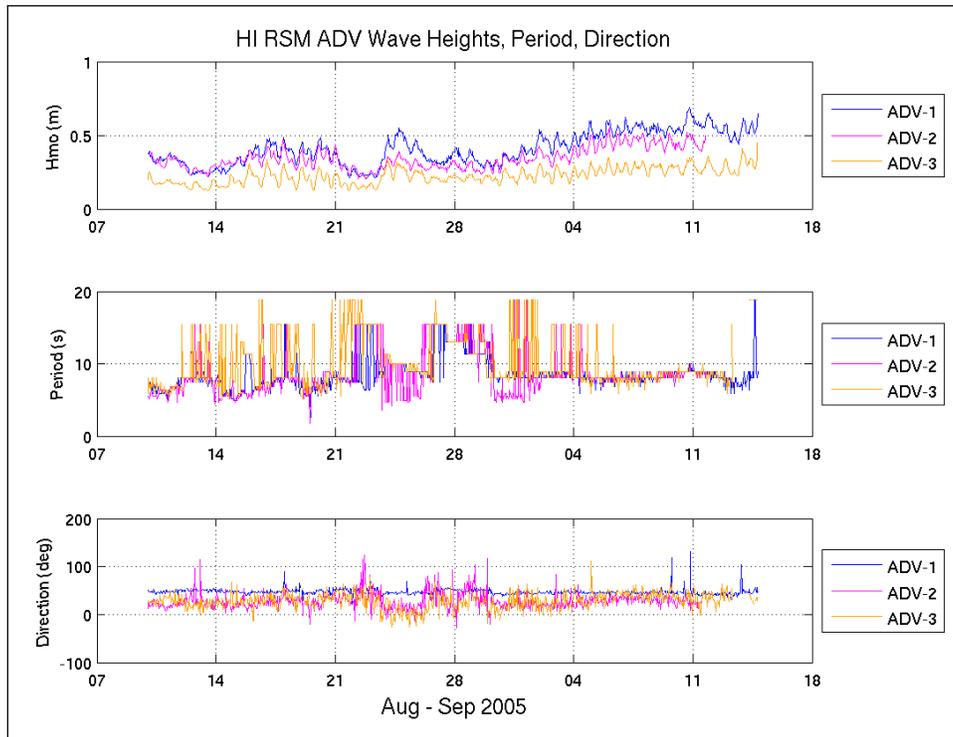


Figure 3. Wave height, period, and direction from the three ADV gauges.

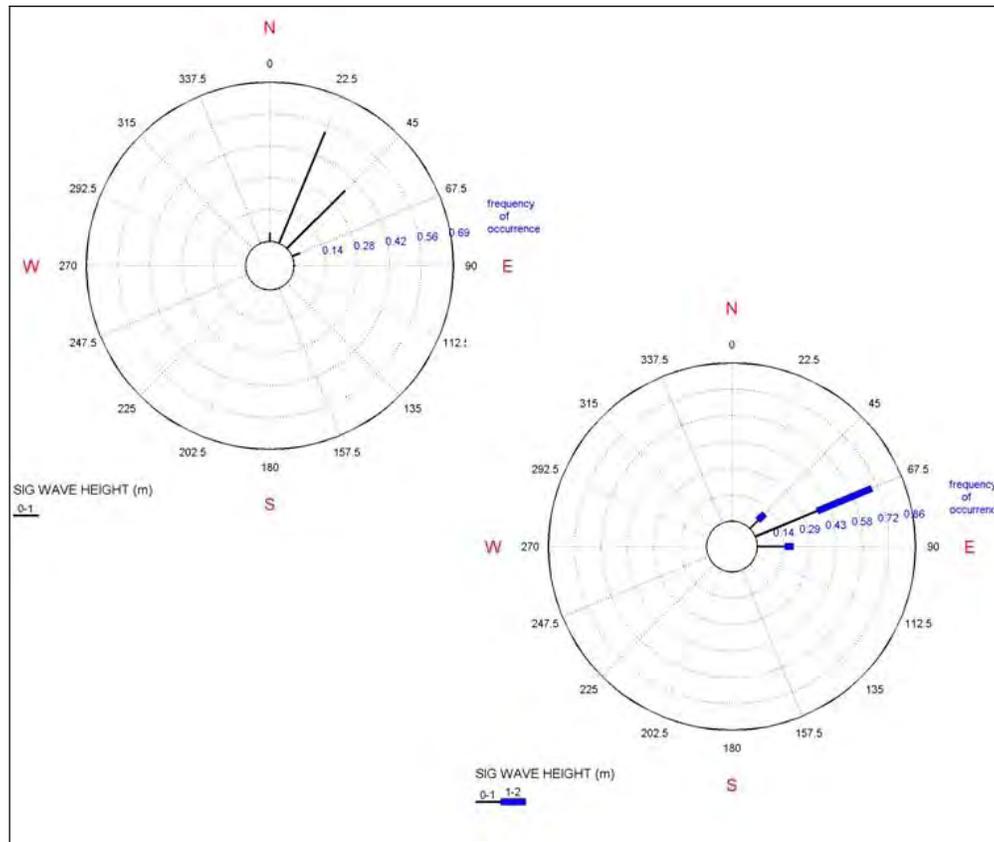


Figure 4. Wave roses for ADCP #1 (left) and #2 (right).



Figure 5. GPS current drogue (left) with traditional drifter (behind grapefruit) and Hawaiian drifter (coconut). Drifter floats just below surface (right).

The drogues floated just below the surface, which placed the bottom of the sail about 1 m from the ocean surface. Difficulty with the radio tracking was experienced because it required line of sight to receive signals from the drifters. Since the drifters were in two different locations (Kailua Bay and Waimanalo Bay), partial tracking was all that could be accomplished. In addition, two antennas and connectors were broken during deployment.

Current drogue tracks for 10 August 2005 and 13 September 2005 are shown in Figure 6. There were two deployments on 10 August, hence the numbers 1 through 8. Some drogues were deployed in the vicinity of the ADV and ADCP gauges for inter-comparison. A track direction reversal of Drogue #2 was observed shortly after deployment on 13 September (Figure 7), starting off on a nearly due west track and then turning back to a southeast trajectory. The nearshore drogues tended to track in a westerly (shoreward) direction at a rate of approximately 0.1–0.2 m/sec, which is comparable to model results. Drogues in Waimanalo Bay moved in a southerly direction during the two deployment periods.

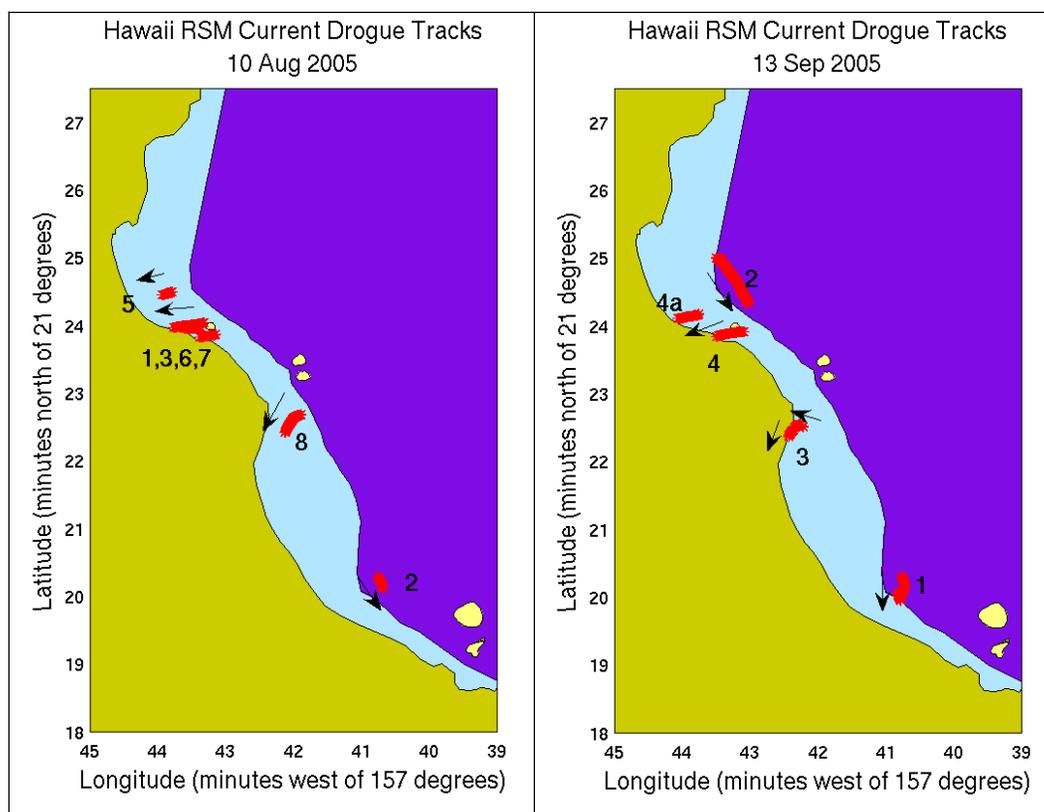


Figure 6. Drogue tracks with track numbers for 10 August (left) and 13 September (right).

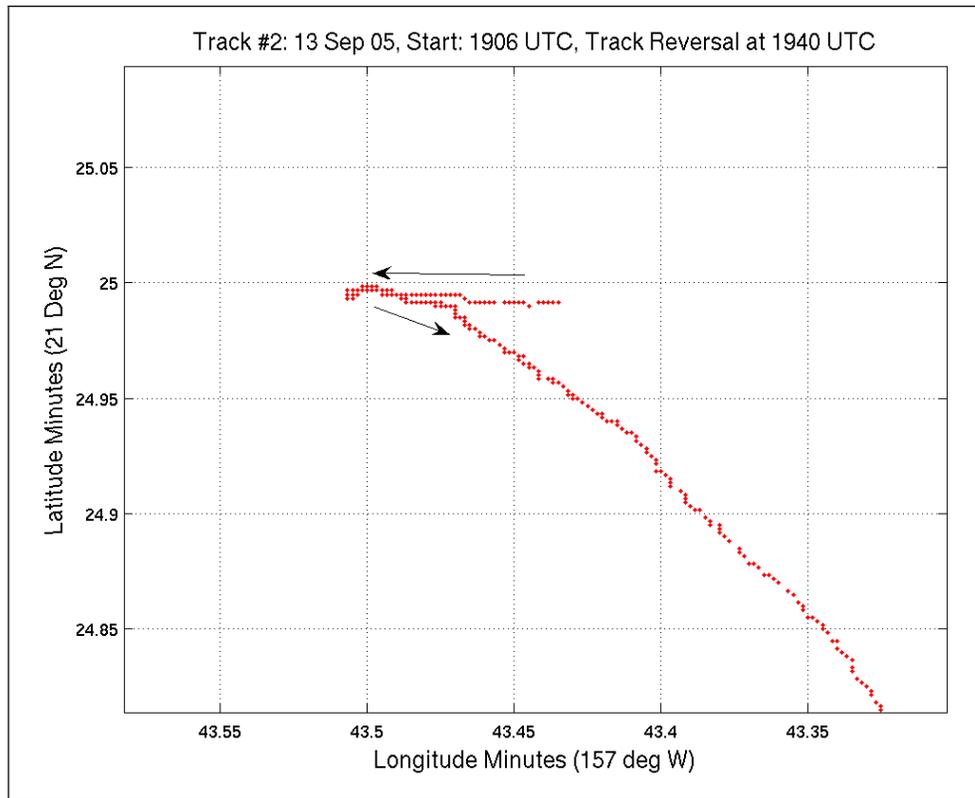


Figure 7. Drogue track reversal on 13 September.

3 Hydrodynamic Modeling

ADCIRC grid development

The ADCIRC (Luettich et al. 1992) numerical model, a regional two-dimensional (2-D) depth-integrated, finite-element hydrodynamic circulation model, was applied in this study to provide water level and depth-averaged current (circulation) information for SEO. The model solves the shallow-water equations in full nonlinear form and can be forced with tide, wind, waves, and flux boundary conditions. Two ADCIRC model grids were developed in the course of this modeling initiative. The first grid was a large circular grid centered on the SEO region and extended from the central point approximately 21 degrees latitude and longitude (2,300 km) in all directions. Initial attempts at validation were unsuccessful because of the existence of two tidal amphidromes that were close to the forcing boundary, shown in Figure 8. (An amphidrome is a location in the ocean where tidal amplitude is zero due to canceling of tidal waves.) To eliminate the problem introduced by the tidal amphidromes, the spatial extent of the ADCIRC model domain was reduced.

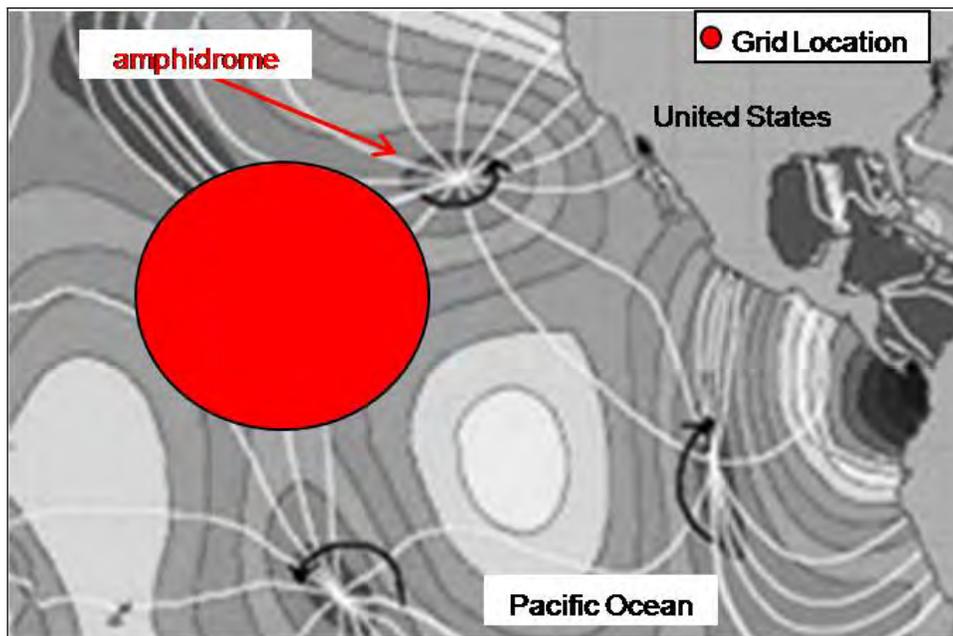


Figure 8. Approximate location of grid and amphidrome locations (background image from http://en.wikipedia.org/wiki/Image:M2_tidal_constituent.jpg).

The final ADCIRC mesh, shown in Figure 9, was a subdomain of the initial grid and is oblong in shape due to the orientation of the Hawaiian Islands. Depths on the mesh were referenced to mean tide level (mtl). The mesh contains 73,305 computational nodes and 140,849 elements. Individual element area ranges from a maximum of 462,500 km² in deep water to a minimum of 60 m² surrounding many of the island features. High resolution was added to the existing ADCIRC mesh in the study area around bathymetric features, such as islands, entrances, and reefs. The refined grid had many improvements over the initial grid:

1. The ADCIRC grid mesh is forced with the free surface position along the open-water boundary that surrounds the Hawaiian Islands. Since the extent of the grid domain for the final grid is smaller than the grid extent for the initial grid, the forcing boundary for the final grid is far away from the influence of the tidal amphidromes shown in Figure 8.
2. The area of Honolulu Harbor is better resolved in the final grid, which improves the comparison between calculated tides and gauge data in this area.

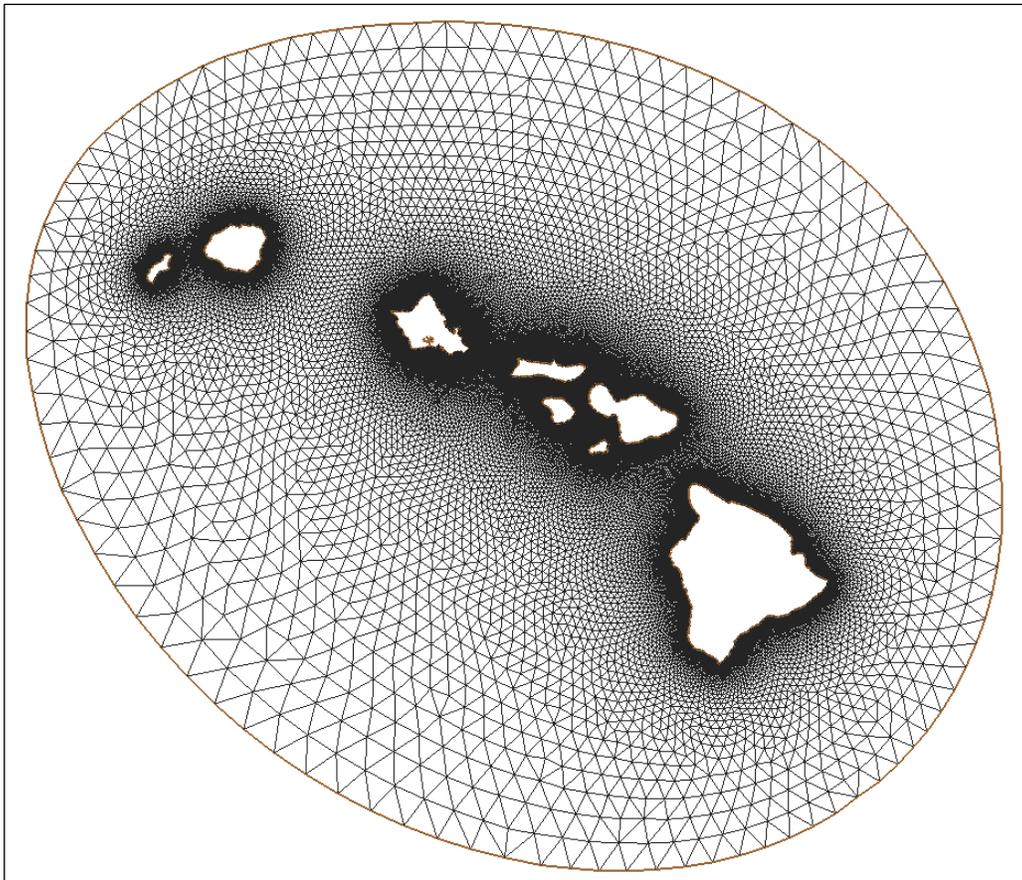


Figure 9. Final ADCIRC mesh domain.

3. Resolution around prominent features in the project reach was added, as well as topographic information for Rabbit and Turtle Islands located in the southern portion of the SEO region.

Wind sources

Three wind sources were investigated for potential application as a forcing condition in the ADCIRC model: National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC) Buoy 51001, National Centers for Environmental Prediction (NCEP) hindcast, and Oceanweather, Inc. (OWI) hindcast wind data. The elevation of NCEP and OWI wind sources was 10 m. The NDBC buoy data were empirically transformed from the 5-m to 10-m elevation. A comparison of the observed (transformed) wind speed and direction at the NDBC Buoy 51001 and the nearest NCEP prediction point was performed for the months of January to June 2001 (Figure 10). Wind directions compared well; however, the NCEP wind speed consistently exceeded the buoy observations by 5 to 10 percent. These differences can be attributed to the buoy anemometer height being empirically transformed from the 5-m to 10-m elevation, whereas the NCEP surface level winds are predicted at an elevation of approximately 10 m. The comparisons suggest that long-term, historic NCEP winds can be applied in this project with a high degree of confidence for the initial validation time period.

NDBC Buoy 51001 winds were also compared to the predicted OWI basin level Pacific hindcast winds for the month of April 2001. A plot of this comparison is shown in Figure 11. Wind speed and directions compared well. These data suggest that OWI winds can also be applied to the project with a high degree of confidence. OWI winds were applied for the second validation (gauge deployment) time period.

ADCIRC model validation – wind and tide for initial validation time period

In the initial validation, the time period 10–24 April 2001 was selected for comparing model results to measured data because the OWI winds compared well with other wind sources for this time period. ADCIRC was forced along the open boundary with tidal information extracted from the OSU TOPEX/POSEIDON Crossover (TPXO) tidal database (Egbert et al. 1994). Wind speed and direction information were obtained from NDBC Buoy 51001. The ADCIRC hydrodynamic time-step was 0.4 sec and results

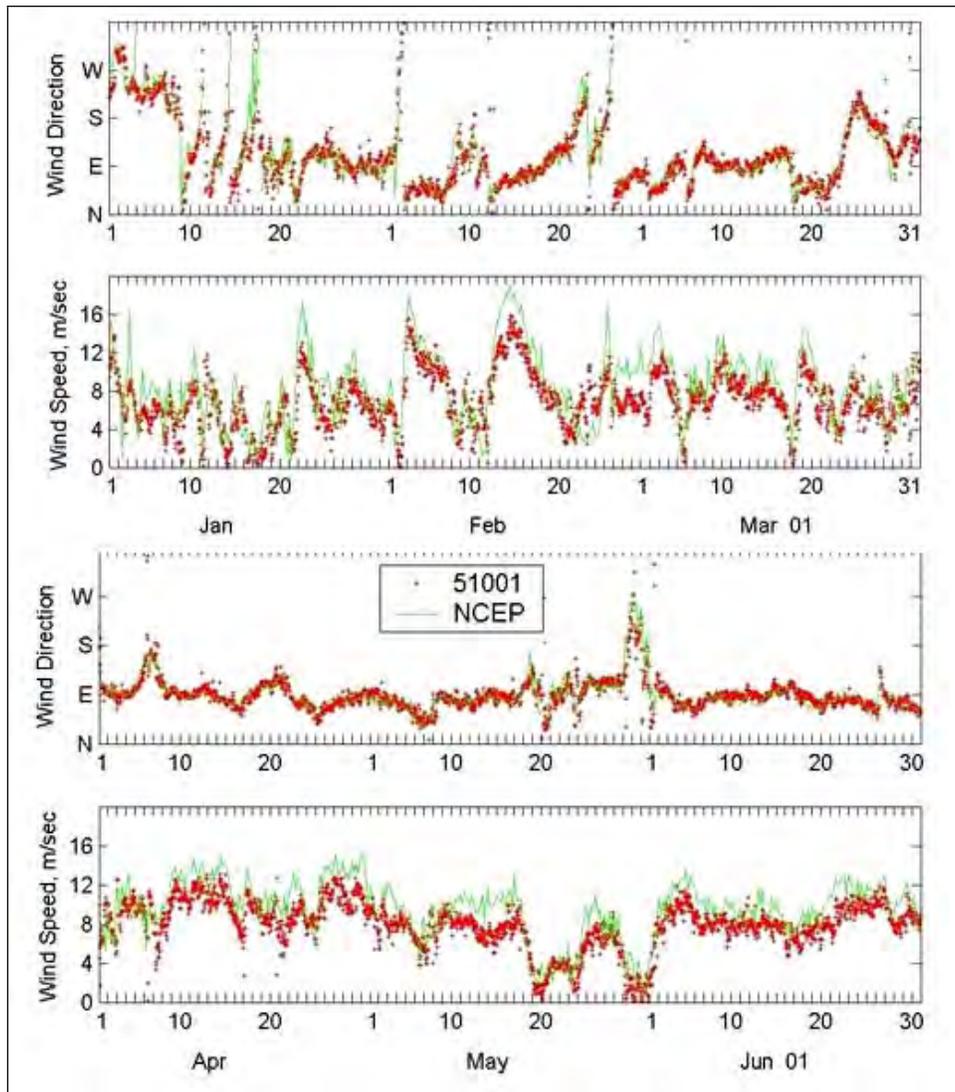


Figure 10. Comparison of observed (NDBC Buoy 51001) transformed to the 10-m elevation and predicted (NCEP) wind speed and direction.

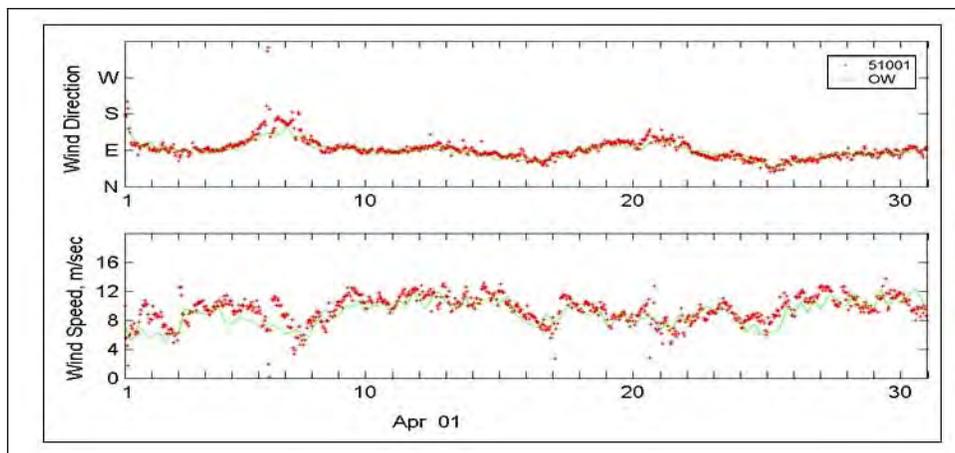


Figure 11. Comparison of observed (NDBC Buoy 51001) and predicted (OWI) wind speed and direction for April 2001.

were reported hourly. Simulations were performed on the U.S. Army Engineer Research and Development Center's (ERDC) High-Performance Computer (HPC) system in Vicksburg, MS, due to the large size of the ADCIRC domain.

For this initial model validation, ADCIRC results for water level were compared with the two NOAA tide gauges available on the southern and eastern portion of the island of Oahu. Figure 12 shows the locations of the two gauges (red circles) and their proximity to the project area (black box). The calculated water levels from the ADCIRC simulation of the April 2001 time period compared relatively well in range and phase with the NOAA gauge measurements, considering that the locations of the gauges were well outside the area of high resolution in the project area. Water level comparisons of the ADCIRC validations to the two NOAA gauges, Honolulu Harbor and Kaneohe Bay, are shown in Figures 13 and 14. Since these gauges were outside the project area and located in less resolved locations, it was determined that another validation would be made with the water level and current data received from ADV and ADCP gauges for the deployment period from 10–31 August 2005. Results of that validation are provided later in section entitled, "ADCIRC validation—wind, tide, and waves for gauge deployment time period."

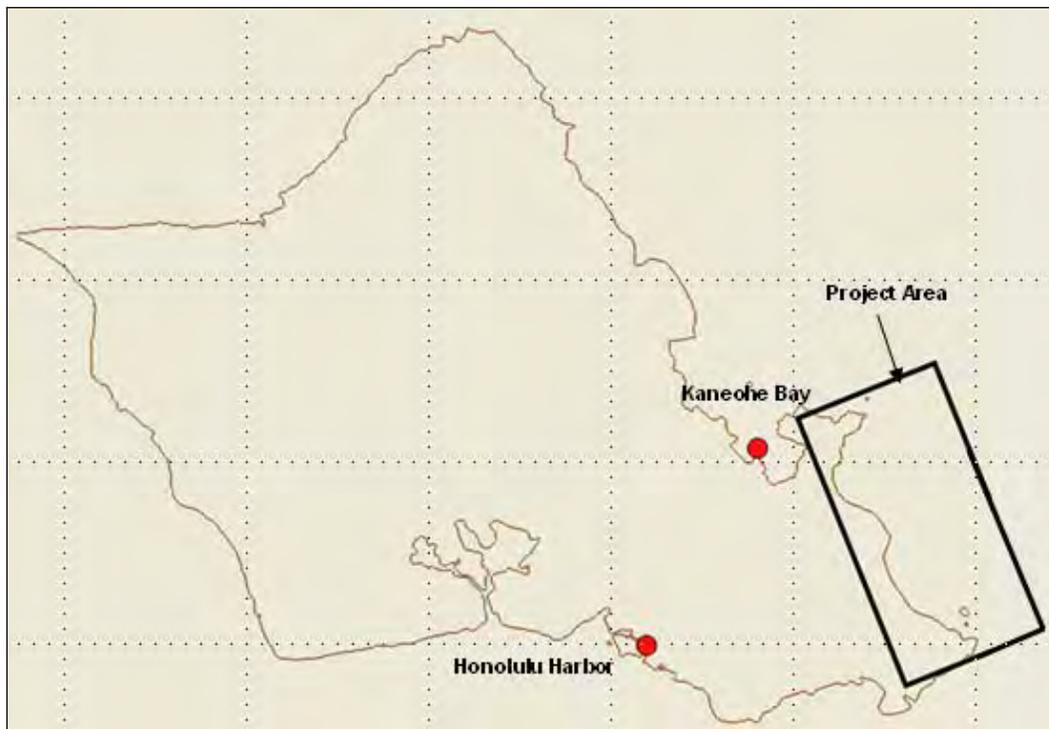


Figure 12. NOAA gauge locations for initial validation time period.

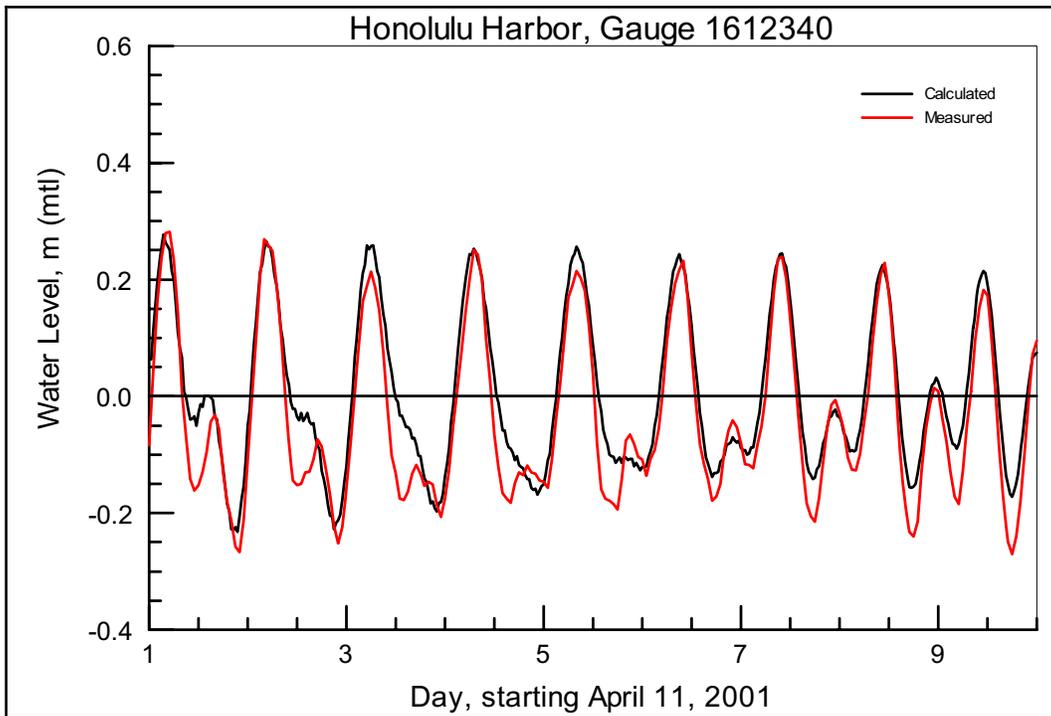


Figure 13. Comparison of calculated and measured water level at Honolulu Harbor gauge for initial validation period.

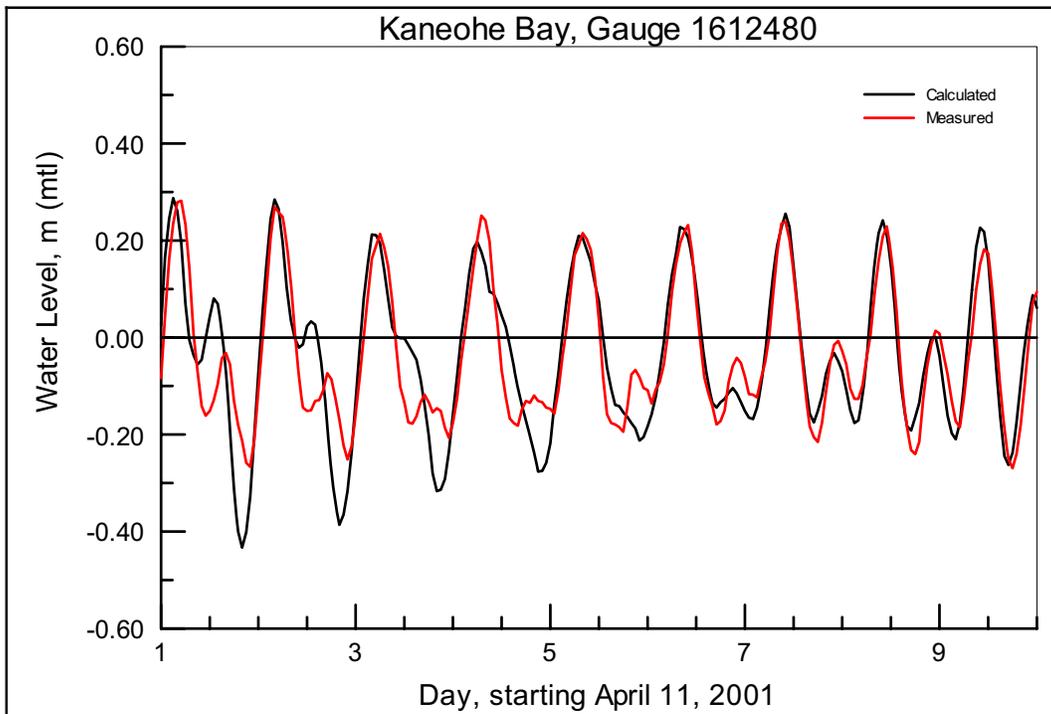


Figure 14. Comparison of calculated and measured water level at Kaneohe Bay gauge for initial validation period.

STWAVE

STWAVE is a steady-state, finite-difference model based on the wave action balance equation (Resio 1988; Smith et al. 2001). STWAVE simulates depth-induced wave refraction and shoaling, current-induced refraction and shoaling, depth- and steepness-induced wave breaking, diffraction, wind-wave growth, wave-wave interaction, and white-capping. The purpose of applying nearshore wave transformation models is to quantitatively describe the change in wave parameters between the offshore and the nearshore and, in this application, include simulating wave transformation over a reef. As previously mentioned, development of a spatially varying bottom friction capability in STWAVE was completed to enable application to the extensive reefs in the SEO study area.

Grid development

An STWAVE finite-difference grid was developed for the study area, with bathymetry interpolated from the ADCIRC grid mesh. The STWAVE grid resolution was 25 m × 25 m with a grid orientation of 210 deg counter-clockwise from east. The original grid was 18 km (720 cells) in the along-shore direction by 6.2 km (248 cells) in the cross-shore direction and extended in the offshore to approximately the 100-m contour, with a maximum 344 m depth (Figure 15). After initial testing and consultation with the Honolulu District, it was determined that the lateral extent of the grid should be expanded around the headlands and the offshore boundary should be extended beyond the shallow water offshore from Mokapu Point and Makapu'u Point. The extended grid was 24.2 km (968 cells) in the alongshore direction by 7.8 km (310 cells) in the cross-shore direction and extended in the offshore to approximately the 300-m contour, with a maximum 480-m depth (Figure 15). The initial grid was applied for wave climate development and nearshore database generation. The extended grid was applied for comparison to field data and linkage to the ADCIRC model.

Wave climate -- model forcing conditions

Directional wave data were available at CDIP Station 098 (Mokapu Point) from August 2000 through 2004 (the study started in March 2005). Non-directional wave data were available at Station 034 (Makapu'u) from 1981 to 1996. Directional wave data were available for Station 099 (Kailua Bay) for 2 months (November–December 2000). Station locations are shown in Figure 16.

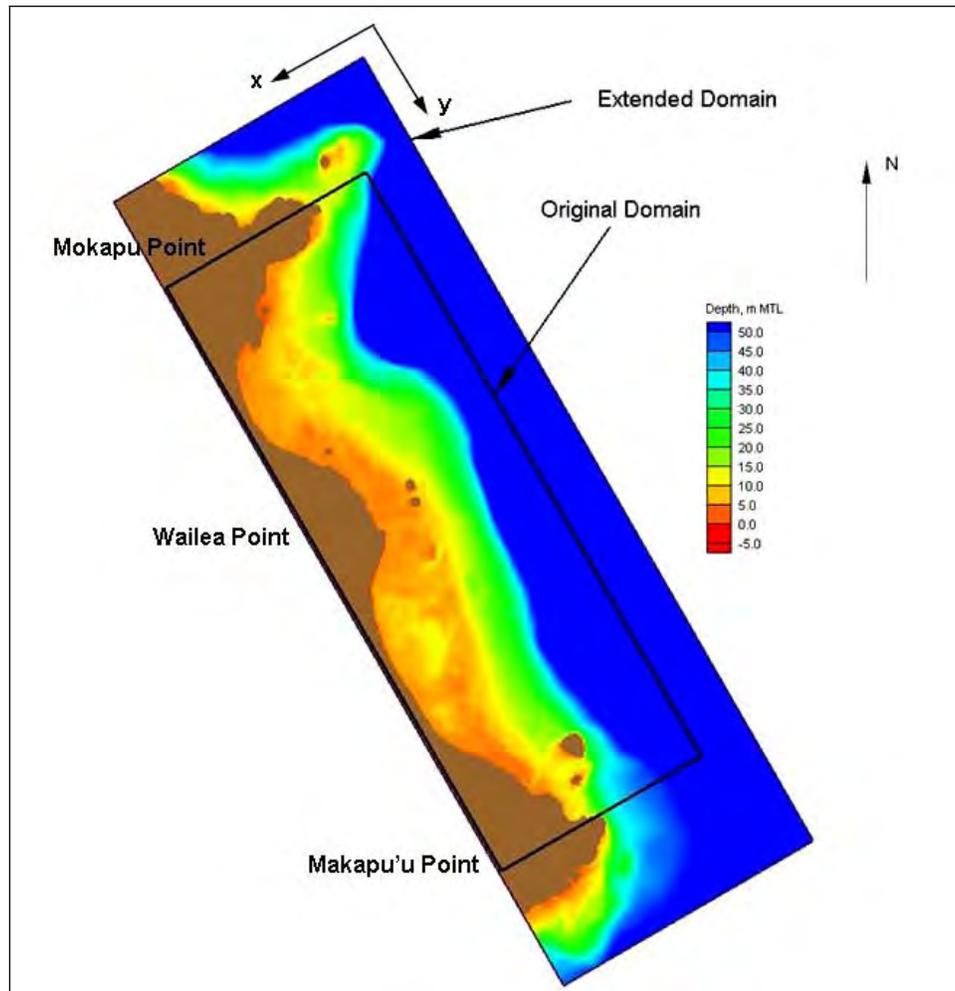


Figure 15. STWAVE grid domain.

For this study, the long-term data record (2000–2004) for Station 098 was analyzed with the Coastal Engineering and Data Analysis Software (CEDAS) 3.0 – Nearshore Evolution Modeling System (NEMOS) software. Since the purpose of this procedure was to determine all conditions that occurred at Station 098, the longest record possible, including the incomplete years 2000 and 2004, were included in the analysis. A 3-month gap in the data in 2004 and the small portion of 2005 data available at the time the study started (1 March 2005) were not included in the analysis.



Figure 16. CDIP buoy locations courtesy of CDIP web site (<http://cdip.ucsd.edu>).

Figures 17 and 18 show that waves are generally from the east-northeast quadrant and range in height from 0.5 to 6.0 m. Peak wave periods are generally 6 to 16 sec. From these tabulations, a set of discrete conditions was selected for simulation (Table 2). From the 216 possible height-period-direction combinations, 134 conditions occurred in the 2000–2004 time period. The wave height range was defined at 0.5-m intervals from 0.75 m to 2.75 m and at a 0.75-m interval to 3.5 m. The wave period range was 6 to 16 sec at a 2-sec interval. The wave directions were incremented every 22.5 deg from -22.5 deg to 90 deg, relative to True North. For each of the 134 selected wave conditions, Texel Marsden Arsloe (TMA) shallow-water spectra were generated by applying the SMS spectral wave generation software, and with those spectra applied at the model boundary; wave transformation was simulated by applying STWAVE over the project domain.

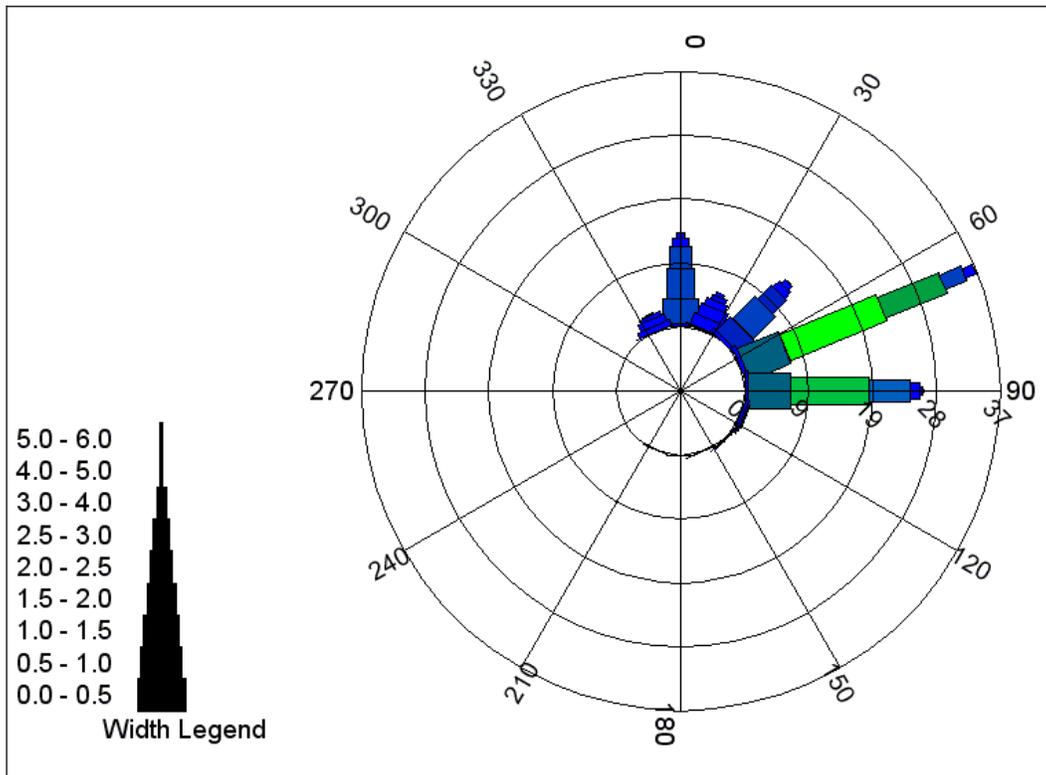


Figure 17. Wave height versus wave direction percent occurrence rose for CDIP Buoy 098 - Mokapu Point, HI (data from August 2000 through December 2004).

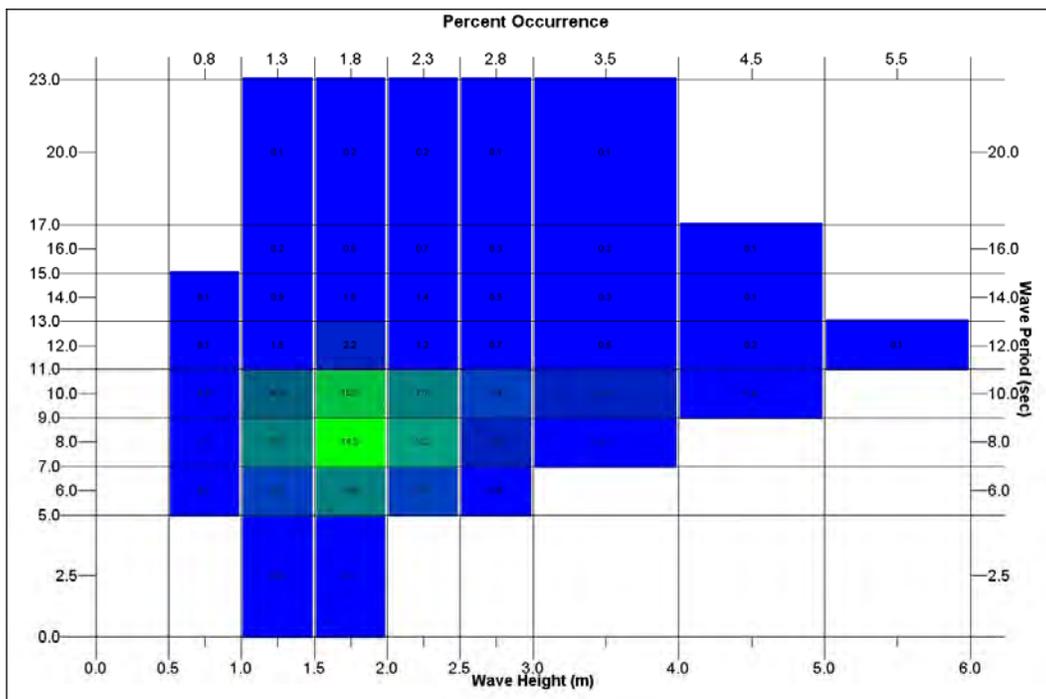


Figure 18. Block diagram of wave height versus wave period for CDIP Buoy 098 - Mokapu Point, HI (data from August 2000 through December 2004).

Table 2. Wave conditions.

Significant Wave Height, m	Wave Period sec	Wave Direction deg from North	Wave Direction deg from STWAVE axis
0.75	6	-22.5	82.5
1.25	8	0	60
1.75	10	22.5	37.5
2.25	12	45	15
2.75	14	67.5	-7.5
3.5	16	90	-30

Wave climate analysis

Nearshore conditions at a point in Waimanalo Bay [Figure 19, cell (229,506)] were extracted from the STWAVE model results for each of the 134 simulations. Since these simulations were to illustrate the technique for developing a wave climate, they did not include the detail of applying friction to the domain. A transformation correlation between the offshore

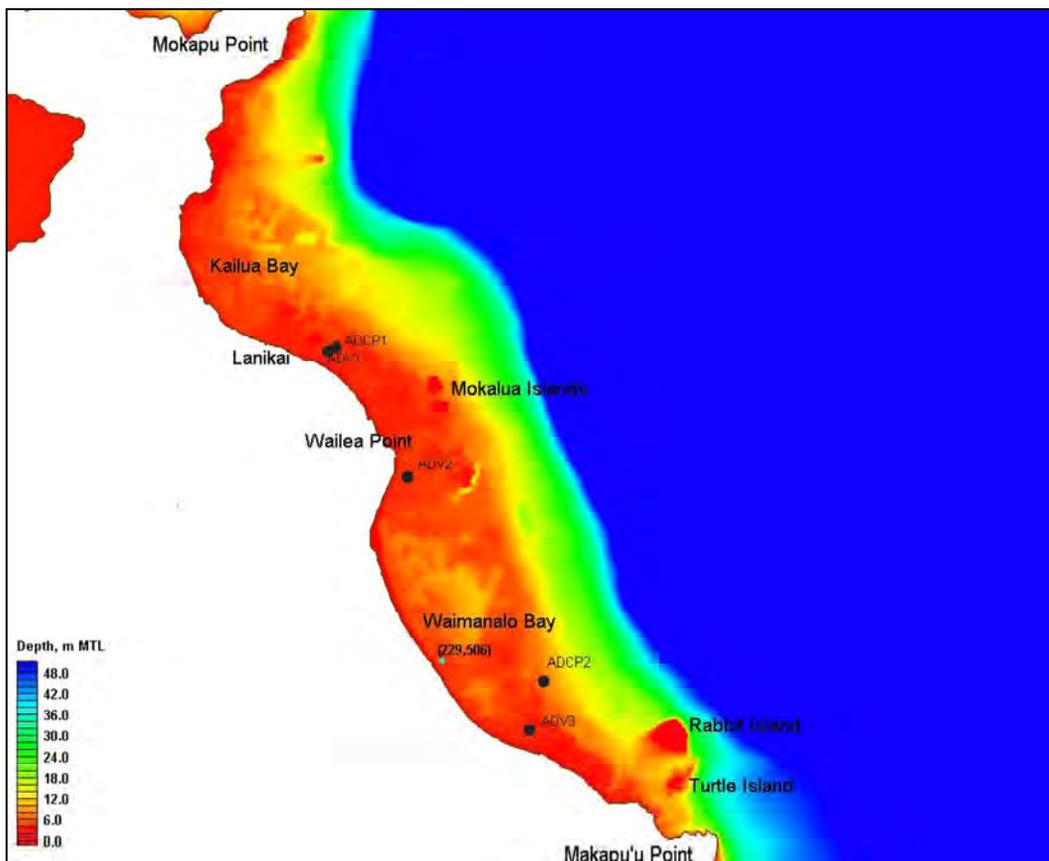


Figure 19. Location of extracted STWAVE model results (cell 229,506).

and nearshore conditions was then determined for each of the 134 simulations. By applying the appropriate transfer function to each wave condition in the 2000–2004 offshore time series at Station 098, a long-term (2000–2004) nearshore time series was generated (Figure 20). Note that the 3-month gap in the time series corresponds to 15 February to 19 May 2004 when the offshore CDIP Buoy 098 gauge was not operational. The nearshore time series demonstrates that there is a reduction in wave height from the offshore location to the nearshore location, landward of the extensive reef system due to depth-limited breaking and refraction. The time series, however, appears generally contained or banded between the 1.25 and 2.25 m wave height bins that were selected to represent the overall wave climate. Further analysis was required to determine if a more detailed representation of the offshore wave climate would better resolve the nearshore wave climate, and is discussed in the following.

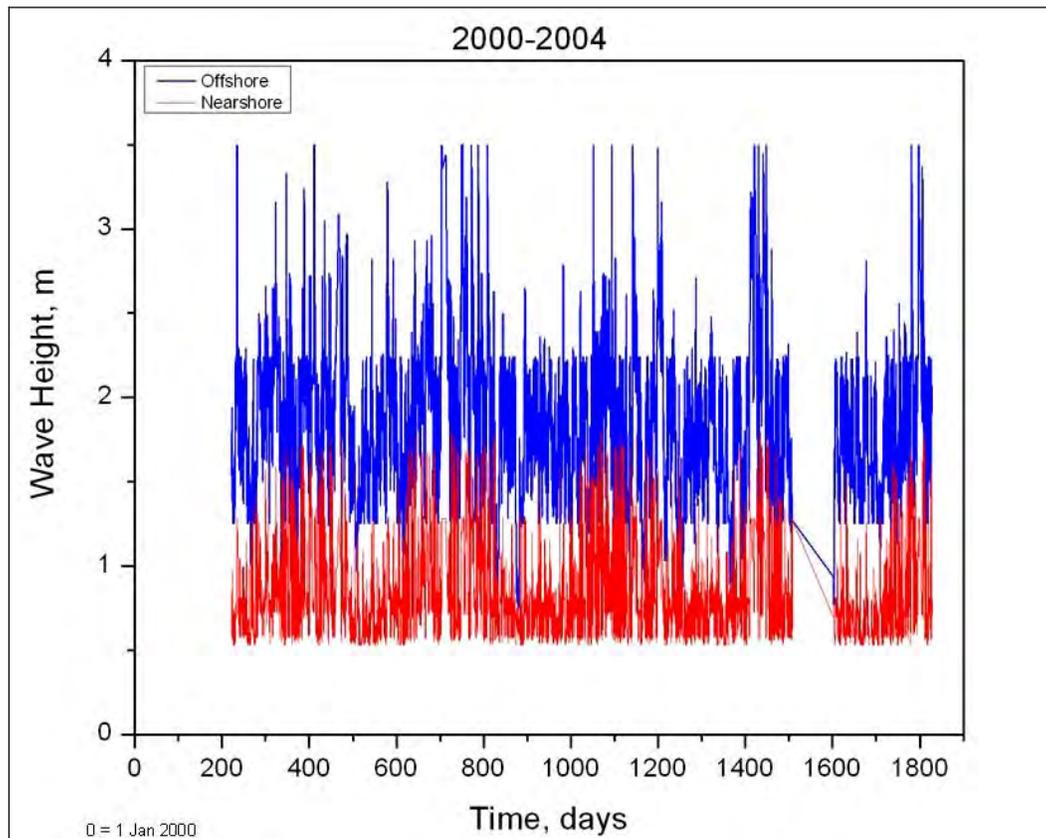


Figure 20. Nearshore time series (without friction) generated from offshore time series with 134 correlation conditions.

In order to capture the nearshore transformation time series more precisely and to include all wave conditions occurring in the time series, the range and refinement of the wave conditions simulated was expanded (Table 3). Wave heights ranged from 0.5 to 5.0 m with the finest increment being 0.25 m. Wave periods were expanded to include 20 sec. Wave angles were expanded to include waves from the east-southeasterly direction (representing waves 106–118 deg from True North) and were refined to 11.25 deg bands. For each of the 1274 selected wave conditions, TMA (shallow-water) spectra were generated by applying the SMS spectral wave generation software, and wave transformation was simulated by applying STWAVE over the project domain for each of the 1274 wave spectra. Again, nearshore conditions at cell (229,506) were extracted from the model results for each of the simulations. A transfer function between the offshore and nearshore conditions was then determined for each of the simulations. By applying the transfer function to each wave condition in the offshore time series at Station 098, a refined nearshore time series was generated (Figure 21), which shows a more realistic variation in the wave height. Note from the wave rose that wave directions converge to 35–73 deg relative to True North at the same point location shoreward of the reef and are predominantly directed shore-normal (60 deg). (In a follow-on study, the 1274 STWAVE simulations included bottom friction, and nearshore wave climates were developed for 10 nearshore locations.)

Table 3. Expanded (1274) wave conditions.

Significant Wave Height, m	Wave Period, sec	Wave Direction, deg from North	Wave Direction, deg from STWAVE axis
0.50	6	-22.5	82.5
0.75	8	-11.25	71.25
1.00	10	0	60
1.25	12	11.25	49.75
1.50	14	22.5	37.5
1.75	16	33.75	26.25
2.00	20	45	15
2.25		56.25	3.75
2.50		67.5	-7.5
2.75		78.75	-18.75
3.00		90	-30
3.50		101.25	-41.25
4.00		112.5	-52.5
5.00			

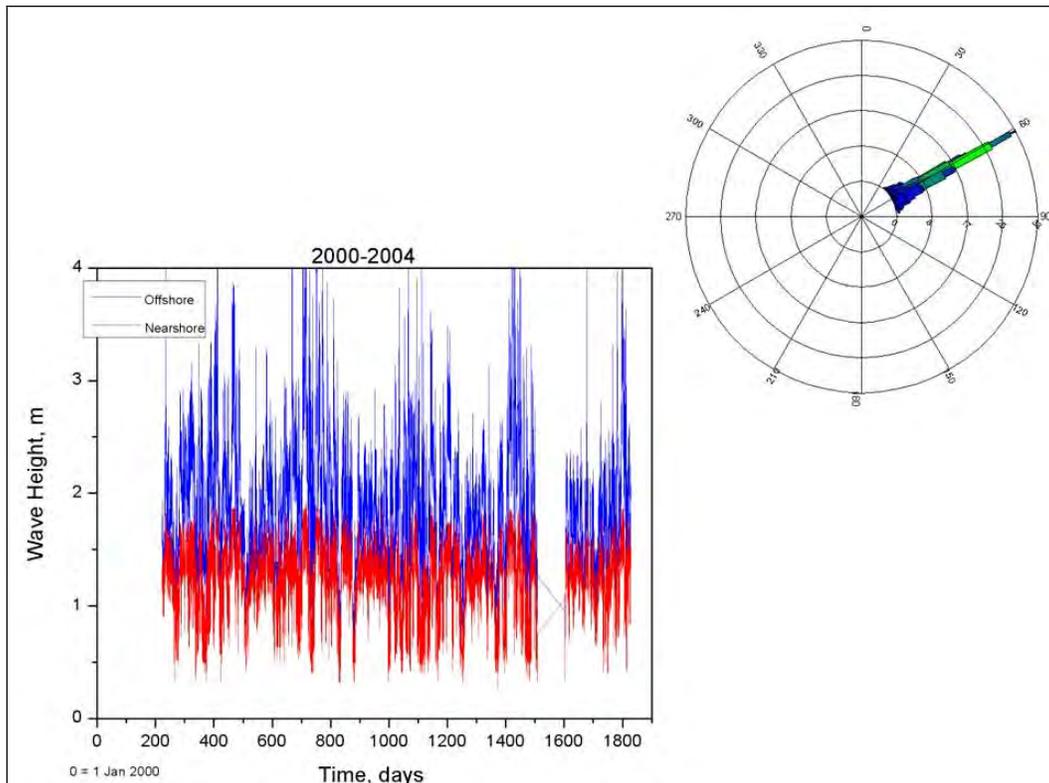


Figure 21. Nearshore time series (without friction) and wave rose generated from offshore time series with 1274 correlation conditions.

Bottom friction

Development of a bottom friction capability in STWAVE was completed for application to the extensive reefs in the SEO study area. STWAVE includes two formulations for bottom friction. The first is the JONSWAP formulation (Hasselmann et al. 1973; Padilla-Hernandez and Monbaliu 2001), where the spectral energy loss from bottom friction is formulated as a sink term, S_{bf} , in the energy balance equation,

$$S_{bf} = \frac{-1}{g} c_f \frac{\sigma^2}{\sinh^2 kd} E(f, \alpha) \quad (1)$$

where:

- g = acceleration of gravity
- c_f = bottom friction coefficient
- σ = angular frequency
- k = wave number
- d = total water depth

- E = spectral energy density divided by ($\rho_w g$), where ρ_w is density of water
 f = wave frequency
 α = wave direction.

The dissipation is summed over all frequencies and directions in the spectrum. A single friction coefficient, c_f , can be applied to the entire STWAVE domain, or a range of friction values can be applied on a cell-by-cell basis in a spatially varying manner. For the JONSWAP bottom friction formulation, c_f is specified as Γ/g , where the recommended values of Γ are in the range 0.038 to 0.067 m²/sec³ (or model input values of $c_f = 0.004$ to 0.007 m/sec) for sand beds based on the JONSWAP experiment and North Sea measurements (Hasselmann et al. 1973; Bouws and Komen 1983). Values of c_f applied for coral reefs range from 0.05 to 0.40 m/sec (Hardy 1993; Hearn 1999; Lowe et al. 2005). Equation 1 has a weak inverse dependence on water depth related to the increase in bottom wave orbital velocity as the relative depth, kd , decreases.

A Manning formulation is also available in STWAVE, based on Holthuijsen (2007),

$$S_{bf} = \frac{-1}{g} \left(\frac{gn^2}{d^{1/3}} \right) \frac{\sigma^2}{\sinh^2 kd} E(f, \alpha) u_{rms} \quad (2)$$

where the value of the Manning coefficient, n , is specified as input to STWAVE (either spatially constant or variable) and u_{rms} is the root-mean-square bottom velocity. With the Manning formulation, bottom friction dissipation has an additional inverse dependence on water depth. Estimates of Manning coefficients are available in most fluid mechanics reference books (e.g., 0.01 to 0.05 for smooth to rocky/weedy channels). Converting c_f values applied for coral reefs (0.05 to 0.40 m/sec) to Manning coefficients yields a range of 0.10 to 0.25. However, it is recommended that the specification of c_f or n be validated with field measurements. Application of this model capability to a specific site requires validation to field data.

A single friction value can be applied to the entire STWAVE domain or a range of friction values can be applied on a cell-by-cell basis. As an example, the 134 wave conditions first simulated were repeated with the revised STWAVE, applying a JONSWAP bottom friction coefficient typical for

reefs of $c_f = 0.05$ m/sec over the entire model domain. A comparison of nearshore waves at cell (229,506) was made (Figures 22 and 23). The offshore (blue) to nearshore without bottom friction (black) comparison shows a reduction in wave height of 38% (Figure 22). With bottom friction (red), the reduction in wave height is 84%. A comparison of the nearshore wave heights with and without bottom friction shows that, with the inclusion of bottom friction, wave heights range from 18–38% of the previous results that did not include bottom friction. On average, the wave height was 26% of the frictionless value at the selected location. Waves refract less with the inclusion of bottom friction, likely due to the reduction in energy at lower frequency (Figure 23).

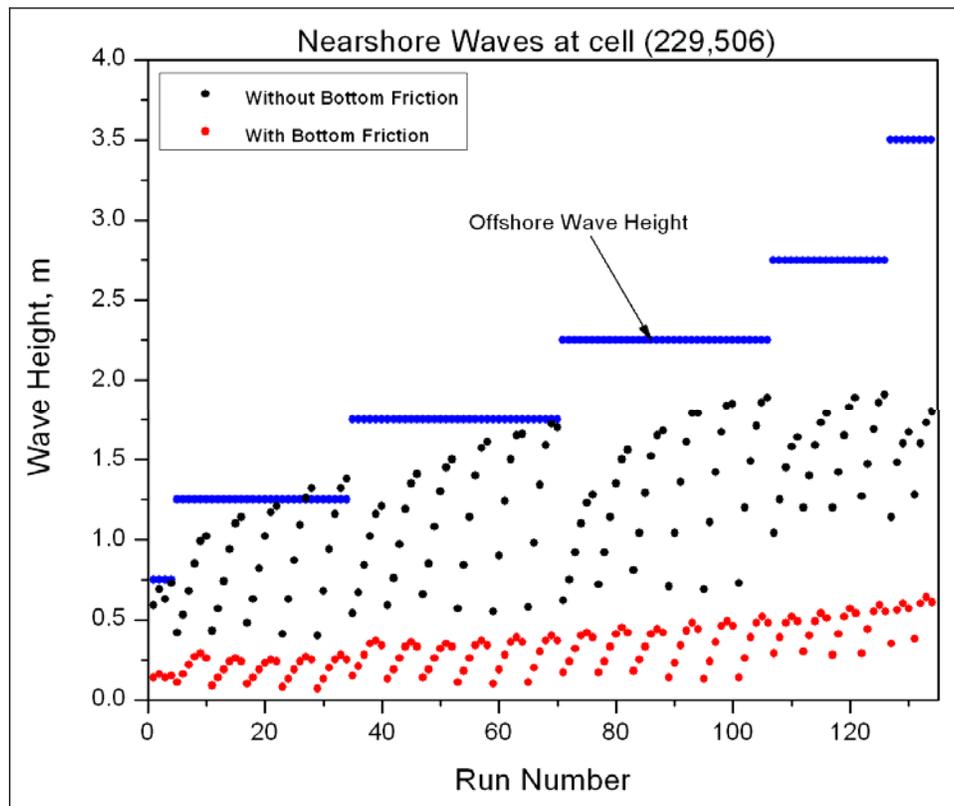


Figure 22. Comparison of predicted wave heights at cell (229,506) with and without the STWAVE bottom friction feature.

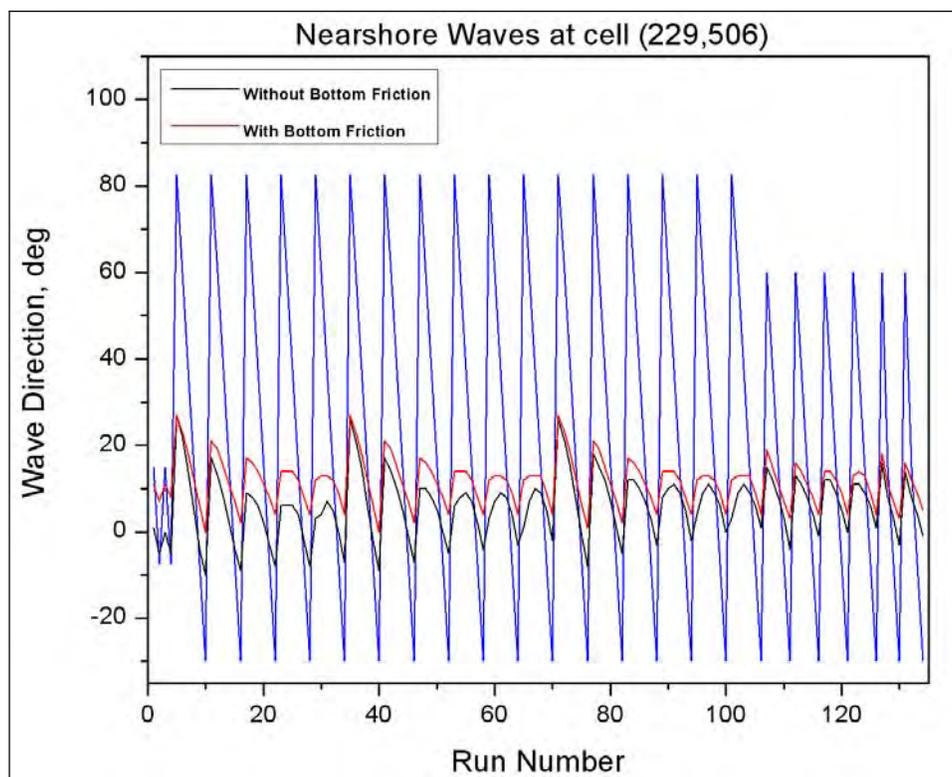


Figure 23. Comparison of predicted wave direction at cell (229,506) with and without the STWAVE bottom friction feature.

As another example, for each of the 1274 selected wave conditions simulated subsequently to achieve a more detailed wave climate, wave transformation *including spatially constant bottom friction* of 0.05 m/sec was simulated by applying STWAVE over the project domain for each of the 1274 wave spectra. Again, nearshore conditions at cell (229,506) were extracted from the model results for each of the simulations. A transfer function between the offshore and nearshore condition was then determined for each of the simulations. By applying the transfer function to each wave condition in the offshore time series at Station 098, a refined nearshore time series with bottom friction was generated (Figure 24). A comparison of Figures 21 and 24 shows that the constant 0.05 value for the JONSWAP bottom friction coefficient reduces nearshore wave heights by approximately 73%.

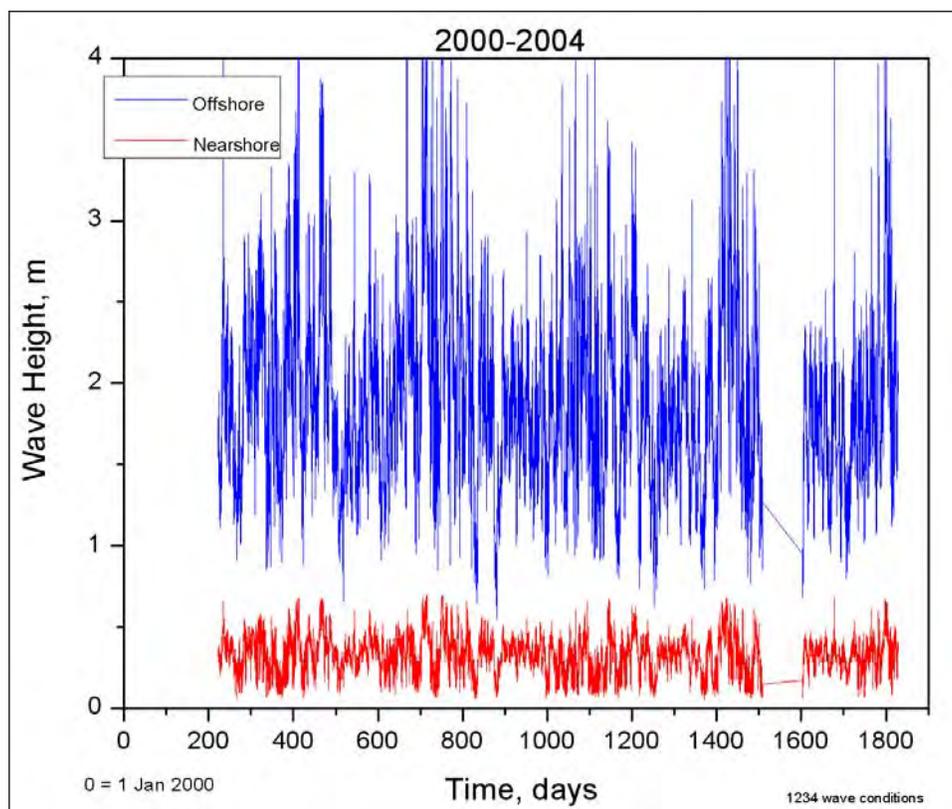


Figure 24. Nearshore time series (including spatially constant bottom friction) generated from offshore time series with 1274 correlation conditions.

Model validation

As previously discussed, the extended domain STWAVE grid was applied in the model validation process. The August 2005 model validation time period corresponded to a portion of the field data collection time period (9 August through 14 September 2005). CDIP Buoy data for August 2005 (Figure 25) were extracted from the CDIP website for every 3-hr interval of August 2005. For each of these measured wave conditions, TMA (shallow-water) spectra were generated by applying the SMS spectral wave generation software. These spectra were then applied to the offshore boundary of the model domain. Note that analysis was done to compare the waves at the 300-m depth STWAVE boundary and the 100-m depth gauge location by applying the University of Delaware Hydrodynamic Wave Calculator applet application (<http://www.coastal.udel.edu/faculty/rad/wavetheory.html>). It was found that the difference in wave height from the 300-m to 100-m depth is small (approximately 4% for periods <15 sec, which accounts for 98% of the waves) and the offshore gauge data were applied at the STWAVE boundary without back refracting to the 300-m water depth.

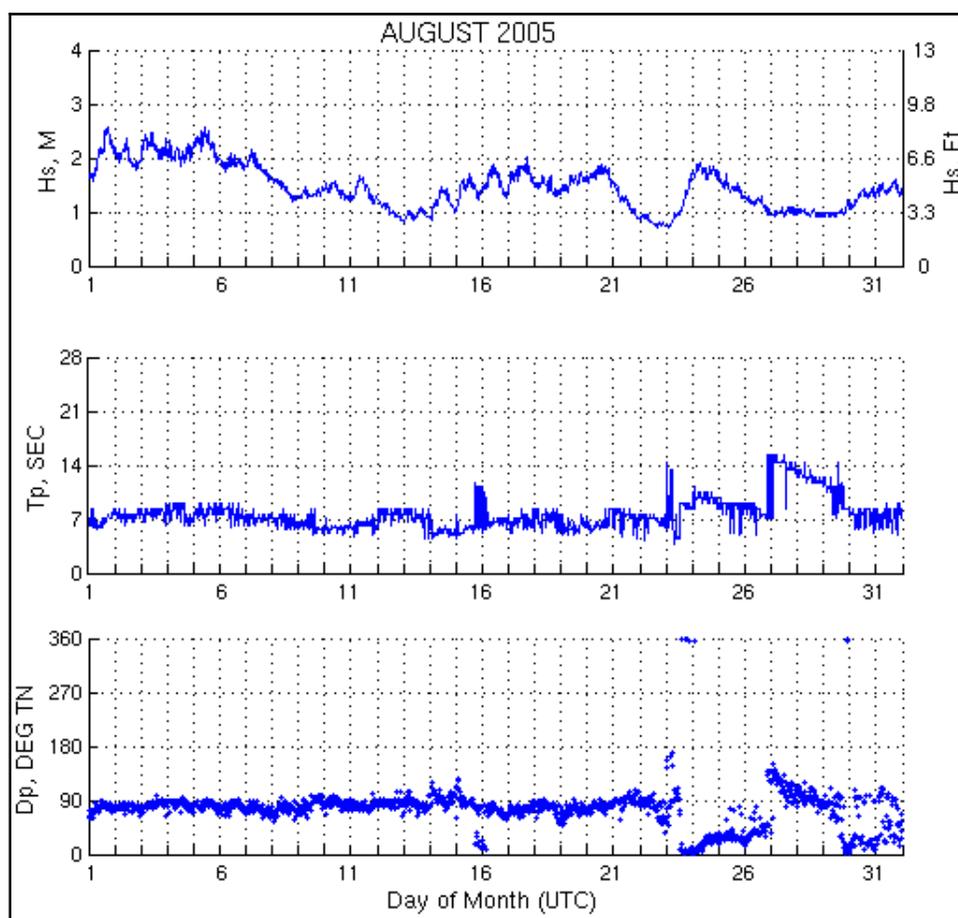


Figure 25. CDIP buoy data at station 098 (Mokapu Point, Hawaii) for August 2005.

Initially, a constant bottom friction value was applied to each cell of the STWAVE domain. Several simulations with different constant JONSWAP bottom friction values ranging from 0.04 to 0.12 m/sec were made to examine the range of response (wave height) at the gauge locations. Figure 26 shows the wave height time series generated by STWAVE at the location where ADV1 was placed, without bottom friction and for four simulations with bottom friction. These initial simulations indicated that, without bottom friction, wave heights at ADV1 are reduced on average by 21% relative to the offshore wave height due to depth-limited breaking. Bottom friction reduces wave height at ADV1's location by 64% for a JONSWAP bottom friction coefficient of 0.04 m/sec (wave height is 36% of the offshore wave height), by 71–76% for a bottom friction value of 0.05 m/sec (wave height is 24–29% of the offshore wave height), and by 93% for a bottom friction value of 0.12 m/sec (wave height is 7% of the offshore wave height). Applying a Manning friction coefficient of 0.15 to 0.25 to the reef resulted in average wave height reductions of 62–80%.

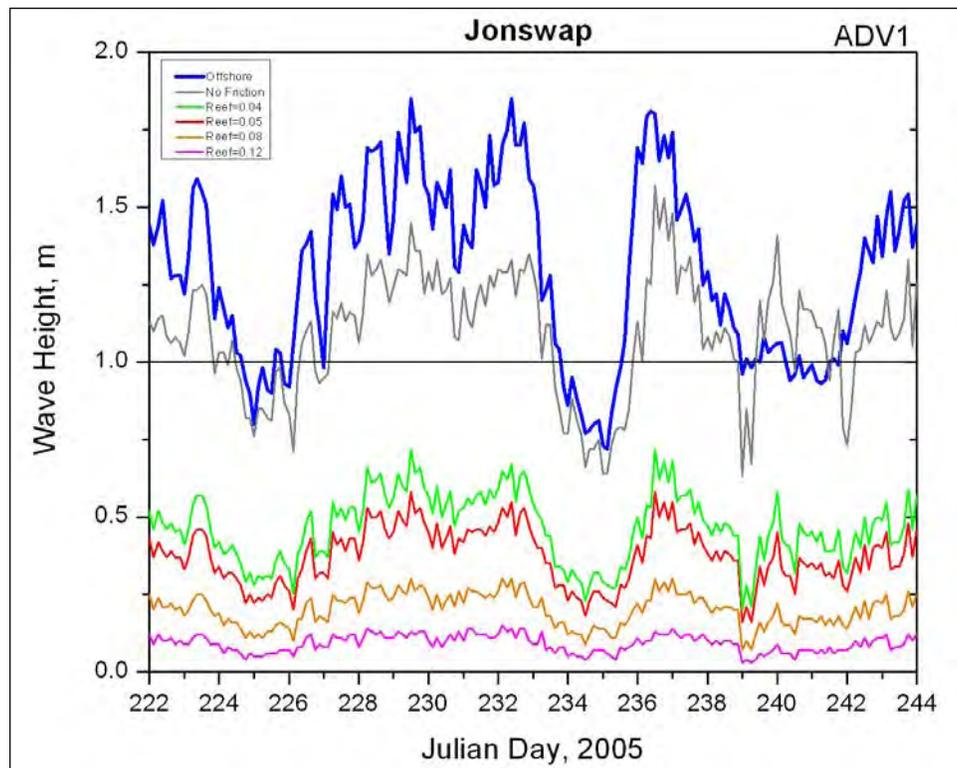


Figure 26. Simulated wave height time series at ADV1 with and without bottom friction.

The range of response indicates the importance of selecting the appropriate bottom friction value to represent the reefs in the study area. In addition, a variable friction field with a larger friction value applied only over the reef areas would be the most appropriate representation of the study area.

In the first set of validation simulations, a variable bottom friction field with JONSWAP friction coefficients of 0.05 m/sec applied to the reef region, 0.09 m/sec around the offshore islands (for compatibility/linkage to the ADCIRC model), and 0.006 m/sec in the offshore regions was utilized. A Manning validation simulation was also made with friction coefficients of 0.20 applied to the reef region (which is within the valid range of reef coefficients applied in the literature), 0.19 around the offshore islands, and 0.02 in the offshore regions. The simulations also included water level fluctuation due to tide. A comparison of field data collected at the three ADV locations (Figure 19) to the simulated wave heights was made. Figures 27–32 show the wave height time series generated by STWAVE at the gauge locations without bottom friction and for two simulations with bottom friction (with and without tide), along with the field measurements at these locations.

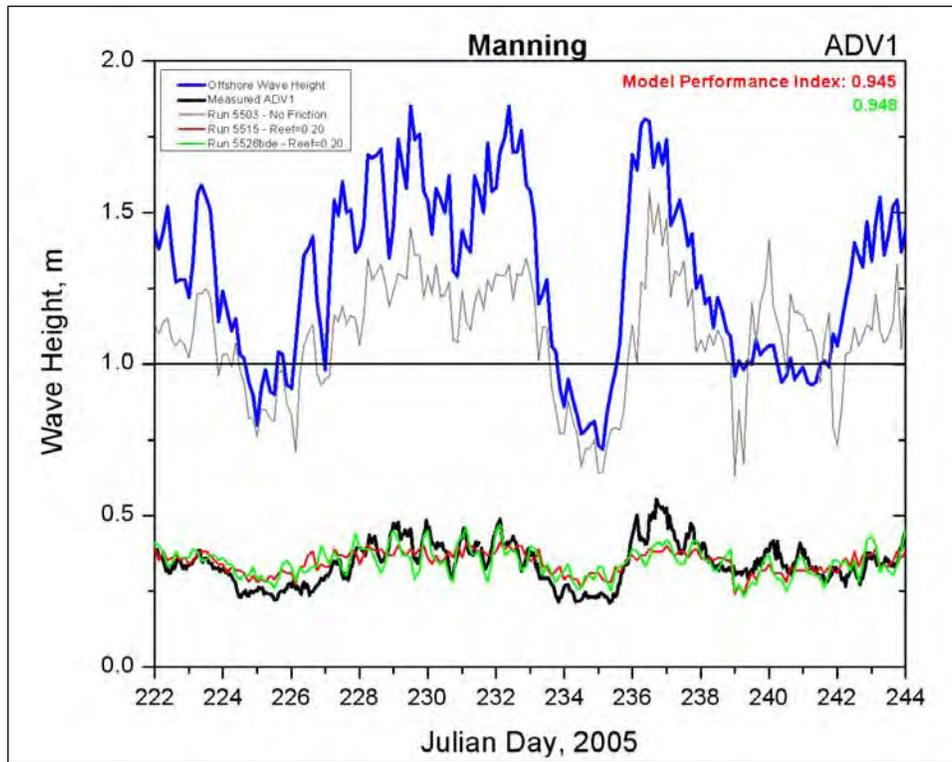


Figure 27. Comparison of measurements and STWAVE results at ADV1 with reef Manning bottom friction coefficient of 0.20.

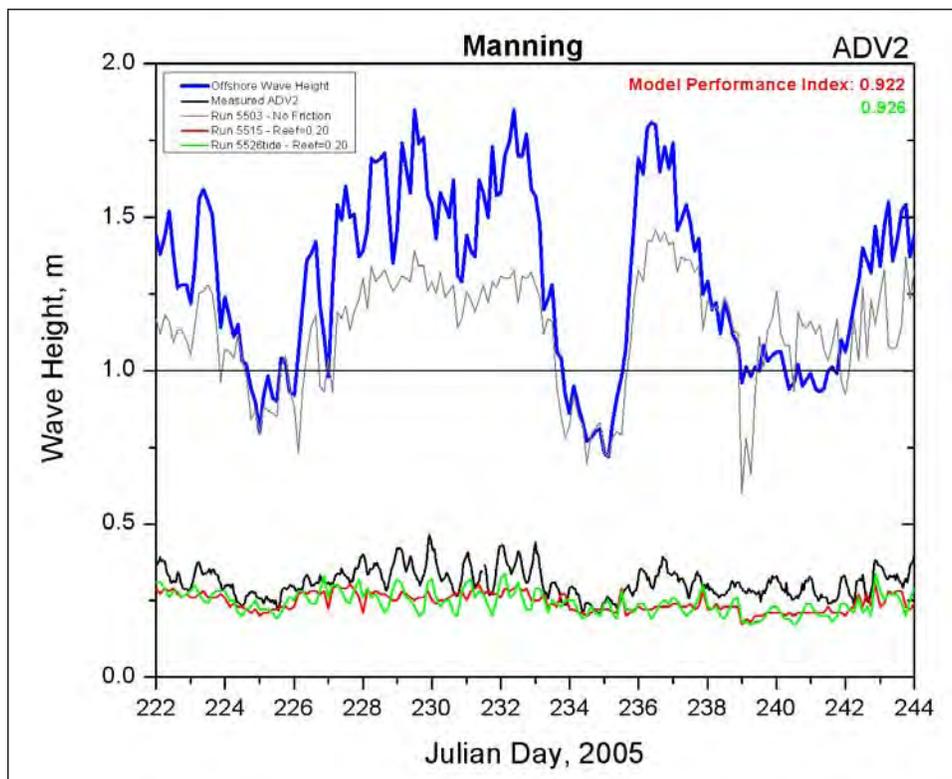


Figure 28. Comparison of measurements and STWAVE results at ADV2 with reef Manning bottom friction coefficient of 0.20.

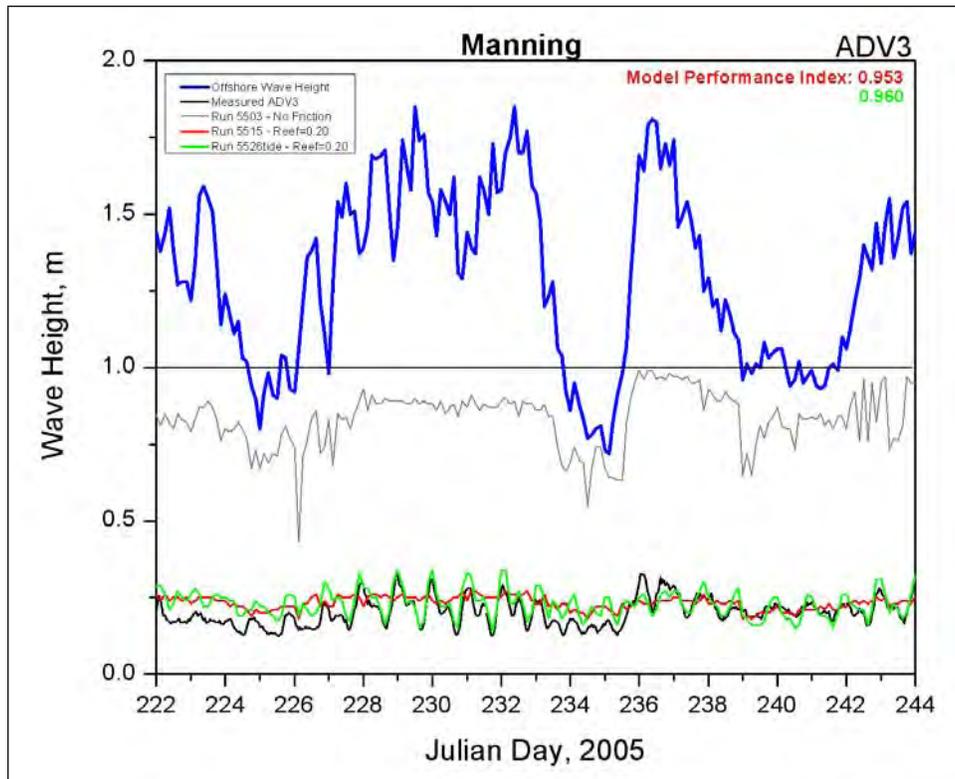


Figure 29. Comparison of measurements and STWAVE results at ADV3 with reef Manning bottom friction coefficient of 0.20.

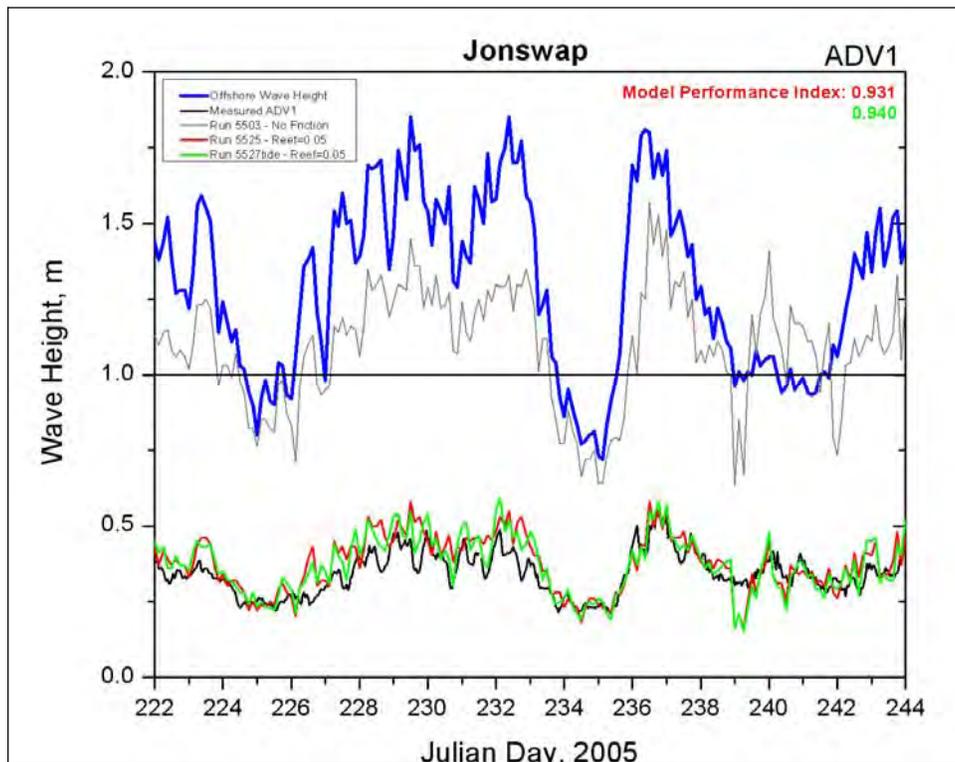


Figure 30. Comparison of measurements and STWAVE results at ADV1 f with reef JONSWAP bottom friction coefficient of 0.05.

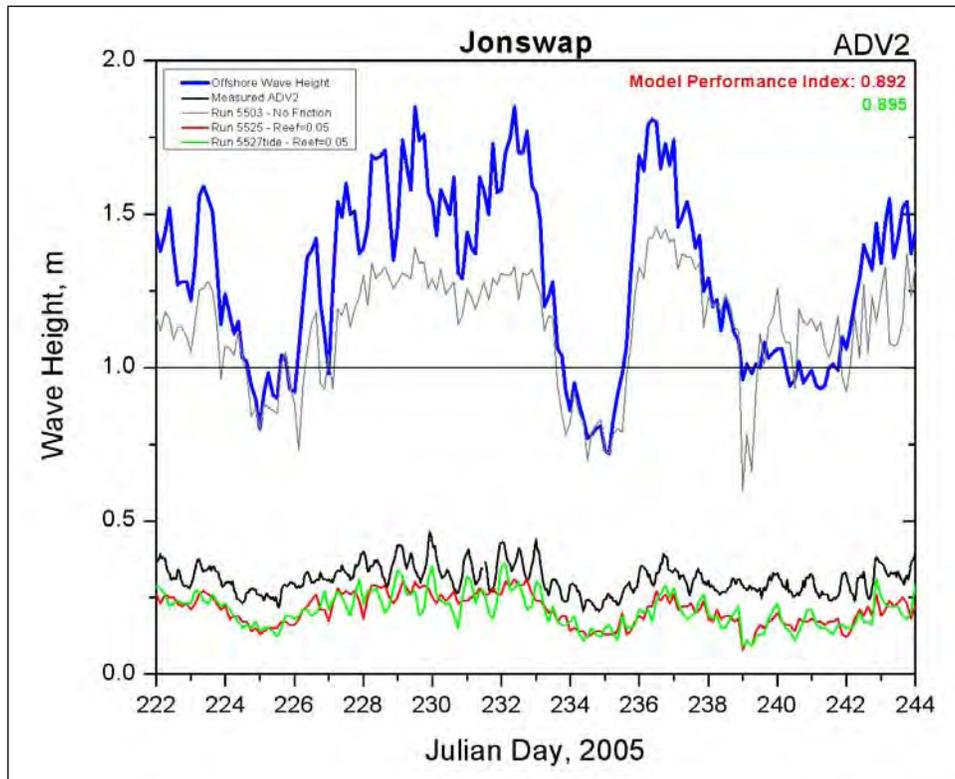


Figure 31. Comparison of measurements and STWAVE results at ADV2 with reef JONSWAP bottom friction coefficient of 0.05.

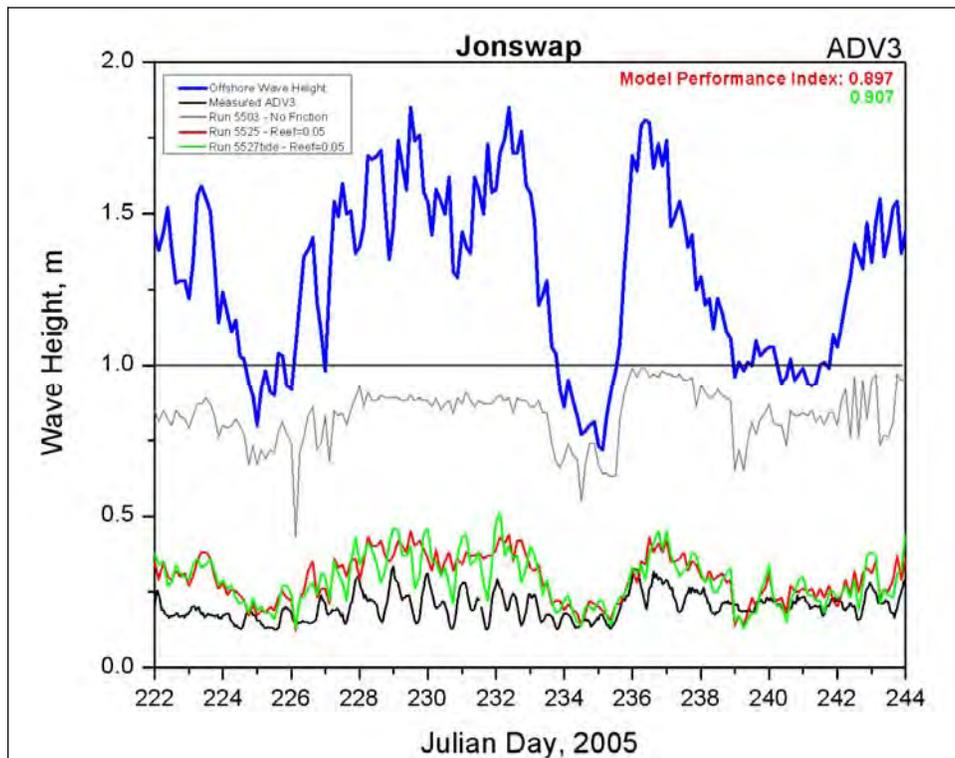


Figure 32. Comparison of measurements and STWAVE results at ADV3 with reef JONSWAP bottom friction coefficient of 0.05.

The field measurements range in wave height from 0.12 to 0.69 m for the data collection time period and the model results range from 0.08 to 0.59 m. The STWAVE model captures the large reduction in wave height from the offshore location to the three nearshore locations. The model results for the ADV1 location follow the magnitude and trend of the data well, particularly with the JONSWAP friction formulation. The inclusion of tidal fluctuation in the model improves the comparison to gauge data, particularly with the Manning friction formulation. Model results at the ADV2 location tend to underpredict the measured wave height with the selected validation friction coefficient. Model results at the ADV2 location show greater wave height variation with time, whereas the measurements show much less variability. Model results at ADV3 tend to over-predict the measured wave height when the offshore waves are greater than 1.3 m.

Another indicator of the model ability to estimate wave transformation over a reef is the Model Performance Index (MPI) (Smith 2000). The MPI is a measure of the models ability to capture the transformation from offshore to nearshore that is observed in the field data.

$$MPI = (1 - Error_{rms})/Changes_{rms} \quad (3)$$

where $Error_{rms}$ is the root-mean-square error of the model compared to the ADV gauge data and $Changes_{rms}$ is the root-mean-square change from the offshore data to the nearshore data. Values of the MPI near unity indicate good agreement. For the initial simulations with constant bottom friction applied to the reef, the MPI values are 0.92 to 0.96 for the Manning representation of bottom friction ($n = 0.20$) and 0.89 to 0.94 for the JONSWAP representation of bottom friction ($c_f = 0.05$).

Improvements to the results, particularly at ADV3, could be made by revising the friction coefficients to represent the spatial variability of the reef roughness. (The coral reefs in this region are described as “mushroom fields.” Some areas of the reef are more solid and some areas have gaps and holes in the reef.) Without detailed knowledge of the contiguous/noncontiguous areas of the reef, an educated attempt was made to represent the variations in the reef. The center section of the reef was given a smaller friction coefficient and the southern portion of the reef was given a larger coefficient (Figure 33). These adjusted values were selected based upon the under/overprediction of wave height at ADV2 and ADV3,

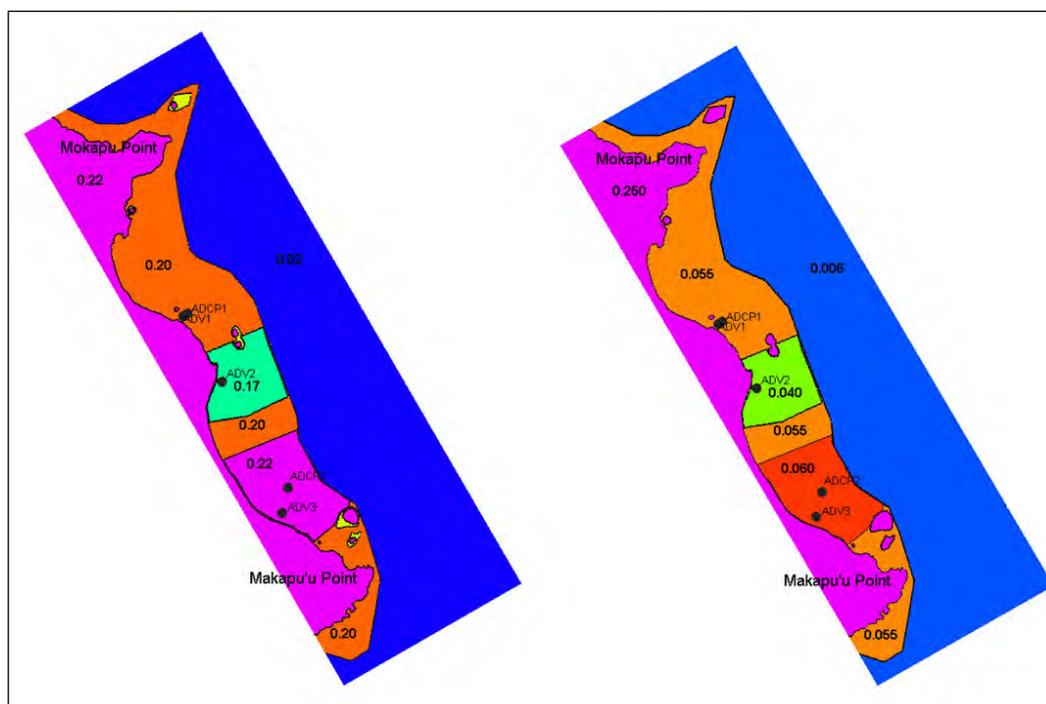


Figure 33. Variable Manning (left) and JONSWAP (right) friction fields.

respectively, in the previous simulation. The final validation simulation was made with JONSWAP friction coefficients of 0.04/0.055/0.06 variably applied to the reef region, 0.09 around the offshore islands (for compatibility/linkage to the ADCIRC model), and 0.006 in the offshore regions. A Manning validation simulation was also made with variable friction coefficients of 0.17/0.20/0.22 applied to the reef region, 0.19 around the offshore islands, and 0.02 in the offshore regions. Tidal fluctuation was included in these simulations.

As shown in Figures 34–39, with a variable bottom friction coefficient to represent variability in the reef structure, model results compare extremely well with the data at all three gauge locations with both the Manning and the JONSWAP friction formulations. The MPI values are 0.948 to 0.970 for the Manning simulations and 0.951 to 0.953 for the JONSWAP simulations. The magnitude and trend as well as the tidal fluctuation exhibited by the data are all captured by the model.

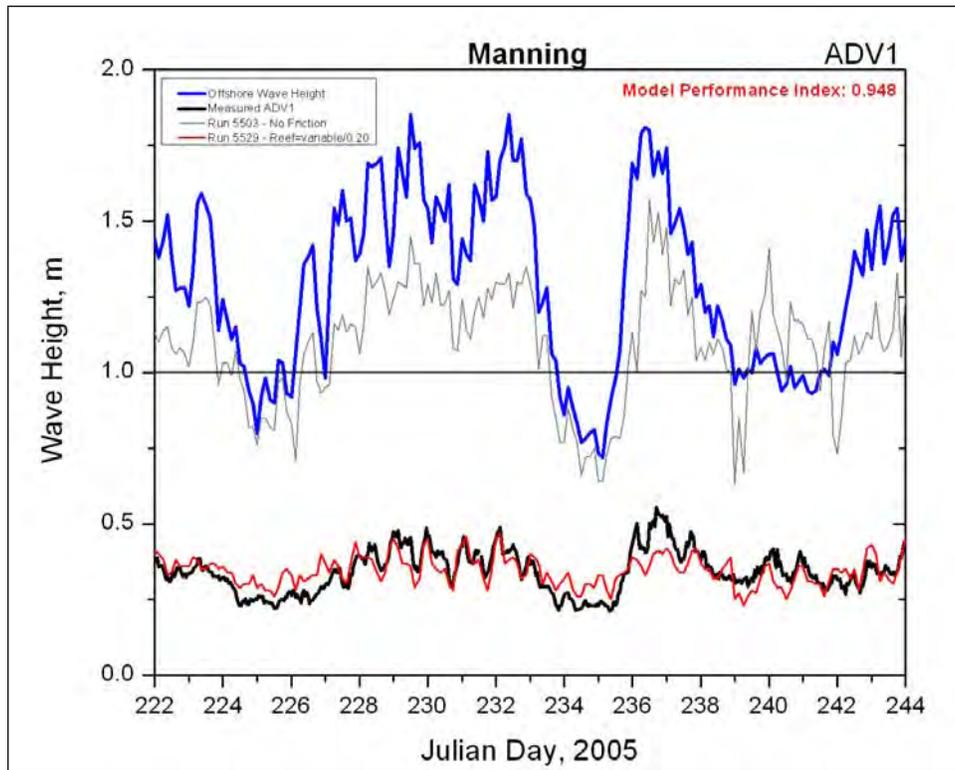


Figure 34. Comparison of measurements and STWAVE results at ADV1 for spatially varying Manning bottom friction.

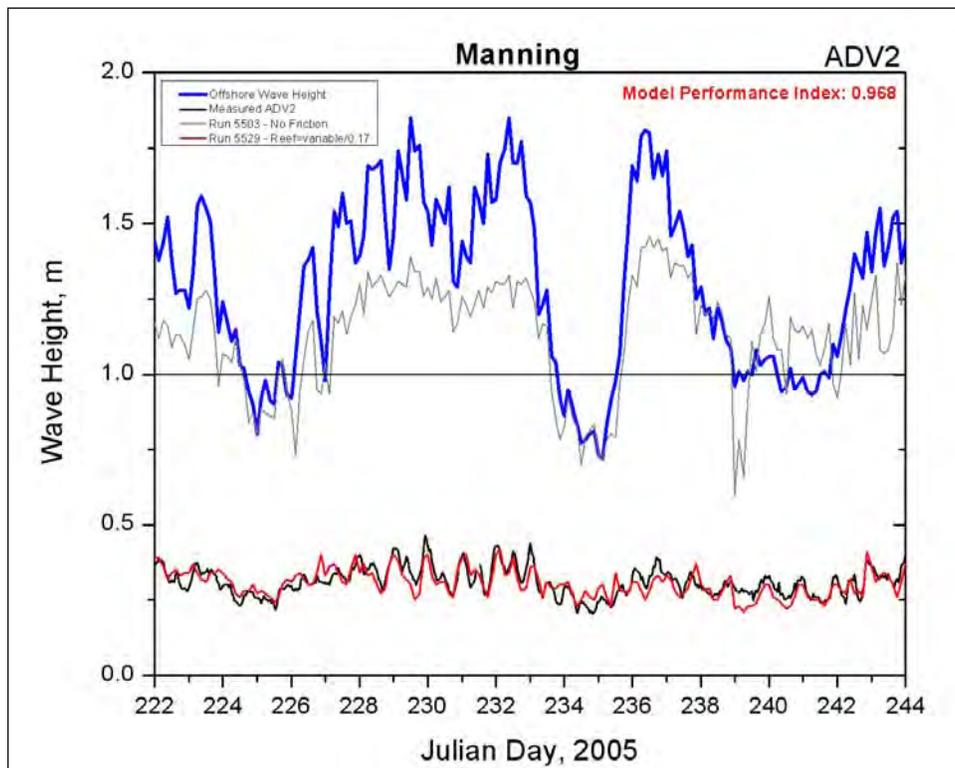


Figure 35. Comparison of measurements and STWAVE results at ADV2 for spatially varying Manning bottom friction.

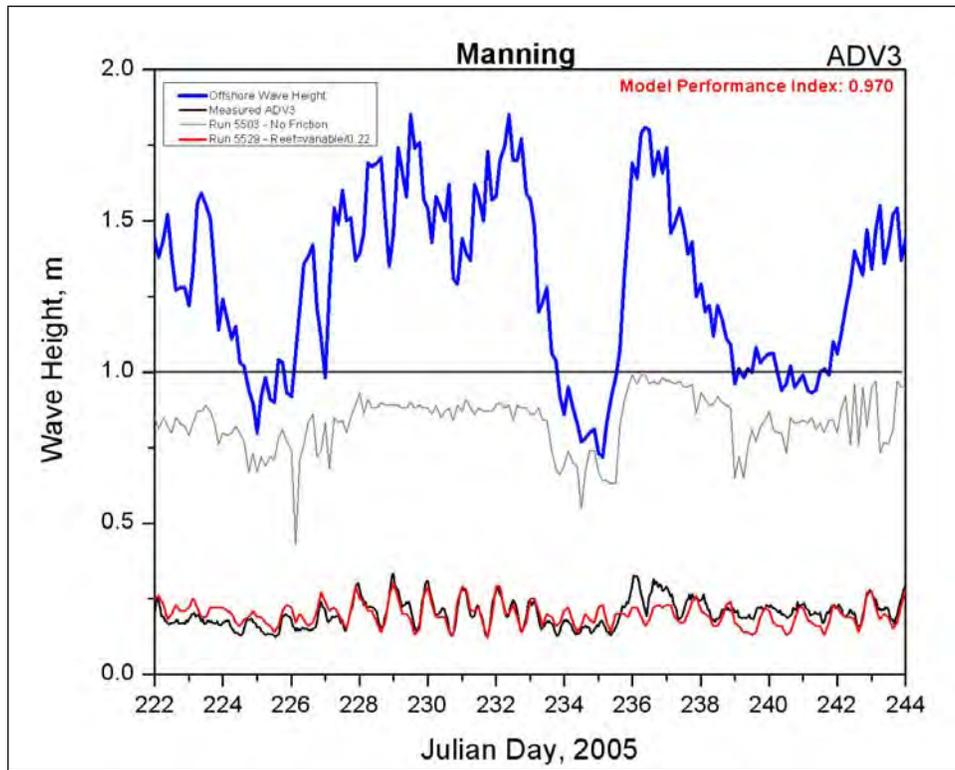


Figure 36. Comparison of measurements and STWAVE results at ADV3 for spatially varying Manning bottom friction.

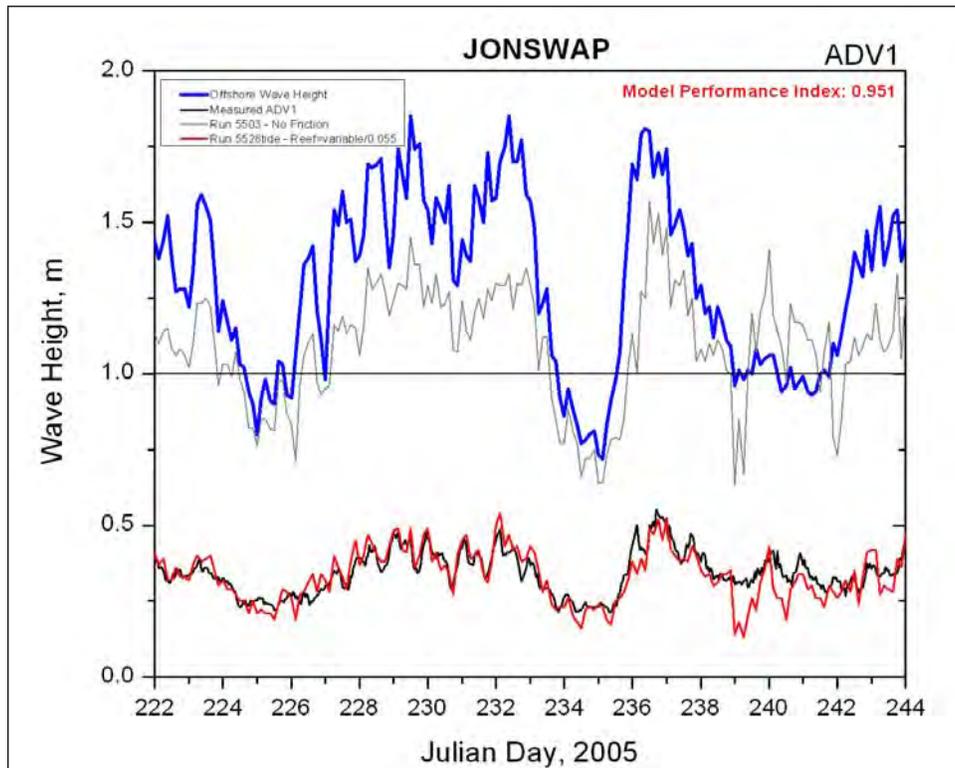


Figure 37. Comparison of measurements and STWAVE results at ADV1 for spatially varying JONSWAP bottom friction.

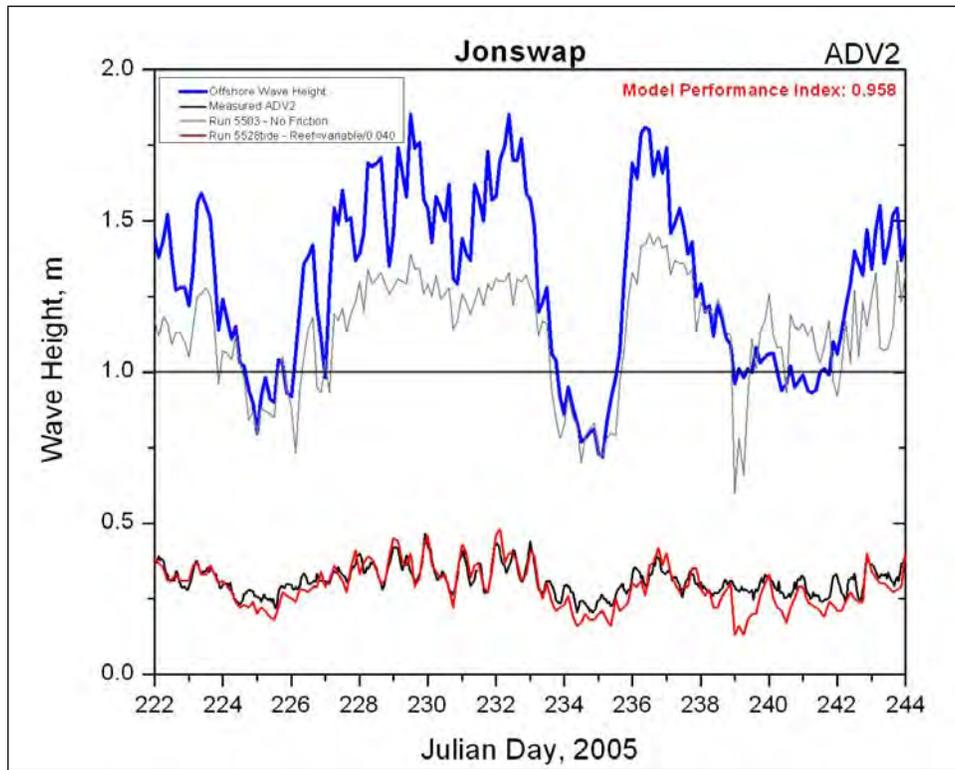


Figure 38. Comparison of measurements and STWAVE results at ADV2 for spatially varying JONSWAP bottom friction.

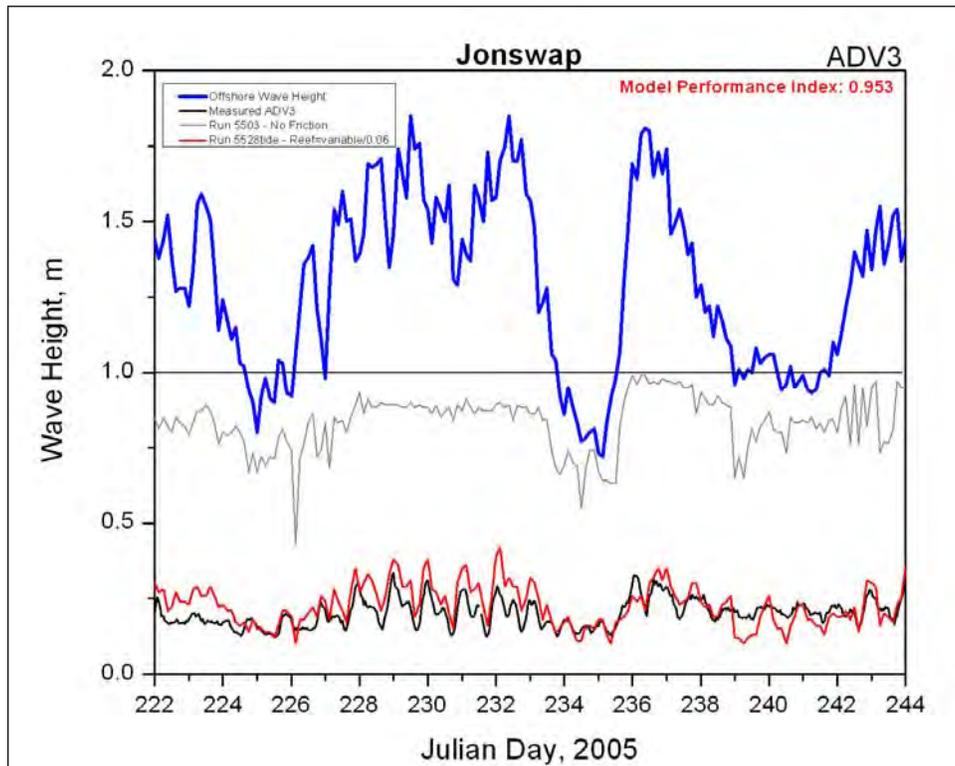


Figure 39. Comparison of measurements and STWAVE results at ADV3 for spatially varying JONSWAP bottom friction.

ADCIRC validation – wind, tide, and waves for gauge deployment time period

In the final validation, ADCIRC was applied to the study area for the August 2005 time period. This month overlapped the gauge deployment time period by approximately 2.5 weeks. ADCIRC was forced along the open boundary with tidal variation data extracted from the LeProvost tidal database. Wind speed and direction information were obtained from the OWI winds described in the wind sources section earlier in this document. Wave forcing information was provided from the STWAVE simulation driven by CDIP Buoy 098 data. A series of ADCIRC simulations were run for the selected month in the validation procedure. The ADCIRC simulations varied in the hydrodynamic parameters, bottom friction values, including with and without wind and wave forcing as part of this validation process. Some issues with the steep bathymetric gradients near the offshore island caused energetic wave breaking and created large radiation stress gradients, which led to ADCIRC model instability. This was overcome by applying a large bottom friction value (0.09) in STWAVE near the offshore islands and limiting radiation stress gradients to a maximum of $0.0001 \text{ m}^2/\text{sec}^2$. The final ADCIRC simulation applied a hybrid bottom friction formulation with a minimum c_f value of 0.003 m/sec (similar to the minimum value applied in the STWAVE validation — 0.006 m/sec), then increased in value in shallow depths (less than 1.0 m). The eddy viscosity was set to $4.0 \text{ m}^2/\text{sec}$, and the time step was 0.4 sec.

Simulation analysis

Currents and water levels were compared with field data obtained from the gauge deployment described earlier. Calculated water levels compared well in range and phase to measurements, but underestimated some lower peaks while overestimating some higher peaks. This may have been caused by localized interaction of the tides with the reefs surrounding the gauge locations. Water level comparisons with the three ADV gauges are shown in Figures 40–42. A harmonic analysis may prove useful in obtaining a better comparison to the tidal constituents. However, since the measured current velocities are so small, an improved tidal constituent forcing would not greatly influence the total range of water level and therefore would not increase the current velocities significantly. Therefore, no harmonic analysis was performed.

Current velocity data from the three ADV gauges (near-bottom point measurements) and two ADCP gauges (depth-averaged) were extremely small during the overlapping deployment time period—generally less than 10 cm/sec. (The near-bottom ADV measurements would be expected to be lower than depth-averaged values and therefore less than the ADCIRC-computed values.) Due to these small measured depth-averaged current magnitudes, depth-averaged current velocities calculated at these locations from the ADCIRC circulation model were not expected to compare well; however, the range of velocity model results (0.2–27.2 cm/sec) is well within one order of magnitude of the range of measurements (0.1–16.8 cm/sec) and generally very close to the measurements. Comparisons of ADCIRC circulation results to ADV and ADCP gauge measurements are shown in Figures 43–47. Note that this analysis indicates that tidal and wave-induced currents for this time period were not significant enough in this region to bring forward to sediment transport analysis. This reaffirms the typical conclusion that potential sediment transport mechanisms are more likely to be waves and storm-induced currents for the open coast. A follow-on study to examine the effects of waves and storm-induced currents on sediment transport is ongoing.

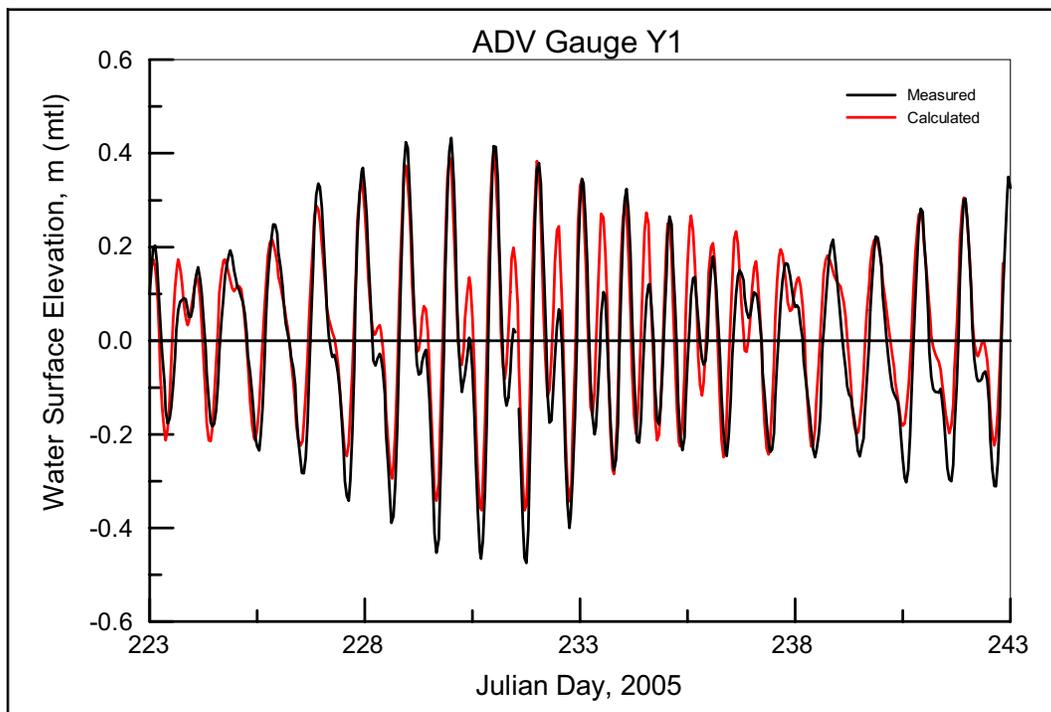


Figure 40. Water level comparison for ADV Gauge 1.

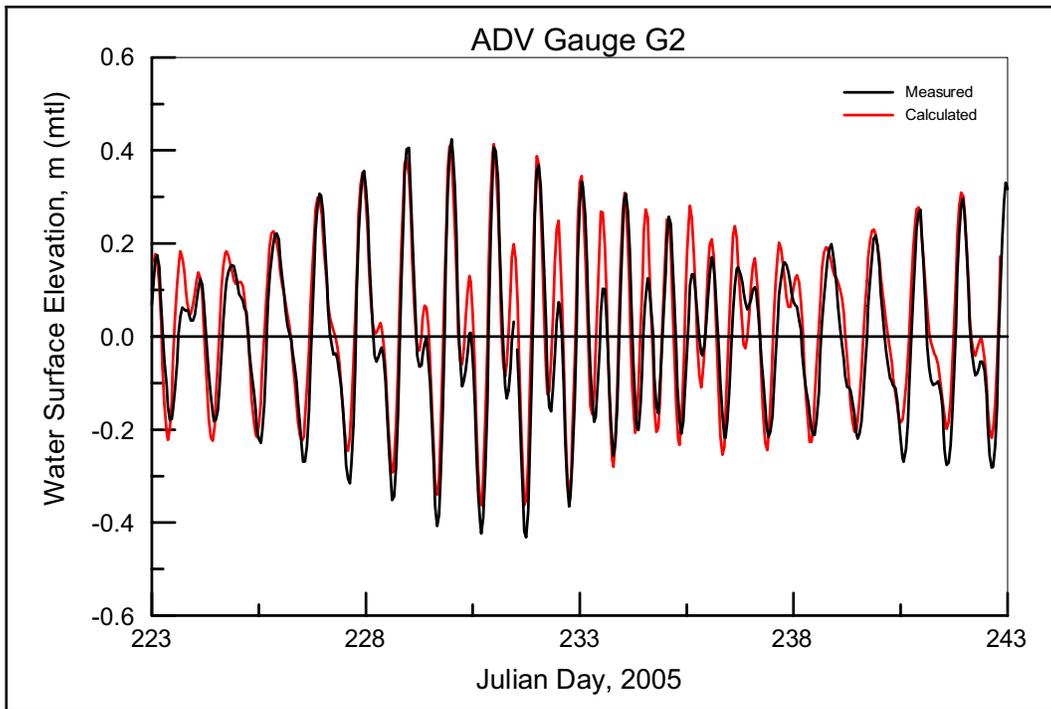


Figure 41. Water level comparison for ADV Gauge 2.

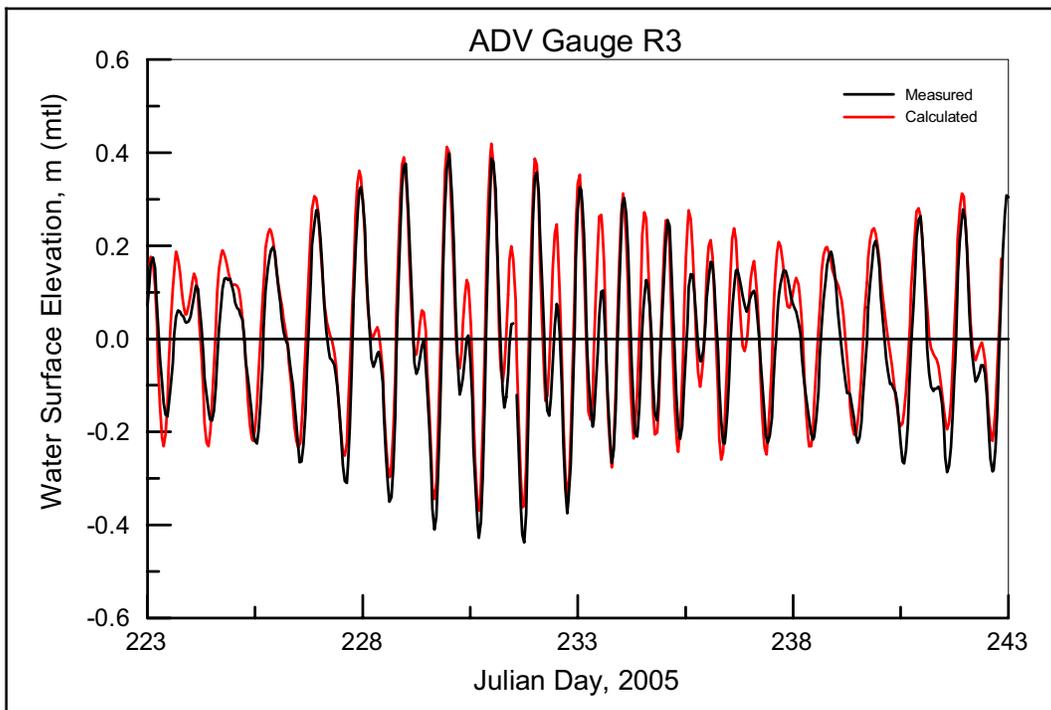


Figure 42. Water level comparison for ADV Gauge 3.

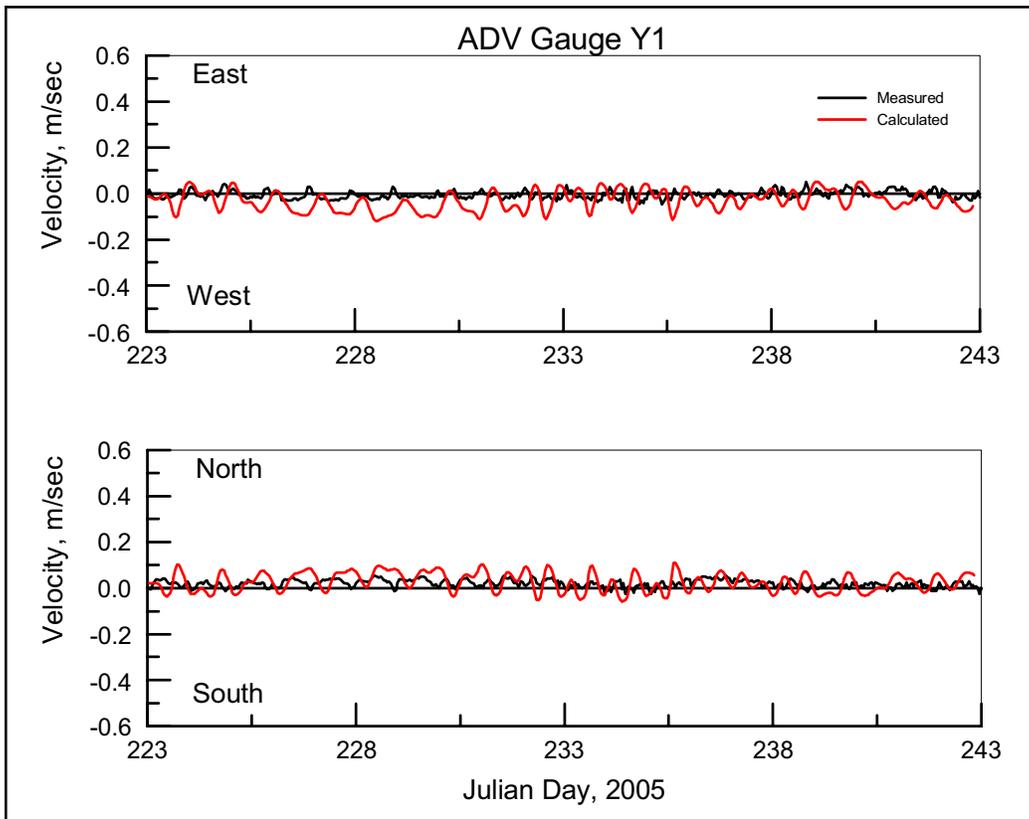


Figure 43. Velocity comparison for ADV Gauge 1.

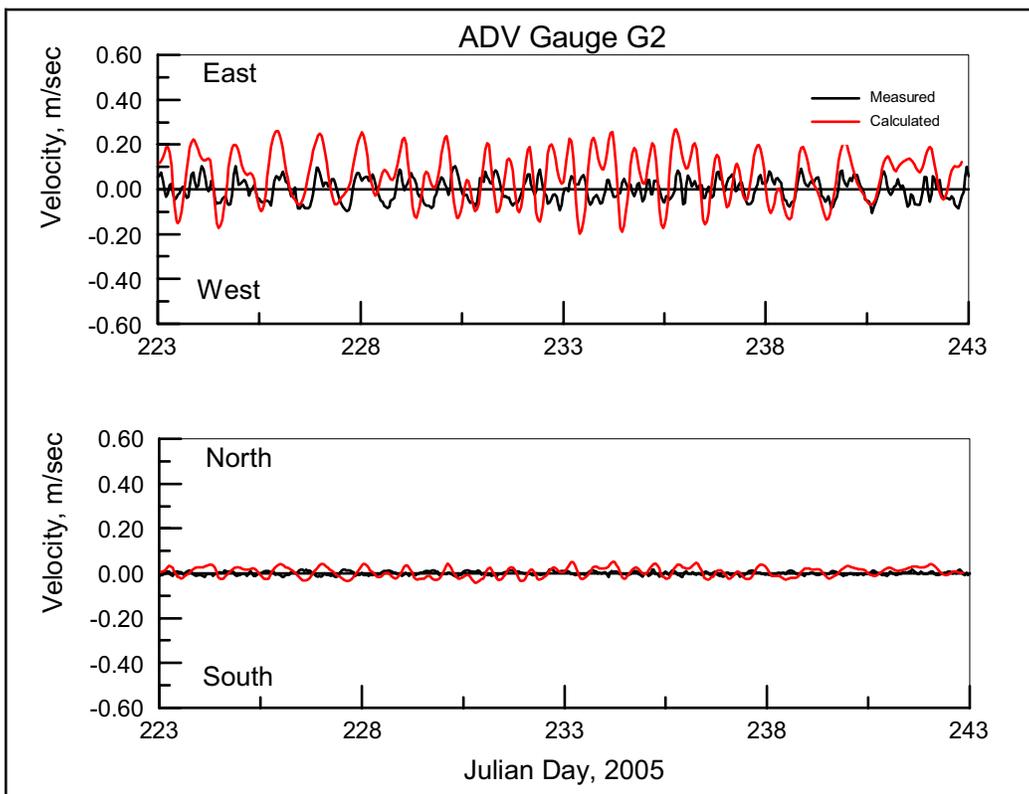


Figure 44. Velocity comparison for ADV Gauge 2.

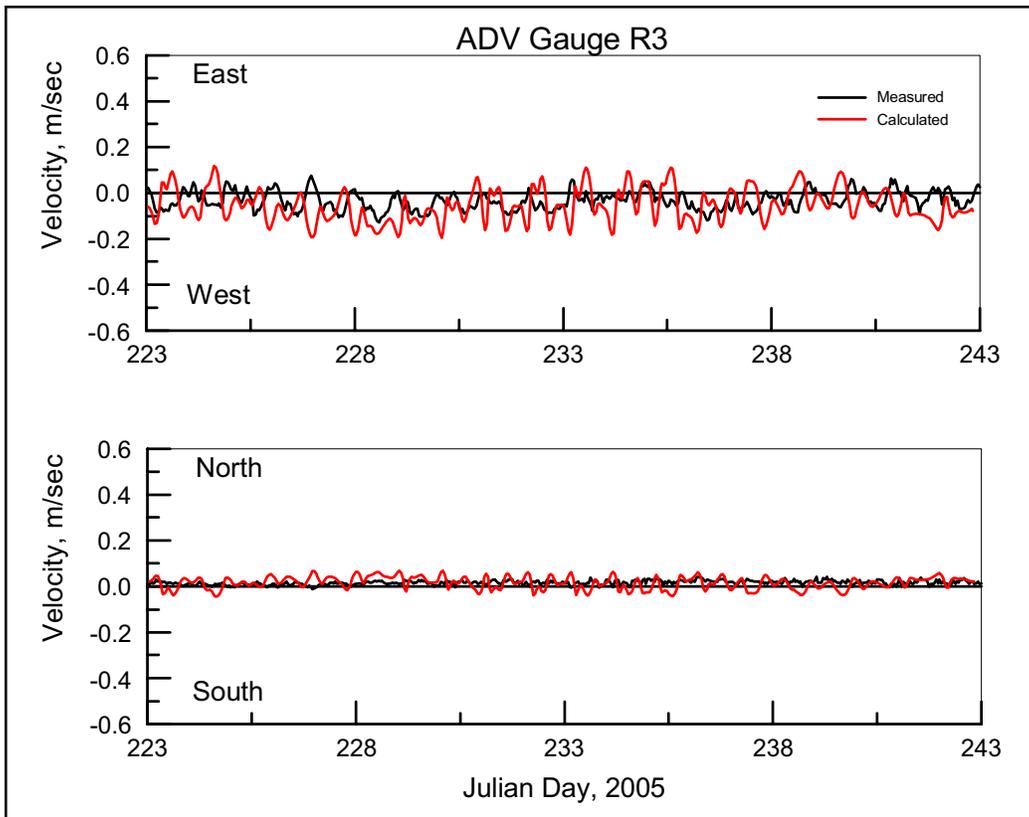


Figure 45. Velocity comparison for ADV Gauge 3.

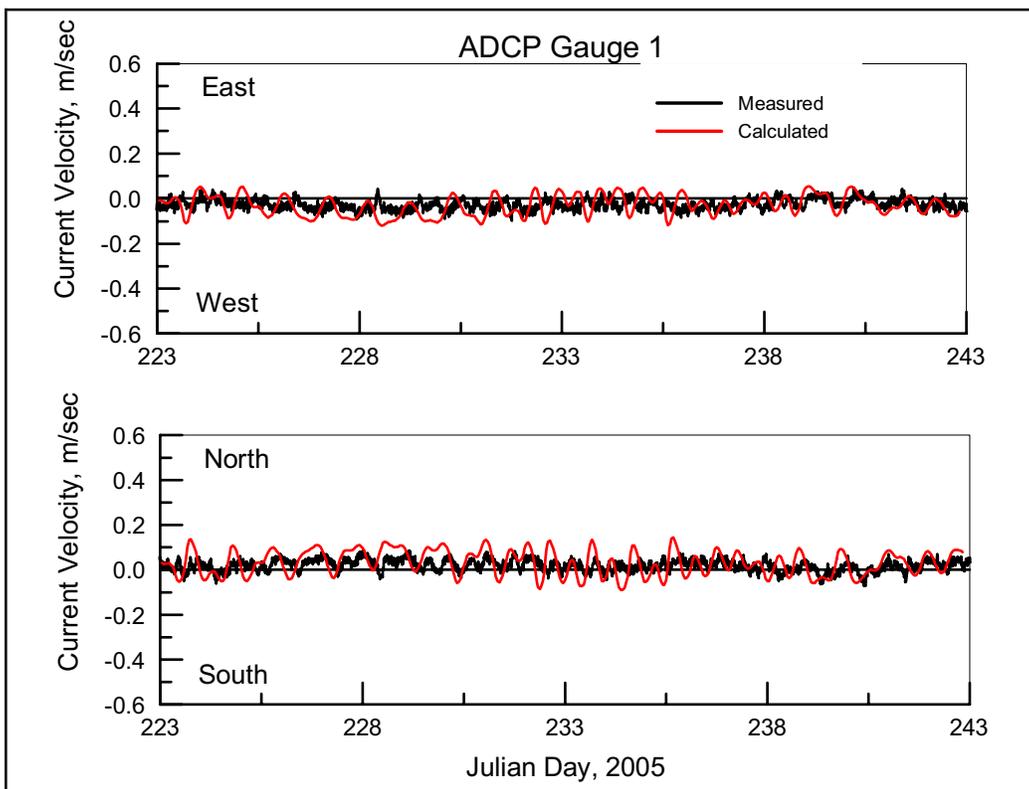


Figure 46. Velocity comparison for ADCP Gauge 1.

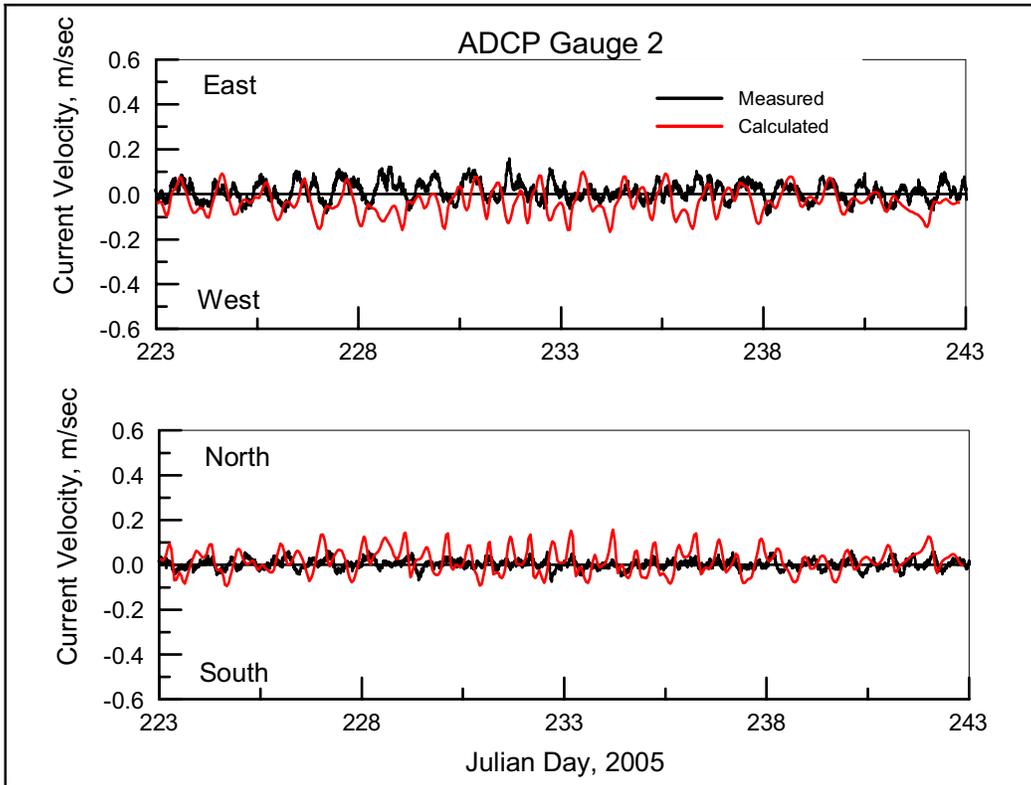


Figure 47. Velocity comparison for ADCP Gauge 2.

4 Summary

The purpose of the study was to provide POH with validated hydrodynamic and wave models for the project site. POH could then apply the models with various forcing conditions to develop a better understanding of nearshore circulation and sediment transport potential in the region and determine the likelihood of accretional and erosional areas within the model domain. The nearshore circulation study included six technical tasks: data collection/assessment, finite-element and finite-difference grid development, development of model forcing conditions, model validation, model simulations, and simulation analysis.

Wave, current, and water level data were collected in the field for a 1-month period with ADCP and ADV instruments. In addition, drogues were deployed on the 2 days that the ADCP/ADV were deployed and retrieved. Wave heights during the deployment period ranged from 0.12 to 0.69 m and were generally from the northeast direction, currents measured at the ADV and ADCP locations were small (generally less than 10 cm/sec), and water level ranged from +0.4 to -0.4 m, mtl. The drogue deployment provided general current trends for the two deployments.

A two-dimensional (depth-averaged) version of the hydrodynamic model (ADCIRC) was applied in this study. The ADCIRC modeling component for this study required grid development, validation of the bathymetric grid to known tidal constituents and wind forcing for April 2001, and comparison of the bathymetric grid forced with known tidal constituents, wind, and waves to measurements for the field data collection time period. The ADCIRC grid was developed as a circular mesh, encompassing the Hawaiian Islands, but was revised to an egg-shaped mesh to avoid tidal amphidromes in the Pacific Ocean.

For the initial model validation, ADCIRC results were compared with two NOAA gauges on the eastern half of the island of Oahu. The calculated water levels from the ADCIRC simulation of the April 2001 period compared relatively well in range and phase with the NOAA gauge measurements considering the locations of the gauges were well outside high-resolution sections of the grid in the project area. Since these gauges were outside the project area and in less resolved locations, another validation

was performed by simulating the field data collection time period and comparing model results to field data collected, specifically for this project, in the study area. Calculated water levels compared well in range and phase to measurements, but underestimated some lower peaks while overestimating some higher peaks. This may have been caused by localized interaction of the tides with the reefs surrounding the gauge locations. Current velocity data from the three ADV gauges and two ADCP gauges were extremely small during the overlapping deployment time period – generally less than 10 cm/sec. Velocities calculated at these locations from the ADCIRC circulation model were not expected to compare well to the measurements; however, the range of velocity model results is within one order of magnitude and generally very close. The application and validation of ADCIRC for the SEO study provides POH with the capability of simulating circulation in the study area for any required time period.

The purpose of applying nearshore wave transformation models such as STWAVE is to describe quantitatively the evolution of wave parameters from the offshore to the nearshore where nearshore wave information is required for the design of coastal engineering projects. STWAVE has been applied to numerous sites, and this project has the necessity of simulating wave transformation over a reef. Development of a bottom friction capability in STWAVE was completed for application to the extensive reefs in the SEO study area. Application of STWAVE for this project required development of a computational grid to simulate wave propagation, verification of calculated waves by comparison to measurements, and generation of a wave climate.

For demonstration of the wave climate development technique, nearshore conditions at a point in Waimanalo Bay were extracted from the STWAVE model results for each of the 134 simulations. A transformation correlation between the offshore and nearshore condition was then determined for each simulation. By applying the appropriate transfer function to each wave condition in the 2000–2004 offshore time series at Station 098, a long-term (2000–2004) nearshore time series was generated. The nearshore time series demonstrates that there is a reduction in wave height from the offshore location to the nearshore location, landward of the extensive reef system, as expected. The time series, however, appeared generally contained or banded between the 1.25 and 2.25 m wave height bins that were selected to represent the overall wave climate. In order to capture the nearshore transformation time series more precisely and to

include all wave conditions occurring in the time series, the range and refinement of the wave conditions simulated was expanded to 1274 wave conditions. The refined nearshore time series generated from analysis of these simulations shows a more realistic undulation in the nearshore wave height time series.

Development of a bottom friction capability in STWAVE was completed for application to the extensive reefs in the SEO study area. Based on existing literature, values of the JONSWAP bottom friction applied for coral reefs range from 0.04 to 0.12 m/sec. A single friction value can be applied to the entire STWAVE domain, or a range of friction values can be applied on a spatially varying basis. As an example, the 134 wave conditions simulated in the initial climate development were repeated with the revised STWAVE, applying a bottom friction coefficient typical for reefs of 0.05. With the inclusion of bottom friction, wave height at the nearshore location ranged from 18–38% of the previous results without bottom friction. On average, the wave height is 26% of the frictionless value at the selected location. The total wave spectrum refracts less with the inclusion of bottom friction, likely due to the dissipation of low-frequency energy. As another example, for each of the 1274 selected wave conditions simulated for the revised wave climate, wave transformation *including bottom friction* was simulated by applying STWAVE over the project domain for each of the 1274 wave spectra. The constant 0.05 value of bottom friction reduced nearshore wave heights by approximately 73% compared to wave heights without bottom friction.

The extended domain STWAVE grid was applied in the model validation process for the August 2005 model validation time period. Initially, a constant bottom friction value was applied to each cell of the STWAVE domain. Several simulations with different constant JONSWAP bottom friction values ranging from 0.04 to 0.12 were made to examine the range of response (wave height) at the gauge locations. Bottom friction reduced wave height at the ADV1 location by 64% for a bottom friction value of 0.04 (wave height is 36% of the offshore wave height), by 71–76% for a bottom friction value of 0.05 (wave height is 24–29% of the offshore wave height), and by 93% for a bottom friction value of 0.12 (wave height is 7% of the offshore wave height). The range of response indicates the importance of selecting the appropriate bottom friction value to represent the reefs in the study area.

In the validation simulation, a variable bottom friction field was utilized. Overall, all three measurement locations experience low wave energy relative to the offshore waves. The STWAVE model captures the large reduction in wave height from the offshore location to the three nearshore locations. The coral reefs in this region are described as “mushroom fields.” Some areas of the reef are more solid and some areas have gaps and holes in the reef. Without detailed knowledge of the contiguous/noncontiguous areas of the reef, an educated attempt was made to represent the variations in the reef. The center section of the reef was given a smaller friction coefficient and the southern portion of the reef was given a larger coefficient. These adjusted values were selected based upon the under/overprediction of wave height at ADV2 and ADV3, respectively, in the simulation with a constant reef coefficient. Tidal fluctuation was also included in these simulations. With a variable bottom friction coefficient to represent variability in the reef structure, model results compare extremely well with the data at all three gauge locations with both the Manning and the JONSWAP friction formulations. The MPI values are 0.948 to 0.970 for the Manning simulations and 0.951 to 0.953 for the JONSWAP simulations. The magnitude and trend as well as the tidal fluctuation exhibited by the data were all captured by the model.

Lessons learned from this study include:

1. The technique of developing a nearshore wave climate by applying STWAVE for a large number (range) of offshore wave conditions provides a permanent “look up” table of nearshore wave conditions at any location in the computational domain and can be applied to any time period for which offshore data are available, provided that bathymetric conditions within the model domain remain similar. Note that the creation of a nearshore wave climate was applied to generate a nearshore time series for the 2000–2004 time period, and POH is applying the database-generated time series to develop sediment transport potential estimates in the project area. A follow-on study extended the time series through 2005 and expanded to 10 save point locations;
2. From the ADCIRC validation for the deployment time period and also from examination of the retrieved deployment data, it was concluded that the tidal and wave-induced currents in the project area are small and not sufficient to significantly transport sediment. A follow-on study is being conducted to examine simulation of higher energy (storm) conditions,

- which may produce waves and currents that are strong enough to transport sediment; and
3. An improved model capability was developed for this study. Bottom friction was added to STWAVE to simulate wave transformation over reefs. It was shown that bottom friction is extremely important and has a pronounced effect on modeling transformation over reefs, decreasing wave heights from the without-friction condition by 71–76% for a constant JONSWAP bottom friction value of 0.05. Simulation of the transformation process over reefs could be improved further by including wave ponding, applying a more detailed breaking formulation such as Battjes and Janssen (1978), and implementing a coupling scheme between ADCIRC and STWAVE. In addition, field data collected for this project can be further analyzed to examine spectral energy dissipation from gauge location to gauge location and nonlinear interactions. These research topics may be examined in future STWAVE model development and application.

CHL assisted POH by documenting the methodologies and procedures used in this study and providing consultation in executing simulations and analyzing simulation results. STWAVE and ADCIRC working sessions have been conducted at POH and the completed modeling system was transferred to POH within the SMS framework.

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				5c. PROGRAM ELEMENT NUMBER	
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14. ABSTRACT This study provides the Honolulu District (POH) with numerical modeling tools for understanding nearshore circulation and sediment transport for Southeast Oahu (SEO). Circulation and wave models are developed and validated for this region and can be applied to assess sediment transport potential for various forcing conditions and to determine the likelihood of accretional and erosional areas within the model domain. Application of a wave model includes the generation of a wave climate. In the wave climate development technique, nearshore conditions are extracted from the wave model results for each simulation. A transformation correlation between the offshore and nearshore condition is then determined for each simulation. By applying the appropriate transfer function to each wave condition in the offshore time series, a long-term nearshore time series is generated. The nearshore time series demonstrates that there is a reduction in wave height from the offshore location to the nearshore location, landward of the extensive reef system as expected. The technique of developing a nearshore wave climate by applying the wave model for a range of offshore wave conditions provides a permanent "look up" table of nearshore wave conditions at any location in the (Continued)					
15. SUBJECT TERMS ADCIRC Circulation model		Hydrodynamic model Oahu, HI STWAVE		Two-dimensional model Wave model	
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED			19b. TELEPHONE NUMBER (include area code)

14. ABSTRACT (Concluded)

computational domain and can be applied to any time period for which offshore data are available, provided that bathymetric conditions within the model domain remain similar. POH is applying the database-generated time series to develop sediment transport potential estimates in the project area.

Development of a bottom friction capability in the wave model was completed for application to the extensive reefs in the SEO study area. It is shown that bottom friction is extremely important and has a pronounced effect on modeling transformation over reefs, decreasing wave heights from the without-friction condition by 71-76% for a constant JONSWAP bottom friction value of 0.05.

APPENDIX D

GEOTECHNICAL INVESTIGATIONS

SAND SAMPLE MAP

SAND FROM CRUSHED CORAL RUBBLE



Geotechnical Investigations

23 Aug 2006

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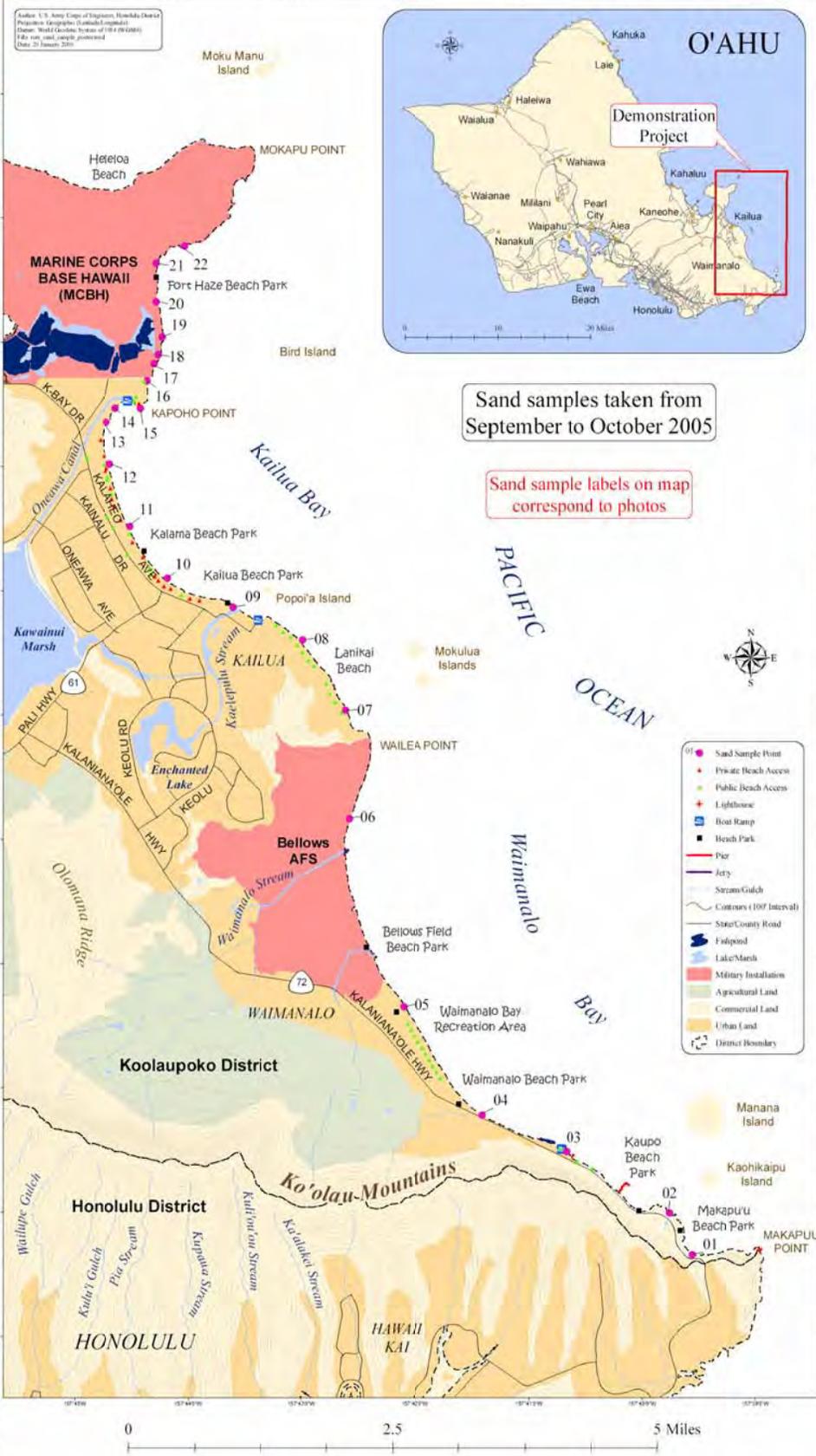
SOUTHEAST OAHU REGIONAL SEDIMENT MANAGEMENT DEMONSTRATION PROJECT SAND SAMPLE MAP

Author: U.S. Army Corps of Engineers, Honolulu District
 Project: Sediment Management Demonstration
 Date: 2005
 File name: sand_sample_map.mxd
 Date: 20 January 2006



Sand samples taken from September to October 2005

Sand sample labels on map correspond to photos



- 01 Sand Sample Point
- Private Beach Access
- Public Beach Access
- Lighthouse
- Boat Ramp
- Beach Park
- Pier
- Jetty
- Stream/Gulch
- Contours (100' Interval)
- State/County Road
- Fishpond
- Lake/Marsh
- Military Installation
- Agricultural Land
- Commercial Land
- Urban Land
- District Boundary



SAND from CRUSHED CORAL RUBBLE

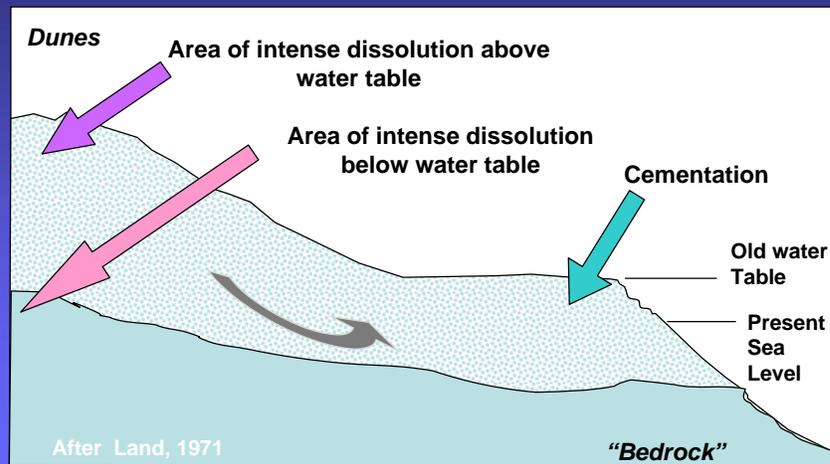
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Beachrock Formation



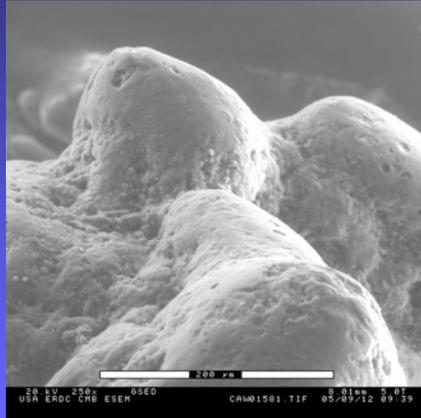
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Washed Carbonate Sand Surface



- Carbonate sand grains were treated by washing in boiling hydrogen peroxide to remove microbial overgrowth
- Surface is polished
- Fractures show porous skeletal carbonate structure

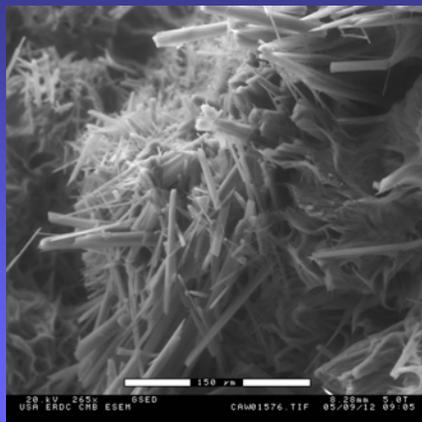
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Overgrowth on Sand Surface



- Sand grain treated by using carbonate and calcium solution to produce overgrowth of aragonite needles on surface
- Grains are cemented into beachrock by carbonate overgrowth

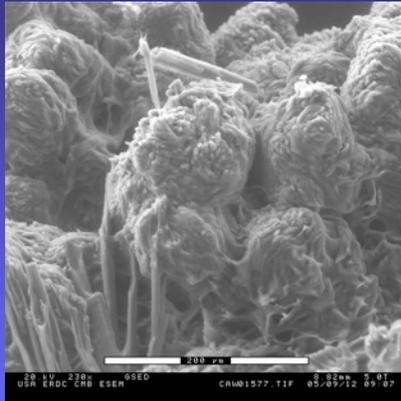
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Aragonite and Calcite Overgrowth



- Carbonate precipitation can produce calcite and aragonite overgrowth
- Aragonite is typically unstable and can redissolve and recrystallize as calcite
- Small crystals are less stable than large crystals and small crystals dissolve and large crystal grow larger (Ostwald crystal ripening).

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Fatty Acids for Coating Materials



- Inexpensive, non-toxic
- Available in large quantities
- Available in all grades
- Slowly biodegradable
- React with and coat all carbonates
- End product is the calcium salt of the fatty acid (soap film)

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What Loading Rate is Required?



- Assume the fine sediment is the source of the cement
- Three-micron diameter calcite fragments have a specific area of approx. $0.7 \text{ m}^2/\text{g}$
- Each molecule of stearic acid covers 20.5 sq. \AA
- One gram of calcite has area of $7 \times 10^{16} \text{ sq. \AA}$
- Molecular wt of stearic acid = 284.5 (6×10^{23} molecules per mole)
- Approx. 6×10^{-9} moles stearic acid cover one gram
- Theoretically a metric ton of calcite requires less than 2 grams of stearic acid

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Industrial Grade Fatty Acids



Commercial soaps are salts (typically sodium salts) of a mixture of fatty acids

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Summary on Inhibiting Re-Cementing



- **Coatings can isolate the surface of carbonate grains to make solution of carbonates and overgrowth of cements slower**
- **Process of preserving the sand mimics natural processes that inhibit re-cementing of carbonates**
- **Fatty acid coatings can promote clustering of fine-grained carbonates reducing turbidity**
- **Coating process is inexpensive and can be integrated into manufacturing sand along with crushing and sieving steps**
- **A sieved, coated sand should provide a better beach than quarry-run crushings**

APPENDIX E

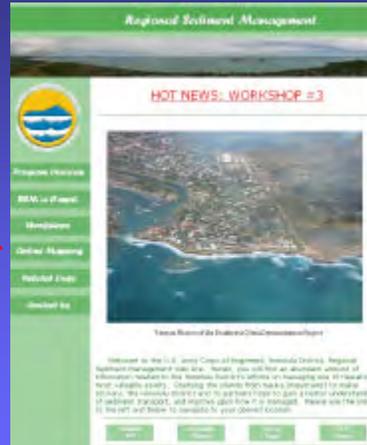
**REGIONAL SEDIMENT MANAGEMENT
WEB-ENABLED GIS PLATFORM
e-GIS**



GIS and the Internet



All of the RSM geospatial data is available over the Internet with new "Online Mapping" Tools



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1



Data Layers



Layers on the site include:

- satellite imagery
- watershed boundaries
- land parcels
- roads
- soil types
- wetlands
- hydrography
- shoreline profiles
- historical shoreline change
- shoreline structures
- coastal habitat & reefs
- sediment deposit information
- revetments
- bathymetry
- wave gauges
- nautical charts
- and much more!

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2



What Does the Standard Toolbar Do?



	Toggles the overview map on or off		Zoom-in on the map with user defined AOI		Zoom-out on the map with user defined AOI
	Zoom to the full extent of the map		Zoom to the extents of the active map layer		Zoom back to the previous extent of the map
	Pan the map in any direction		Retrieve attribute data by identifying a feature		Display standard query builder form
	Search the attributes of the specified layer		Measure linear distance on the map in specified units of measure.		Select map features and retrieve attribute data using a dynamically dragged window
	Select map features and retrieve attribute data by using a user defined polygon or line		Place a dynamic point on the map that is labeled with the point's coordinates		Calculate area of a user defined polygon in specified units of measure
	Add user defined text to the map where clicked		Place a user defined grid over the map with labeled rows and columns		Print the map
	Clears the map of any temporary selections				

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How Can I Calculate Acreage?



- 1) Zoom into the area on the map where you would like to calculate the area. This can be performed by using the "Zoom In" button, which is found on the Standard Toolbar.
- 2) After you have zoomed in to the area you would like to calculate, click on the "Calculate Area" button, which will activate the "Polygon Area" dialog box.
- 3) In the "Polygon Area" dialog box, set the Area Units you would like (acres, square feet, square meters, etc), as well as the fill color and transparency.
- 4) After you are happy with your settings, begin clicking on the map to designate the vertices of your area calculation. Before you reach your last vertex, click on the **Complete Polygon** button in the "Polygon Area" dialog box to auto complete the polygon.
- 5) The area information will appear on your map.



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How Do I Print My Map?



- 1) Zoom into the area on the map where you would like to print. This can be performed by using the "Zoom In" button, which is found on the Standard Toolbar.
- 2) Add any coordinate labels, text, grids, etc that you want visible for printing.
- 3) After you have the map set just like you want, click on the "Print" button, which will activate the "Print Map" dialog box.
- 4) In the "Print Map" dialog box, type in your map title and any other comments you would like.
- 5) After you have your title and comments set, then select the paper size you want your map to print at.
- 6) After your paper size has been selected, click the **Generate Map** button.
- 7) Select File > Print to print the map out.



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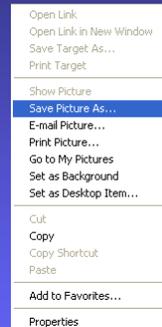
7



How Do I Save My Map?



- 1) Zoom into the area on the map where you would like to save. This can be performed by using the "Zoom In" button, which is found on the Standard Toolbar
- 2) Turn on/off any layers you would like visible/not visible.
- 3) Add any customized coordinate labels, text, grids, etc that you desire.
- 4) Right-click on the map, and select **Save Picture As...** from the context menu (highlighted in blue in the graphic to the right).
- 5) In the "Save Picture" dialog box, select where you would like the image saved, and then click the **Save** button.
- 6) Your image will be saved to your computer, and you can now insert it into e-mails, PowerPoint Presentations, project documents, etc.



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APPENDIX F

REGIONAL SEDIMENT PROCESSES

**DEPARTMENT OF GEOLOGY AND GEOPHYSICS
UNIVERSITY OF HAWAII**

A Reconnaissance of Reef Top Sediment Bodies in Windward Oahu, Hawaii
Draft (December 11, 2006)

by

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INTRODUCTION

Fringing reefs in Hawaii display sand fields on their surfaces (Figure1) that potentially play a role in littoral sediment budgets, provide substrate for important components of reef ecology, and may serve as a resource for sand and gravel aggregate. These shallow sand fields may also potentially provide quantities of affordable sand for beach replenishment projects (Moberly *et al.*, 1975; Casciano and Palmer, 1969; Moberly and Chamberlain, 1964). However, the degree of sand storage they provide and their role in littoral sediment budgets has not been defined.

Past Studies: Several studies review offshore and onshore carbonate sand sources on the island of Oahu, Hawaii. Moberly *et al.* (1975) present a general survey of offshore sand resources surrounding Oahu in the 0 – 18 m depth zone. At three sites, Sand Island, North Shore, and Penguin Bank, sand thickness

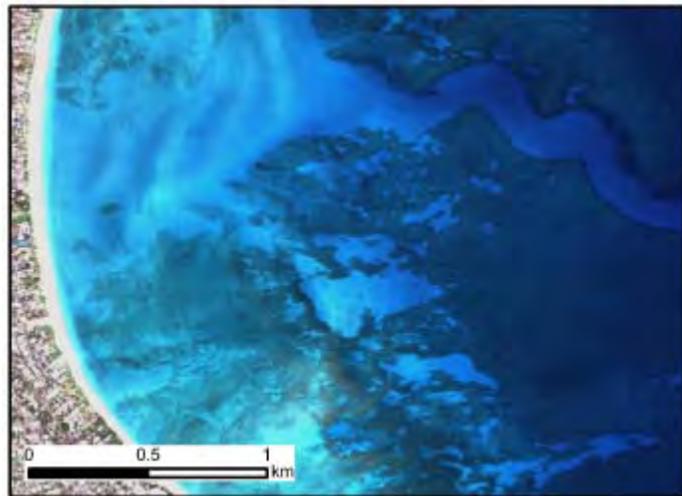


Figure 1. Bodies of sand fill depressions on the near-shore carbonate platform.

is measured using a sub-bottom seismic profiler and sand volumes are estimated. Ocean Innovators in conjunction with the US Army Corps of Engineers completed jet probe surveys and sediment sampling at a number of shallow and deep sand resource areas around Oahu (Ocean Innovators, 1977a – c, 1978a – b, 1979).

Coulbourn *et al.* (1988) perform detailed statistical analysis on sand samples taken by Ocean Innovators to identify grain size correlations to depth and depositional environment. Sea Engineering (1993) presents a summary of sand exploration studies performed around the island of Oahu as well as comparative ratings for exploitable deposits. Hampton *et al.* (2003) and Hampton *et al.* (2004) identify significant bodies of

sediment stored in the deep, 18 –100 m, fore-reef area at various Oahu locations using sub-bottom seismic imaging. Neither of Hampton's reports makes significant mention of sand bodies in water < 18 m.

The NOAA Benthic Habitat Mapping Program (Coyne *et al.* 2003) mapped sandy substrate from the shoreline to 30 m depth as part of a benthic habitat classification for the whole of Oahu. Conger *et al.* (2006) created detailed maps of sandy substrate to 20 m depth at sites around Oahu via supervised classification of multispectral satellite imagery, but these lack volume estimates.

Present Study: Past studies describe sand resources at sites around Oahu in varying degree of detail. The focus of this report pertains to three adjoining locations on the eastern Oahu shore: Kailua Bay, Lanikai, and Waimanalo Bay. Previous studies that provide detailed subsurface sampling within our area of interest include: Ocean Innovators (1978a), Coulbourn *et al.* (1988), Hampton *et al.* (2003), and Hampton *et al.* (2004). Sea Engineering (1993) provides a summary of data in Kailua Bay.

This study is an initial large-scope investigation of sediment volume within the study area. The intent of this study is to highlight areas of significant volume that could be the subject of more detailed measurement and study in the future. Here we report the results of 205 jet probe thickness measurements obtained from 54 distinct sand bodies in the 0 – 20 m depth zone across the reef platform of Kailua Bay, Lanikai, and Waimanalo Bay. Volume estimates and uncertainties are presented with discussion of sand body morphologies. The focus of this research is to quantify the volume geometry of reef-top sand bodies, improve our understanding of controls on variations in thickness of these sand resources, and infer the role of reef top sand bodies in littoral sediment processes.

STUDY AREA: KAILUA BAY, LANIKAI, AND WAIMANALO BAY

Wave Climate: Wave energy influences coastline stability, nearshore submarine sand transport, and mechanical abrasion on the reef. Hawaii's regional wave climate (Figure 2) is described in four components by Bodge and Sullivan (1999):

- 1) High-energy northeast Pacific swell created during the winter by storms north of Hawaii. Waves are incident on WNW to NNE shorelines; typical heights of 1.5 – 4.5 m and periods of 12 – 20 seconds.
- 2) Lower energy south Pacific swell between the months of April and October. Waves are incident on most south facing shorelines and have typical heights of 0.3 – 1.8 m and periods of 12 – 20 seconds.
- 3) Kona storms infrequently produce from the south and west wave heights of 3 – 4.5 m and periods of 6 – 10 seconds.
- 4) Trade wind waves consistently approach from the general northeast quadrant for 90% of the summer months and 55 – 65% of the winter months (Fletcher et al. 2002). Trade wind wave heights are 1.2 – 3 m with periods of 4 – 10 seconds.

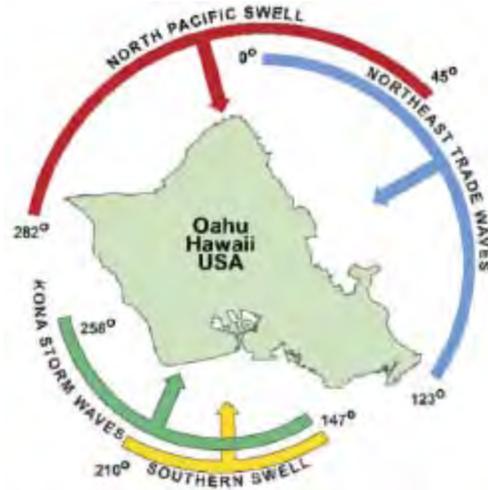


Figure 2. Components of Oahu's wave environment.

Additionally, large but infrequent hurricane waves can have significant impact on the reef (Fletcher et. al, 2002). Rooney et al. (2004) discuss the occurrence of extraordinarily large winter swell associated with strong El Nino episodes. They conclude that these events exert control over fringing reef accumulation and have essentially terminated most shallow water accretion on north-exposed coasts in Hawaii since approximately 5,000 yrs B.P (before present).

The primary wave regime for our windward study area is governed by the consistent full strength of trade wind swell. This swell is modified by annual and decadal

North Pacific wave events that wrap around Mokapu Peninsula into the study area. Large south swell affects the study area to a lesser extent. Easterly storms may also impact the study with high winds and/or high waves approaching on an interannual basis from the northeast, east, or southeast. Calmest conditions in the study area occur during Kona wind conditions as trade winds diminish, frequently producing offshore air flow.

Shelf Origin: The underlying carbonate framework of the study area is the product of reef accretion over recent interglacial cycles. Specifically, the shallow shelf of Oahu is a fossil reef complex dating from Marine Isotope Stage (MIS) 7 (~190,000 – 210,000 yrs B.P., Sherman et al., 1999; Grossman and Fletcher, 2004). The front of this shelf accreted separately during MIS 5a-d (ca. 80,000 – 110,000 yrs B.P.). Eolianites of late last interglacial age (ca. 80,000 yrs B.P., Fletcher et al., 2005) are found on the nearshore and coastal plain regions of windward Oahu.

Modern Holocene reef accretion is limited to deeper environments on the front of the reef where wave energy is not destructive. Grossman and Fletcher (2004) and Conger et al. (2006) infer that rugosity in depths less than 10 m atop the fringing reef is the result of karstification of limestone during times of lower sea-level, most recently since the last interglacial. Modern wave scour has prevented accretion in this zone. In depths greater than 10 m the karst surface has largely been over grown by Holocene accretion (Conger et al., 2005).

Coastal Plain: Harney and Fletcher (2003) provide a synthesis of drill cores and radiometric dating obtained in the Kailua coastal plain over the last 60 years. It is demonstrated that sediments underlying the town of Kailua and the Kawainui Marsh reflect 5,000 years of coastal sedimentation during a sea-level highstand (+2 m) and subsequent declines in sea-level position (Grossman and Fletcher, 1988). A 3-10 m thick sandy accretion strand plain is deposited over lagoonal sediments (marine silt with shell and coral fragments) >40 m in thickness. Under modern Kawainui Marsh, cores penetrate 15 m of peat, terrestrial mud, and lagoonal sediments. The presence of lagoonal sediment is attributed to formation of a marine embayment ca. 3,500 yrs B.P. during the high-stand followed by formation of a terrestrial marsh following sea-level fall ca. 2,200 years B.P. (Kraft, 1982, 1984; Athens and Ward, 1991). The accretion strand

plain is lies between the marsh and the beach face of modern Kailua Bay and has an especially thick central portion attributed to shoreward expression of the offshore paleo-stream channel that has filled with sand (Harney and Fletcher, 2003). The strand plain formed by shoreline regression as sea-level fell to its modern position following the mid-Holocene highstand. Coastal plain deposits underlying Kawainui Marsh and the town of Kailua are found by Harney and Fetcher (2003) to contain $10,049 (+/- 1,809) \times 10^3 \text{ m}^3$ of carbonate sand and silt of Holocene age.

General Sediment Characteristics: Moberly and Chamberlain (1964) characterize Kailua Bay, Lanikai, and Waimanalo Bay as having very poorly sorted highly calcareous beach sands and large but thin patches of offshore sand. Kailua and Lanikai sands are described as poorly sorted, with Kailua tending towards bimodality. Waimanalo sands are described as coarse- to medium- grained and vary from well sorted to poorly sorted with high *foraminifera* fractions. Landward of Kailua and Waimanalo beaches are modern vegetated dunes and older lithified eolianites, consisting of coarse well-sorted sand, in which *foraminifera* constitute the highest compositional fraction.

Sediment Production: Harney et al. (2000) completed a detailed study of beach, channel, and reef-top sand bodies in Kailua Bay. Harney determined >90% of sediments were biogenic carbonate, dominated by coralline (red) algal fragments. They identified two primary sources of sediment for Kailua Bay. The offshore reef platform is a primary source of framework sediments (coral and coralline algae) while nearshore hardgrounds and landward portions of the reef platform are sources of direct sediment production (*Halimeda*, mollusks, and benthic *foraminifera*).

Radiometric dating of sand grains indicate middle to late Holocene age for surficial sediment stored in Kailua Bay. Most surficial sediments were found to be older than 500 yrs, suggesting relatively long storage times in the immediate sediment budget. Harney et al. (2000) concluded that sand stored in Kailua Bay represents production under a higher sea-level stand (+ 2 m; Grossman and Fletcher, 1998) that retreated during the late Holocene.

Coralline algae, the primary compositional element of Kailua sands, are primary reef framework producers in high wave energy environments (Harney et al, 2000). High

coralline algae composition suggests that a strong wave environment is a major controlling factor on sediment production in Kailua Bay during the past 5000 yrs. Grossman (2001) and Rooney *et al.* (2004) analyzed drill cores from reef platforms exposed to strong modern north swell and concluded that positive fringing reef accretion was halted by an increase in wave energy ca. 5000 yr ago. Rooney *et al.* conclude the increase in northern swell ca. 5000 yr ago corresponds to amplification of El Nino/Southern Oscillation (ENSO), which is responsible for unusually large northern wave events in Hawaii during particularly strong El Nino episodes. It stands that sediment storage in Kailua Bay reflects a diminishing sediment production regime over the last 5000 years, brought on by stronger ENSO induced north swell and reduced accommodation space due to sea-level fall.

Benthic organism data collected at the Kailua sand channel by Harney (2003) shows a 50% decrease in living coral cover (57% to 7%) along the channel margin where depth decreases from 10 m to 3 m. This reduction in coral cover is the result of higher wave shear stress in shallower waters (Grossman, 2001) aided by higher suspended sediment concentrations. A combination of higher shear stress and less accommodation space likely led to reduced reef framework growth at shallow depths around windward Oahu (Grossman and Fletcher, 2004).

PREVIOUS SAND RESOURCE INVESTIGATIONS IN THE STUDY AREA

Onshore Resources: Inventory and mapping of sand resources in Kailua and Waimanalo began with Moberly and Chamberlain (1964). Kailua Bay, Lanikai, and Waimanalo Bay beach sands are described as very poorly sorted and highly calcareous. Offshore sand bodies are described as large but thin and patchy. Moberly *et al.* (1975) identify lithified eolianites in Kailua, Bellows, and Waimanalo as a potential source of beach sand. Moberly describes the deposits as the most extensive on windward Oahu, but adds that houses and beach parks cover a majority of these. As of 1975, island-wide deposits of lithified dune lacking development and available for mining were estimated at less than $2 \times 10^6 \text{ m}^3$ (2.7 million yd^3). Existing modern vegetated dunes are mentioned, but considered a great deal more valuable intact than mined, as removed would yield

relatively small volumes of sand and have negative impacts on wildlife habitat and flood protection.

Pacific Rock & Concrete (PR&C) began crushing limestone mined in a Waimanalo quarry in the late 1960's. The intent of PR&C was to use the sand as material for beach replenishment (personal interview relayed by Casciano and Palmer, 1969).

Offshore Resources: Moberly et al. (1975) completed the first intensive survey of offshore sand resources around Oahu. Spatial extent of offshore sand fields was roughly mapped by aerial surveys. Major sand bodies from sea-level to 18 m depth were mapped for the Kailua and Waimanalo areas, however the survey of deeper sand bodies (18 m – 90 m) excluded the region between central Kailua and Koko Head. None of the areas selected for detailed thickness measurements were within the Kailua or Waimanalo regions.

Ocean Innovators (1978, 1979) completed a jet probe survey of the Kailua sand channel and an adjacent sand body for the U.S. Army Corps of Engineers in 1978. Jet probing was performed in a series of 13 transects perpendicular to the channel axis in depths of 5 to 24 m and 3 transects between 5 and 6 m in the adjacent sand body. Minimum volumes were estimated for the sand channel, $3.7 \times 10^7 \text{ m}^3$ ($4.84 \times 10^7 \text{ yds}^3$), and the adjacent sand body, $2.08 \times 10^6 \text{ m}^3$ ($2.72 \times 10^6 \text{ yds}^3$).

Surface and subsurface sampling in Kailua channel performed in the same locations revealed a variability in grain size, sorting and color with no discernable pattern. Median grain sizes of samples varied from fine to coarse sand (0.11 to 1.4 mm) with the percentage of samples finer than 0.15 mm varying between 1% and 81%. In only 7 out of 36 samples were less than 10% of the grains found to be finer than 0.15 mm. The average percentage of material finer than 0.15 mm was 38%. The color varied between slightly gray and yellow. Initial results indicated the sand channel contained very thick sand, in excess of 9 m in most instances and occasionally over 15 m. Sediment washed out by the jet probe initially appeared suitable for use in beach replenishment. However, subsurface samples analyzed by Casciano (US Army Corps of Engineers, 1978) concluded that the sand was highly stratified in terms of grain size and would ultimately be too fine for beach replenishment.

Sea Engineering (1993) conducted a beach nourishment viability study for the Hawaii Coastal Zone Management Program. The study synthesized all data taken on offshore sand resources around Oahu and scored each deposit based on site depth and wave exposure, interaction with adjacent littoral cells, deposit volume, and sediment grain size characteristics. Using these criteria it was concluded that the Kailua channel sand body was unsuitable for mining. The primary negative criteria were unsuitably fine grain sizes and the concern that reducing sediment volume in the channel posed a considerable risk to the stability of the immediate and adjacent littoral cells (Richmond, 2002).

Hampton et al. (2004) mapped sediment thickness in the Kailua sand channel using a tunable, swept-frequency (0.6 kHz to 3 kHz) acoustic profiler (see Barry et al. 1997 and Sea Engineering, 1993) supplemented by analysis of sediment recovered from 13 vibracores in 2000 and 14 vibracores in 1997. Thickness mapping in Kailua was performed in 60 -100 m of water. Sand deposits extend for about 4 km in an arc parallel to the Kailua reef front with a maximum thickness of 40 m, a mean thickness of 11 m, and is strongly skewed towards the smaller thickness. The total volume calculated for the deposit is $5.3 \times 10^7 \text{ m}^3$ ($6.9 \times 10^7 \text{ yds}^3$). Grain size analysis of vibracored sediments revealed the sediment is finer than that which is usually used in beach replenishment. Compositional and abrasion analysis shows the sand has a low resistance to abrasion due to a high portion of *Halimeda* skeletal grains.

Conger et al. (in press) analyzes the surficial spatial distribution of benthic sand bodies across Oahu's insular shelf (to 20 m depth) at nine locations around Oahu, totaling 125 km² (39% of Oahu's shoreline). For each region, shallow benthic sand bodies are delineated, totaling 14,037 sand bodies for the study. Of the 125 km² of reef area studied 25 km² (~20%) was identified as sand, with a majority (64%) located in sand channels and fields. Sand bodies were classified in deposit shape classes by an automated classification algorithm accounting for a combination of individual shape characteristics such as area, orientation, and roundness. The resulting dataset of 14,037 sand body polygons was mapped to 2.4 m resolution, and each assigned a classification based on its shape.

A quantitative comparison of regional variations in sand bodies (number, shape, and size) to regional geomorphic setting (deep vs. wide reef) and wave climate (high,

medium, or low-energy) shows that the distribution of reef-top sediment is strongly influenced by reef geomorphology and, to a lesser extent, wave energy. Sand coverage is most extensive in two depth zones: <10 m depth zone (24% of total) and straddling the 10 m contour (72% of total). Conger *et al.* concludes that sand coverage is greatest in these regions because, the sub-10 m depth zone precludes the possibility of depressions being closed by modern reef growth due to high shear stress. Sand conduits crossing the 10 m depth contour provide both storage and transport between near and –offshore sand bodies. The 0-10 m depth range is also likely the zone of highest sediment production.

Reef types supporting the highest sand coverage are low wave-energy, have offshore sand bodies, and a wide shallow back reef. Least sand coverage is found in reefs with high wave-energy, no offshore sand bodies, and no wide shallow back reef. Study areas were categorized by sand coverage (highest to lowest): 1) Honolulu and Keehi Lagoon, 2) Lanikai and South of Laie Point, 3) Waianae, 4) Kailua, Kaneohe, Mokapu Point, and North of Laie Point. Lanikai is a medium-energy wide reef falling into the second highest category of sand coverage. Kailua is classified as a medium-energy deep reef falling into the lowest category of sand coverage.

Potential Effects of Sand Mining on Adjacent Beaches: The threat of increasing beach erosion through the mining of offshore sand bodies stems from the nature of a littoral cell as a naturally organized, interconnected, system of sand production, storage, and loss. An offshore sand body in Keauhou Bay, Hawaii was mined during 1977 as part of a two-month field test of a new sand mining and delivery system (Maragos *et al.*, 1977). A total of 10,000 m³ of sand were mined from a sand body located 120 m offshore in 15 – 25 m of water. The sand body was 150 m wide by 300 m long and 6 m in thickness and surrounded by flourishing coral community. A detailed environmental survey was performed before, during, and after the mining operation, the results of which are presented in Maragos *et al.*, (1977). The study showed that mining sand had no immediate effect on nearby beaches at Kahaluu (1.5 km north) and Disappearing Sands (3.5 km north). It was noted that there exists no clear pathway between the sand deposit mined and either beach, suggesting that the mining of well-isolated and distant sand fields will not have an effect on nearby coastlines. Sea Engineering’s 1993 sand resource viability study considered sand deposits offshore of a rocky shoreline and with low

proximity to a local beach littoral cell to be less hazardous mining objectives than deposits offshore of a sand beach near an active littoral sediment cell (Sea Engineering, 1993).

Moberly and Chamberlain (1964) state that sand channels potentially support circulation that delivers sand to adjacent beaches, seaward into deeper water, or a seasonal exchange between sand channels and the beach. Cacchione and Tate (1998) noted in a study of Kailua sand transport that fossil channels almost always connect to both nearshore and offshore sand fields and act as conduits for sand movement in both onshore and

offshore directions. Cacchione and Tate showed sand ripples in the Kailua sand channel migrate shoreward at a rate of 0.5 m/day during trade wind conditions and seaward at a rate of 0.5 m/day during winter swell conditions. This is supported by common observations of sand ripples and well-sorted sediments fining in shoreward direction, both signs of active transport occurring between deep and shallow fields at the terminal ends of the channel. Special consideration should be taken with regard to removing sand from this type of sand body as sediment supply to a pre-existing shore face or littoral cell could be diminished (Cox, 1975; Dollar, 1979).

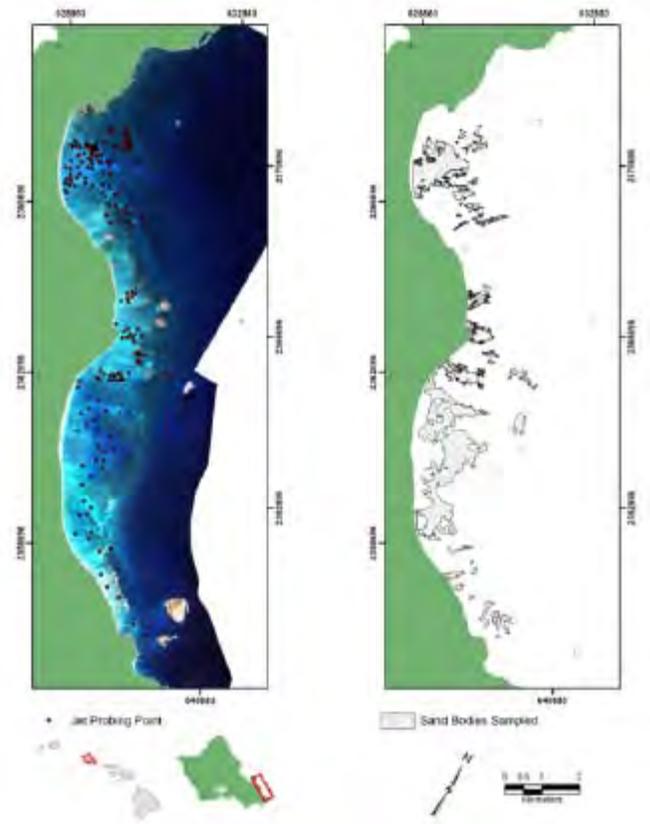


Figure 3. a) 205 jet probe measure were taken in the study area. b) 54 sand bodies are delineated for study.

MATERIALS AND METHODS

Boundaries of 54 sand bodies (Figure 3) in the study area were delineated for study using satellite imagery, LIDAR bathymetry, benthic slope maps (a product of LIDAR), NOAA benthic habitat maps, and sand classification maps produced by Conger *et al.*, 2005. Sand bodies were classified by morphology (Figure 4). Sampling with a jet probe (Figure 5) provided a total of 205 measurements of sand thickness. Thickness interpolation and gridding of point data is accomplished using Kriging and Voronoi methods. Volumes estimates are calculated with for all sand bodies.

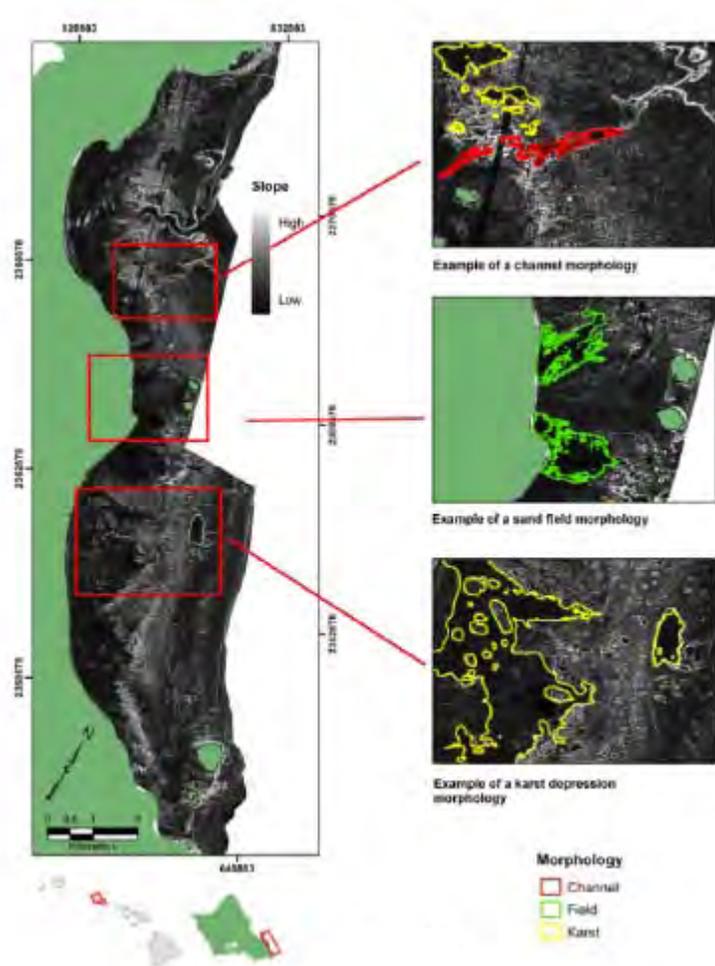


Figure 4. A slope map created from LIDAR bathymetry assists in classification of sand body morphology.

Morphology Classification:

Conger (2006) determined antecedent topography to be the primary control on morphology of reef top sand bodies. Karstification of the carbonate platform during periods of lower sea-level creates depressions which, once flooded, serve as basins that accumulate sand. Variations in relief, shape, and orientation of depressions are likely due to differing processes of karstification.

Following the work of Conger, a generalized morphology classification has been created for this study. Sand bodies sampled are classified as one of three morphologies: Sand Field, Fossil Channel, or Karst Depression. Variance in topographic relief, distribution of thickness, and generalized shape are used as major distinguishing factors used to classify sand body morphologies. Segregating sand bodies in this manner adds a

morphology component to the process of interpolating measured thicknesses and constructing a coverage map of estimated thickness, thereby increasing estimation confidence.

In addition to field observations, slope maps generated from LIDAR bathymetry were used to evaluate the topographic relief between the reef platform and the surface of the sand body. Figure 4 illustrates distinctions between morphologies by highlighting examples on a slope map of the study area. Table 1 summarizes sand body morphology classifications and location.

NUMBER of SAND BODIES	Fossil Channel	Karst Depression	Sand Field	Total
Kailua Bay	7	26	0	33
Lanikai	1	3	4	8
Waimanalo Bay	0	5	8	13
Total	8	34	12	54

Table 1. Number of sand bodies organized by morphology (columns) and region (rows).

Sand Fields: Sand fields are defined, in this study, as areas of continuous sand cover deposited over a broad topographic swale in the reef platform. Boundaries generally have little to no topographic relief and irregular borders. Sand fields are generally found near to shore in shallow (0 - 5.0 m) areas, have broad landward openings toward the beach face that separate and thin into separate fingers of sand that continue seaward and terminate on shallow reef locations. Of the 54 sampled sand bodies, a total of 13 were designated as sand fields.

Fossil Channel: Fossil channels are seaward extensions of watershed systems, incised into the carbonate shelf during low sea-level stands. The high topographic relief of the channel allows fossil channels to act as effective traps for littoral sediment. Channels in Kailua and Waimanalo are typically shore-normal in orientation and cross the -10 m isobath. Major channels, such as the Kailua sand channel, have steep walls of fossil reef and widen shoreward into large sand fields that lack significant bounding relief. Shoreward transition from bounding walls to a more gradual surface occurs in water shallower than 5 m, at which point sand is no longer confined to a channel and spreads

out into a sand field. Large sand channels can contain sediment over 9 m thick (Ocean Innovations, 1978) and remain thickest along the axis of the channel, thinning to 1.0 – 1.5 m at the margins and adjoining landward field. Of the 54 sampled sand bodies, a total of 7 were designated as fossil channels.

Karst Depression: Karst depressions are similar to fossil channels in that they are likely the result of subaerial exposure causing a sinkhole style karst incision. They differ from fossil channels in that they occupy smaller areas, have no dominant orientation, and do not serve as a connection between sand fields. Karst depressions have steep boundaries, generally dropping 1-3 m below the carbonate platform thus distinguishing them from sand fields. Of the 54 sampled sand bodies, a total of 34 were designated as karst depressions.

Thickness Measurements: Sediment thickness measurements were obtained with a jet probe (Figure 5) deployed from a small boat, and operated by a researcher on SCUBA. The jet probe is built from a small diameter pipe connected to a shipboard water pump via fire hose. High-pressure water is pumped out of the pipe in order to displace sediment as the SCUBA diver pushes it into sandy substrate. The probe stops penetrating when it contacts a boundary with bedrock or an impenetrable layer of consolidated sediment. The depth of penetration provides a measure of unconsolidated sediment thickness. The probe length is 3.0 m. If the sand

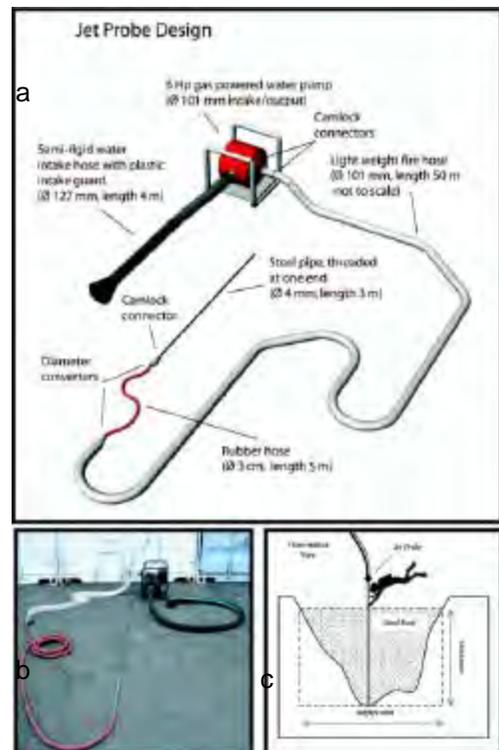


Figure 5. a) Jet probe schematic. b) Jet Probe. c) The jet probe is inserted into sand bodies until it ceases to penetrate. Thickness is measured in 10 cm increments off the probe.

body thickness exceeds 3.0 m, the value of 3.1 m is recorded. Appendix B contains tabulated jet probing results.

Sampling Locations: Using the jet probe, a total of 205 thickness measurements were obtained from 54 distinct sand bodies on the Kailua, Lanikai, and Waimanalo reef platforms. At each sample location 3 thickness measurements were taken within a 20 m radius of the anchored boat and the average thickness recorded for that site. Water depth at sample locations was recorded from a hull-mounted fathometer at an accuracy of +/- 0.5 m. Water depth varied from 1.5 m to 16.8 m, with an average of 5.2 m. General sediment characteristics were noted at each site. The probe was completely removed and inserted multiple times with each measurement to insure repeatable results. All sample locations were predetermined by examining aerial photos and bathymetry in conjunction with NOAA benthic habitat maps (Coyne et al., 2002) and previous substrate studies in the region (Sea Engineering, 1997; Conger et al., 2006). Survey points were located with a GPS receiver at an accuracy of +/- 5 m. Once anchored, drift of the boat was adjusted to match sample location so a diver could use the boat as a reference point for placing the jet probe. Figure 3 illustrates jet probe sample locations and sand body delineation.

Volume Calculations: Estimates of sand volume were obtained for each sand field by using one of two methodologies: 1) a Kriging method or 2) a Voronoi method with a volume correction factor. The selection of either methodology was based on the spatial density of available thickness measurements as well as the size and complexity of the given sand body. In instances of good data coverage a Kriging method was used. The Voronoi method was used for sand bodies with sparse coverage, where a single measurement must be representative of a large area, as it does not require a high data density. A total of 54 sand bodies are analyzed; Kriging was applied to a 9 sand bodies while the Voronoi model was applied the remaining 45 bodies. Table 2 summarizes sand body morphologies as applied to each methodology. Appendix C contains details on all volume estimations.

MORHOLOGY				
	Channel	Field	Karst	Total

Kriging	1	5	4	9
Voronoi	6	8	30	45
Total	7	13	34	54

Table 2. Summary of interpolation methods (column) applied to sand body morphologies classes.

Reporting of Volumes: In order to make volume estimates a more useful product, volume is not reported over the entire surface of every sand body sampled. In areas where the Kriging method could be used, volume was only calculated for the areas of greatest thickness (> 0.50 m). Similarly, volume results are given in a section-by-section basis for sand bodies using the Voronoi method. In many cases a single sand body, identified by a Sand Body ID, is broken into multiple sections, each reported as an Area ID. Volumes are reported for each Area ID individually. Table 3 summarizes volume estimations by region and Table 4 summarizes measured area of sand bodies. A series of maps and tables detailing thickness and volume estimations are included in Appendix A.

VOLUME (m³)	Channel	Error	Karst	Error	Field	Error	Total	Error
Kailua Bay	825,115	75,056	150,715	15,244	0	0	975,830	90,300
Lanikai	23,616	5,432	43,703	9,719	129,987	3,089	197,306	18,240
Waimanalo Bay	0	0	504,396	47,999	20,136	1,660	524,532	49,659
Total	848,731	80,488	698,814	72,962	150,123	4,749	1,697,668	158,199

Table 3. Volume estimates with error in cubic meters presented as morphology class (column) and region (row).

AREA (m²)	Fossil Channel	Karst Depression	Sand Field	Total
Kailua Bay	668,701	290,399	0	959,100
Lanikai	67,923	169,469	1,148,858	1,386,251
Waimanalo Bay	0	653,341	235,144	888,485
Total	736,624	1,113,209	1,384,002	3,233,836

Table 4. Sand body surface area presented as morphology class (column) and region (row).

Kriging Method: The Kriging approach is a more statically robust method of estimation than the Voronoi method and was preferentially used whenever data density was suitable. Boundaries of sand bodies are assumed to be zero thickness and were represented by

points of zero thickness generated at 1 m spacing around each sand body. Modeling the variation between measurement points and the edges was accomplished with a semi-variogram. A semi-variogram model quantifies the relationship between variability of a native dataset and spatial location as an equation for a line. The equation for each semi-variogram model is used to model the rate of change between points where thickness is known, i.e. jet probe thickness measurements and edges (Webster and Oliver, 2001). In this usage, the changing slope of the semi-variogram line is analogous to the changing slope of the reef-top depression.

A separate variogram equation was produced for each sand body so that the thickness model would be individualized to the unique characteristics of each body. A spherical semi-variogram model was used in all cases. Points of zero thickness along the edge were included when producing semi-variogram. Rasterized thickness estimation maps were created at a resolution of 1 m. Volume calculations were made for areas of sediments estimated to be >0.50 m thick, each reported as a separate Area ID. Thickness and volume calculation results are presented in Appendix A.

Voronoi Method: The Voronoi method assumes that sand body thickness is perfectly uniform up to the edge of the sand body. See Figure 5 for an illustration of the method. This method is used when thickness data is too sparse for a Kriging approach to be useful. Perimeters of each sand body and thickness measurements were mapped and entered into ArcGIS. An ArcGIS Voronoi function was used to subset each sand body into series of smaller adjoining polygons or sub-polygons; each sub-polygon formed around a single thickness measurement. The Voronoi function draws sub-polygon boundaries so that any location within a given sub-polygon is closer to its associated measurement point than to the measurement point of any other sub-polygon (Webster and Oliver, 2001).

The sediment thickness within each sub-polygon is assumed to be the same as the thickness measurement it contains. Volume of sediment is calculated for each sub-polygon as the product of the area and thickness. The volumes for all sub-polygons within a single sand body are summed to calculate a total sediment volume for the entire sand field (see Appendix C). Afterwards, a correction is applied to account for over-

estimation of volume. Sub-polygons created by this process form the boundaries for the individual Area ID's.

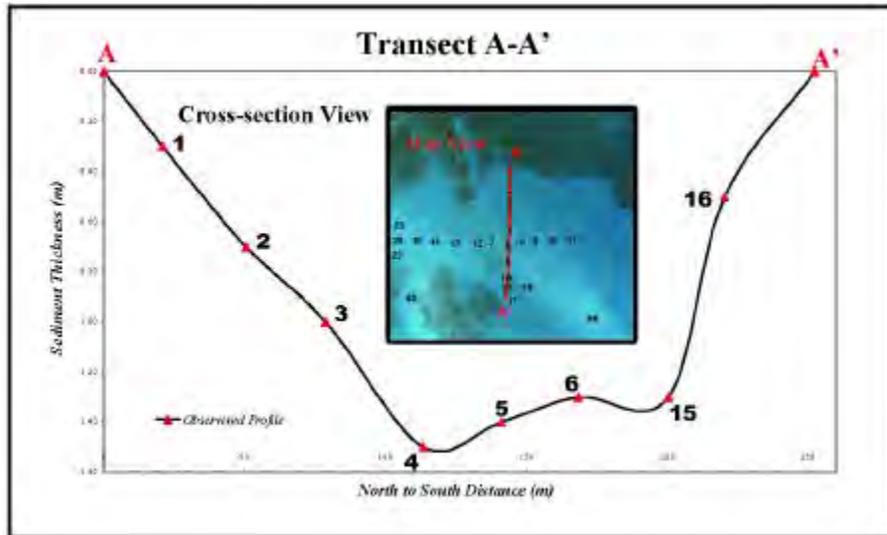


Figure 6. Kailua Bay. Thickness profile generated from a transect of point measurements. Note the thickness irregularity in sand bodies.

Voronoi Volume Correction: A major source of uncertainty with the Voronoi model is the assumption that the walls of reef top depressions are at right angles to the base of the depression. A transect of thickness measurements (transect A-A' in Figure 6) from Kailua Bay suggests that sand bodies are thickest in the center and gradually thin toward the edges.

Given the high range of variability in sand body thickness, failing to account for sand body morphology likely produces an over-estimate of sand volume. Correction of over-estimated sand volumes is accomplished by calculating an empirically derived reduction factor. Reduction factors are calculated as the average percent difference between Kriging and Voronoi estimations performed on the same set of sand bodies. Results from comparative volume estimations of 10 sand bodies are segregated by sand body morphology and averaged so as to calculate reduction factors that are morphology specific.

Of the 10 bodies used, 4 were classified as sand fields, while the remaining 6 were classified as karst fields. No bodies classified as channel morphology were used due to a lack of adequate examples, however the assumption is made that channel and karst morphologies share similar aspects of genesis, possess similar subsurface-

topography, and thus can utilize the same reduction factor. The reduction factor calculated for sand field morphologies is $88.25\% \pm 8.25\%$ (i.e. Voronoi estimations are reduced by $88.25\% \pm 8.25\%$), while $64.67\% \pm 23\%$ is used for karst and channel morphologies. Uncertainty calculation is described below, in the section *Prediction Uncertainty*. These reduction factors cause dramatic decreases when applied to the Voronoi-based volume estimates, but provide a more informed and realistic estimate.

Prediction Uncertainty: Measurement uncertainties are ± 5 cm vertical uncertainty associated with jet probe measurement and ± 5 m of horizontal uncertainty associated with accuracy of the GPS receiver. These uncertainties are taken into account during the Kriging process as a nugget variable and thus are propagated through the interpolation process as a pixel-by-pixel error value. Therefore, every map of estimated volume created via Kriging also has a map of the pixel-by-pixel estimation uncertainty in meters. Areas defined for volume estimations are used with error maps to calculate the error in volume estimation for each area.

Percent difference between estimated volume and estimated error was calculated for each sand body. These percent differences were averaged simultaneously with values used for calculating the reduction factors, resulting in the uncertainty values reported for Voronoi estimates. The error results are presented as tables in the maps of estimated sediment volumes (Appendix A).

RESULTS AND DISCUSSION

Fossil Channel: Of the 54 sampled sand bodies, 8 were classified as fossil channels. Fossil channels are estimated to contain $848,731 \pm 80,488$ m³ of sediment and cover an area of $736,624$ m². The average volume-to-surface area ratio is 1.15 m³/m², the highest ratio in the study area. Most sediment in this morphology class is contributed by the Kailua sand channel, of which only the shoreward section is being considered in this study. Previous jet probe studies in the deeper channel have shown sediment thickness to exceed 3.0 m. In southern Kailua, a group of smaller channels form the fragmented

remnants of what is most likely a channel closed by reef growth. Another smaller intact channel exists in Lanikai, but does not connect with a significant shoreward sand body.

Defining a specific morphology for the shoreward end of the Kailua sand channel is difficult as the channel widens landward, loses the high bounding topographic relief, and transitions into sand field type morphology. However, a linear trace of high thickness continues landward through the sand field along the central axis of the channel. This indicates that the shoreward portion of the channel has been filled and overtopped by sand, producing a sand body that qualifies as both a channel and a field. For the purpose of estimating sand volume the Kailua sand channel is considered a member of channel morphology class.

Sand deposits in fossil channels tend to be consistently thick and yellow to white coloration. Surface sediments in these channels appear medium- to coarse-grained, however subsurface sampling in the Kailua channel has shown significant amounts of fine-grained sediment (US Army Corps of Engineers, 1978). Channels likely serve as surge channels for waves breaking over the fringing reef. The focusing of wave energy through these channels would cause preferential grain sorting as grains transported, leaving a varied stratigraphy of fine and coarse sediments related to variations in transport energy.

Sand Field: Of the 54 sampled sand bodies, 12 were classified as sand fields. Sand fields are estimated to contain $150,123 \pm 4,749 \text{ m}^3$ of sediment and cover an area of $1,384,002 \text{ m}^2$. The average volume-to-surface area ratio is $0.11 \text{ m}^3/\text{m}^2$, the lowest ratio in the study area.

Sediment thickness tends to grade from 0.5 m near to shore thickening to over 3.0 m near the seaward edge. Sediments are fine to medium sand with a mixture of sandy and gravelly substrata. Nearshore sand fields are generally connected to the adjacent beach where they potentially function as sediment storage and source locales participating in volume fluctuations on the beach.

Karst Depressions: Of the 54 sampled sand bodies, 34 are classified as karst depressions. Karst depressions are estimated to contain $695,814 \pm 47,999 \text{ m}^3$ of sediment and cover

an area of 1,113,209 m². The average volume-to-surface area ratio is 0.63 m³/m², the mid-range ratio in the study area.

Sediments in karst depressions are observed to contain one or both of two characteristic strata: 1) medium to coarse light-colored sand and 2) coral gravel varying between 5 cm fragments to hand-sized branches. Sediment bodies in karst depressions consist of either 1.0 – 2.0 m thick sand, 0.5 – 1.0 m sand overlaying coral rubble, or an absence of sand with coral rubble outcropping on the surface. Coral rubble deposits were not included in thickness and volume analysis. Sandy bodies without coral rubble tend to lie directly on fossilized reef platform.

Coral accretion on the perimeter of karst depressions suggests Holocene growth has shrunk the area of many depressions, possibly isolating one large depression into a number of smaller depressions. Sediment produced on the reef is thought to be transported to the beach in a series of steps between depressions (Moberly and Chamberlain, 1964) making karst depressions a potentially important component of shallow (3.0 – 5.0 m depth) sediment storage in the littoral system.

An expansive system of interconnected, sand-filled karst depressions dominates the topography of the central-south Waimanalo area. This feature resembles a sandy lagoon in that it runs shore-parallel between a fringing reef and outcropping back reef in 4-7 m of water. Sediment thickness is greatest in two isolated semi-circular areas. The lack of any linear zones of thickness exclude this feature from consideration as a channel feature.

CONCLUSIONS

Jet probing of shallow sand bodies allows volume estimates to be made for a total of 54 sand bodies. Sand channels appear to have the greatest overall volume-to surface area ratio (1.15 m³/m²), however if data from the Kailua sand channel is excluded, the ratio drops to 0.29 m³/m², indicating that the volume of sediment infilling channels in the study area varies greatly. Most sand channels in the study area lack the size, continuity, and terminal sand fields of the Kailua sand channel. Absence of a major terminal sand body attached to either end of the smaller channels most likely indicates a lack of active transport, which could account for low volume relative to the larger Kailua sand channel.

Karst depressions have a volume-to surface area ratio of $0.63 \text{ m}^3/\text{m}^2$ and lack major anomalies such as the Kailua sand channel. The relative abundance of karst depressions in the study area suggests that karst depressions play a major role in reef-top sand storage. Sand fields have the lowest volume-to-surface area ratio ($0.11 \text{ m}^3/\text{m}^2$). Given that a lack of significant confining topographic relief is the differentiating feature for sand fields, it is likely that topography is the foremost control in reef-top sand storage.

APPENDICES

- A. Maps of Sediment Thickness and Volume Estimates
- B. Tabulated Jet Probing Results
- C. Tabulated Sediment Thickness and Volume Estimates

632314

157°43'30"W

631814

631314

157°44'0"W

2369730

2369730

2369230

2369230

632314

157°43'30"W

631814

631314

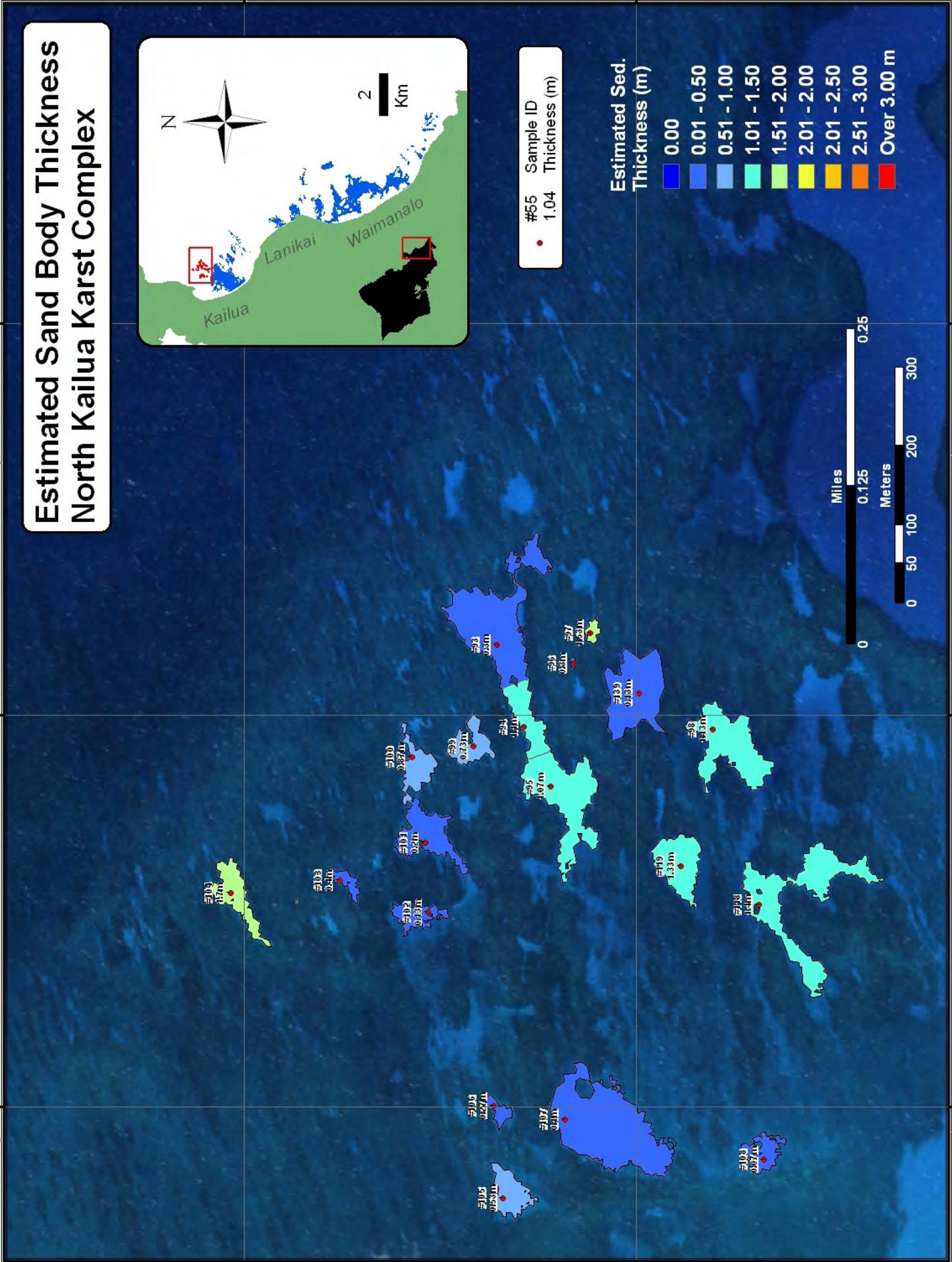
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Estimated Sand Body Thickness North Kailua Karst Complex

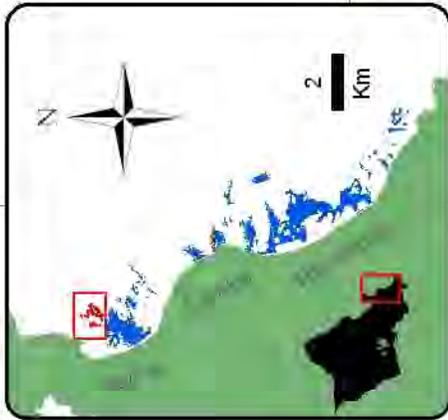


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• 1.04 Thickness (m)

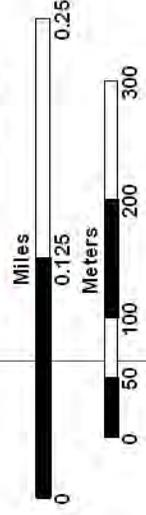
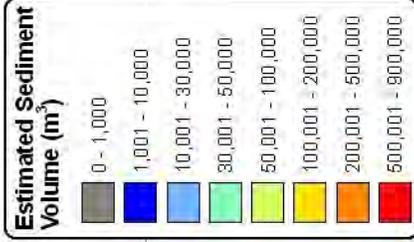
Estimated Sed.
Thickness (m)

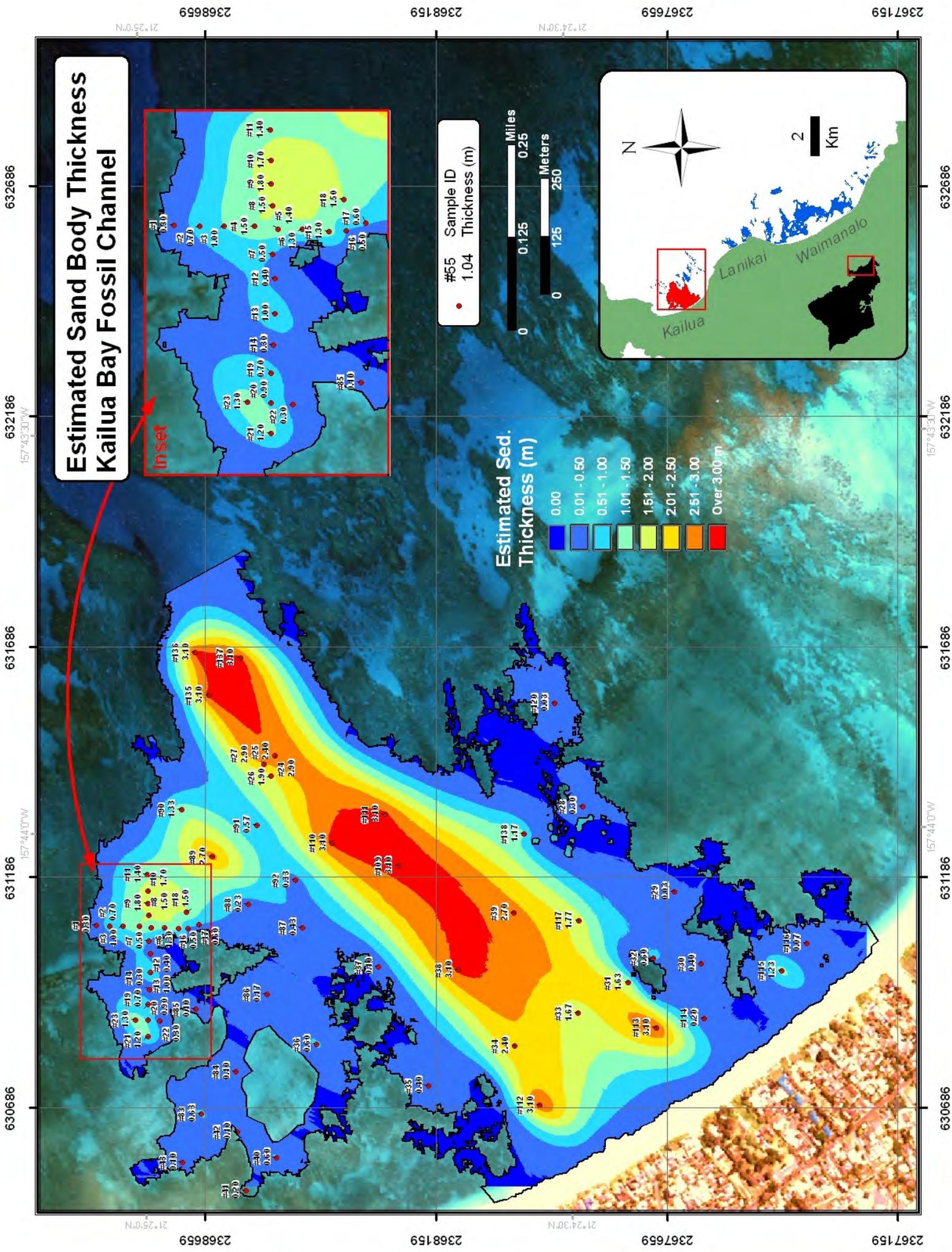


Estimated Sediment Volume North Kailua Karst Complex



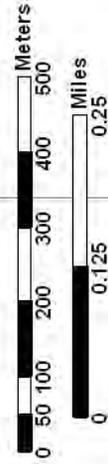
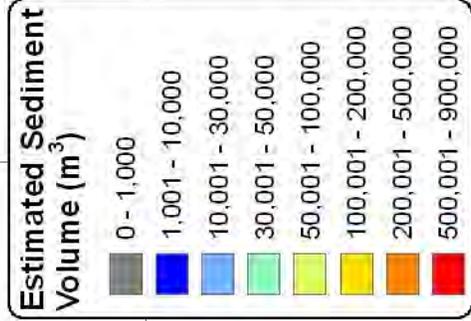
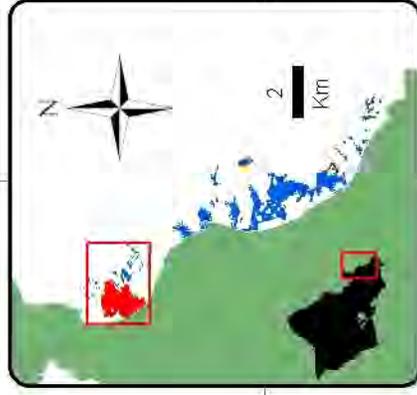
Area ID	Area m ²	Volume m ³	Error m ³	Vol/Area m ³ /m ²	Method
4	2,602	1,716	± 395		Voronoi
5	710	110	± 25	0.15	Voronoi
6	1,996	674	± 155	0.34	Voronoi
7	1,450	73	± 17	0.05	Voronoi
8	3,483	270	± 62	0.08	Voronoi
9	1,917	543	± 125	0.28	Voronoi
10	653	68	± 16	0.10	Voronoi
11	2,141	440	± 101	0.21	Voronoi
12	2,597	1,108	± 255	0.43	Voronoi
13	9,328	1,086	± 250	0.12	Voronoi
14	79	9	± 2	0.11	Voronoi
15	7,123	2,957	± 680	0.42	Voronoi
16	399	237	± 55	0.59	Voronoi
17	6,206	313	± 72	0.05	Voronoi
18	11,958	464	± 107	0.04	Voronoi
19	3,575	1,845	± 424	0.52	Voronoi
20	6,003	2,632	± 605	0.44	Voronoi
21	1,601	43	± 10	0.03	Voronoi
22	8,221	4,466	± 1027	0.54	Voronoi





Estimated Sediment Volume Kailua Bay Fossil Channel

Area ID	Area m ²	Volume m ³	Error m ³	Vol/Area m ³ /m ²	Method
1	586,831	801,695	+/- 70,484	1.37	Kriging
2	7,394	2,513	+/- 455	0.34	Kriging
3	4,572	1,027	+/- 350	0.22	Kriging



632686

632186
157°43'30"W

631686

631186
157°44'0"W

630686

21°25'0"N

2368659

2368159

21°24'30"N

2367659

2367159

632686

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157°44'0"W

630686

21°25'0"N

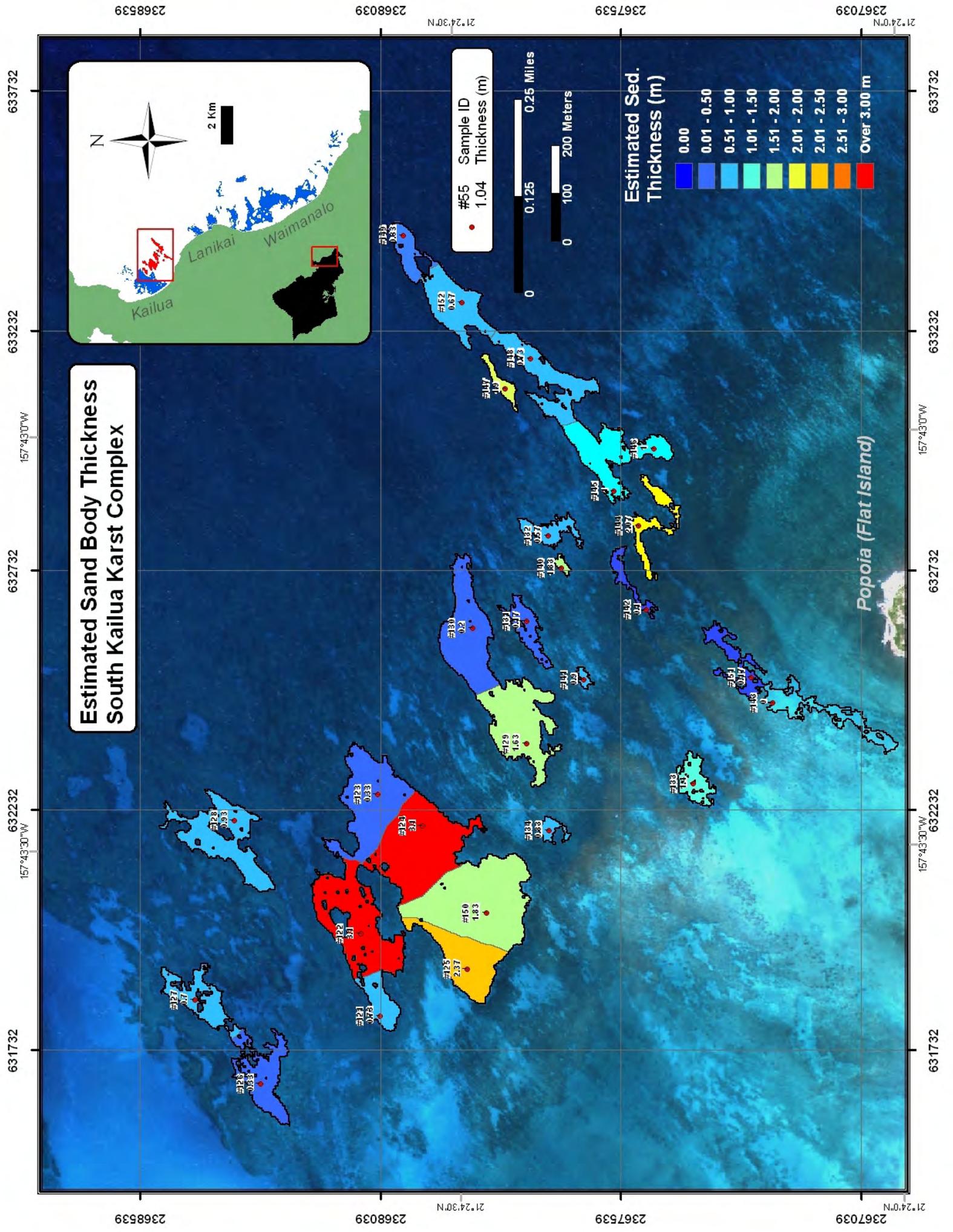
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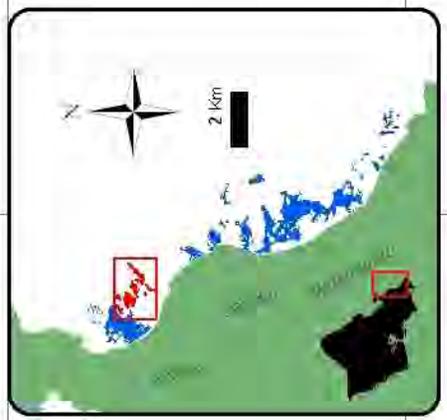
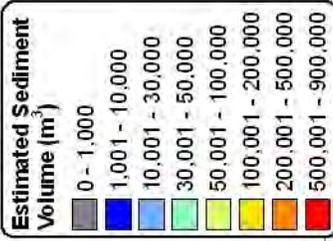
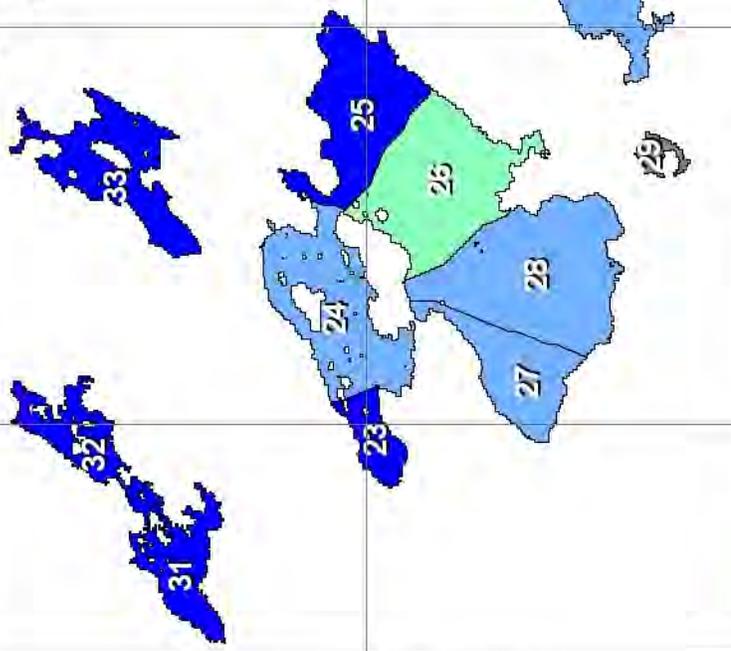
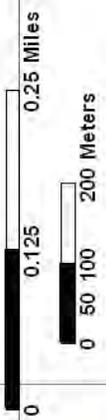
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2367659

2367159



Estimated Sediment Volume South Kailua Karst Complex



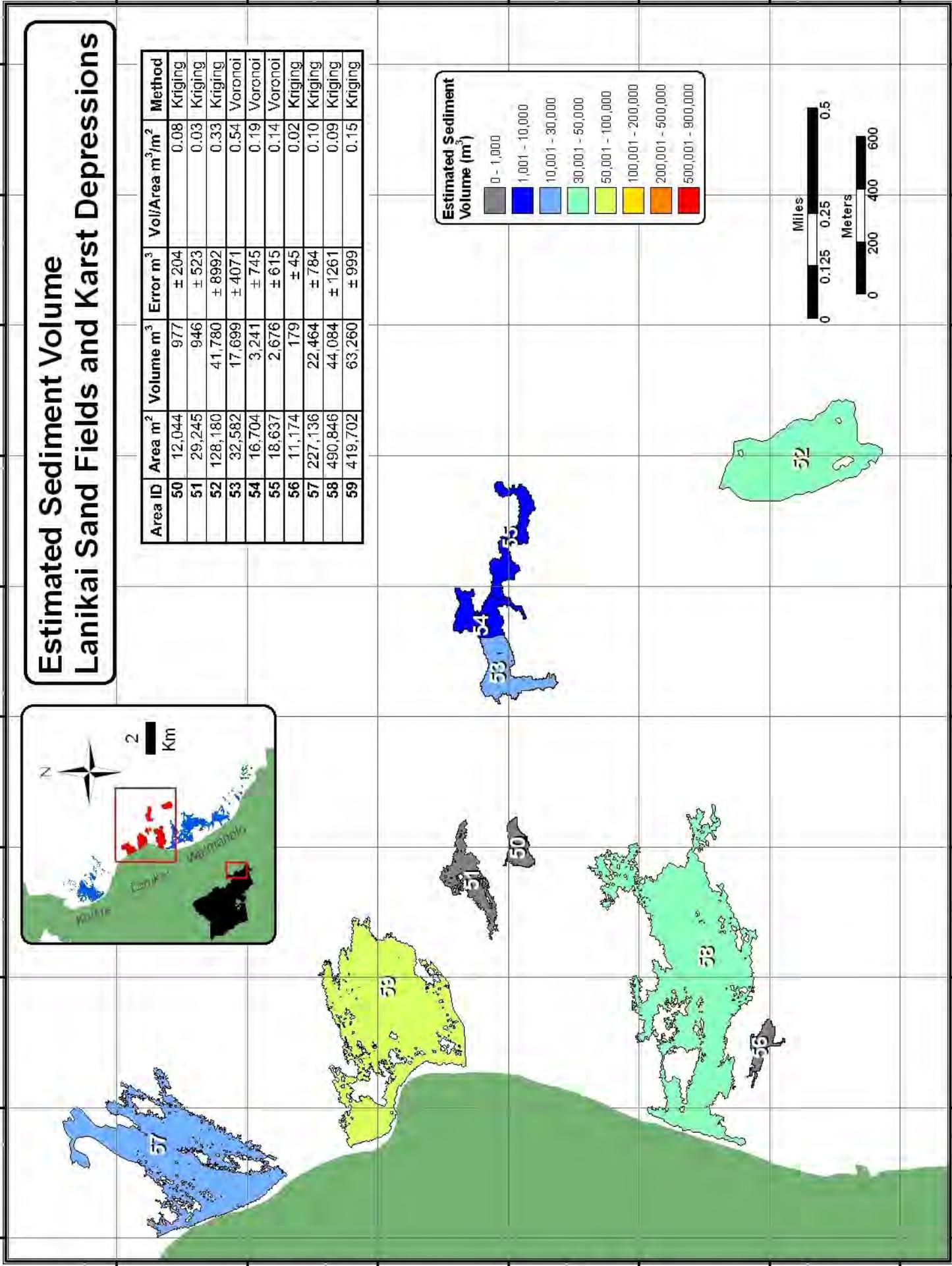
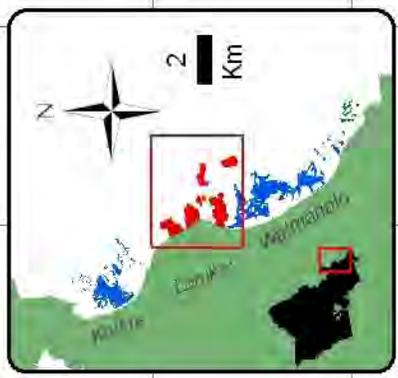
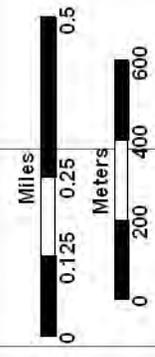
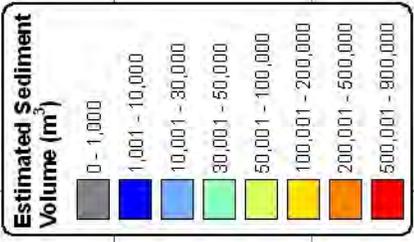
Area ID	Area m ²	Volume m ³	Error m ³	Vol/Area m ³ /m ²	Method
23	5,450	1,544	± 127	0.28	Voronoi
24	22,971	27,630	± 2279	1.20	Voronoi
25	21,041	2,694	± 222	0.13	Voronoi
26	27,962	33,633	± 2775	1.20	Voronoi
27	14,104	12,969	± 1070	0.92	Voronoi
28	33,961	24,114	± 1989	0.71	Voronoi
29	1,793	577	± 48	0.32	Voronoi
30	790	561	± 46	0.71	Voronoi
31	11,163	1,429	± 118	0.13	Voronoi
32	8,586	2,332	± 192	0.27	Voronoi
33	16,853	6,081	± 502	0.36	Voronoi
34	5,112	337	± 28	0.07	Voronoi
35	19,513	12,341	± 1018	0.63	Voronoi
36	18,917	1,468	± 121	0.08	Voronoi
37	4,333	958	± 79	0.22	Voronoi
38	838	293	± 24	0.35	Voronoi
39	4,970	2,700	± 223	0.54	Voronoi

Area ID	Area m ²	Volume m ³	Error m ³	Vol/Area m ³ /m ²	Method
40	4,792	614	± 141	0.13	Voronoi
41	12,302	3,198	± 736	0.26	Voronoi
42	2,344	1,728	± 397	0.74	Voronoi
43	13,217	3,744	± 861	0.28	Voronoi
44	11,467	4,449	± 1023	0.39	Voronoi
45	2,701	105	± 24	0.04	Voronoi
46	3,172	1,231	± 283	0.39	Voronoi
47	5,508	4,424	± 1018	0.80	Voronoi
48	5,868	387	± 89	0.07	Voronoi
49	8,534	0	± 0	0.00	Voronoi

633851 157°42'30"W 633351 2368549 2368049 2367549 2367049 21°24'0"N 21°24'30"N 21°24'0"N 157°42'30"W 157°43'0"W 157°43'30"W 157°43'0"W 157°43'30"W 157°43'0"W 157°43'30"W 633851 633351 632851 632351 631851 2368549 2368049 2367549 2367049

Estimated Sediment Volume Lanikai Sand Fields and Karst Depressions

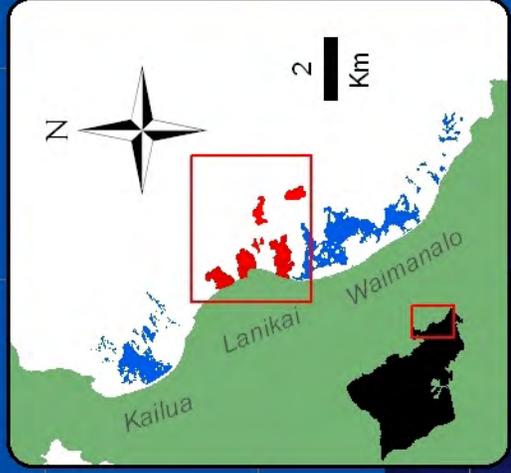
Area ID	Area m ²	Volume m ³	Error m ³	Vol/Area m ³ /m ²	Method
50	12,044	977	± 204	0.08	Kriging
51	29,245	946	± 523	0.03	Kriging
52	128,180	41,780	± 8992	0.33	Kriging
53	32,582	17,699	± 4071	0.54	Voronoi
54	16,704	3,241	± 745	0.19	Voronoi
55	18,637	2,676	± 615	0.14	Voronoi
56	11,174	179	± 45	0.02	Kriging
57	227,136	22,464	± 784	0.10	Kriging
58	490,846	44,084	± 1261	0.09	Kriging
59	419,702	63,260	± 999	0.15	Kriging



633535 157°42'30"W 634035 157°42'30"W 634535 157°42'00"W 635035 157°41'30"W 635535 157°41'00"W 636035 157°40'30"W 636535 157°40'00"W 637035 637535 638035

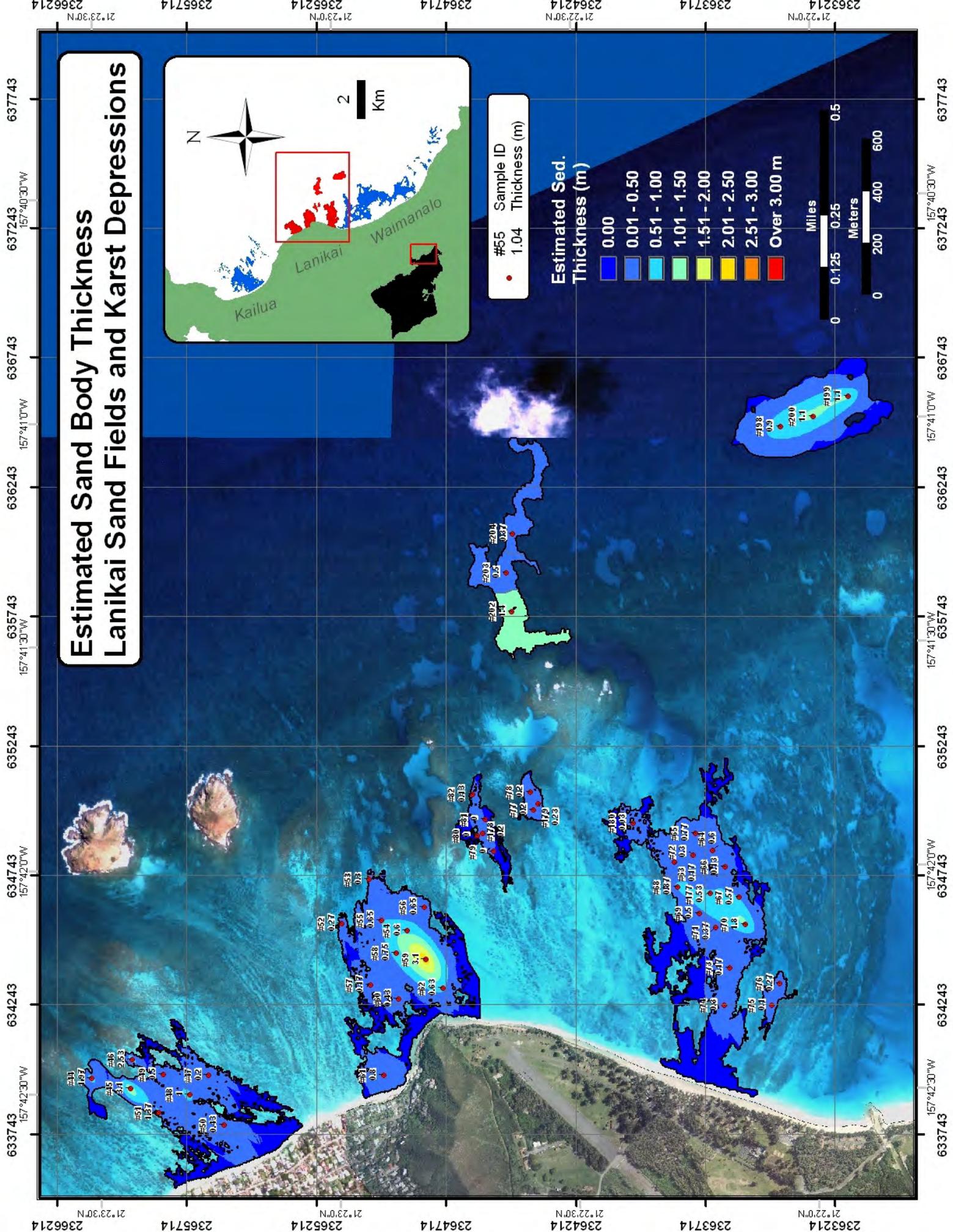
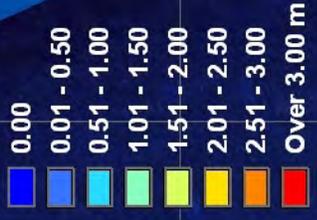
2362920 2363420 2363920 2364420 2364920 2365420 2365920 21°22'0"N 21°22'30"N 21°23'0"N 21°23'30"N 21°24'0"N

Estimated Sand Body Thickness Lanikai Sand Fields and Karst Depressions



#55 Sample ID
1.04 Thickness (m)

Estimated Sed. Thickness (m)

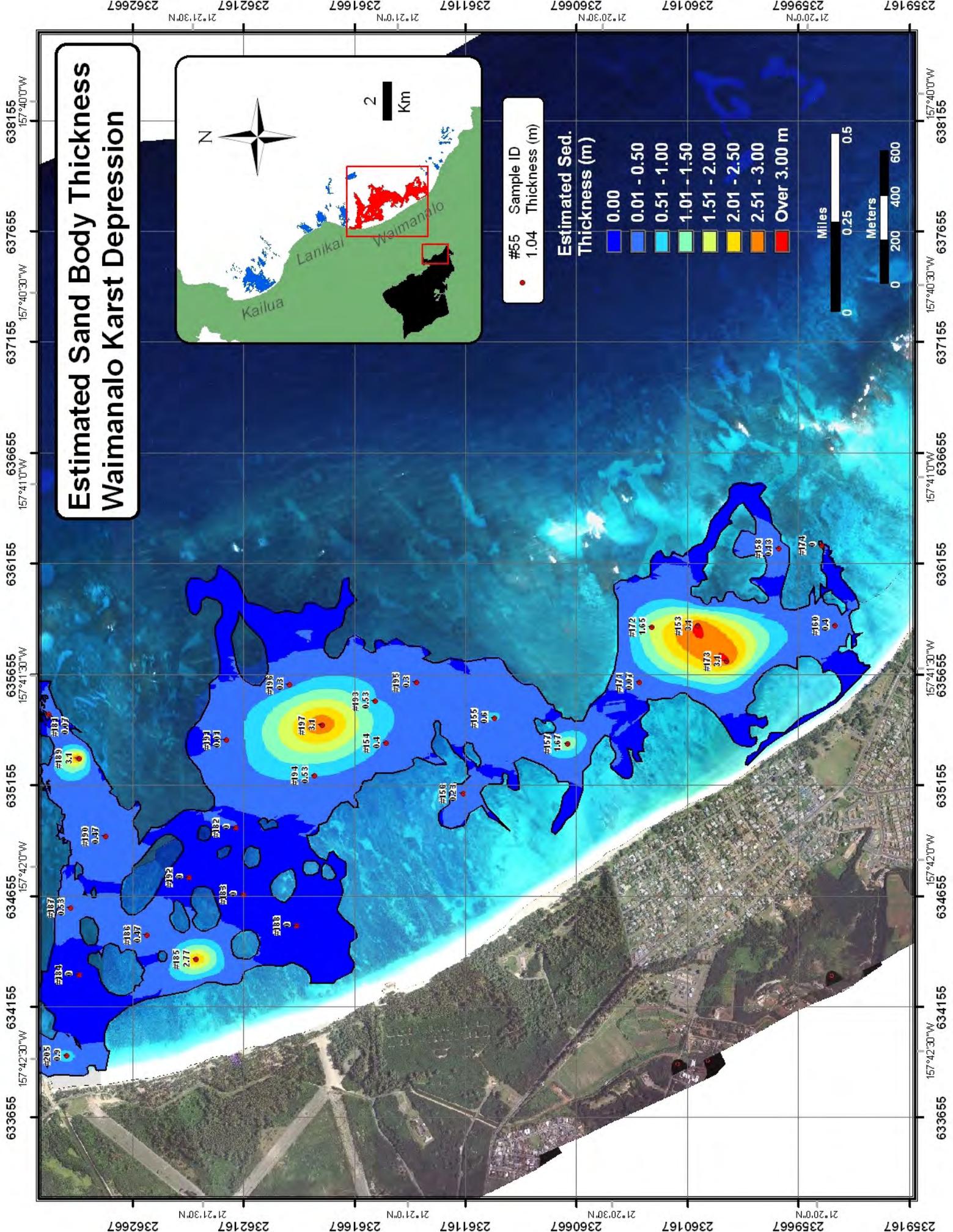
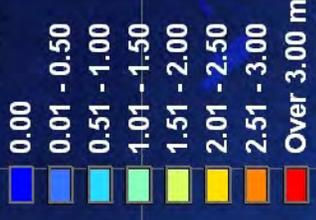


Estimated Sand Body Thickness Waimanalo Karst Depression



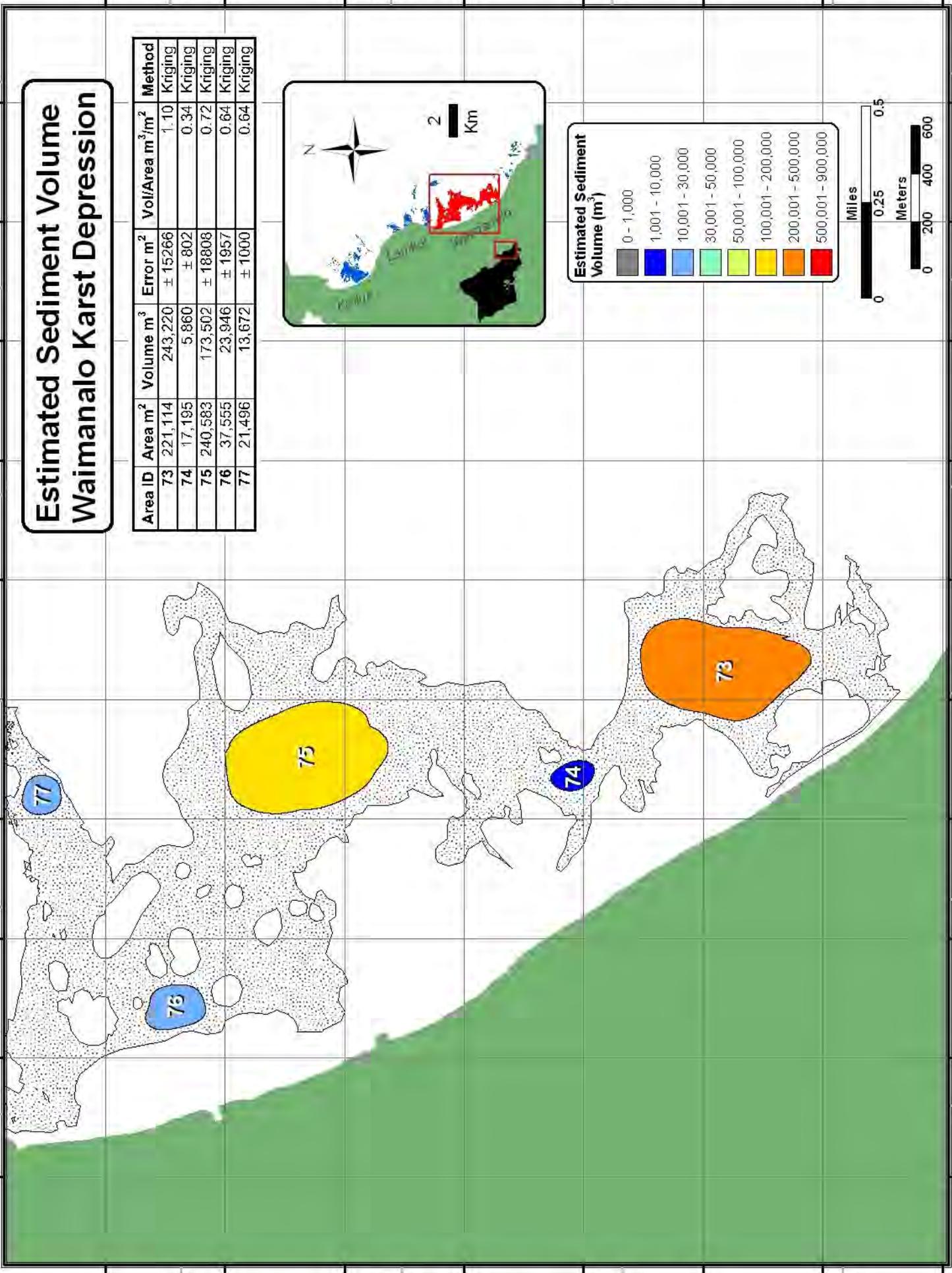
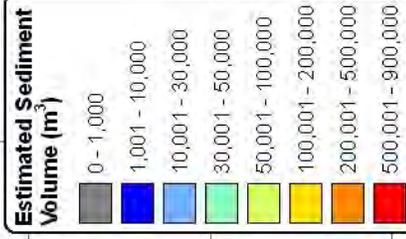
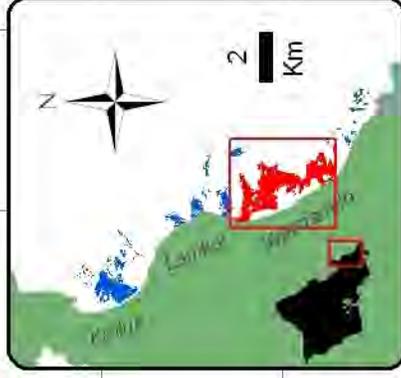
#55 Sample ID
1.04 Thickness (m)

Estimated Sed. Thickness (m)



Estimated Sediment Volume Waimanalo Karst Depression

Area ID	Area m ²	Volume m ³	Error m ²	Vol/Area m ³ /m ²	Method
73	221,114	243,220	± 15266	1.10	Kriging
74	17,195	5,860	± 802	0.34	Kriging
75	240,583	173,502	± 18808	0.72	Kriging
76	37,555	23,946	± 1957	0.64	Kriging
77	21,496	13,672	± 1000	0.64	Kriging

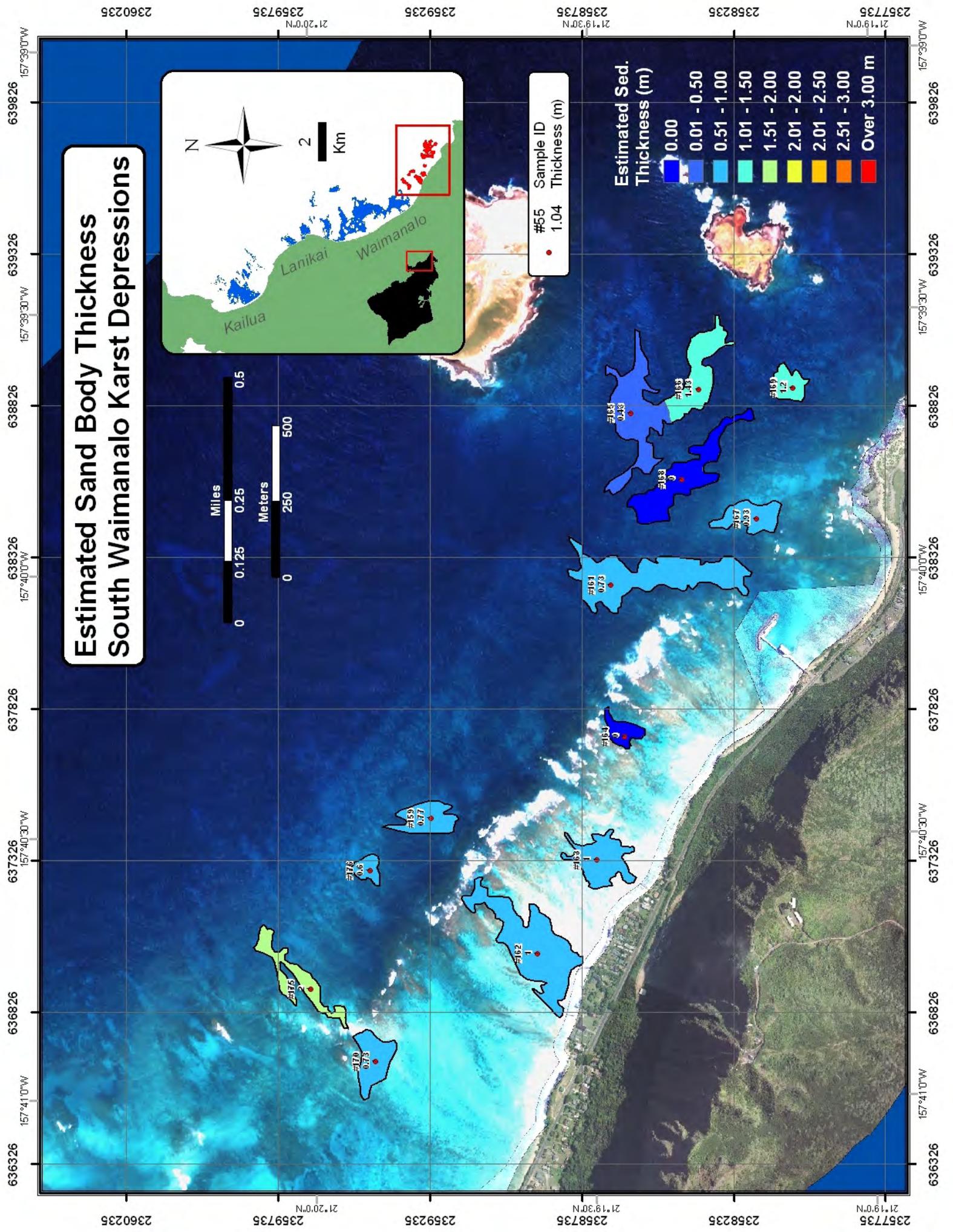


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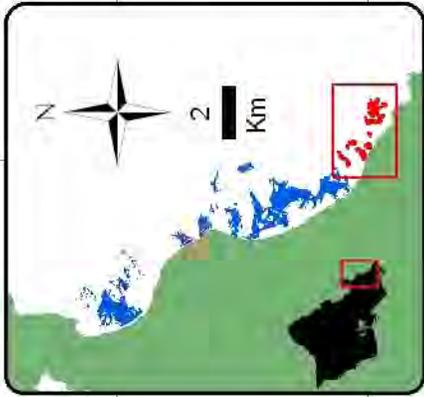
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21°20'0"N 21°20'30"N 21°21'0"N 21°21'30"N

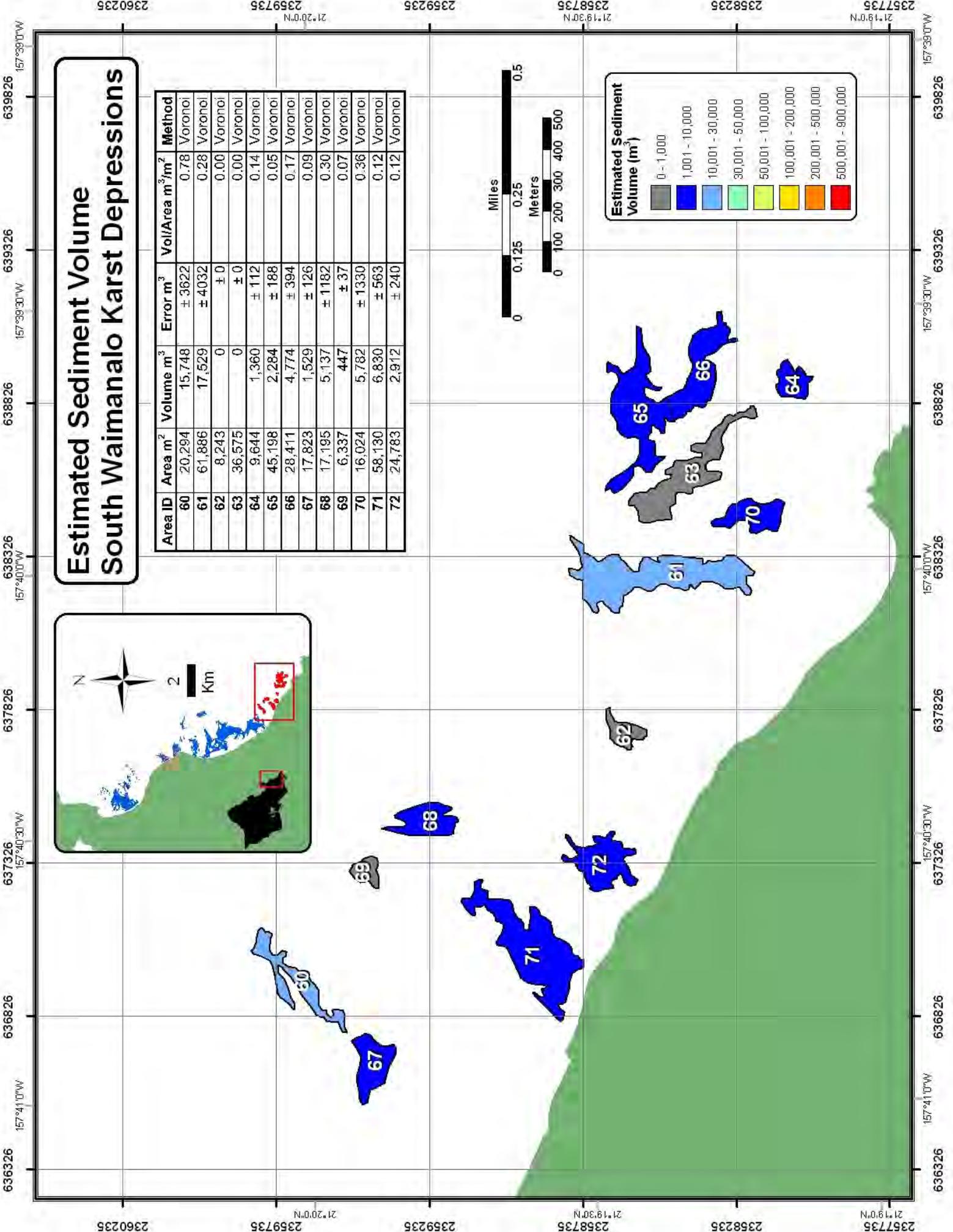
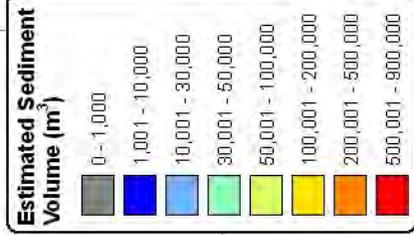
Estimated Sand Body Thickness South Waimanalo Karst Depressions



Estimated Sediment Volume South Waimanalo Karst Depressions



Area ID	Area m ²	Volume m ³	Error m ³	Voll/Area m ³ /m ²	Method
60	20,294	15,748	± 3622	0.78	Voronoi
61	61,886	17,529	± 4032	0.28	Voronoi
62	8,243	0	± 0	0.00	Voronoi
63	36,575	0	± 0	0.00	Voronoi
64	9,644	1,360	± 112	0.14	Voronoi
65	45,198	2,284	± 188	0.05	Voronoi
66	28,411	4,774	± 394	0.17	Voronoi
67	17,823	1,529	± 126	0.09	Voronoi
68	17,195	5,137	± 1182	0.30	Voronoi
69	6,337	447	± 37	0.07	Voronoi
70	16,024	5,782	± 1330	0.36	Voronoi
71	58,130	6,830	± 563	0.12	Voronoi
72	24,783	2,912	± 240	0.12	Voronoi



Appendix B
Thickness
Measurement Data

POINT LOCATION <i>MORPHOLOGY</i>	MEASUREMENT POINT ID	WATER DEPTH (m, MSL)	SEDIMENT THICKNESS (m)	OBSERVATIONS
Kailua Bay				
<i>Fossil Channel</i>				
	1	-5.5	0.30	Sand overlaying hardbottom
	2	-5.0	0.70	Sand overlaying hardbottom
	3	-5.0	1.00	Sand overlaying hardbottom
	4	-4.5	1.50	Sand overlaying hardbottom
	5	-4.0	1.40	Sand overlaying hardbottom
	6	-3.6	1.30	Sand overlaying hardbottom
	7	-4.0	0.50	Sand overlaying hardbottom
	8	-4.5	1.50	Sand overlaying hardbottom
	9	-4.5	1.80	Sand overlaying hardbottom
	10	-5.0	1.70	Sand overlaying hardbottom
	11	-5.7	1.40	Sand overlaying hardbottom
	12	-3.6	0.40	Sand overlaying hardbottom
	13	-3.8	1.00	Sand overlaying hardbottom
	14	-3.7	0.30	Sand overlaying hardbottom
	15	-3.6	1.30	Sand overlaying hardbottom
	16	-3.2	0.50	Sand overlaying hardbottom
	17	-3.0	0.60	Sand overlaying hardbottom
	18	-3.5	1.50	Sand overlaying hardbottom
	19	-3.6	0.70	Sand overlaying hardbottom
	20	-3.7	0.90	Sand overlaying hardbottom
	21	-3.8	1.20	Sand overlaying hardbottom
	22	-3.6	0.30	Sand overlaying hardbottom
	23	-4.0	1.30	Sand overlaying hardbottom
	24	-4.6	2.90	Sand overlaying hardbottom
	25	-4.6	2.40	Sand overlaying hardbottom
	26	-4.3	1.90	Sand overlaying hardbottom
	27	-5.1	2.90	Sand overlaying hardbottom
	28	-4.0	0.30	Sand overlaying hardbottom
	29	-3.7	0.03	Limestone outcropping in thin sand
	30	-3.8	0.40	Sand overlaying hardbottom
	31	-4.0	1.63	Sand overlaying hardbottom
	32	-4.1	0.60	Sand overlaying hardbottom
	33	-4.1	1.67	Sand overlaying hardbottom
	34	-3.7	2.40	Sand overlaying hardbottom
	35	-3.5	0.40	Sand overlaying hardbottom
	36	-3.4	0.60	Sand overlaying hardbottom
	37	-3.0	0.10	Limestone outcropping in thin sand
	38	-3.5	3.10	Sand beyond probing thickness (>3.0 m)

Appendix B

LOCATION	MEASUREMENT	WATER DEPTH	SEDIMENT THICKNESS	
<i>MORPHOLOGY</i>	POINT ID	(m, MSL)	(m)	OBSERVATIONS
Kailua Bay				
<i>Fossil Channel</i>				
	43	-3.2	0.10	Limestone outcropping in thin sand supporting algae
	83	-2.7	0.63	Sand overlaying hardbottom
	84	-3.7	0.10	Limestone outcropping in thin sand
	85	-3.0	0.10	Limestone outcropping in thin sand supporting algae
	86	-3.7	0.17	Limestone outcropping in thin sand
	87	-3.7	0.43	Sand overlaying hardbottom
	88	-3.7	0.23	Sand overlaying hardbottom
	89	-3.0	2.70	Sand overlaying hardbottom
	90	-5.5	1.33	Sand overlaying hardbottom
	91	-4.0	0.57	Sand overlaying hardbottom
	92	-3.7	0.33	Sand overlaying hardbottom
	109	-4.3	3.10	Sand beyond probing thickness (>3.0 m)
	110	-3.7	3.10	Sand beyond probing thickness (>3.0 m)
	111	-4.3	3.10	Sand beyond probing thickness (>3.0 m)
	112	-3.7	3.10	Sand beyond probing thickness (>3.0 m)
	113	-3.7	3.10	Sand beyond probing thickness (>3.0 m)
	114	-3.7	0.20	Sand overlaying hardbottom
	115	-2.7	1.23	Sand overlaying hardbottom
	116	-3.0	0.07	Limestone outcropping in thin sand supporting algae
	117	-3.4	1.77	Sand overlaying hardbottom
	120	-4.6	0.03	Limestone outcropping in thin sand
	135	-5.5	3.10	Sand gravel mixture beyond probing thickness (>3.0 m)
	136	-8.2	3.10	Sand gravel mixture beyond probing thickness (>3.0 m)
	137	-7.0	3.10	Sand gravel mixture beyond probing thickness (>3.0 m)
	138	-4.9	1.17	Sand overlaying limestone, grey sands observed
	142	-6.1	0.10	Gravel and rubble with little sand
	143	-3.0	0.00	Gravel and rubble
	144	-5.5	2.07	Sand overlaying hardbottom
	145	-6.4	1.00	1.0 m of sand overlaying resistant layer of shell and coral rubble
	146	-7.3	1.00	1.0 m of sand overlaying resistant layer of coral rubble
	147	-10.4	1.90	Sand overlaying hardbottom
	148	-10.4	0.73	0.73 m sand overlaying resistant layer of coral rubble
	149	-13.7	0.33	Sand overlaying hardbottom
	151	-3.0	0.17	Gravel and rubble with little sand
	152	-12.2	0.67	Sand overlaying hardbottom

Appendix B

LOCATION <i>MORPHOLOGY</i>	MEASUREMENT POINT ID	WATER DEPTH (m, MSL)	SEDIMENT THICKNESS (m)	OBSERVATIONS
Kailua Bay				
<i>Karst Depression</i>				
	95	-7.3	1.07	Sand overlaying hardbottom
	96	-5.2	0.30	Sand overlaying hardbottom
	97	-6.7	1.53	Sand with a thin resistive layer at -1.0 m
	98	-9.1	1.13	Sand and carbonate discs 5 - 40 cm in diameter
	99	-7.6	0.73	Sand overlaying hardbottom
	100	-6.1	0.87	Sand overlaying hardbottom
	101	-7.6	0.20	Sand overlaying hardbottom
	102	-7.9	0.13	Sand overlaying hardbottom
	103	-6.4	0.40	Sand overlaying hardbottom
	104	-7.3	1.70	Sand overlaying hardbottom
	105	-6.4	0.53	Sand overlaying hardbottom
	106	-6.4	0.27	Sand overlaying hardbottom
	107	-7.6	0.10	Gravel and rubble with little sand
	108	-6.7	0.07	Limestone outcropping in thin sand
	118	-7.9	1.40	Sand overlaying hardbottom
	119	-8.5	1.33	1.33 m of sand overlaying resistant layer of shell and coral rubble
	139	-8.2	0.13	Gravel and rubble with little sand
	121	-6.7	0.73	Sand overlaying hardbottom
	122	-6.1	3.10	Sand beyond probing thickness (>3.0 m), resistive layer at -0.3 m
	123	-8.2	0.33	0.4 m of sand overlaying resistant layer of shell and coral rubble
	124	-6.1	3.10	Sand beyond probing thickness (>3.0 m), resistive layer at -0.6 m
	125	-3.0	2.37	Sand overlaying hardbottom
	126	-6.1	0.33	Limestone outcropping in thin sand
	127	-7.6	0.70	Sand overlaying hardbottom
	128	-7.6	0.93	Sand overlaying hardbottom
	129	-4.9	1.63	Sand overlaying hardbottom
	130	-7.6	0.20	Sand overlaying hardbottom
	131	-6.1	0.17	Limestone outcropping in thin sand
	132	-4.6	0.57	Sand overlaying hardbottom
	133	-5.5	1.40	Very fine sand overlaying hardbottom
	134	-4.9	0.83	Sand overlaying hardbottom
	140	-6.1	1.83	Sand overlaying hardbottom
	141	-4.3	0.90	Sand overlaying hardbottom
	150	-2.4	1.83	Sand overlaying hardbottom
	63	-3.1	0.17	Thin sand over hard bottom
	64	-3.3	0.60	Sand over hard bottom
	65	-3.1	0.77	Sand over hard bottom
	66	-3.8	0.13	Limestone outcropping in thin sand
	67	-3.8	0.57	Sand overlaying hardbottom
	68	-3.7	0.87	0.87 m of sand overlaying resistant layer of shell and coral rubble

Appendix B

LOCATION <i>MORPHOLOGY</i>	MEASUREMENT POINT ID	WATER DEPTH (m, MSL)	SEDIMENT THICKNESS (m)	OBSERVATIONS
Kailua Bay				
<i>Karst Depression</i>				
	73	-3.5	0.17	Limestone outcropping in thin sand
	74	-3.0	0.30	Limestone outcropping in thin sand
	75	-3.9	0.10	Limestone outcropping in thin sand
	76	-4.5	0.27	Limestone outcropping in thin sand
	177	-3.4	0.53	0.53 m of sand overlaying resistant layer of shell and coral rubble
	180	-3.7	0.03	Thin sand over hard bottom
	202	-9.1	1.40	Sand overlaying hardbottom
	203	-10.7	0.50	Sand overlaying hardbottom
	204	-11.3	0.37	Sand overlaying hardbottom
Lanikai				
<i>Sand Field</i>				
	44	-2.4	1.97	0.5 m of sand overlaying resistant layer of shell and coral rubble
	45	-2.4	3.10	Sand beyond probing thickness (>3.0 m)
	46	-2.4	2.53	2.53 m of sand overlaying resistant layer of shell and coral rubble
	47	-2.4	0.20	Sand overlaying hardbottom
	48	-2.4	1.00	Sand overlaying hardbottom
	49	-2.1	0.50	0.5 m of sand overlaying resistant layer of shell and coral rubble
	50	-2.1	0.43	Sand overlaying hardbottom
	51	-2.4	1.37	0.5 m of sand overlaying resistant layer of shell and coral rubble
	52	-4.0	0.27	0.27 m of sand overlaying resistant layer of shell and coral rubble
	53	-4.6	0.30	Sand overlaying hardbottom
	54	-3.4	0.60	0.6 m of sand overlaying resistant layer of shell and coral rubble
	55	-4.0	0.65	0.65 m of sand overlaying resistant layer of shell and coral rubble
	56	-3.7	0.65	0.65 m of sand overlaying resistant layer of shell and coral rubble
	57	-3.7	0.17	Thin sand overlaying hardbottom
	58	-3.4	0.75	0.75 m of sand overlaying resistant layer of shell and coral rubble
	59	-3.4	3.10	Sand beyond probing thickness (>3.0 m)
	60	-3.4	0.43	Sand overlaying hardbottom
	61	-2.4	0.80	Sand overlaying hardbottom
	62	-3.4	0.63	0.63 m of sand overlaying resistant layer of shell and coral rubble

Appendix B

LOCATION	MEASUREMENT	WATER DEPTH	SEDIMENT THICKNESS	OBSERVATIONS
<i>MORPHOLOGY</i>	POINT ID	(m, MSL)	(m)	
Lanikai				
<i>Karst Depression</i>				
	77	-4.9	0.20	0.20 m of sand overlaying resistant layer of shell and coral rubble
	78	-4.6	0.20	0.20 m of sand overlaying resistant layer of shell and coral rubble
	79	-3.7	0.00	Gravel and rubble with little fine sand
	80	-3.4	0.00	Gravel and rubble with little fine sand
	81	-4.0	0.00	Gravel and rubble with little fine sand
	82	-4.3	0.13	Gravel and rubble with little sand
	178	-3.4	0.20	Sand overlaying hardbottom
	179	-4.3	0.23	Sand overlaying hardbottom
	198	-16.8	0.90	Coarse sand with sparse carbonate rubble throughout
	199	-16.8	1.10	Coarse sand with sparse carbonate rubble throughout
	200	-16.8	1.10	Coarse sand with sparse carbonate rubble throughout
Waimanalo Bay				
<i>Fossil Channel</i>				
	181	-7.3	0.07	Gravel and rubble with little sand
	184	-6.4	0.00	Halimeda rich gravel with partially hardened surface
	187	-6.4	0.53	Sand overlaying hardbottom
	189	-5.5	3.10	Sand beyond probing thickness (>3.0 m)
	190	-6.4	0.47	Sand overlaying hardbottom
	201	-4.3	0.90	0.9 m of fine sand overlaying halimeda rich gravel
	205	-4.6	0.90	0.9 m of fine sand overlaying halimeda rich gravel
Waimanalo Bay				
<i>Sand Field</i>				
	162	-1.5	1.00	Sand overlaying hardbottom
	163	-1.5	1.00	Sand overlaying hardbottom
	164	-3.4	0.00	Gravel and rubble
	170	-1.5	0.73	Sand overlaying hardbottom
Waimanalo Bay				
<i>Karst Depression</i>				
	153	-5.5	3.10	Coarse gravely sand beyond probing thickness (>3.0 m)
	154	-7.9	0.40	Reddish sand overlaying hardbottom
	155	-7.6	0.60	0.6 m of fine sand overlaying halimeda rich gravel
	156	-6.1	0.23	0.23 m of fine sand overlaying halimeda rich gravel
	157	-4.9	1.67	Sand overlaying hardbottom
	160	-4.6	0.40	Fine sand overlaying hardbottom
	171	-3.4	0.07	Limestone outcropping in thin sand
	172	-3.7	1.65	Gravely sand overlaying hardbottom
	173	-7.0	3.10	Coarse sand beyond probing thickness (>3.0 m)

Appendix B

LOCATION	MEASUREMENT	WATER DEPTH	SEDIMENT THICKNESS	
<i>MORPHOLOGY</i>	POINT ID	(m, MSL)	(m)	OBSERVATIONS
Waimanalo Bay				
<i>Karst Depression</i>				
	188	-6.4	0.00	Gravel and rubble
	191	-9.1	0.01	thin sand overlaying halimeda rich gravel
	192	-6.7	0.00	Halimeda rich gravel
	193	-9.1	0.53	0.53 m of fine sand overlaying halimeda rich gravel
	194	-7.9	0.53	Sand overlaying hardbottom
	195	-9.1	0.30	0.30 m of sand overlaying halimeda/coral gravel
	196	-9.8	0.30	0.30 m of sand overlaying halimeda/coral gravel
	197	-8.8	3.10	Sand beyond probing thickness (>3.0 m)
	158	-4.6	0.13	Limestone outcropping in thin sand
	159	-6.7	0.77	Sand overlaying hardbottom
	161	-7.9	0.73	Very fine sand overlaying hardbottom
	165	-8.2	0.43	Sand with fossil reef and coral rubble outcropping
	166	-8.8	1.43	Gravelly sand with fossil reef outcropping
	167	-3.4	0.93	Coarse sand overlaying hard bottom
	168	-7.6	0.00	Limestone supporting alga
	169	-7.9	1.20	1.20 m of sand overlaying coral gravel
	174	-3.4	0.00	Limestone surface with no sand
	175	-4.6	2.00	Sand overlaying hardbottom
	176	-5.2	0.60	Spur and groove reef with sand infill

Appendix C
Volume Estimates

LOCATION	SAND BODY ID	AREA ID	AREA	VOLUME	ERROR	VOL/AREA	METHOD
<i>MORPHOLOGY</i>			(m ²)	(m ³)	(m ³)	(m ³ /m ²)	
Kailua Bay							
<i>Fossil Channel</i>							
	26	1	586,831	801,695	± 70,484	1.37	Kriging
	26	2	7,394	2,513	± 455	0.34	Kriging
	26	3	4,572	1,027	± 350	0.22	Kriging
	46	40	4,792	614	± 141	0.13	Voronoi
	46	41	12,302	3,198	± 736	0.26	Voronoi
	53	42	2,344	1,728	± 397	0.74	Voronoi
	46	43	13,217	3,744	± 861	0.28	Voronoi
	46	44	11,467	4,449	± 1023	0.39	Voronoi
	54	45	2,701	105	± 24	0.04	Voronoi
	15	46	3,172	1,231	± 283	0.39	Voronoi
	47	47	5,508	4,424	± 1018	0.80	Voronoi
	25	48	5,868	387	± 89	0.07	Voronoi
	25	49	8,534	0	± 0	0.00	Voronoi
<i>Karst Depression</i>							
	1	23	5,450	1,544	± 127	0.28	Voronoi
	1	24	22,971	27,630	± 2279	1.20	Voronoi
	1	25	21,041	2,694	± 222	0.13	Voronoi
	1	26	27,962	33,633	± 2775	1.20	Voronoi
	1	27	14,104	12,969	± 1070	0.92	Voronoi
	1	28	33,961	24,114	± 1989	0.71	Voronoi
	13	29	1,793	577	± 48	0.32	Voronoi
	14	30	790	561	± 46	0.71	Voronoi
	24	31	11,163	1,429	± 118	0.13	Voronoi
	24	32	8,586	2,332	± 192	0.27	Voronoi
	41	33	16,853	6,081	± 502	0.36	Voronoi
	42	34	5,112	337	± 28	0.07	Voronoi
	43	35	19,513	12,341	± 1018	0.63	Voronoi
	43	36	18,917	1,468	± 121	0.08	Voronoi
	44	37	4,333	958	± 79	0.22	Voronoi
	45	38	838	293	± 24	0.35	Voronoi
	48	39	4,970	2,700	± 223	0.54	Voronoi
	3	4	2,602	1,716	± 395	0.66	Voronoi
	4	5	710	110	± 25	0.15	Voronoi
	38	6	1,996	674	± 155	0.34	Voronoi
	5	7	1,450	73	± 17	0.05	Voronoi
	38	8	3,483	270	± 62	0.08	Voronoi
	6	9	1,917	543	± 125	0.28	Voronoi
	7	10	653	68	± 16	0.10	Voronoi
	8	11	2,141	440	± 101	0.21	Voronoi

Appendix C

LOCATION	SAND BODY ID	AREA ID	AREA	VOLUME	ERROR	VOL/AREA	METHOD
<i>MORPHOLOGY</i>			(m ²)	(m ³)	(m ³)	(m ³ /m ²)	
Kailua Bay							
<i>Karst Depression</i>							
	10	17	6,206	313	± 72	0.05	Voronoi
	51	18	11,958	464	± 107	0.04	Voronoi
	11	19	3,575	1,845	± 424	0.52	Voronoi
	39	20	6,003	2,632	± 605	0.44	Voronoi
	12	21	1,601	43	± 10	0.03	Voronoi
	40	22	8,221	4,466	± 1027	0.54	Voronoi
Lanikai							
<i>Karst Depression</i>							
	49	50	12,044	977	± 204	0.08	Kriging
	28	51	29,245	946	± 523	0.03	Kriging
	37	52	128,180	41,780	± 8992	0.33	Kriging
<i>Fossil Channel</i>							
	29	53	32,582	17,699	± 4071	0.54	Voronoi
	29	54	16,704	3,241	± 745	0.19	Voronoi
	29	55	18,637	2,676	± 615	0.14	Voronoi
<i>Sand Field</i>							
	50	56	11,174	179	± 45	0.02	Kriging
	27	57	227,136	22,464	± 784	0.10	Kriging
	29	58	490,846	44,084	± 1261	0.09	Kriging
	28	59	419,702	63,260	± 999	0.15	Kriging
Waimanalo Bay							
<i>Karst Depression</i>							
	2	60	20,294	15,748	± 3622	0.78	Voronoi
	20	61	61,886	17,529	± 4032	0.28	Voronoi
	34	68	17,195	5,137	± 1182	0.30	Voronoi
	36	70	16,024	5,782	± 1330	0.36	Voronoi
<i>Sand Field</i>							
	22	62	8,243	0	± 0	0.00	Voronoi
	30	63	36,575	0	± 0	0.00	Voronoi
	31	64	9,644	1,360	± 112	0.14	Voronoi
	32	65	45,198	2,284	± 188	0.05	Voronoi
	32	66	28,411	4,774	± 394	0.17	Voronoi
	33	67	17,823	1,529	± 126	0.09	Voronoi
	35	69	6,337	447	± 37	0.07	Voronoi
	21	71	58,130	6,830	± 563	0.12	Voronoi
	17	72	24,783	2,912	± 240	0.12	Voronoi

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Sediment Transport Study—Lanikai and Bellows Beaches

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1. INTRODUCTION

Beach loss poses a serious hazard to the economy, ecology, and safety of many coastal regions. Over the latter part of the 20th century nearly 70% of the world's beaches have experienced net erosion (Bird, 1985). Much of this is attributed to the combined affect on coastal sediment budgets of rising sea level and increasing shoreline development (NRC, 1995). On the island of Oahu, Hawaii, historical analysis of beach length shows 24% of all beaches have either narrowed or disappeared over a ~60 year interval (Fletcher et al, 1997; Coyne et al., 1999). The impact of this beach loss is particularly profound in Hawaii as sandy beaches drive a multi-billion dollar tourism industry that accounts for 60% the jobs in the state and represents an important element of cultural identity.

Beach volume and shoreline position are largely governed by locally unique trends in longshore and cross-shore sediment transport. These are difficult to observe and predict over the long time scales needed in order to develop sustainable coastal management plans. Hence, where historical observations are available, it is important to investigate the processes driving shoreline change on poorly understood beaches.

Lanikai Beach on windward (east-facing) Oahu is a developed shoreline threatened by long-term and enigmatic beach erosion. Lanikai has experienced a series of decadal-scale erosion and accretion events producing > 50 m changes in beach width over a 60-year period. The net trend has been erosional and the total beach length has decreased from 2.3 km to 800 m over the period from 1950 to 2007. Discussion regarding appropriate management of Lanikai Beach has continued for over 30-years without resolution. Central to this debate is the source and fate of beach sand, and specifically whether sediment is exchanged around a rocky headland marking the southern littoral cell boundary of Lanikai Beach with Bellows Beach (Figure 1).

In this study, we test the hypothesis that littoral sediment transport occurring between Bellows and Lanikai beaches controls historical shoreline change at Lanikai. We examine the direction of this exchange and assess factors that have potentially altered sand transport over time. We integrate grain-size trend analysis and hydrodynamical modeling (Delft 3D) and compare the results with a detailed review of historical shoreline change (derived from aerial photographs) to evaluate littoral sediment transport across the Lanikai-Bellows boundary and along the greater shoreline. We expand our analysis to include historical shifts in wind direction as a driving factor in shoreline change. Results indicate a significant southeast to northwest trend in net sand transport that governs shoreline behavior.

We conclude that sediment transport does occur around Wailea Point linking Bellows and Lanikai Beach and hardening of the Bellows shoreline has starved Lanikai Beach by impounding its sediment supply. We also find strong evidence that wind direction has had a strong influence on sediment transport in this area. These results also indicate that future integration of sediment grain-trend analysis into shoreline change studies could be beneficial to coastal authorities tasked with managing poorly understood shorelines. This study is the first major reconstruction of shoreline dynamics along the Lanikai-Bellows Beach and represents the first application of sediment grain-size trend analysis (GSTA) to studying shoreline change.

2. STUDY SITE

The Lanikai-Bellows region encompasses roughly 4.3 km of coastline along a broad, embayed headland marking the boundary between Kailua and Waimanalo Bays on the southeastern or windward coast of Oahu, Hawaii. The northern reach of the study area terminates at Alala Point, while the southern terminus is defined by the mouth of Waimanalo Stream in Waimanalo Bay. The center of the study area is Wailea Point, which marks the boundary between northeast facing Lanikai Beach and southeast facing Bellows Beach. Wind conditions are dominated by northeast trade winds with an average speed of 10-20 kn over 90% of the summer season (April-September) and 50-80% of the winter season (October-March) (Harney, 2000). Trade wind waves dominate during summer months, with average deepwater significant wave heights of 1-3 m and periods of 6-9 s. During the winter, refracted deepwater swell from the North Pacific occasionally reach significant wave heights of 4 m with periods of 10-20 s. Wave heights reaching the beach are substantially lower (less than 0.5 m) as a shallow reef crest and the twin Mokulua Islands dissipate most incoming swell energy. Typical tidal range in Hawaii is less than 1 m.

The coastal plain at Lanikai ends abruptly at Ka'iwa Ridge, creating a narrower coastal zone at Lanikai than at Bellows, exacerbating the effect of shoreline erosion on the crowded properties. Landward of the shoreline in both areas are unconsolidated carbonate marine and dune sediments (Grossman and Fletcher, 1998; Harney and Fletcher, 2003). An expansive reef flat fronts the majority of the site with widths between 0.5 and 1.0 km in water generally 2.0 to 3.5 m deep. Three large sand fields extend from the beach face to near the reef crest, containing a total of $130 \times 10^3 \text{ m}^3$ of sediment with average thicknesses of 0.7-1.3 m (Bochicchio et al., 2009). Thin, isolated veneers of sediment, occasionally observed with ripple marks, are found over the reef flat. The reef flat shallows quickly seaward as it transitions to an irregular 100 m wide reef crest, parts of which are exposed during low tide. The twin volcanic Mokulua Islands stand among the reef crest, seaward of these islands the fore-reef slopes to >20 m depth.

Beaches at Lanikai and Bellows are generally narrow with gentle slopes and are made up of poorly sorted medium to fine-grained calcareous sand (Noda, 1989). Changes in beach volume along this coast tend to be related to chronic fluctuations in alongshore sand transport and sediment deficiencies, rather than event-based erosion because the offshore reef platform diminishes incoming swell (Fletcher et al., 1997). Currently, the northern and southern regions of Lanikai as well as northern Bellows Beach are without a beach and protected by seawalls.

Sediment transport on Hawaiian beaches occurs within littoral cells that span less than several kilometers of shoreline and cross-shore transport for nearshore sediment bodies often plays an important role in the sediment budget (Gerritsen, 1978). Noda (1989) investigated transport processes at Lanikai and stated that longshore transport is responsible for substantial historical shoreline change at Lanikai Beach despite a relatively mild wave climate. Noda found no evidence of sediment transport occurring around Alala Pt. to the north, indicating that the Kailua-Lanikai cell boundary is closed. A series of profiles extending from the southern Lanikai shoreline shows two sandbars at 15 and 30 m from the seawall, which corresponds with the node and anti-node of the mean incoming wave (Lipp, 1995). This indicates strong wave reflection off the Lanikai seawalls is, to some degree, preventing the accretion of a beach.

3. METHODS

To test our hypothesis that sand transport between Bellows and Lanikai cells controls shoreline change at Lanikai, we use grain-size trend analysis, hydrodynamic modeling, and historical shoreline change analysis.

3.1 Sediment grain-size trend analysis

3.1.1 Sample collection and analysis

A total of 214 sediment samples were collected on a grid surrounding Wailea Point (Figure 2). Spacing between sample sites varied from 37.5 m near Wailea Point, to 75 m within sand fields, and 150 m between sand fields. Samples were recovered from the ocean bottom using a sediment dredge, which removed between 10 and 30 cm of the surface sediment. Between 1000 and 2000 g of sediment were recovered in each sample. The upper 5 cm layer of sample within the dredge was discarded to reduce error caused by fine sediment potentially billowing out of the dredge mouth as it was pulled to the surface. A Global Positioning System (GPS) receiver with Wide Area Augmentation System (WAAS) correction was used to locate sample positions within 4 m. Grain-size distributions were based on the weight percent of each size fraction determined from standard sieve analysis method ASTM C 136 (ASTM, 2006) using sieve openings ranging between -2 and $5 \text{ } \phi$ at $0.5 \text{ } \phi$ intervals. The statistics mean size, sorting, and skewness were calculated from each distribution for use as parameters in the trend analysis.

3.1.2 General background on method

Spatial trends in the grain-size of surficial sediments are a direct result of natural sediment transport processes (Russell, 1939; McCave, 1978; Swift et al., 1972; Harris et al., 1990). The development of these trends is primarily the effect of transport processes selectively sorting and abrading sediment by grain-size according to the direction of transport (McLaren, 1985; Gao and Collins, 1992; Le Roux and Rojas, 2007). Using the parameters mean size, sorting, and skewness, four trends have been found to be reliable indicators of transport direction (McLaren and Bowles, 1985; Gao and Collins, 1992; Gao et al., 1994; Le Roux 1994b). Accordingly, transport pathways can be identified if a series of sediment samples follows one of the trends listed below (using ϕ units after Folk and Ward, 1957):

- Trend 1: finer, better sorted, and more negatively skewed
- Trend 2: coarser, better sorted, and more positively skewed
- Trend 3: coarser, better sorted, and more negatively skewed
- Trend 4: finer, better sorted, and more positively skewed

Type 2 and 3 trends show a distinctive coarsening of grain size along the direction of transport that at first appears counterintuitive. These trends are interpreted as indicators of more rapid transport processes in which a majority of the surficial fine-grained material is removed creating a thin coarse-grained lag deposit that “shields” underlying fine-grained material. This coarse upper layer is mixed with underlying fine sediments during sampling, which results in an overall finer-grained texture upstream of the transport direction (McLaren and Bowles, 1985).

GSTA encompasses a range of techniques for recovering net transport direction from naturally sorted seafloor sediments by identifying the above grain-size trends in a series of discrete sediment samples collected around an area of interest. McLaren and Bowles (1985) first proposed a one-dimensional methodology to accomplish this task, which was followed by a number of two-dimensional approaches (e.g., Gao and Collins, 1992; Le Roux, 1994b,c; Asselman, 1999; Rojas et al., 2000; Rojas, 2003). These methods have been used to characterize sediment transport in a range of aquatic settings for a variety of engineering, environmental, and sedimentological investigations.

In this study we apply two separate methods put forth by Gao and Collins (1992) and Le Roux (1994) to a dataset collected offshore of Lanikai and Bellows beaches. These two methodologies use significantly different mathematical approaches for locating trends in the data, yet are shown to detect sediment transport at similar spatial scales (Rios et al., 2002). This study utilizes two methods to confirm that similar conclusions can be reached through two different means and to provide a comprehensive view of the regional transport processes. An overview of each method is provided below to highlight the methodological differences, provide an instructive reference, and aid in discussion of the results. Likewise, the respective authors of each method provide full descriptions in Gao and Collins (1992) and Le Roux (1994b). The Gao-Collins method is described in more detail using practical

examples (Appendix A), because current publications on this method are limited to theoretical application.

3.1.3 Gao-Collins and Le Roux methodologies

The method put forth in Gao and Collins (1992) determines sediment transport direction by comparing grain-size parameters among a group of sampling sites. Parameters at each site are compared with those of neighboring sites within a predefined characteristic distance. The characteristic distance is defined as the spatial scale over which transport is expected to occur in the study area, generally given as the maximum interval between any two adjacent sampling sites. This study uses a characteristic distance of 200 m, which reflects the spatial scale of transport processes anticipated for this region and maximum distance between potentially related sites. In every case where either Trend 1 or Trend 2 is identified, component vectors with the unit length (i.e. equal to 1) are drawn in the direction of the neighboring site (Figure 3A). Summing all component vectors at each site produces a single vector referred to as a transport vector (large arrow in Figure 3A and 3B). Component vectors are relevant only in terms of direction. Their lengths do not reflect differences in grain-size parameters or distance between points. As all component vector lengths are equal, the number and direction of neighboring sites showing a positive transport trend determine both the direction and length of the resulting transport vector. Determining transport vectors for every point produces a field of transport vectors (Figure 3B), which can be filtered to reduce noise and reveal the dominant trends, by averaging the vector at each site with surrounding transport vectors (Figure 3C). Details of the steps and calculations used in Figure 3 are included in Appendix A.

The method of Le Roux (1994b) functions by comparing grain-size parameters of a central site with the closest four neighboring sites in all cardinal directions (i.e. one site is selected from the North, East, South, and West quadrants) (Figure 4A). The Le Roux method searches for all four trend types individually, producing a vector field of transport for each trend.

Trend determination begins with the normalization of all three grain-size parameters between all five sites. These values are combined into a single value (E) representing the strength of transport along that axis. The process of normalizing and combining the parameters is modified in a manner depending on the trend type. For example, Equation 1 is used in the case of Trend 3, where all parameters are expected to decrease along the direction of transport.

In this process, sites with the smallest values receive the highest score (E) indicating stronger transport potential in the direction of that site. Conversely, to achieve the same effect with Trend 1, Equation 1 must be modified so that increasing mean grain-size results in a lower value of E . This is done simply by subtracting 33.33 from the normalized mean size parameter (Equation 2).

$$E = \frac{33.33}{mn_{\max} - mn_{\min}} (mn - mn_{\min}) + \frac{33.33}{var_{\max} - var_{\min}} (var - var_{\min}) \quad \text{Equation (1)}$$

$$+ \frac{33.33}{sk_{\max} - sk_{\min}} (sk - sk_{\min})$$

$$E = \left(33.33 - \left[\frac{33.33}{mn_{\max} - mn_{\min}} (mn - mn_{\min}) \right] \right) + \frac{33.33}{var_{\max} - var_{\min}} (var - var_{\min}) \quad \text{Equation (2)}$$

$$+ \frac{33.33}{sk_{\max} - sk_{\min}} (sk - sk_{\min})$$

Similar adjustments are made to the normalized skewness parameter for Trend 2 and the normalized variance parameter for Trend 4 to so that increasing values on these parameters result in higher values of E .

Values (E) are defined for every site (Figure 4B) then the value of the central site is subtracted from each adjacent site and the relative difference between sites is used to define the length of component vectors, which are summed to produce a final transport vector (Figure 4C). This process is repeated at every site to produce a field of transport vectors for each trend type. Trend 1 results are shown in Figure 4D. Commonly, the strongest vectors from each trend type are incorporated into a final vector field. The Watson (1966) non-parametric test is used to ensure that the final transport vectors are sufficiently non-random before smoothing the data to reduce noise (Le Roux et al., 2002).

The Gao-Collins and Le Roux methods both determine transport direction by searching for predefined trends between a single site and adjacent sites, but Gao-Collins uses only Trends 1 and 2, while Le Roux checks for all four trends. The Gao-Collins method checks a variable number of sites (all those that fall within the characteristic distance), while Le Roux only uses a central site and four adjacent sites. With Gao-Collins, direction of transport is determined by relative position of all neighboring sites showing a trend to the central site, with transport occurring in the direction of the most trend positive sites. In contrast, using Le Roux, transport direction and strength is determined from the calculated difference between the actual grain-size parameters of all five sites. Both methods have been shown to give comparable and informative results (Rios et al, 2002).

3.3 Computer hydrodynamic model (DELFT 3D)

The Delft3D-FLOW module (v. 3.24.03 used here) solves the unsteady shallow-water equations with the hydrostatic and Boussinesq assumptions. In 2D mode the model solves two horizontal momentum equations (see Eq. 3-4), a continuity equation (Eq. 5) and a transport (advection-diffusion) equation (Eq. 6) shown below:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + g \frac{\partial \eta}{\partial x} - fv + \frac{\tau_{bx}}{\rho_w(h+\eta)} - \frac{F_x}{\rho_w(h+\eta)} - \nu_e \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) = 0 \quad (3)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + g \frac{\partial \eta}{\partial y} - fu + \frac{\tau_{by}}{\rho_w(h+\eta)} - \frac{F_y}{\rho_w(h+\eta)} - \nu_e \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) = 0 \quad (4)$$

$$\frac{\partial \eta}{\partial t} + u \frac{\partial[(h+\eta)u]}{\partial x} + v \frac{\partial[(h+\eta)v]}{\partial y} = 0 \quad (5)$$

$$\frac{\partial[hc]}{\partial t} + \frac{\partial[huc]}{\partial x} + \frac{\partial[hvc]}{\partial y} = h \left[\frac{\partial}{\partial x} \left(D_H \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_H \frac{\partial c}{\partial y} \right) \right] \quad (6)$$

where u and v = the horizontal velocities in the x and y directions respectively; t = time; g = gravity; η = free surface height; h = water depth; f = coriolis force; ρ_w = density of water; τ_b = bed friction; F = external forces due to wind and waves, ν_e = horizontal eddy viscosity; D_H = horizontal eddy diffusivity; and c = concentration of suspended sediment. The equations are solved on a staggered finite difference grid using the Alternating Direction Implicit (ADI) method after Stelling (1984).

In this study the Delft 3D model is employed to examine the potential for different transport regimes developing under changing forcing conditions. This element of the study focuses on trade winds, as it is the most persistent type of forcing on Oahu's windward shore and most likely to determine equilibrium shoreline conditions.

Figure 5 shows a 58-year time series of trade wind direction recorded at Kaneohe Marine Corps, located on the coastline approximately 9 kilometers north of the study area. These data show periodic shifts in trade wind direction that persist over decadal-scale time periods and are in some cases rapid (e.g. 1964, 1974, and 1987). These changes in trade wind direction were first documented by Wentworth (1949) and implicated as a possible factor in shoreline change in Lanikai in a report by Noda (1988). This study is the first to extend the directional dataset presented by Wentworth (1949). The exact cause of these directional shifts is not currently understood. Using the range of observed wind directions, this study uses Delft 3D to model the potential influence that changing wind direction could have on sediment transport in the Lanikai region.

The model was calibrated using current and sea-level data collected by two acoustic doppler velocimeters deployed from August 10th to September, 12th 2005 on the southern and northern bounds of the study area. The model parameters included wind driven currents, tidal forcing, open ocean waves, and wave-driven currents. Ocean swell direction and height was simulated using a representative dataset from a deepwater directional wave buoy located 2 km north-east of the study area in

Kailua Bay (National Data Buoy Center number 51001). Tidal forces were modeled using standard harmonic components. Separate model runs used directional extremes from the historical dataset to simulate time periods when north-east (51°), east-north-east (71°), and east (85°) wind conditions dominated.

3.2. Shoreline change analysis

Analysis of shoreline change in this study draws from a portion of data collected in a separate study of the entire southern coastline of Oahu by Romine et al. (in press). Historical shoreline positions were hand digitized from survey quality aerial photos and T-sheets of the study area acquired during the following years: 1911, 1928, 1949, 1951, 1959, 1963, 1967, 1971, 1975, 1982, 1988, 1989, 1996, and 2005. Distortion errors from scanning the photos were corrected (Thieler and Danforth, 1994). Following the methodology of Fletcher et al. (2003), all photos were orthorectified and mosaicked using software from PCI Geomatics, Inc. Seaward and landward boundaries of the beach were defined as the position of mean lower low water (MLLW) (Bauer and Allen, 1995) and the vegetation line. Horizontal error in shoreline position was calculated to be $\pm 4.49 - 10.78$ m. The position of MLLW and observations of seawall construction were used to create a timeline of shoreline change and armoring activity for the study area. In the case of a hardened shoreline where no beach currently exists, the vegetation and MLLW lines are the same.

4. RESULTS

4.1. Textural and transport trend analyses

Sediment texture over much of the study area is characterized by distinct, isolated zones of varying size. As a whole, sediments offshore of Lanikai tend to be coarser (Fig. 7), more poorly sorted (Fig. 8), and positively skewed (Fig. 9) than those at Bellows. While sediment textures directly adjacent to shore tend to be finer and more negatively skewed along the entire sample area. Offshore of Wailea Point, in the central portion of the study area, sediments are generally finer, better sorted, and more negatively skewed towards the tip of the point. However, closer examination of the entire study area shows a close juxtaposition of alternating sediment textures indicative of lag and lead deposits. In order to aid the description of textural and trend analysis results common regions, referred to in the text, are defined on both gridded textual data (Figures 7, 8, 9) and grain-size trend analysis results (Figure 10 and 11).

Results of the Gao-Collins (Figure 10) and Le Roux (Figure 11) methods indicate the direction and relative probability of sediment transport. A fundamental difference between the two methodologies is well illustrated by the smooth appearance of the Gao-Collins results and the noisier appearance of the Le Roux results. As described in the methodology, the Le Roux method is more sensitive to small differences in grain-size and to small-scale, isolated trends than the Gao-Collins method. Results of the two methodologies generally agree, with the only major exception being Region A in the southern part of the study area, where results differ considerably. In

this area the Gao-Collins results (Figure 10) show primarily north-to-northeast trends, while the Le Roux results (Figure 11) show an opposing southeast trend converging with a north-to-northwest trend.

Directly offshore of Bellows Beach (within 100 m), sediment textures alternate between coarse-positively skewed and fine-negatively skewed with all sediments becoming better sorted to the north (Region B). Results from the Le Roux method show a majority of transport to the north and Gao-Collins also shows a consistent northern trend adjacent to Bellows Beach.

Offshore sediment immediately south of Wailea Point (Region C) becomes finer, better-sorted, and more negatively skewed toward the north, which is the signature of a type 1 transport trend. Gao-Collins transport vectors along this section of coastline indicate uniform northern transport of sediment from the Bellows nearshore area towards Wailea Point. Similarly, Le Roux results show northwesterly transport toward Wailea Point where it meets an opposing transport trend. This trend is mirrored to the north in Region D, where sediment becomes finer, better-sorted, and more negatively skewed toward the south. Resulting transport vectors in Region D from both Le Roux and Gao-Collins methods are southeasterly and directly oppose transport in Region B.

Near the northern slightly embayed portion of Wailea Point (Region E), sediment within 250 m of southern Lanikai Beach shows two distinct textures. Nearshore sediments are finer, better-sorted, and more negatively skewed than sediment farther offshore. This contrast in sediment texture produces onshore and southeasterly transport vectors in the both Gao-Collins and Le Roux methodologies. To the north, both sets of results show an opposite northwesterly trend in Region F along Lanikai Beach. Sediment in the northern sample area tends to be relatively coarser, more poorly sorted, and positively skewed than the southern part of the sample area. In general, transport trends in areas F and E show divergence between northerly and southerly transport. Similar divergence occurs between Regions A and B, while both result show convergence near Wailea Point between Region C and D. Le Roux transport vectors seem to indicate a gyre-like circulation pattern across Regions C and D.

4.2. Shoreline change analysis

Changes in shoreline position are visible in historical aerial photographic sets of the Lanikai-Bellows study area (e.g. Fletcher et al., 1997, Romine et al., in review). A subset of vectorized historical shoreline positions that represent major fluctuations are overlain on a modern (2005) aerial photograph in Figures 12 and 13. Plots show relative shoreline position over time along transects (transects A through G) centered on sites with the greatest shoreline movement.

Lanikai Beach (Figure 12) shows multi-decadal historical trends of either accretion or erosion. These trends are indicated on transects B, C, and D. Shoreline position is relatively stable across the entire length of the beach from the beginning of the

record in 1912 through to the 1949 shoreline. This could be the effect of little data during this time period causing features to be missed in analysis. In southern Lanikai from 1949 and 1967 the shoreline accreted significantly, adding a maximum of approximately 60 m of new coastal land (transect D). During this period, central and northern Lanikai (transects C, B, and A) show little change.

After 1967, the accretion trend in southern Lanikai reversed until seawalls halted the erosion by 1990. Farther north, central and northern Lanikai (transects C and B) began accreting significantly during this period. Central Lanikai added approximately 30 m of coastal land by 1987, after which an erosional trend developed that has persisted through 2008. No erosional trend is evident at transect B, but an erosional trend has migrated southward from transect A since the 1975 shoreline.

Figure 13 summarizes a generally erosive trend on the Bellows shoreline south of Wailea Point. Shoreline positions at transect E indicate an erosional trend was present at the beginning of the dataset, between 1916 and 1928. Farther to the south, transect F indicates an accretionary trend between 1916 and 1928, followed by erosion between 1928 and 1961, resulting in the loss of approximately 40 m of coastal land. At transect G, shorelines remain stable until a general erosional trend developed during the 1961 to 1962 time period that continued until halted by seawalls in 1998. Erosional trends at transects E and F were also halted by seawall emplacement.

4.3. Hydrodynamic modeling results

A hydrodynamic model is useful for envisioning near shore currents that can develop under different forcing conditions. Our results show substantially different near shore current configurations in the Lanikai region when north-east (51°), east-north-east (71°), and east (90°) winds are used to force the model. Figures 14, 15, and 16 show the resulting mean current field for each wind condition. The most noticeable effect of changing wind direction is the shifting of the locations where longshore currents converge and diverge. Eastern winds induce northward transport along the entire study area (Figure 14). East-North-East winds create a divergence point in longshore currents near transect 40 along the Bellows shoreline and induced circulation similar to a gyre on the northern flank of Wailea Point (Figure 15). Under North East winds the divergence point shifts north along the Bellows coast to transect 20 and divergence develops in southern Lanikai near transect 95 (Figure 16). In general, southern transport becomes more common along both shorelines as the northern component of wind direction becomes more prominent, which is reasonable considering the geometry of the shoreline.

5. DISCUSSION

5.1. Historical Transport Patterns

What follows is a timeline of shoreline change in the Lanikai Bellows region. This discussion of historical transport will center on Figure 17, which shows an interpolated grid created from all available shoreline position data for the study area over time. Grid cell color indicates the rate of change (gradient in meters-per-year) in the shoreline during that time period (horizontal axis) and for a particular length of beach (vertical axis). As described earlier, the Lanikai-Bellows shoreline has been subject to considerable accretion and erosion. Viewing shoreline position data in as a running average of accretion or erosion rates allows these trends to be more readily apparent. For ease of discussion, the historical data is divided into eight time periods (I through VIII) that show common trends of localized accretions and erosion. Littoral sub-cell boundaries and the associated longshore transport patterns can both be inferred from this presentation of the data. Vertical and horizontal arrows indicate the direction of longshore transport over a time period as it is implied by shoreline change. This timeline of inferred littoral transport trends forms empirical control that the results of hydrodynamic modeling and sediment grain-size trends can be compared to.

I. 1910 – 1928

The relative scarcity and wide distribution of shoreline position data during this era makes only a basic analysis of shoreline movement feasible. Lower Lanikai eroded over the first half of this period (1911 to 1928), while the remainder of Lanikai and Bellows both accreted. Sand that eroded from this area either moved north, contributing to accretion in Upper Lanikai or to the south, where Bellows experienced a general accretion trend.

II. 1928 – 1953

The major feature of this period is a switch from accretion to erosion over the entirety of Bellows Beach, with the worst erosion seen on Upper Bellows. Sections of Upper and Central Lanikai began to erode, but the majority of the beach is either stable or accreting slightly. The strongest accretion is in southern Lower Lanikai that shifts northward by the end of this period. Timing of this accretion suggests Bellows Beach is providing the material for this accretion.

III. 1953 – 1964

The erosion trend along Bellows beach continues and intensifies near Wailea Point. During this time period the first sizable revetments appear in aerial photographs along the region of Bellows Beach with the highest erosion rates. Accretion that began in northern Lower Lanikai during period II continues along a 400 meter section of beach. This trend added approximately 60 meters of new coastal land in this area and reached its maximum accretion rate during this period of time. Coincident with this accretion, both Southern Lower Lanikai and Central Lanikai

switch to an erosive trend. This suggests that the source material for the large Lanikai accretion is from both Bellows Beach and Central Lanikai. It is possible that two opposing longshore currents converge at Lower Lanikai maintaining a bulge in the shoreline between transects 80 and 100.

A similar point of convergence might have occurred to the north in Upper Lanikai between transects 10 and 30. The northern reach of Upper Lanikai began eroding almost simultaneously with Central Lanikai and the southerly propagation of the trend suggests southern longshore drift. There is, however, no major accretion between this erosion center and the erosion in Central Lanikai to support a converging center here. This divergence point could still exist if the relatively low erosion rate in Upper Lanikai was not providing a great deal of sand and the majority of the sand released in Central Lanikai was moved south.

IV. 1964 – 1972

During this period the large accretion in Lower Lanikai becomes an erosive trend that continues throughout the rest of the dataset until the mid-1990's when there is no appreciable beach remaining and seawalls have halted the erosion. During this period the area that was previously eroding in southern Lower Lanikai (transect 100 to 116) and Central Lanikai (transect 30 to 70) began accreting again. To the north, Central Lanikai begins accreting over a broad section of beach while erosion intensifies in Upper Lanikai. Further south, the erosion rate in Upper Bellows (transects 20 – 30) drops sharply, but is preceded by short-lived accretion to the north (transects 0 to 15) and the beginning of a longer accretion trend in Lower and Central Bellows (transects 45 to 85).

The onset of erosion in Lower Lanikai indicates a reduction in sediment supply to that section of coastline. Likewise, the previous current structure had allowed for sand accretion, but no northward drift. During this shift currents were restructured to allow northward movement of the already accreted sand toward Central Lanikai. It is possible to then that the new accretion in Lower Bellows is the result of Upper Lanikai sediments being transported south instead of north. The erosion in Lower Lanikai could be due changes in the nearshore current structure that lead to the rerouting of its sand supply and a simultaneous increase in northward transport along the Lanikai coastline. Another factor to consider is the further expansion of revetments along the Upper Bellows shoreline in response to decades of chronic erosion. Revetments along this reach of shoreline would effectively lockup the sand supply that fueled accretion in Lower Lanikai. If eroded material from Upper Bellows was driving shoreline expansion in this region, this introduction of revetments could explain the lack of large accretion events in the dataset for the Bellows shoreline.

V. 1972 – 1984

Central Lanikai accretes significantly over this time period, accompanied by peak erosion rates in both Lower and Upper Lanikai. Given the timing of erosion in Lower Lanikai, longshore transport is likely moving north from Lower Lanikai to Central

Lanikai during this time period. As with the previous accretion event in Lower Lanikai, the shoreline accretes consistently over one section of beach for 14 years with only a slight northward drift. This is further evidence convergent longshore currents effectively “holding” the sediment in one location and allowing a significant amount of new shoreline to form. If this process is occurring then it can be assumed that the northern component of longshore convergence is transporting eroded material from Upper Lanikai southward.

Upper Bellows shows isolated accretion (transect 15 to 30) that wanes to erosion by the end of the period. Accretion continues in Lower Bellows during the first half of this time period, but later transitions to erosion in all but the most southern region of Lower Bellows. The accretion pattern in Upper Bellows can again be interpreted as local convergence of longshore currents. The southward shift in accretion in Lower Bellows indicates a dominant southern longshore current direction. By this point in time, two jetties are in place at the southern boundary of the Bellows study area. Accretion occurring along the northern boundary of these jetties is likely a farther indicator of southern littoral transport.

VI. 1984 – 1987

Unlike the other periods defined in this section, this period does not reflect a system-wide change in transport patterns. The most notable feature during this period is the gradual expansion and decline of accreting shoreline along the most southern boundary of Lanikai Beach (transects 105 – 116). The rapid switch to erosion along this small reach of shore is an indication that conditions which had allowed accretion changed suddenly. It is necessary to single out this feature as it is important in the next section for the discussion of wind direction. This period also marks the beginning of a northward drift in the accretion and erosion trends in Lanikai.

VII. 1987 – 1995

This period is characterized by a sharp return to erosion across the entirety of the Bellows shoreline and the continued northward drift of the pre-existing accretion and erosion pattern in Lanikai. Central Lanikai begins to experience erosion as the accreting area shifts toward Upper Lanikai.

VIII. 1995 – 2008

The northward shift of accretion observed in Lanikai during the previous two periods continues until all of Upper Lanikai is accreting. Interestingly, the southern boundary of this accretion remains fixed until the most recent shoreline. As erosion in Central and Lower Lanikai continues there is effectively no beach left along the southern coast of Lanikai. The erosion appears to begin near transect 90 in Lower Lanikai and radiate north and south from there. This is a possible indication that nearshore currents are diverging near this point in Lower Lanikai, creating a relatively faster rate of erosion than at the southern edge of Lanikai.

Erosion continues in Upper Bellows until no beach remains. The shape of this erosion trend suggests it is migrating to the south. The reappearance of accretion against the jetty on the southern boundary of Bellows Beach is farther evidence of southern transport occurring during this time.

5.3. Influence of wind direction and sediment supply

Wind direction is identified in the hydrodynamic simulations as having strong possible control littoral sediment transport direction. Figure 18 overlays the time periods defined in Figure 17 on the record of wind direction. The close degree of fit between shoreline movement and changes in wind direction indicates wind is a likely driving force behind the fluxuation in transport direction along the Lanikai-Bellows shoreline.

These results show that the material accreted in Lanikai during the 1950s through to the 1970s was eroded from the Bellows shoreline. While wind direction seems to play an important role in transport on this coastline, the influence of coastal hardening must also be considered. The north Bellows shoreline is currently hardened by coastal revetments. These revetments were constructed in Bellows to halt the erosion of the shoreline that has occurred over much of the 20th century. Given the sediment exchange between Bellows and Lanikai documented in this study, it is likely that the source of accretion in Lanikai was cut off by revetment construction.

The effect of Bellows revetments can be seen in periods III, IV, and V in Figure 17. Wind direction in period III was inducing transport from Bellows to Lanikai. This transport was shutdown by more northerly winds during period IV (Figure 18) and during this time Bellows began seeing isolated sediment accretion along reaches of beach that could remain stable under that wind direction. In period V winds once again became more easterly, which reestablished the northern Bellows-to-Lanikai transport pathway, but much sediment was impounded within the Bellows shoreline by the revetments. This resulted in little sediment entering Lower Lanikai to replace the sand that migrated north to Central Lanikai, which eventually lead to a major sediment deficit in Lower Lanikai. This presents a situation in which erosion is caused by a lack of sand supply not a lack of a mechanism to move the sand. Understanding the interplay between wind direction, littoral transport, and sediment supply gives coastal managers of this area, and potentially any other windward shoreline, a strong foundation on which to build a remediation plan to control coastal erosion.

5.2 Evaluation of methods

5.2.1 Hydrodynamic modeling

While it is changes in wind direction can be correlated with changes in erosion/accretion patterns, understanding the exact physical mechanism for driving these changes is more difficult. Tradewind direction has been near perpendicular to

Lanikai-Bellows shoreline. It stands to reason then that small changes in wind directions could produce relatively large changes in littoral current configuration. We use a hydrodynamic model to predict these possible littoral current patterns and understand beach change in context of dominant wind direction.

Results of the hydrodynamic model (Figures 14, 15, and 16) show a relationship between the increasing northern component of trade winds and the existence of southerly littoral currents and more complex flow patterns. Littoral convergence and divergence creates an overall more dynamic shoreline over time. For example, period II is characterized by consistent erosion of Bellows and accretion in Lanikai under easterly winds, which the model shows will create mostly northern littoral currents (Figure 16). During period III winds become more northerly, introducing a more complex littoral currents (Figure 15) which lead to more discrete areas of accretion and erosion. During this time the concentration of sediment in Lower Lanikai is at the presumed expense of Central Lanikai. Period IV shifts the winds further north, which is accompanied by a shut down of accumulation and possible reversal of transport direction in Lanikai. This period of more northerly wind, during which north transport seems weaker and less uniform, could be the cause of stabilization and accretion on the Bellows shoreline.

Winds return to a more eastern bearing in Period V. This shift is accompanied by a renewal of northern transport in Lanikai, but an accumulation in Central Lanikai as apposed to Lower Lanikai. This illustrates the potentially high degree of sensitivity this system has to wind direction, as the actual different between winds in period III and V is slight (period V is more eastern by approximately 5 degrees). Not seen in the hydrodynamic model is a southerly longshore current in Upper Lanikai. A possible reason for this discrepancy is that the model does not perform as well in close proximity to the model boundary. This missing southerly trend could be the result of an accounted for influence from neighboring Kailua Bay.

Period VI shows a rapid and short lived spike in wind direction toward the northeast. During this period, a small area on the southern boundary of Lanikai accretes as through a mini-convergence zone has developed on Wailea Point. This convergence near the Point is predicted to happen in northeasterly winds by the hydrodynamic model (Figure 16). As the wind shifts to a more easterly bearing, this small accretion area also disappears, further indicating the relevance of the modeled predictions.

5.2.2 Grain-size trend analysis in coastal change studies

The combined results of the historical shoreline and hydrodynamic modeling provide both an empirical record of change and process information. The GSTA results further support the transport pathways established by these other two methods. Figure 19 shows a combined interpretation of both GSTA methods. The points of divergence or convergence on Figure 19 are approximately transects 10 and 30 in Bellows and transects 110, 90, 70 in, transect 90 in Lanikai. It is important to note

many of these points of littoral transport divergence and convergence are similar between all three datasets.

An interesting secondary observation is a chance to evaluate how GSTA integrates the signal of multiple overlapping and sometimes opposite transport trends into a single transport pattern. The question of what time frame GSTA results represent can be addressed in this study by comparing the result to the historical shoreline change record. Comparing Figures 17 and 19, it is evident that the GSTA results of the Lanikai-Bellows shoreline retains an integration of all major littoral processes from approximately 1964 (Period IV) to present (Period VIII). The beginning of erosion in Lower Lanikai (Period IV, transect 90) is recorded as a diverging trend over the same area in Figure 19. The northern edge of the GSTA sample area shows convergence in Central Lanikai in the same location that accretion has been observed in the historical record (Periods IV, V, VI; transect 70). Sediment accumulation on either side of Wailea Point, two-way transport around the Wailea Point, and the offshore gyre observed in modeling results in northeast winds (Figure 14) are also represented in the GSTA results. In Upper Bellows, diverging littoral transport is shown in the GSTA results at transect 30. This area of shoreline shows a diverging trend during Periods IV and VIII in the historical results. In the offshore a general northward trend exists, most likely reflecting the dominate mode of northward wind driven transport in this region.

The results of this study indicate that grain-size trend analysis can be a useful component of a coastal sediment budget if nearshore transport vectors are used as indicators of dominant longshore transport direction. The transport vectors obtained from GSTA of the benthic sediment shows that grain-size transport signatures persist even after the original transport process has stopped. This would need to be accounted for when interpreting GSTA results in sediment systems that have experienced multiple transport patterns through time. GSTA serves a valuable role as “ground truthing” transport pathways that can be hypothesized from models and historical results. It can also be used to identify possible littoral cell boundaries and test for the possibility of transport between littoral cells.

The Lanikai-Bellows shoreline has experienced a number of transport patterns in recent decades. The GSTA results contain many of the transport patterns known to have existed at the Lanikai-Bellows. It is possible that shorelines which have undergone a number of different transport patterns will all encounter trend that are no longer active. Over all GSTA proved valuable for defining major areas of transport activity, evaluating the complexity of transport in a region, and validating the results of the hydrodynamic model.

5.3 Directional changes in the wind record

The cause of the decadal directional shift in trade winds is not fully understood. A potential explanation for the directional shifts might lie in small shifts in the North Pacific High pressure system, north of the Hawaii islands. This system already controls the occurrence of Kona storms in Hawaii. It is possible that influence of a

decadal scale cycle, such of Pacific Decadal Oscillation could be effecting the North Pacific High and resulting in the directional shifts seen in the data.

6. CONCLUSIONS

This study integrates sedimentological data, hydrodynamic computer modeling, historical shoreline change analysis to investigate the dynamics controlling enigmatic and large coastal change on Lanikai-Bellows shoreline. The results of the study show wind direction to be a major controlling factor in the patterns of shoreline movement. Most major accretion and erosion events can be linked to periodic shifts in the dominate tradewind direction. Revealing this aspect of the Lanikai-Bellows beach system represents a major step in the creation of a regional sediment budget and allows an excellent opportunity to practice integration of multiple analysis techniques. We reveal the hypothesis of sediment transfer across Wailea Point to be true, indicating Bellows Beach and Lanikai Beach are dynamically linked.

The availability of historical shoreline records allows for a powerful empirical comparison point to evaluate and intemperate the results of GSTA. In general, GSTA results reveal in select elements of a 40-year period of shoreline change and identified most the major transport trends also seen in the historical and hydrodynamic results. This study also represents the first use of sediment trend analysis to study coastline change and has revealed the underlying processes that form the resulting trends using by the analysis.

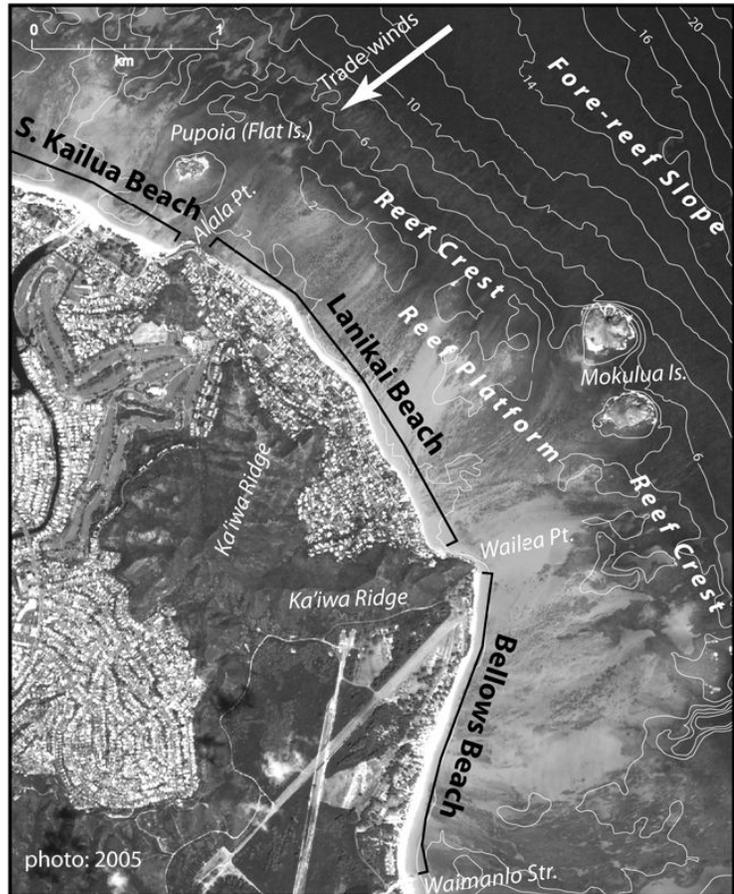
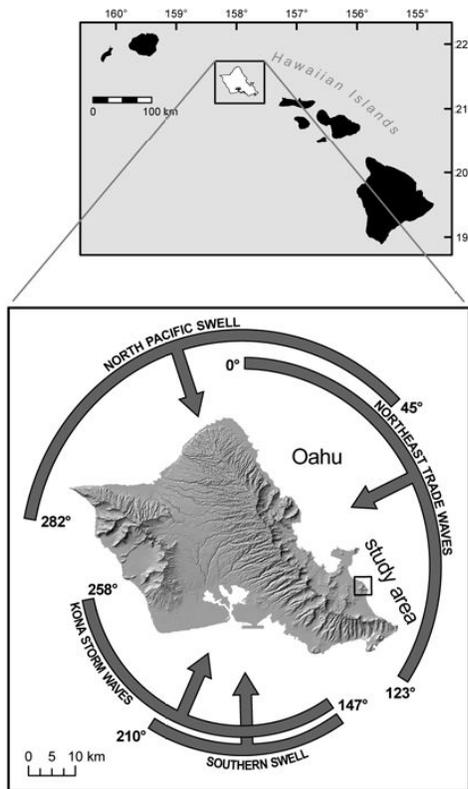


Figure 1. Study area. Bathymetric contours are in meters.

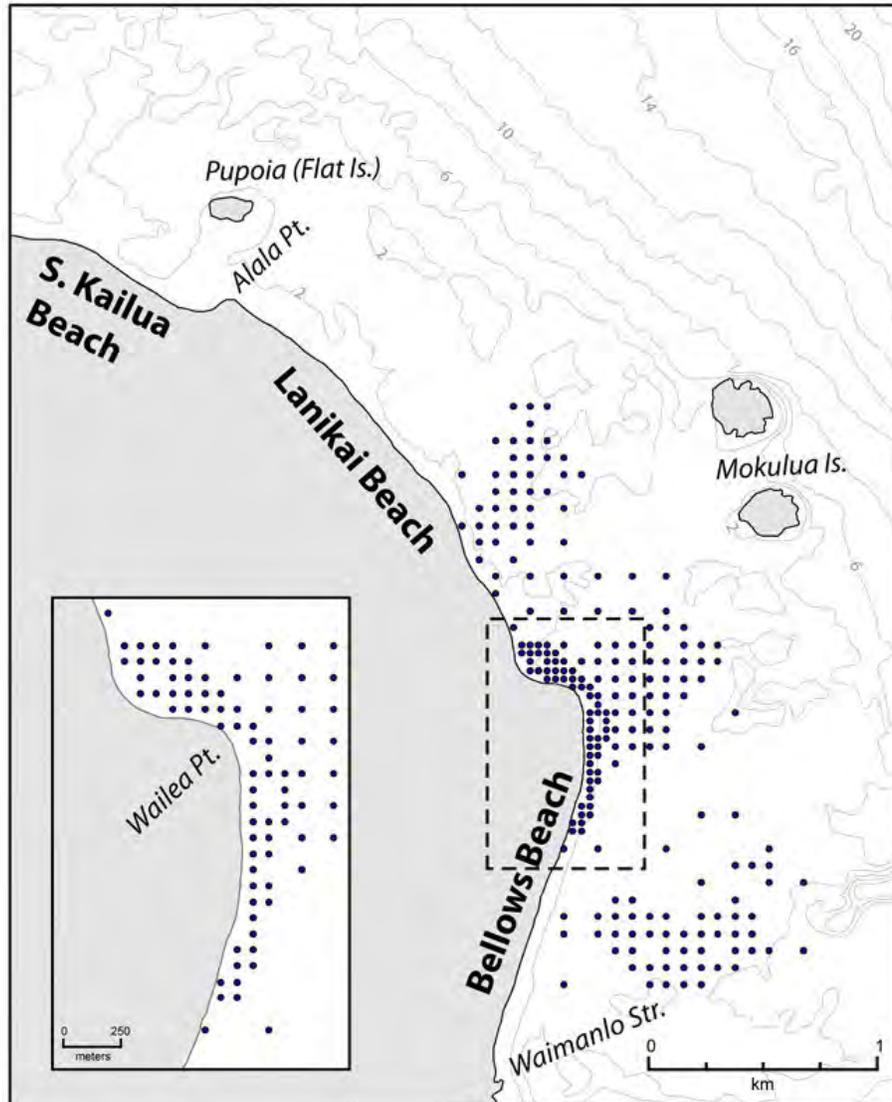


Figure 2. Location of surficial sediment sampling sites for sediment grain size trend analysis. Inset: samples in the vicinity of Wailea Pt.

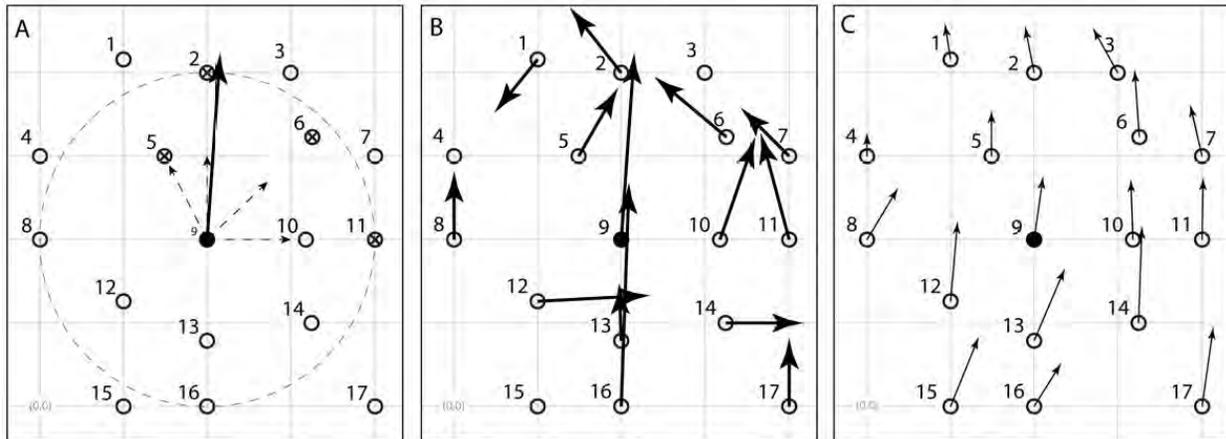


Figure 3. Gao-Collins method for determining sediment transport. See Appendix A for data and calculations used in figure. A) Illustration of transport determination at site 9 with characteristic distance equal to 2 (dashed circle). Circles represent sampling sites; those containing “x” show either a trend 1 or trend 2 relationship in grain size parameter with site 9. Dashed arrows indicate component unit vectors (length = 1) drawn in the direction of each trend positive site, while the bold arrow is the summation of the component vectors. B) The process is repeated at each site producing a transport vector field, which is filtered (C) by averaging adjacent vectors.

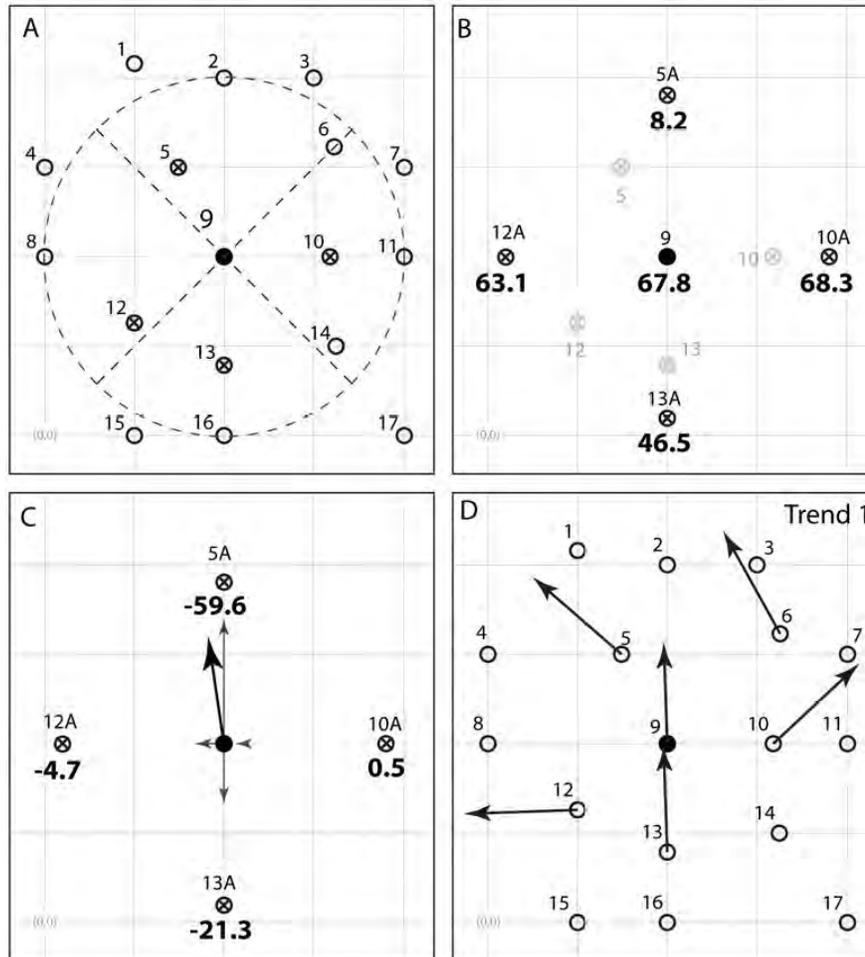


Figure 4. Le Roux method for determining sediment transport. Grain size parameters are identical to those of Figure 3. This method considers each trend type separately, only Trend 1 is considered in this example. A) The closest site in the Northern, Eastern, Southern, and Western quadrants is selected for used; dotted lines illustrate quadrants and “x” on a site indicates selection. B) All sites are transformed to lie at an equal distance of the central site on the cardinal radials; site 5 is at the position of site 5A, 10 is moved to 10A, etc. Grain size parameters are modified to reflect the new positions and summed using the appropriate form of equation (1) for the trend type being investigated. C) The value of the central site is subtracted from all sites. The resulting values indicate transport magnitude in each direction, with negative values indicating transport away from the central site and positive values towards the central point. Summation of component vectors determines the final transport vector. D) The process is repeated at every site with available adjacent sites to produce a vector field for that trend type.

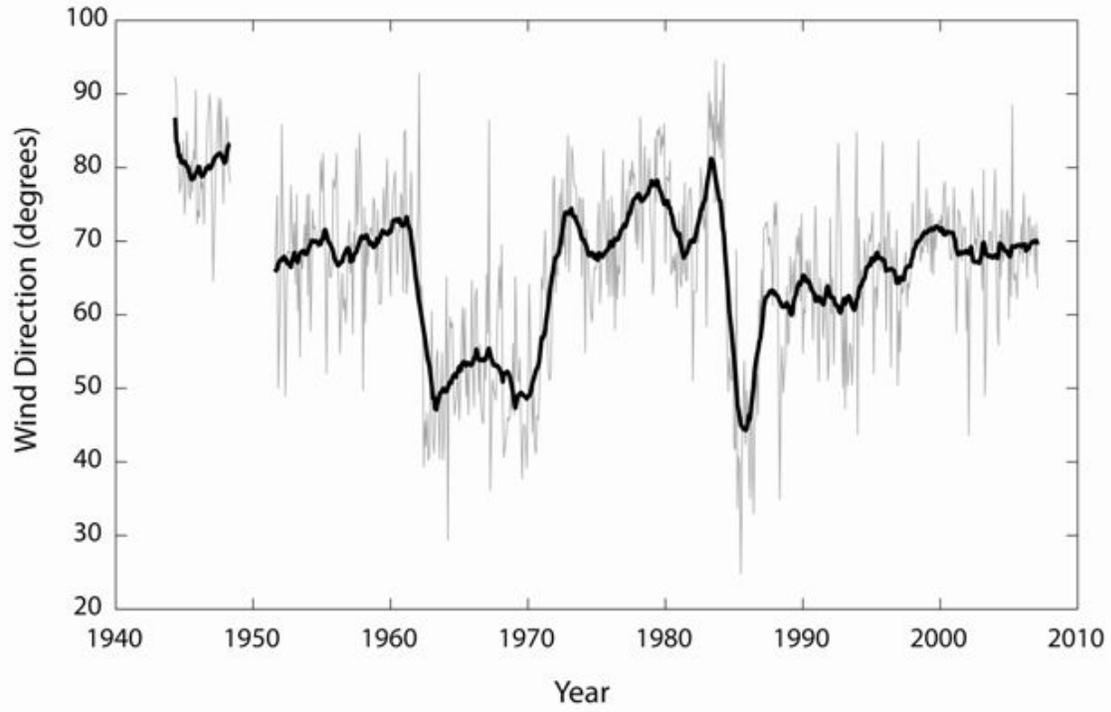


Figure 5. Directional wind data from Kaneohe Marine Corps. Air Base. Values range between 1 and 135 degrees.

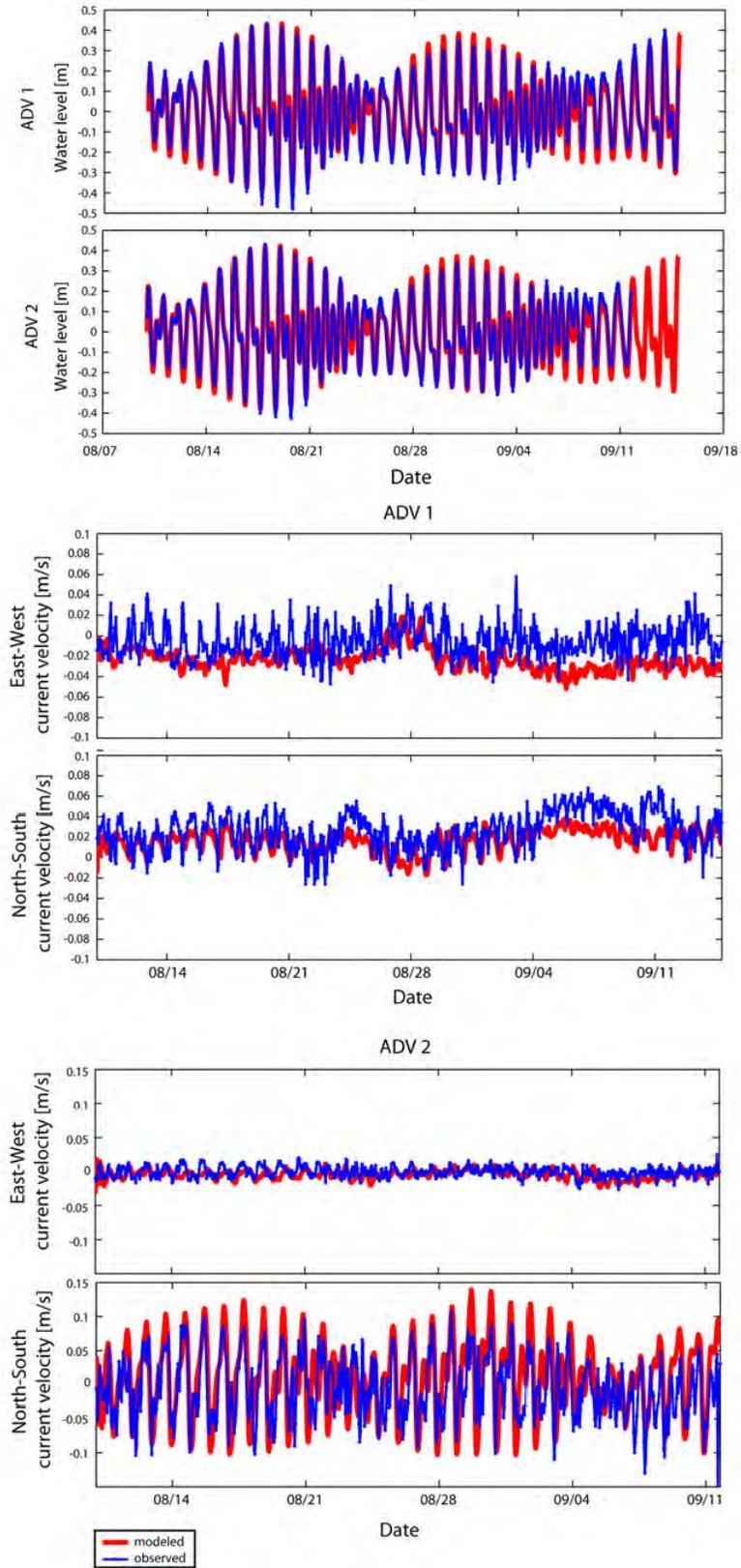


Figure 6. Sea level and wave energy calibration for ADVs.

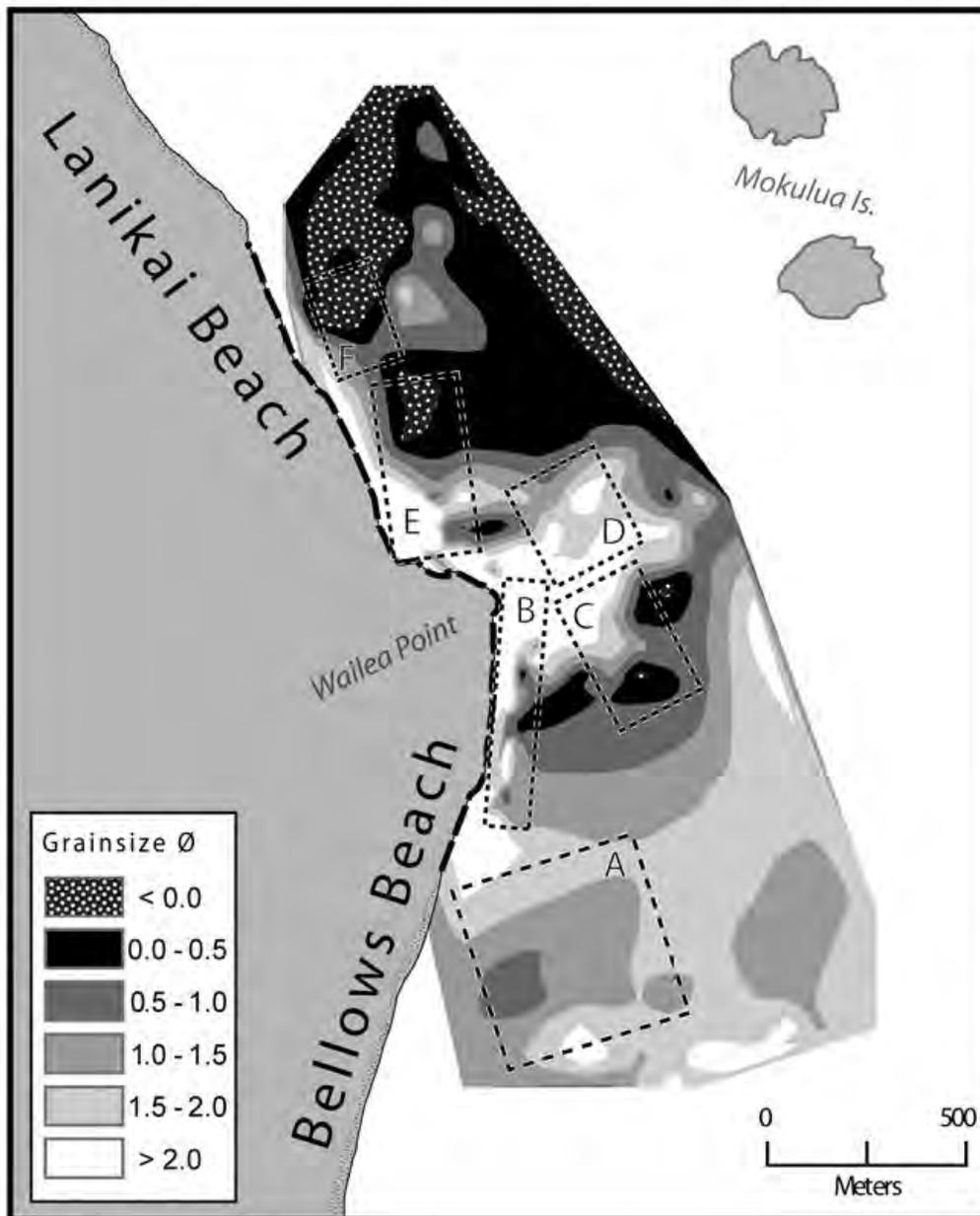


Figure 7. Mean size, sorting, and skewness interpolated from seafloor sediment samples.

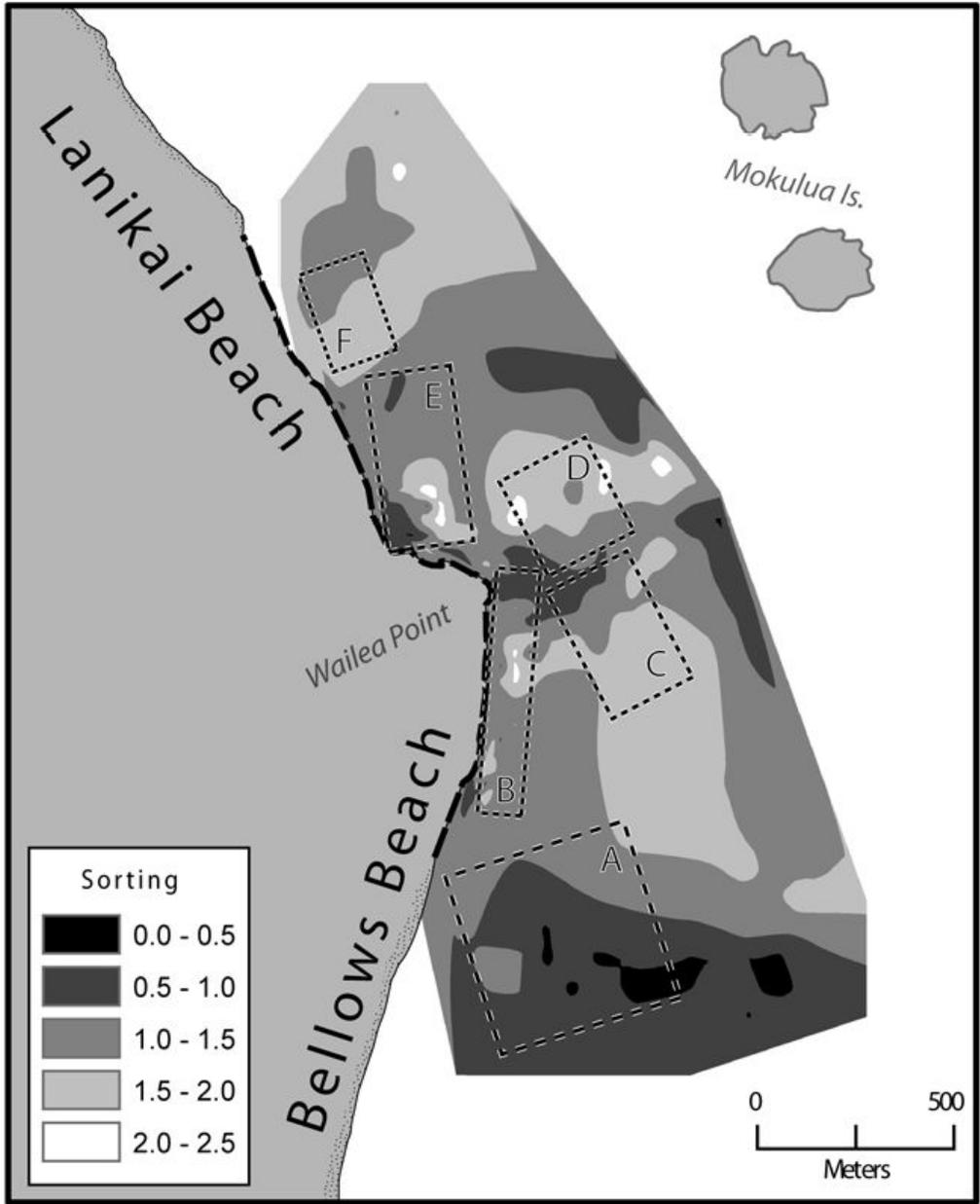


Figure 8. Results of Gao-Collins method for sediment grain trend analysis.

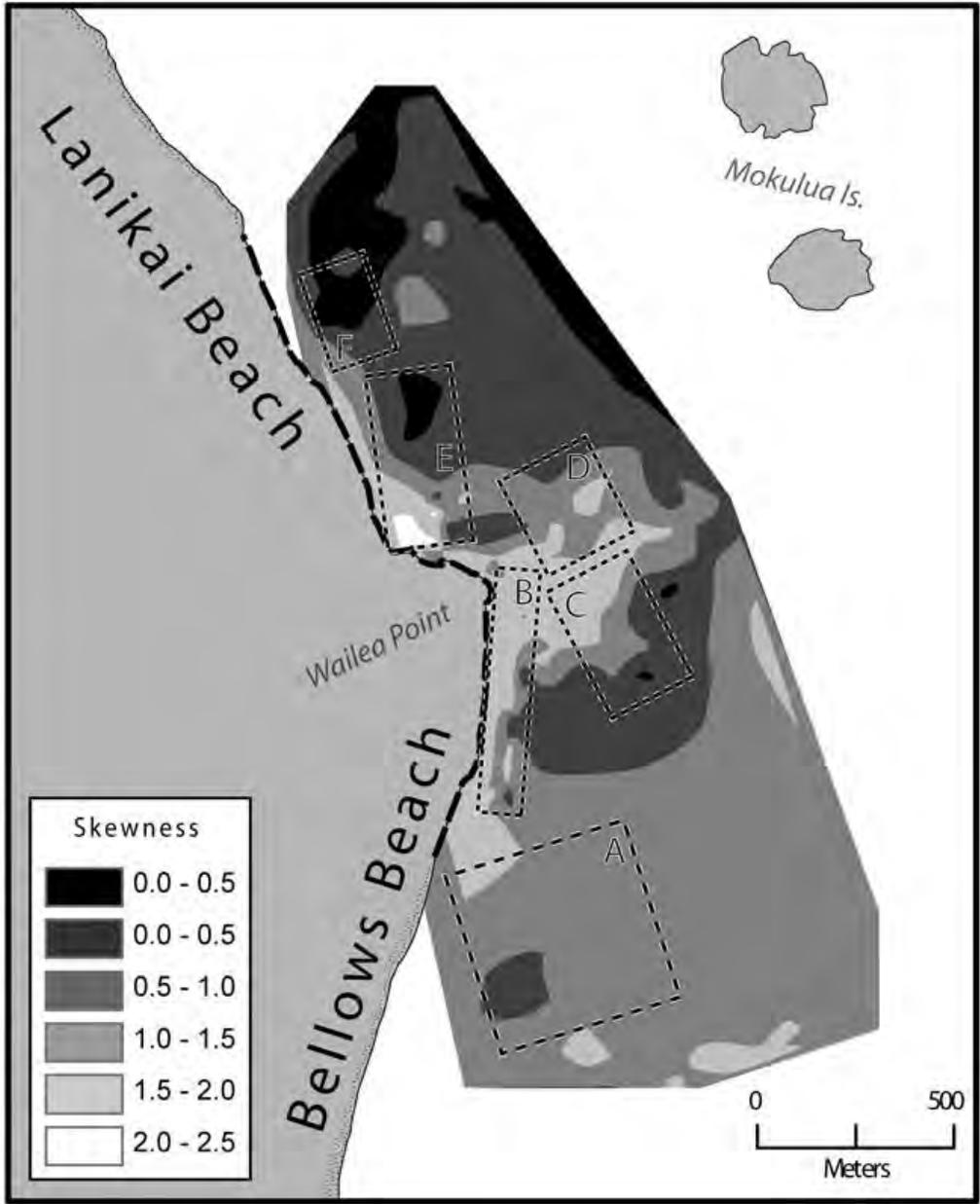


Figure 9. Results of Roux method for sediment grain size trend analysis.

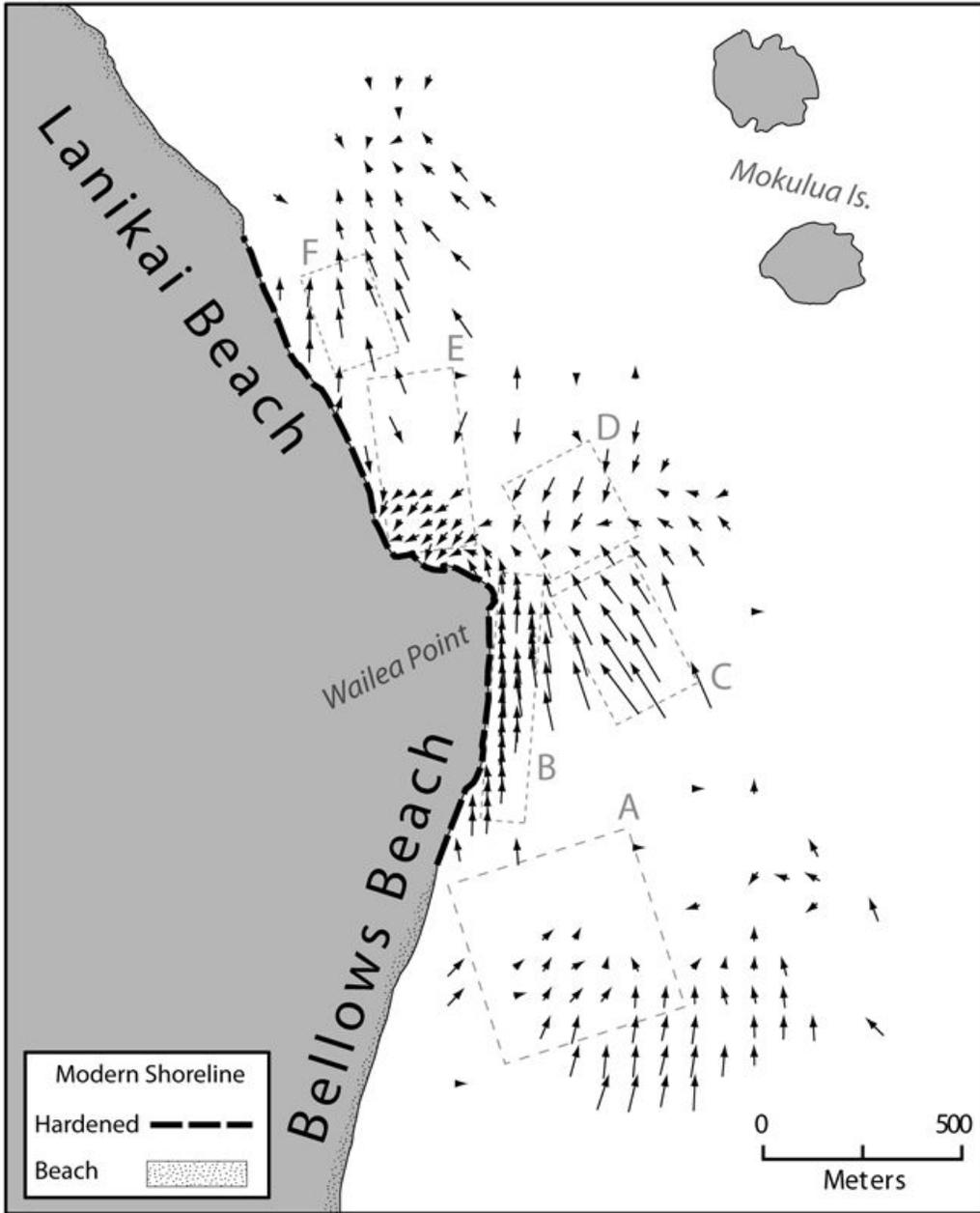


Figure 10. Gao-Collins sediment grain-size analysis results.

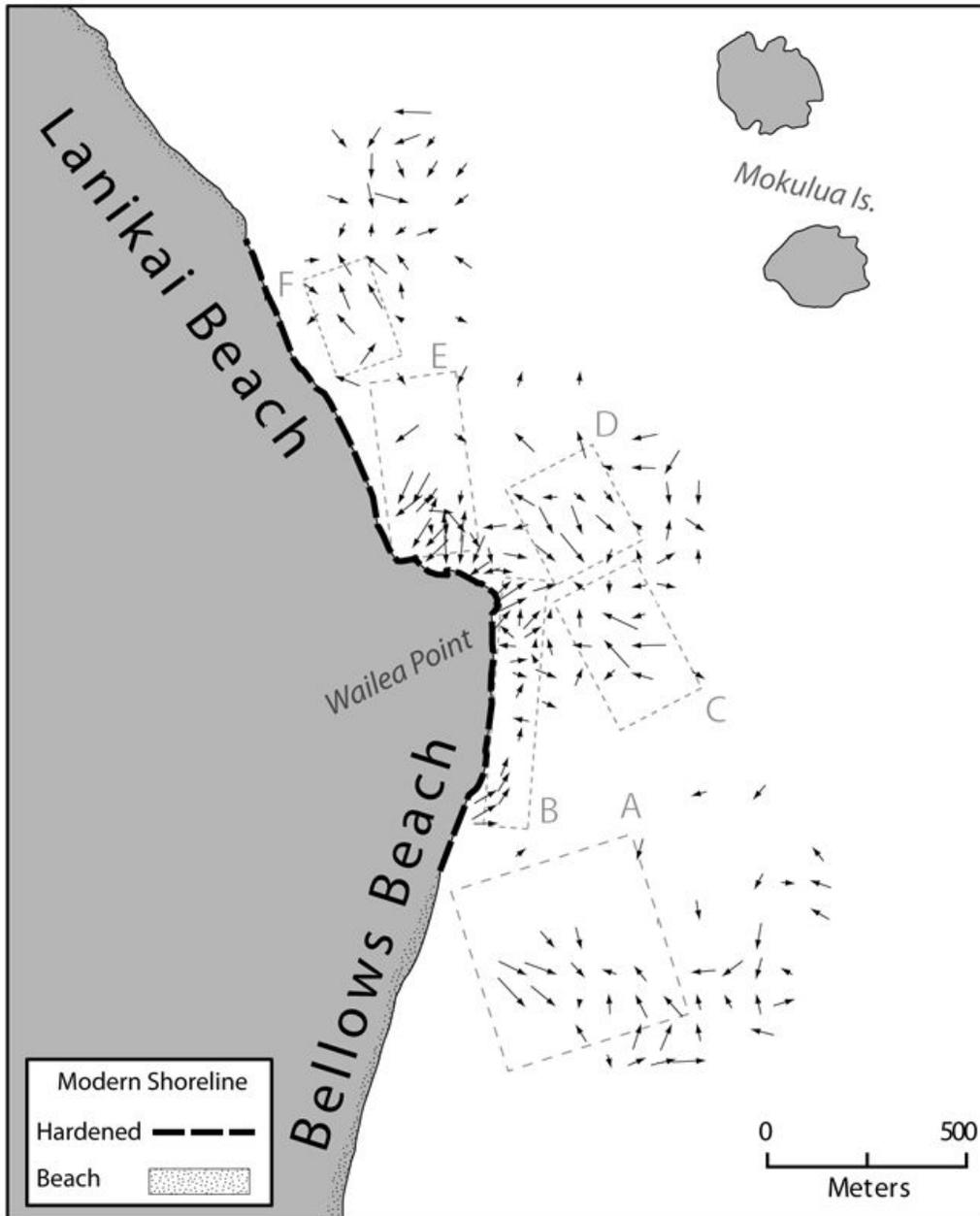


Figure 11. Le Roux sediment grain-size analysis results.

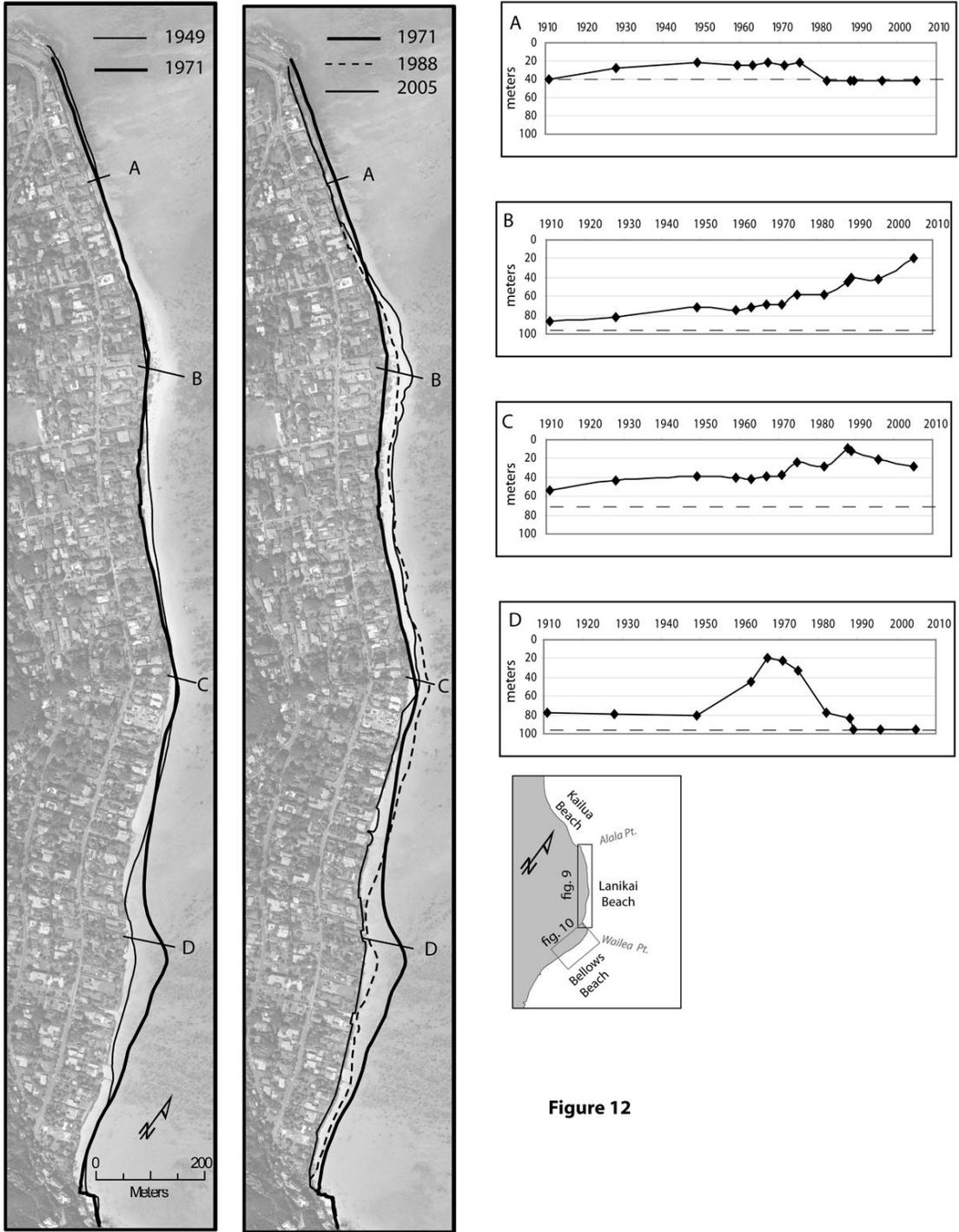


Figure 12. Summary of historical shoreline position at Lanikai Beach. Graphs A, B, C, and D show representative datasets for each corresponding transect location. Positions are given as meters from an offshore baseline, thus positive shifts indicate accretion and negative shifts erosion. Gray boxes track the development of a sudden accretion trend. Left map shows a period of accretion in Southern Lanikai (1949 – 1971). Right map shows erosion trend in the South Lanikai and subsequent accretion at central Lanikai.

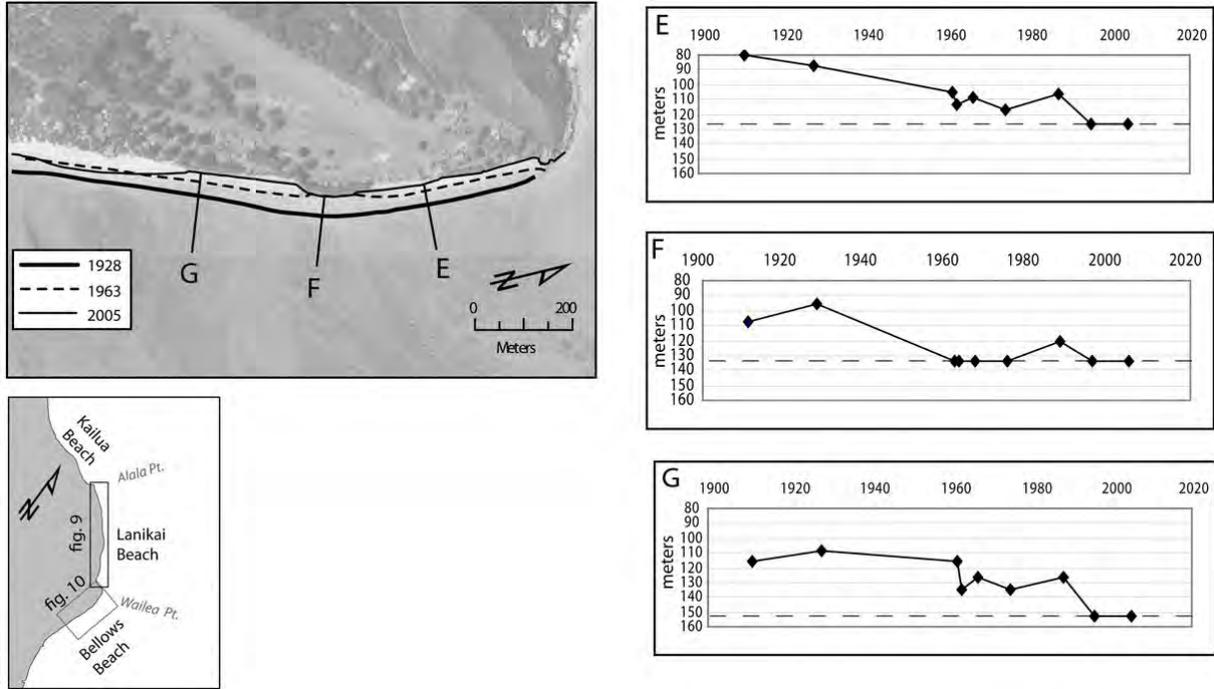


Figure 13. Summary of historical shoreline position at North Bellows Beach. Graphs A, B, and C show representative datasets for each corresponding transect location. Positions are given as meters from an offshore baseline, thus positive shifts indicate accretion and negative shifts erosion. Map shows persistent erosion across region. Arrows mark beginning of seawall construction in response to erosion.

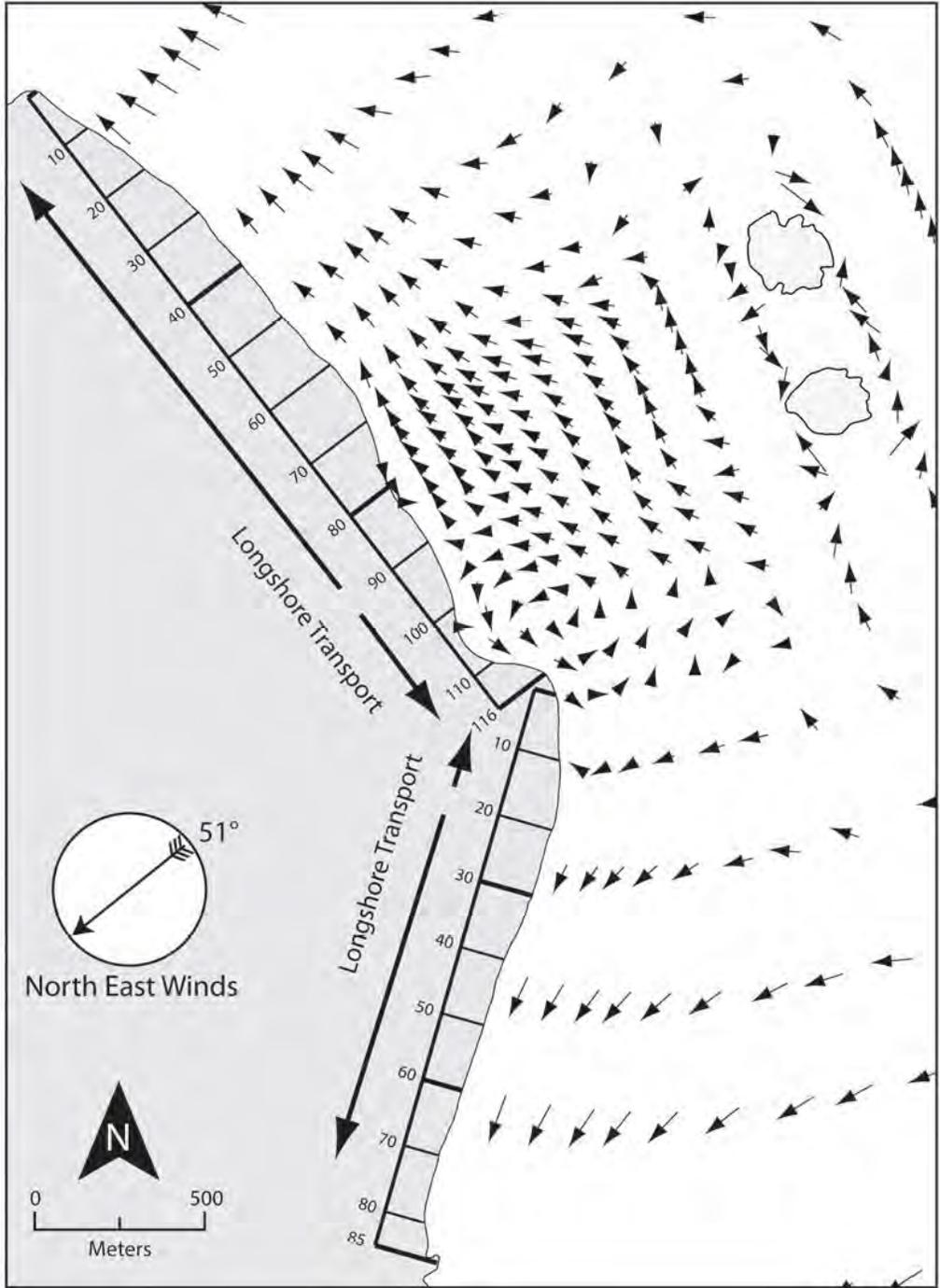


Figure 14. Hydrodynamic model result for 51 degree winds.

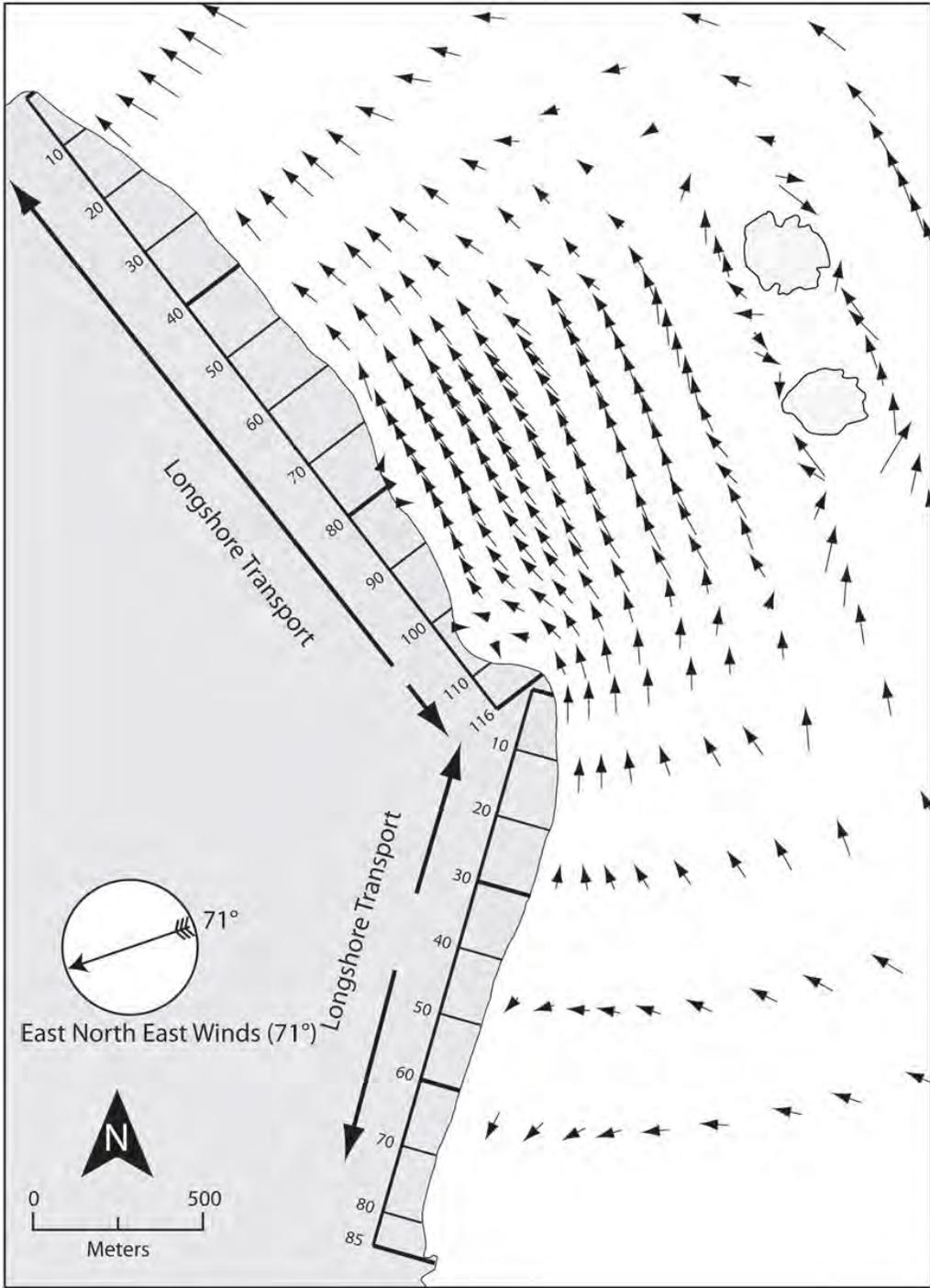


Figure 15. Hydrodynamic model result for 71 degree winds.

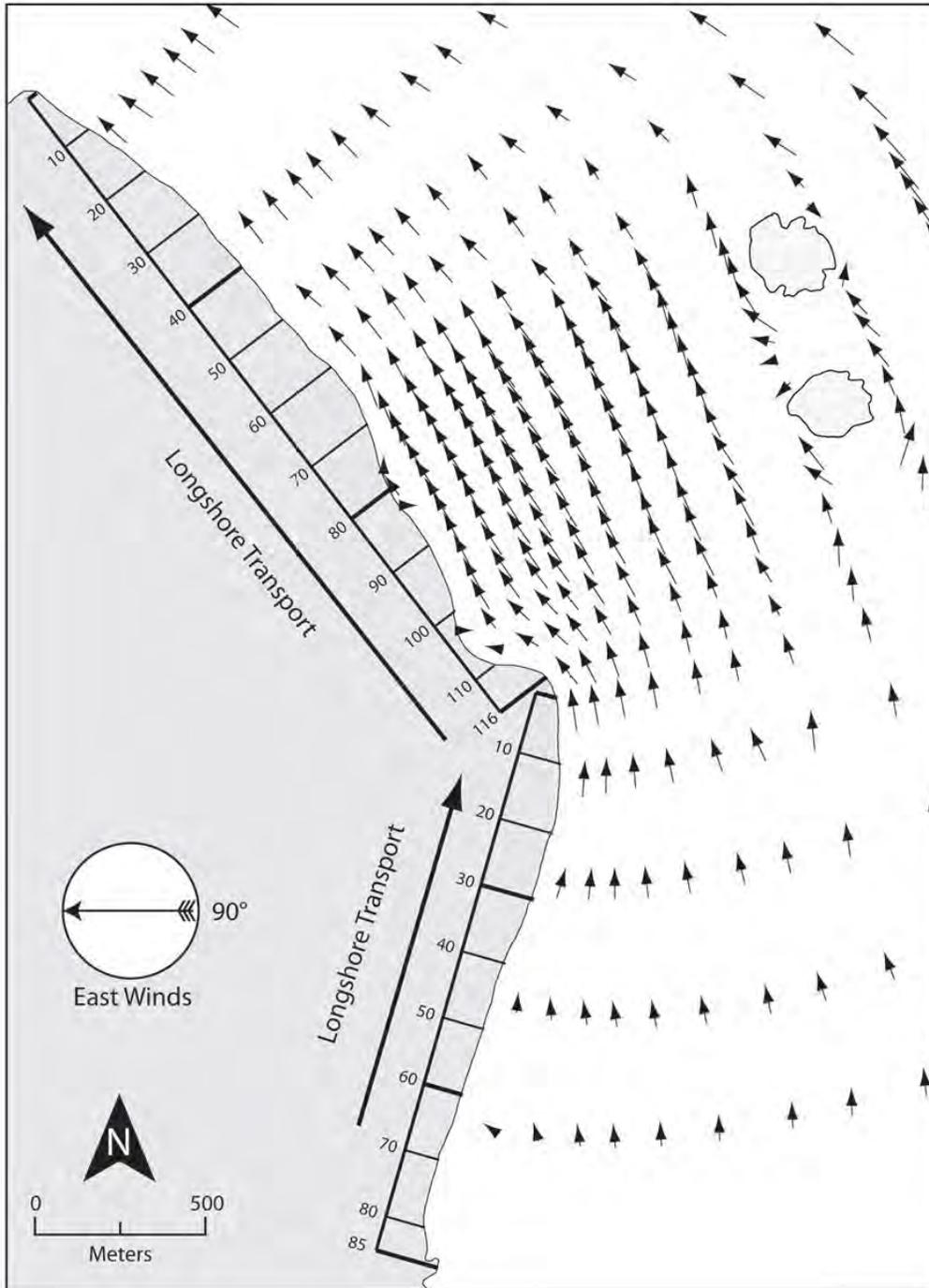


Figure 16. Hydrodynamic model result for 90 degree winds.

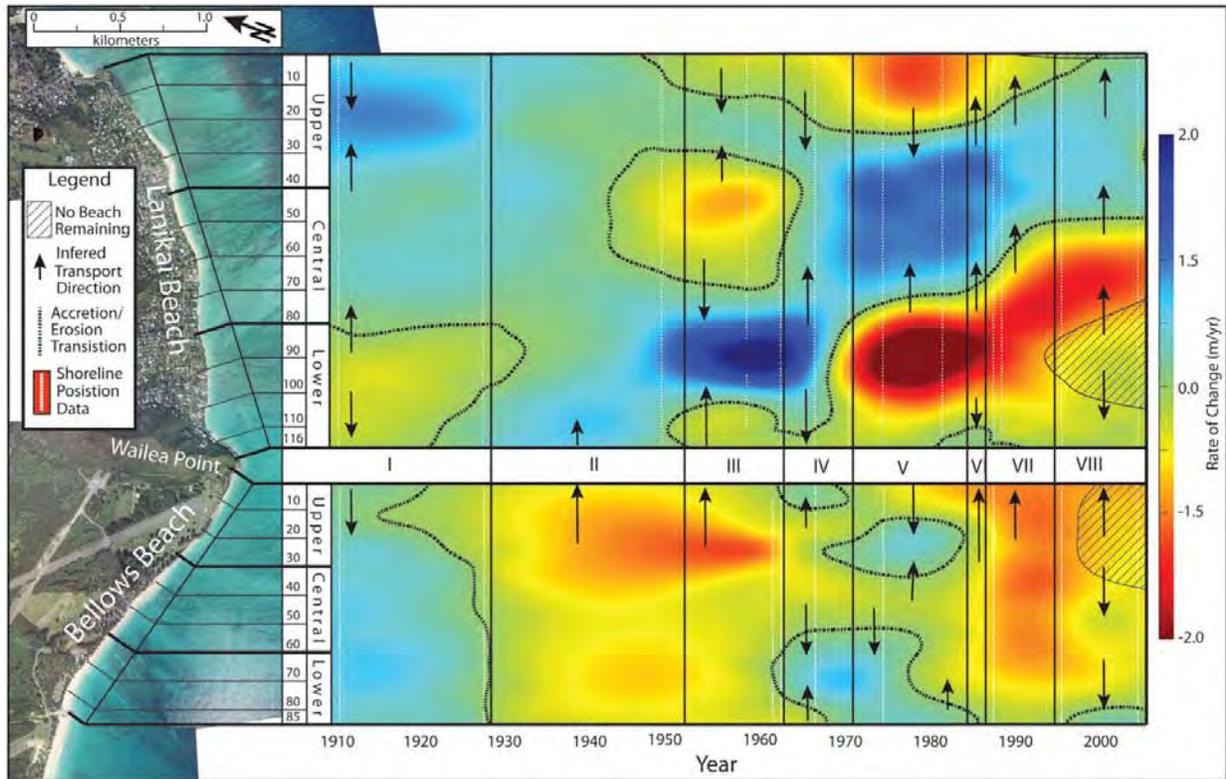


Figure 17. Historical Shoreline record for Lanikai-Bellows beach. Red indicates erosion rate, blue indicates accretion rate.

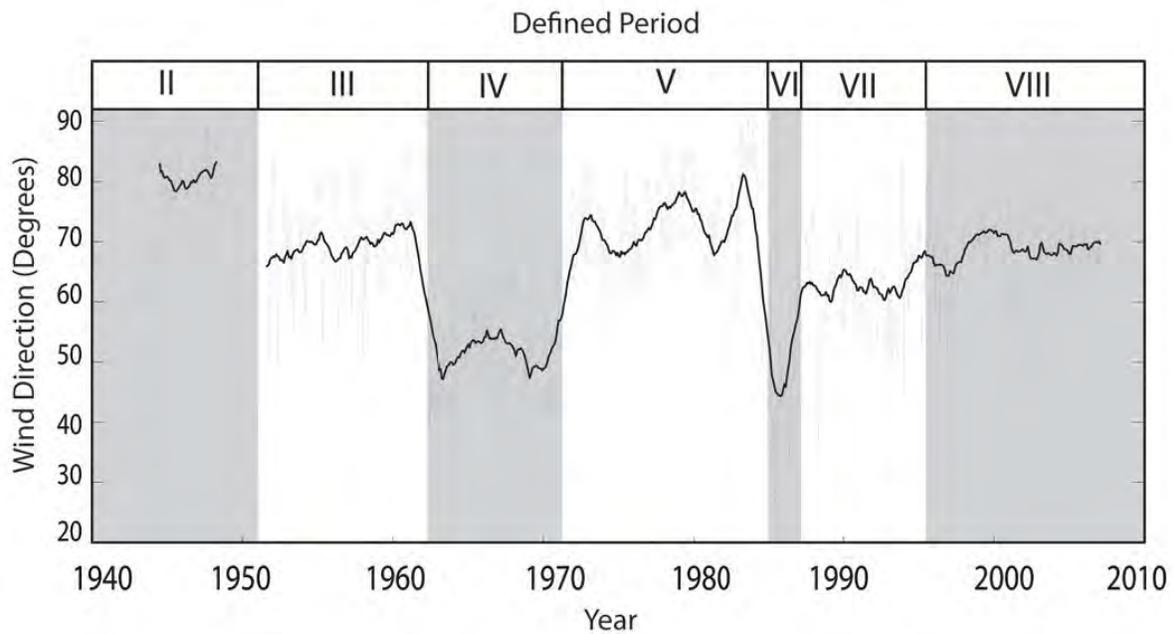


Figure 18. The wind record showing divisions used to separate period of like sediment transport.

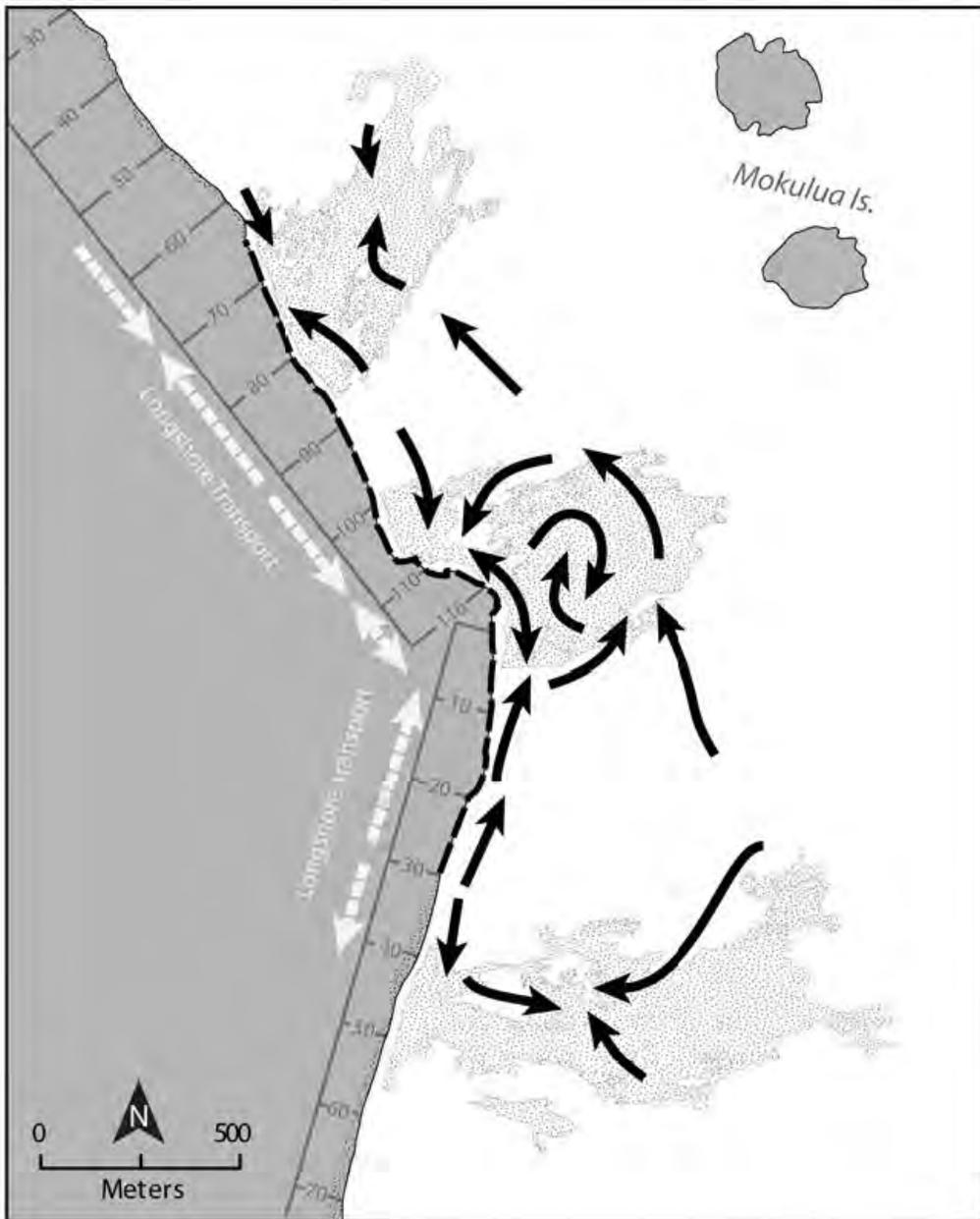


Figure 19. Combined interpretation of results from Le Roux and Gao-Collins methods.

APPENDIX A

Figure 8 illustrates the Gao-Collins method. This appendix details the application of the Gao-Collins method to a synthetic dataset. Calculations associated with site 9 are included.

Table 1. Coordinates and grain-size data for the calculations used in Figure 7.

Site		mean sorting skewness			Trend Type*	Component Vector*	
<i>l</i>	X_i	Y_i	μ	σ	Sk	$r(x)_i$	$r(y)_i$
1	1	4.25	-0.5	1	1.2	-	-
2	2	4	0.3	1	0.8	1	0
3	3	4	-1	0.8	1.5	-	-
4	0	3	0.2	0.3	0.7	-	-
5	1.5	3	1	0.8	0.9	1	-0.45
6	3.25	3.25	-0.7	1.1	1.3	2	0.71
7	4	3	-1.2	0.9	1.8	-	-
8	0	2	-0.1	0.5	1.5	-	-
9*	2	2	-0.3	1.4	1.1	-	-
10	3.2	2	-0.9	1.6	0.7	-	-
11	4	2	-0.9	1.3	1.4	2	1
12	1	1.25	-0.8	1.8	1.3	-	-
13	2	0.75	-0.7	1.3	0.5	-	-
14	3.25	1	-0.4	1.7	0.9	-	-
15	1	0	-0.5	1	1	-	-
16	2	0	1	1.7	0.8	-	-
17	4	0	-0.7	1.4	1	-	-

*Trend type and component vectors calculated in table for site 9 only.

Step 1. Determine which sites are within the characteristic distance from the site of consideration (site 9). In the example, the characteristic distance is equal to two, which encompasses ten sites: 2, 5, 6, 8, 10, 11, 12, 13, 14, and 16.

Step 2. Check for the existence of trends 1 or 2 between the central site (site 9) and the proximal sites listed above. Trend 1: sites 2 and 5. Trend 2: sites 6 and 11.

Step 3. Define component vectors $r(x,y)_i$ between the central site and those showing a transport trend. All component vector magnitudes are assumed to be equal (i.e. value = 1). When a trend is found the vectors is assigned to the site with the highest sorting coefficient. As an example, calculations to determine the component vector from site 9 to site 5 are below:

$$r(x)_5 = \frac{(X_5 - X_9)}{d} = \frac{(1.5 - 2)}{1.118} = -0.45$$

$$r(y)_5 = \frac{(Y_5 - Y_9)}{d} = \frac{(3 - 2)}{1.118} = 0.89$$

where d is the distance between site 2 and the central site 0, given as:

$$d = \sqrt{(X_5 - X_9)^2 + (Y_5 - Y_9)^2} = \sqrt{1^2 + 0.5^2} = 1.118$$

Step 4. Sum all component vectors $r(x,y)_i$ to make a sum vector $R(x,y)$:

$$R(x,y)_9 = \sum_{i=1}^{17} r(x,y)_i = [0.26 \ 3.60]$$

Step 5. Repeat steps 1 – 4 on every site in the data set to define sum vectors at every site. Results of this step are presented in Table 2.

Table 2.

Site	Sum Vector		Average Vector		Azimuth Direction*	Vector Length*
i	$R(x)_i$	$R(y)_i$	$R_{Av}(x)_i$	$R_{Av}(y)_i$	Θ	VL
1	0.72	-1.95	-0.24	0.83	322	0.39
2	-0.97	1.24	-0.18	0.48	333	0.39
3	-0.83	-0.55	-0.58	0.3	316	0.83
4	0	0	0.18	0.85	143	0.3
5	0	0	0.05	1.05	6	0.48
6	-1.22	1.01	-0.35	0.82	340	1.05
7	-0.71	0.71	-0.53	1.12	322	0.85
8	0	1	0.57	0.85	44	0.82
9	0.26	3.6	0.09	0.39	7	0.78
10	-0.07	1.06	-0.22	0.98	345	0.85
11	-0.51	1.86	-0.19	1.18	349	0.98
12	2.59	-0.67	0.15	1.59	7	1.18
13	0	0	0.57	0.67	30	1.15
14	0.42	-0.62	0.07	1.15	2	1.59
15	0	0	0.84	1.23	49	1.12
16	0.78	3.62	0.47	0.39	45	0.67
17	0	1	0.17	1.21	8	1.23

*Result of the average vector.

Step 6. Remove noise by averaging each sum vector with the neighboring sum vectors determined to be within the characteristic distance (i.e. sites identified in

Step 1). This effectively serves as a low-pass filter with a search radius of 2. For site 9 this processes is expressed as:

$$R_{av}(x, y)_9 = \frac{1}{(k+1)} \left[R(x, y)_9 + \sum R(x, y)_q \right] = \frac{1}{(10+1)} ([0.26 \quad 3.6] + [1.03 \quad 8.50])$$

$$= [0.09 \quad 0.77]$$

where q is a list of all sites within the characteristic distance of site 0:

$$q = [2 \quad 5 \quad 6 \quad 8 \quad 10 \quad 11 \quad 12 \quad 13 \quad 14 \quad 16]$$

and k is the total number of such sites:

$$k = 10$$

Thus, the final averaged transport vector at site 0 has an x-component of 0.09 and a y-component of 0.77.

Step 7. Convert average vector into azimuth direction Θ (exact formula will vary) and vector length VL :

$$\Theta = 90 - \arctan\left(\frac{0.77}{0.09}\right) \approx 7 \text{ degrees}$$

$$VL = \sqrt{(R_{av}(x)_i)^2 + (R_{av}(y)_i)^2} = \sqrt{(0.77)^2 + (0.09)^2} = .78$$

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Historical Shoreline Change, Southeast Oahu, Hawaii; Applying Polynomial Models to Calculate Shoreline Change Rates

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ABSTRACT

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Here we present shoreline change rates for the beaches of southeast Oahu, Hawaii, calculated using recently developed polynomial methods to assist coastal managers in planning for erosion hazards and to provide an example for interpreting results from these new rate calculation methods. The polynomial methods use data from all transects (shoreline measurement locations) on a beach to calculate a rate at any one location along the beach. These methods utilize a polynomial to model alongshore variation in the rates. Models that are linear in time best characterize the trend of the entire time series of historical shorelines. Models that include acceleration (both increasing and decreasing) in their rates provide additional information about shoreline trends and indicate how rates vary with time. The ability to detect accelerating shoreline change is an important advance because beaches may not erode or accrete in a constant (linear) manner. Because they use all the data from a beach, polynomial models calculate rates with reduced uncertainty compared with the previously used single-transect method. An information criterion, a type of model optimization equation, identifies the best shoreline change model for a beach. Polynomial models that use eigenvectors as their basis functions are most often identified as the best shoreline change models. Polynomial models with linear fit in time indicate chronic erosion along 36% of the length of southeast Oahu beaches. Polynomial models including acceleration indicate recent increasing rates of erosion along 33% of the length of the study area.

ADDITIONAL INDEX WORDS: Coastal erosion, shoreline change, erosion rate, polynomial, PX, PXT, EX, EXT, ST, single-transect, information criterion, Hawaii.

INTRODUCTION

Tourism is Hawaii's leading employer and its largest source of revenue. Island beaches are a primary attraction for visitors, and some of the most valuable property in the world occurs on island shores. Beaches are also central to the culture and recreation of the local population. During recent decades many beaches on the island of Oahu, Hawaii, have narrowed or been completely lost to erosion (Fletcher *et al.*, 1997; Hwang, 1981; Sea Engineering, 1988), threatening business, property, and the island's unique lifestyle.

Results from a Maui Shoreline Study (Fletcher *et al.*, 2003) resulted in the first erosion rate-based coastal building setback law in the state of Hawaii (Norcross-Nu'u and Abbott, 2005). Concerns about the condition of Oahu's beaches prompted federal, state, and county government agencies to sponsor a similar study of shoreline change for the island of Oahu. The primary goals of the Oahu Shoreline Study are to analyze trends of historical shoreline change, identify future

coastal erosion hazards, and report results to the scientific and management community.

It is vital that coastal scientists produce reliable, *i.e.*, statistically significant and defensible, erosion rates and hazard predictions if results from shoreline change studies are to continue to influence public policy. To further this goal, Frazer *et al.* (2009) and Genz *et al.* (2009) have developed polynomial methods for calculating shoreline change rates. The new methods may calculate rates that are constant in time or rates that vary with time (acceleration, both increasing and decreasing). The polynomial models without rate acceleration are generally referred to as PX models (for polynomials in the alongshore dimension, X) and the models with rate acceleration are PXT (polynomials in X and time). The PX methods, with a linear fit in time, best characterize the trend of the whole time series of historical shorelines and, therefore, describe the long-term change at a beach. The PXT methods may provide additional information about recent change at a beach and can show how rates may have varied with time. These methods are shown here and in the Frazer *et al.* and Genz *et al.* papers (2009) to produce statistically

significant shoreline change rates more often than the commonly used single-transect (ST) method using the same data. Here we employ the polynomial methods to calculate shoreline change rates for the beaches of southeast Oahu.

PHYSICAL SETTING

The study area consists of the northeast-facing beaches along the southeast coast of Oahu, Hawaii. The area is bounded to the north and south, respectively, by basalt Mokapu and Makapuu points (Figure 1). This shoreline is fronted by a broad fringing reef platform extending 1 to 3.5 km from the shoreline except in the far south. The reef crest shallows to -5 to 0 m depth, 0.3 to 1.0 km from shore, along 70% of the study area. This fringing reef protects most beaches from the full energy of open-ocean waves (Bochicchio *et al.*, 2009).

The beaches in the study area face predominantly toward the northeast. The study area is exposed to trade wind swell from the northeast (typically 1–3 m with 6- to 8-second period) throughout the year (Bodge and Sullivan, 1999). Trade winds are most common during the summer (April to September, 80% of the time) and are less persistent, though still dominant, in winter. Moderately high to very high energy refracted long period swells from the north (typically 1–5 m with 12- to 20-second period) impinge in winter. Significant offshore wave heights of 8 m (average of largest one-third of wave heights) recur annually (Vitousek and Fletcher, 2008). The fraction of open-ocean wave energy reaching the inner reef and shoreline varies throughout the study area and is controlled by refraction and shoaling of waves on the complex bathymetry of the fringing reef.

The study area contains four beach study sections, which are additionally subdivided into 14 beach study segments by natural and anthropogenic barriers to sediment transport and/or gaps in reliable shoreline data.

Kailua Beach

Kailua Beach is a 3.5-km crescent-shaped beach bounded to the north by limestone Kapoho Point and to the south by basalt Alala Point. Between Mokapu Point and Kapoho Point is primarily hard limestone and basalt shoreline (no beach). A sinuous 200 m wide sand-floored channel bisects the reef platform. The channel widens toward the shore into a broad sand field at the center of Kailua Beach. The inner shelf and shoreline are protected from large, long period swell by the fringing reef. Wave heights become progressively smaller toward the southern end of Kailua Beach because shallow reef crest and Popoia Island refract and dissipate more of the open ocean swell.

The residential area of Kailua is built on a broad plain of Holocene-age carbonate dune ridges and terrestrial lagoon deposits (Harney and Fletcher, 2003). Low vegetated dunes front many of the homes on Kailua Beach. Kaelepulu Stream empties at Kailua Beach Park at the southern end of Kailua Beach.

For shoreline change analysis, Kailua Beach is divided into two study segments with a boundary at the Kaelepulu stream mouth. The boundary is required because of a gap in reliable

shoreline data at the stream mouth. Shoreline positions from the stream mouth are not considered reliable because they are prone to high variability related to stream flow, and this is not accounted for in our uncertainty analysis.

Lanikai Beach

The Lanikai shoreline is a slightly embayed 2 km wide headland between the basalt outcrops of Alala Point and Wailea Point. Lanikai Beach is a narrow 800 m long stretch of sand in the north-central portion of the Lanikai shoreline. The remainder of Lanikai has no beach at high tide, except for a small pocket of sand stabilized by a jetty in the far south. Waves break against seawalls in areas without beach.

The fringing reef fronting Lanikai is shallower than the reef fronting the adjacent areas of Kailua and Waimanalo. The shallow reef platform extends 2 km offshore to the Mokulua Islands. Wave heights along the Lanikai shoreline are typically small (<1 m) because of refraction and breaking of open-ocean waves on the shallow fringing reef and shores of the offshore Mokulua Islands. The community of Lanikai is built on the foot of the basalt Keolu Hills and on a narrow coastal plain composed of carbonate sands and terrigenous alluvium (Sherrod *et al.*, 2007).

Bellows and Waimanalo Beach

Bellows and Waimanalo Beach is a nearly continuous 6.5 km long beach extending from near Wailea Point to southern Waimanalo. In the northern end of the Bellows shoreline (from Wailea Point 700 m to the south), waves break against stone revetments at high tide. The beach was lost to erosion in the northern portion by 1996. The beach is partially interrupted at two other locations by stone jetties at Waimanalo Stream and remains of a similar structure at Inaole Stream.

A broad reef platform extends to a shallow reef crest 1.5–0.5 km offshore. Paleochannels, karst features, and several large depressions on the reef platform contain significant sand deposits and likely play an important role in storage and movement of beach sand (Bochicchio *et al.*, 2009). Bellows Field and the town of Waimanalo are built on a broad plain of carbonate and alluvial sediments.

Bellows and Waimanalo Beach are divided into three study segments for analysis with boundaries at the Waimanalo and Inaole stream mouth jetties. These boundaries are needed because of gaps in reliable shoreline data at the stream mouths, though sand is undoubtedly transported around the jetties.

Kaupo and Makapuu Beaches

Between Southern Waimanalo and Makapuu beaches are a series of narrow pocket beaches separated by natural and anthropogenic hard shoreline, which divide this study section into eight beach segments for shoreline change analysis. The broad carbonate coastal plain found to the north is absent from most of this section. The steep basalt Koolau cliffs rise within a few hundred meters behind the shoreline. Beaches in the northern two-thirds of the study section are generally narrow (5–20 m). Seawalls front homes along the northern

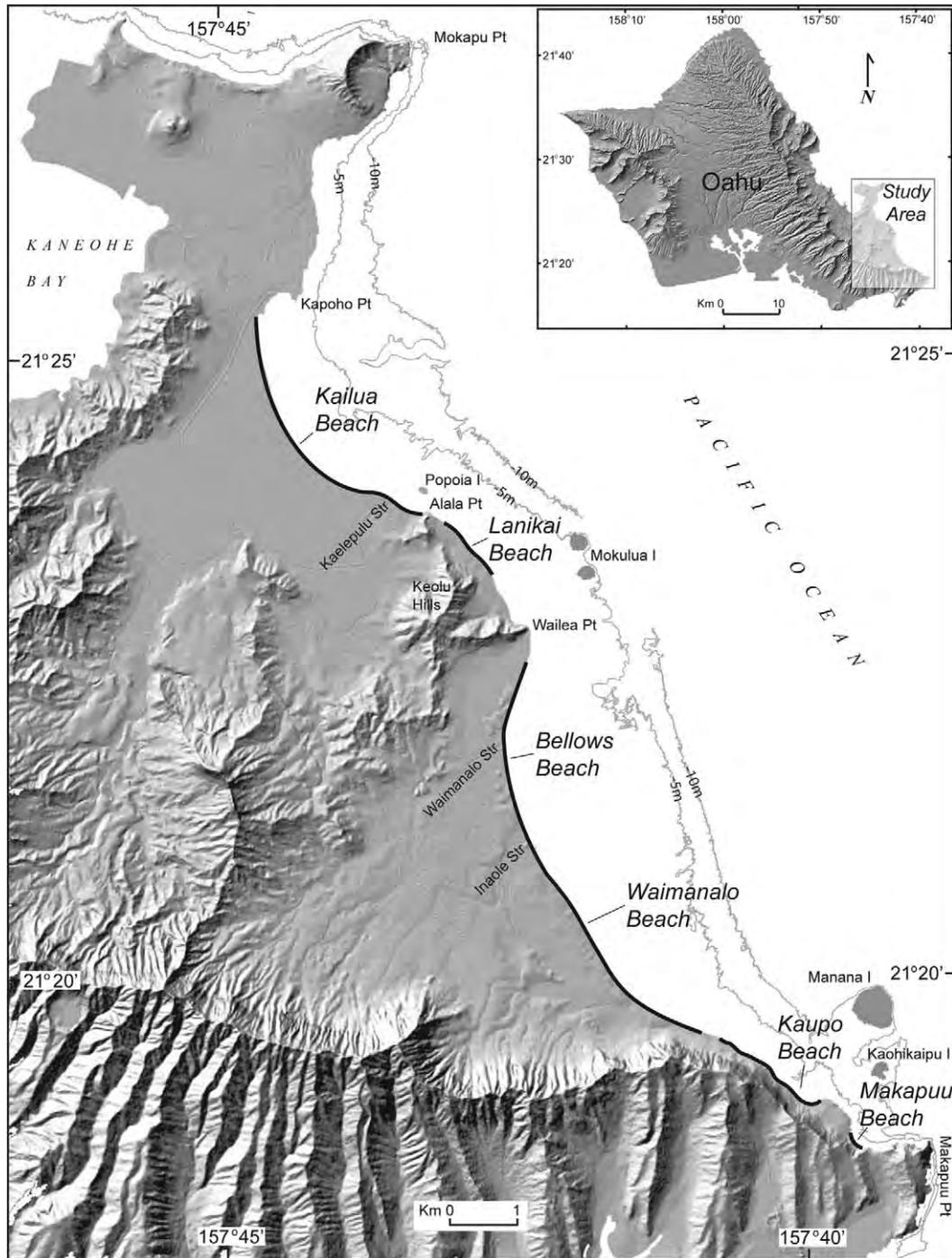
Romine *et al.*

Figure 1. Southeast Oahu study area and beaches. The -5- and -10-m bathymetry contours mark the approximate seaward edge of the nearshore reef platform.

portion of Kaupo Beach. To the south the beaches are backed by a low rock scarp (1–2 m) or by man-made revetments.

Along Kaupo Beach the shallow fringing reef blocks most wave energy. The fringing reef disappears offshore of Makapuu Beach allowing the full brunt of easterly trade wind

waves and refracted northerly swells to reach the shoreline there. Makapuu Beach, popular with bodysurfers, is well known for its large shore-breaking waves. Makapuu Beach is wide (50 m) and sediment-rich compared with beaches to the north. The back-beach area is characterized by vegetated

dunes sloping against the base of the Koolau cliffs. A sand-filled channel extends offshore.

PREVIOUS WORK

Hwang (1981) was the first to compile historical shoreline change for beaches of Oahu. His study utilized a vegetation line and a waterline as the shoreline proxies. Historical shoreline positions were measured from aerial photographs along shore-perpendicular transects roughly every 1000 ft (328 m). His study reported position changes of the vegetation line from one aerial photo to another and from these the net change in the vegetation line and waterline through the time span of the study. Annual rates were not calculated from the data. Movement of the vegetation line at Kailua Beach indicated long-term (net) accretion along the whole length of the beach. Historical shorelines at Kailua Beach Park indicated erosion between 1971 and 1978. Long-term accretion was found at most transects at Lanikai Beach, except at the north and south ends. Erosion was also noted at north and south Lanikai for the more recent years of historical shorelines (the beach has since disappeared in these areas). Most transects at Bellows and Waimanalo beaches indicated erosion over the long term. Hwang reports the beach was effectively lost (submerged at high tide) at north Bellows Beach by 1980.

Sea Engineering (1988) produced an update to the Hwang (1981) study with a more recent aerial photo set, while using the same methods and transects. More recent aerial photographs (1988) indicated that long-term accretion continued at all transects at Kailua Beach. Erosion slowed or turned to accretion at Kailua Beach Park from 1980 to 1988. Their study reported extensive areas of erosion and beach loss at north and south Lanikai between 1980 and 1988. However, this erosion was not apparent in their shoreline change measurements because the vegetation line was effectively fixed at the seawalls now fronting homes along the eroded portions of the Lanikai shoreline.

Norcross, Fletcher, and Merrifield (2002) calculated annual shoreline change rates and interannual beach volume change at Kailua Beach. They used orthorectified aerial photographs and NOAA topographic maps (T-sheets) to map a low water mark as a shoreline proxy. Annual shoreline change rates were calculated using the single-transect (ST) method. Interannual beach volume changes were calculated using data from beach profile surveys. The study concluded that Kailua Beach experienced annual shoreline accretion from 1926–1996 and recent (prior to 1996) net increase in beach sand volume.

Our study provides an important update and comparison to the results of previous studies. We aim to improve on all of the previous studies by utilizing improved photogrammetric methods for measuring historical shoreline positions and statistical methods for calculating shoreline change rates. In addition, a modern aerial photograph set (2005) provides more recent shoreline positions for our study beaches.

METHODS

Mapping Historical Shorelines

For this study we adhere closely to the methods of Fletcher *et al.* (2003) for mapping historical shorelines on Maui, Hawaii.

Historical shorelines are digitized from NOAA NOS topographic maps (T-sheets) and 0.5-m spatial resolution (pixel) orthorectified aerial photo mosaics. Only large-scale (typically <0.5 m scanned pixel resolution, media-dependent), vertical, survey-quality air photos with sufficient tonal and color contrast to delineate a high-resolution shoreline proxy were chosen for this study. Orthorectification and mosaicking was performed using PCI Geomatics' Geomatica Orthoengine software (2007) to reduce displacements caused by lens distortion, Earth curvature, refraction, camera tilt, radial distortion, and terrain relief. The orthorectification process typically resulted in root mean square (RMS) positional errors of <2 m based on the misfit of the orthorectification model to a master orthorectified image and a digital elevation model (DEM).

New aerial photography of study beaches was acquired in late 2005. Aircraft position (global positioning system locations) and orientation data (*e.g.*, altitude, pitch, roll, and yaw) were recorded in an on-board positional orientation system (POS). The recent images are orthorectified and mosaicked in PCI using polynomial models incorporating POS data and high-resolution (5-m horizontal, submeter vertical) DEMs. The orthorectified 2005 photo mosaics serve as master images for the orthorectification of older aerial photographs.

T-sheets are georeferenced using polynomial mathematical models in PCI with RMS errors <4 m. Rectification of T-sheets is also verified by overlaying them on orthophoto mosaics to examine their fit to rocky shorelines and other unchanged geological features also visible in the modern photography. T-sheet shorelines may be discarded if a satisfactory fit to a hard shoreline cannot be achieved and/or if the RMS error grossly understates the misfit. Previous workers have addressed the accuracy of T-sheets (Crowell, Leatherman, and Buckley, 1991; Daniels and Huxford, 2001; Shalowitz, 1964), finding that they meet national map accuracy standards (Ellis, 1978) and recommending them for use in shoreline change studies as a valuable source for extending the time series of historical shoreline position (National Academy of Sciences, 1990).

The beach toe, or base of the foreshore, is digitized from orthophoto mosaics and is a geomorphic proxy for the low water mark (LWM). The LWM is what we define as the shoreline for our change analysis. Removing or quantifying sources of uncertainty related to short-term (interannual to hourly) changes in shoreline position is necessary to achieve our goal of identifying chronic long-term trends in shoreline behavior. A LWM offers several advantages as a shoreline proxy on Hawaiian carbonate beaches, toward the goal of limiting our uncertainty. Studies from beach profile surveys have shown that a LWM is less prone to spurious position changes typical of other shoreline proxies (*e.g.*, wet-dry line, high water mark) (Norcross, Fletcher, and Merrifield, 2002). The bright white carbonate sands typical of Hawaii beaches often hinder interpretation of water line proxies in aerial photographs—especially in older black and white images with reduced contrast and resolution. The vegetation line was used as the shoreline proxy in some previous Oahu studies (Hwang, 1981; Sea Engineering, 1988). However, on most Oahu beaches the vegetation line is cultivated and therefore often does not track the natural movement of the shoreline. Nonetheless, we create a vector of the vegetation line so that

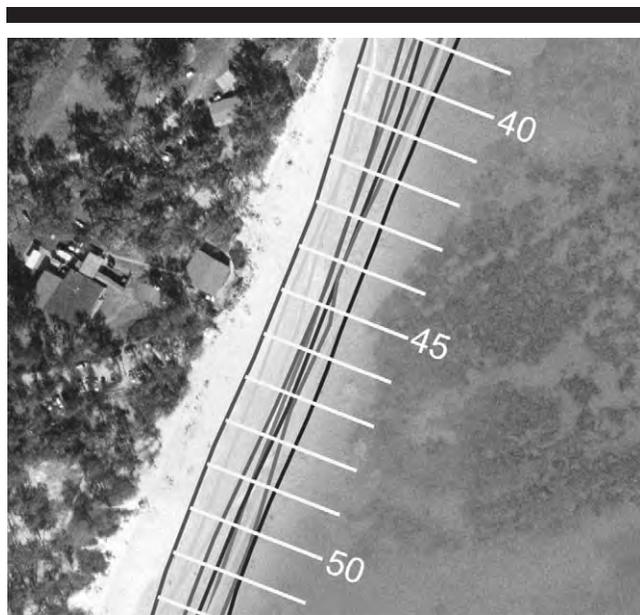


Figure 2. Historical shorelines and shore-perpendicular transects (measurement locations, 20-m spacing) displayed on a portion of a recent aerial photograph.

it is available to track historical changes in beach width between the vegetation line and the LWM.

Surveyors working on T-sheets mapped the high water mark (HWM) as a shoreline proxy. To include the T-sheet shorelines in the time series of historical LWM shorelines, the HWM is migrated to a LWM using an offset calculated from measurements in beach profile surveys. HWM and LWM positions have been measured in beach profile surveys collected at nine locations in the study area in summer and winter for 8 years. The offset used to migrate the T-sheet HWM to a LWM is the median distance between HWM and LWM positions measured in the profiles at a beach or a nearby beach with similar littoral characteristics (e.g., wave exposure, beach morphology).

Six to thirteen historical orthomosaics and T-sheets comprise our time series between 1911 and 2005. To determine patterns of movement, relative distances of the historical shorelines are measured from an offshore baseline along shore-perpendicular transects spaced 20 m apart (Figure 2).

Uncertainties in Shoreline Position

Shoreline position is highly variable on short time scales (interannual to hourly) because of tides, storms, and other natural fluctuations. Procedures for mapping historical shorelines introduce additional uncertainties. It is vital that these uncertainties be identified, rigorously calculated, and included in shoreline change models to ensure that the shoreline change rates reflect a long-term trend and are not biased because of short-term variability (noise). Building on Fletcher et al. (2003), Genz et al. (2007), and Rooney et al. (2003), we calculate seven different sources of error in digitizing historical shoreline position from aerial photographs and T-sheets.

Table 1. Shoreline uncertainties: southeast, Oahu, Hawaii.

Uncertainty Source	± Uncertainty Range (m)
E_d , digitizing error	0.5–5.7
E_p , pixel error, air photos	0.5
E_p , pixel error, T-sheets	3.0
E_s , seasonal error	3.6–6.2
E_r , rectification error	0.6–3.0
E_{td} , tidal error	2.5–3.4
E_{ts} , T-sheet plotting error	5.1
E_{tc} , T-sheet conversion error	3.4–5.7
E_t , total positional error (see text)	4.5–10.8

C1

Identifying the probability distribution (e.g., normal, uniform) for each error process (e.g., tidal fluctuation, seasonal variance) provides the tools to calculate the individual error uncertainty. The total positional uncertainty, E_t , is the root sum of squares of the individual uncertainties. We assume E_t follows a normal distribution because the Central Limits Theorem states that the sum of many sources of uncertainty tends toward a normal distribution (Draper and Smith, 1998). E_t is applied as a weight for each shoreline position when calculating shoreline change models using weighted regression methods. Total positional uncertainties for southeast Oahu historical shorelines are between ±4.5 and ±10.8 m (Table 1). Please note: This is the range of actual uncertainties. No historical shoreline had the highest values for all individual uncertainty sources.

Digitizing Error, E_d . Only one analyst provides the final digitized shorelines from all orthomosaics and T-sheets to ensure consistency in the criteria used to locate each shoreline. Uncertainties in interpreting the shoreline position in aerial photographs are calculated by measuring variability in shoreline position when digitized by several experienced analysts working on a sample portion of shoreline. The digitizing error is the standard deviation of differences in shoreline position from a group of experienced operators. If an E_d value has not been calculated for a particular orthomosaic, a value from a mosaic with similar attributes (e.g., resolution, photo year) is used. E_d values range from ±0.5 to ±5.7 m.

Pixel Error, E_p . The resolution (pixel size) of our orthomosaics limits our ability to resolve the position of a feature (e.g., LWM) finer than 0.5 m. Therefore, E_p equals ±0.5 m. T-sheets are digitally scanned at a lower resolution than aerial photographs. E_p for T-sheets is ±3 m.

Table 2. Average shoreline change rates and ± uncertainties for southeast Oahu beaches.

Beach	ST Avg Rate (m/y)	PX Avg Rate (m/y)	PXT Avg Rate (m/y)
Kailua	0.4 ± 0.2	0.4 ± 0.0	0.1 ± 0.1
Lanikai	0.3 ± 0.2	0.3 ± 0.1	0.5 ± 0.1
Bellows and Waimanalo	0.0 ± 0.3	0.0 ± 0.1	0.0 ± 0.1
Kaupo (all)	-0.1 ± 0.1	-0.1 ± 0.1	0.1 ± 0.1
Makapuu	0.0 ± 0.0	0.0 ± n/a	0.0 ± n/a
Southeast Oahu, all	0.2 ± 0.2	0.1 ± 0.1	0.1 ± 0.1

C2

Rate and uncertainty of all transects averaged along the length of the beach.

Negative = erosion; positive = accretion.

n/a = not applicable.

Seasonal Error, E_s . We do not attempt to identify and remove storm shorelines based on *a priori* knowledge of major storm and wave events for two reasons. One, our study (and most shoreline studies) have limited historical shoreline data (e.g., aerial photography years) and removing one or more shorelines comes at the cost of reducing an already limited data set. Two, storms tend to affect shoreline position in a nonuniform manner in an island setting. Instead, we calculate an uncertainty in shoreline position due to seasonal changes (waves and storms). To measure seasonal variability, we surveyed beach profiles summer and winter for 8 years at 33 beaches on Oahu. The seasonal change is the difference between shoreline (LWM) positions along a survey transect between summer and winter. A randomly generated uniform distribution (>10,000 points) is calculated incorporating the standard deviation of the measured seasonal changes. A uniform distribution is an adequate approximation of the annual probability of shoreline positions resulting from seasonal fluctuations because an aerial photo has equal probability of being taken at any time of year. The seasonal error, E_s , is the standard deviation of this randomly generated distribution. For beaches without profile data, an E_s value from a nearby beach with similar littoral characteristics is used. E_s values range from ± 3.6 to ± 6.2 m.

Rectification Error, E_r . Aerial photographs are orthorectified to reduce displacements caused by lens distortion, Earth curvature, camera tilt, and terrain relief using PCI Orthoengine software. The software calculates an RMS error from the misfit of the orthorectification model to the master orthorectified image and DEM. E_r values range from ± 0.6 to ± 3.0 m for orthophoto mosaics. T-sheets are georeferenced in PCI Orthoengine using polynomial models. E_r for T-sheets ranges from ± 1.4 to ± 2.9 m.

Tidal Fluctuation Error, E_{td} (aerial photographs, only). Aerial photographs are obtained without regard to tidal cycles, and the time of day each photo is collected is typically unknown, resulting in inaccuracies in digitized shoreline position from tidal fluctuations. Rather than attempting to correct the shoreline position, the possible fluctuations due to tides are included as an uncertainty. Hawaii is situated in a microtidal zone of the Pacific Ocean with maximum tidal fluctuations of 1 m. Therefore, tides have less of an effect on shoreline position at Hawaii beaches than at most beaches on the continental United States, where tides typically vary by several meters. Surveys of the horizontal movement of LWMs (beach toe) between a spring low and high tide at three beaches in the study area found that the beach toe migrated horizontally landward 8 to 12 m from low to high tide. The probability of an aerial photograph being taken at low or high tide is assumed to be equal. Thus, a uniform distribution is a conservative estimate of the probability distribution of LWM positions due to tidal fluctuation in an aerial photograph. E_{td} is the standard deviation of a randomly generated uniform distribution derived from the standard deviation of the surveyed tidal fluctuations. E_{td} values range from ± 2.5 to ± 3.4 m for this study.

T-Sheet Plotting Error, E_b (T-sheets only). Surveyors working on T-sheets mapped the high water mark (HWM) as a proxy for shoreline position. The T-sheet plotting error is

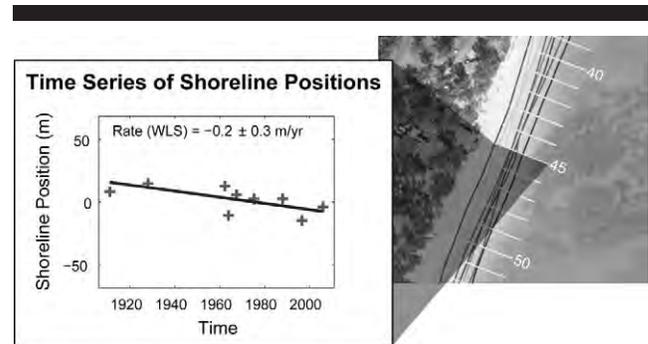


Figure 3. Calculating shoreline change rate using the single-transect (ST) method (weighted least squares regression, WLS). The slope of the line is the annual shoreline change rate.

based on Shalowitz's (1964) analysis of topographic surveys. He identifies three major errors in the accuracy of these surveys: (1) measuring distances, ± 1 m; (2) plane table position, ± 3 m; and (3) delineation of the high water line, ± 4 m. The total plotting error, E_{tsp} , for all T-sheets is the root sum of squares of the three distinct errors, ± 5.1 m.

Conversion Error for T-Sheets, E_{tc} (T-sheets only). To compare historical shorelines from T-sheets and aerial photographs, we migrated the surveyed HWM from a T-sheet to a LWM position using data from beach topographic profile surveys. The offset used to migrate the T-sheet HWM to a LWM is the median distance between HWM and LWM positions measured in surveys at a beach. The uncertainty in this conversion, E_{tc} , is the standard deviation of the distances between surveyed HWM and LWM positions. For beaches without profiles, the offset and E_{tc} value from a similar nearby littoral areas is used (Fletcher *et al.*, 2003). E_{tc} values for southeast Oahu range from ± 3.4 to ± 5.7 m.

Calculating Shoreline Change Rates

Single Transect

In previous studies, our research team and other coastal research groups have utilized the single-transect (ST) method to calculate shoreline change rates (e.g., Fletcher *et al.*, 2003; Hapke *et al.*, 2006; Hapke and Reid, 2007; Morton and Miller, 2005; Morton, Miller, and Moore, 2004) (Figure 3). ST calculates a shoreline change rate and rate uncertainty at each transect using various methods to fit a trend line to the time series of historical shoreline positions (e.g., end point rate, average of rates, least squares).

Our group employs weighted least squares regression with the ST method, which accounts for uncertainty in each shoreline position when calculating a trend line (Fletcher *et al.*, 2003; Genz *et al.*, 2007). The weight for each shoreline position is the inverse of the total shoreline positional uncertainty squared (e.g., $w_i = 1/E_i^2$). Shoreline positions with higher uncertainty will, therefore, have less of an influence on the trend line than data points with smaller uncertainty. The slope of the line is the shoreline change rate. Model (rate) uncertainties are calculated at the 95% confidence interval.

Recent work by Frazer *et al.* (2009) and Genz *et al.* (2009)

identifies a number of shortcomings with the ST method. ST tends to overfit the data by using more mathematical parameters than necessary. Models that overfit data are unpar-simonious. The principle of parsimony, when applied to mathematical modeling, states that a model with the smallest number of parameters that provides a satisfactory fit to the data is preferred. Satisfactory fit is quantified by minimizing the residuals of the model fit. The classic example of an unpar-simonious model is an $n - 1$ degree polynomial used to fit n noisy data points: The model fit to the data is perfect, but the model is so sensitive to noise that its predictions are usually poor. The problem of overfitting with ST is made worse by limited data (often less than 10 historical shore-lines) and high uncertainty (noise) in shoreline positions, both typical of shoreline studies.

Another problem with the ST method is that it treats the beach as if it were a set of isolated blocks of sand centered on each transect, which do not share sand with adjacent transects and move independently of adjacent transects. However, on an actual continuous beach, the positions of each transect share sand with adjacent positions along the shore. Thus, the shoreline positions and shoreline change rates at each transect on a beach are related. Shoreline transects need to be closely spaced to effectively characterize shoreline change along a beach. We use a 20-m transect spacing for easy comparison of our methods and results with other recent studies.

The rates calculated using the ST method tend to have high uncertainty because ST is modeling shoreline change independently at each transect. High rate uncertainty can result in rates at many transects that are not statistically significant. For this study we consider a rate to be insignificant if it is indistinguishable from a rate of 0 m/y (*i.e.*, \pm rate uncertainty overlaps 0 m/y). If we can reduce the uncertainty in shoreline change rates, we will aid coastal managers in making better-informed decisions in planning for future erosion hazards.

Polynomial Methods

Here we provide a summary of the recently developed polynomial methods to assist the reader in interpreting the results and conclusions in this study. Please refer to Frazer *et al.* (2009) and Genz *et al.* (2009) for more detailed information on these rate calculation methods.

The ST method calculates a rate at each transect by fitting a linear trend to shoreline positions plotted in distance along a transect and time. Shoreline change rates vary independently along the shore (from transect to transect) with the ST method. Polynomials can be used to model this variation in shoreline change rates in the alongshore direction. By modeling shoreline data in the alongshore direction as well, we can incorporate shoreline positions from all transects on a beach in a single model. The single model will invariably require fewer mathematical parameters to calculate change rates at each transect than the ST method, leading to more parsimonious models (reducing overfitting). In addition, a single polynomial model correctly assumes that the shoreline data from adjacent transects is related (*e.g.*, dependent).

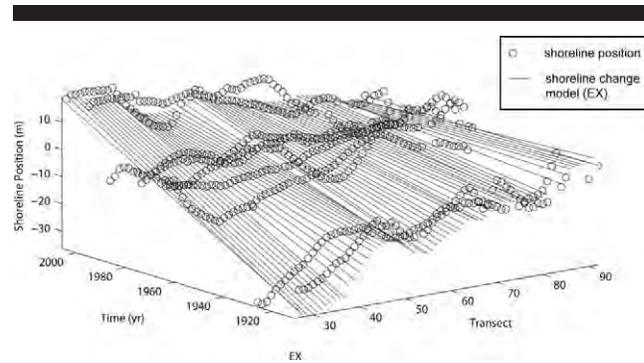


Figure 4. PX (EX) shoreline change model for North Bellows Beach. Rates (slope) vary continuously in the alongshore direction but are constant (linear) in time (no acceleration).

Frazer *et al.* (2009) and Genz *et al.* (2009) have developed polynomial shoreline change rate calculation methods that include the alongshore variation of shoreline change rates in their models. These methods build polynomial models in the alongshore direction using linear combinations of mathematical basis functions. These methods employ data from all transects along a beach to calculate a rate at any one location. Similar to ST, a line is fit in the time and cross-shore dimension at each transect. However, unlike ST, calculation of this line is dependent on data from all transects on a beach.

The polynomial methods allow detection of rate variations (acceleration in time), in addition to modeling rate variations spatially alongshore. Detecting acceleration in the rates is easier with these methods because of the reduced number of parameters in the model compared with ST. The \pm uncertainties with the rates calculated using the polynomial methods are invariably lower than with the ST method because they use all of the data on a beach to calculate the rates. Thus, the basis function methods produce statistically significant rates at a higher percentage of transects than ST.

The polynomial methods use one of three types of basis functions, combined in a finite linear combination, to build a model for the alongshore variation of rates. All of the methods use generalized least squares regression (GLS) to calculate the parameters of the model. GLS incorporates the uncertainty (E_i) of each shoreline position in weighting each shoreline's influence on the model. LXT uses Legendre polynomials as the basis functions. RXT utilizes trigonometric functions (*e.g.*, sines and cosines) as the basis functions. EXT, also known as "eigenbeaches" utilizes eigenvectors (*i.e.*, principal components) of the shoreline data as the basis functions. The eigenvectors are calculated from the shoreline data using all transects on a beach.

Models that do not include acceleration in their rates are referred to as LX, RX, and EX, respectively. Generally, we refer to these as PX models (Figure 4). The rates from PX models are constant in time but vary continuously in the alongshore direction. The rates from the LXT, RXT, and EXT models vary continuously with time as well as in the alongshore dimension, and we refer to these models generally as PXT models (Figure 5). A PXT model that does not identify

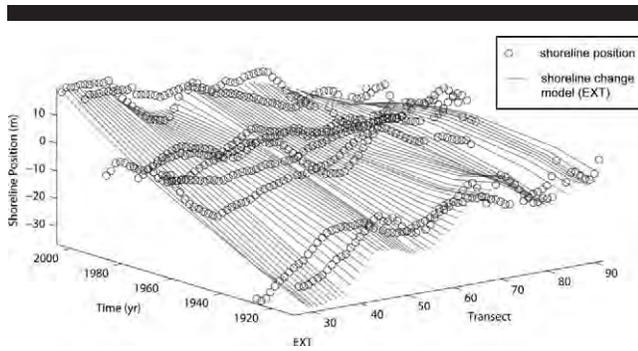


Figure 5. PXT (EXT, includes acceleration in the rate with time) shoreline change model for North Bellows Beach. Rates (slope) vary continuously in the alongshore direction and with time.

acceleration in the rates at a particular beach reverts to a PX model.

Rates are first calculated using the ST method for comparison with the rates from the PX and PXT rates. In addition, results from the ST model are used in estimating the spatial (alongshore) correlation of the noise for the polynomial models. A decaying exponential function is fit to the autocorrelation of the ST data residuals. The best-fit exponential decay function is incorporated in the alongshore polynomial model to represent decreasing dependence of the shoreline data with distance from each transect.

With the Matlab codes developed by Frazer *et al.* (2009) and Genz *et al.* (2009), many possible models are calculated for the three basis function model types, with and without acceleration in the rates (LXT, RXT, EXT, LX, RX, EX). The models vary in the number (parameters) of basis functions of each type used in linear combination.

An information criterion (IC) is used to compare the parsimony of the various models. We use a version of Akaike information criterion (AIC_u) (Burnham and Anderson, 2002; Frazer *et al.*, 2009; Genz *et al.*, 2009). In general, an IC is a comparative statistic or score based on the residual errors of the model (*i.e.*, “goodness of fit”) and the number of mathematical parameters used in the model. As a measure of parsimony or, more accurately, the lack of it, the IC score is increased for models with a greater number of model parameters and reduced for improved fit to the data. The model with the lowest IC score is the most parsimonious model and is the best model to describe shoreline change at a beach. A model with a rate of 0 m/y (showing no change) is also given an IC score for comparison with the models with rates.

The IC scores are used to select the best model within each of the six polynomial model types (LXT, RXT, EXT, LX, RX, EX). The ST model and its IC score are calculated for comparison with the polynomial models. The polynomial models invariably produce results with lower IC scores than ST. Rates from the seven model types (including ST) are plotted together for comparison (Figure 6a), providing a qualitative assessment of the agreement of the rates from the various models. The results may be considered more robust if most or all of the models agree in their rates.

We attempt to provide the best information about long-

term and more recent shoreline change occurring at a beach to help shoreline managers in planning for future erosion hazards. The favored model among the PX models (*i.e.*, models without rate acceleration) and the PXT models (*i.e.*, models with rate acceleration) are identified using IC scores. The PX models provide a better assessment of the trend of the whole time series of historical shorelines. Inspection of PXT models shows that these models typically capture the trend of the most recent few shorelines. Therefore, we use the PX models to estimate the long-term rate and the PXT models to obtain additional information about more recent shoreline change and how the rates may have varied with time. As with the ST method, bounds for the rates are calculated at the 95% confidence interval.

Using the PXT models we attempt to identify erosion hazards not recognized by the PX models. For example, a beach that is shown to be accreting over the long term (with PX) may still present a future erosion hazard if the PXT model indicates the rate of accretion is slowing (decelerating). Conversely, a beach that is eroding presents less of a future erosion hazard if the PXT model indicates the erosion rate is decelerating. We use the rate acceleration from the PXT models to provide more information about the “fitness” of the littoral sediment budget at a beach. Beaches with decelerating erosion rates and accelerating accretion rates have improving fitness because these beaches present less of a future erosion hazard. Beaches with accelerating erosion rates and decelerating accretion rates have deteriorating fitness because they present a greater future erosion hazard.

Rates presented from the PXT models (*e.g.*, Figure 6) are from time of the most recent shoreline and are referred to as the “present rate.” This distinction is important because the rates from the PXT models can vary with time and a rate may be calculated for any point in the time series of historical shorelines. In any case, it is helpful to compare the model fit to individual transect plots (ST) to better understand the shoreline change behavior through time as described by the PX and PXT models.

Shoreline change rates are reported to the nearest tenth of a meter resulting in some rates with uncertainty ± 0.0 m/y. To clarify for the reader, these rates do not have zero uncertainty. This is simply a result of rounding to the nearest tenth of a meter.

RESULTS

Historical Shoreline Change

Kailua Beach

The EX shoreline change model has the lowest IC score among the PX (nonaccelerated) models at both beach study segments at Kailua Beach (separated by Kaelepulu Stream). The EX method calculates erosion rates similar to those of the ST method (Figure 6b–6d), indicating long-term accretion throughout most of Kailua Beach. However, the average rate uncertainty is reduced with the EX model compared with the ST model (± 0.1 m/y *vs.* ± 0.2 m/y, respectively) (Table 1), resulting in a greater percentage of transects that have significant rates with the EX model (Figure 7).

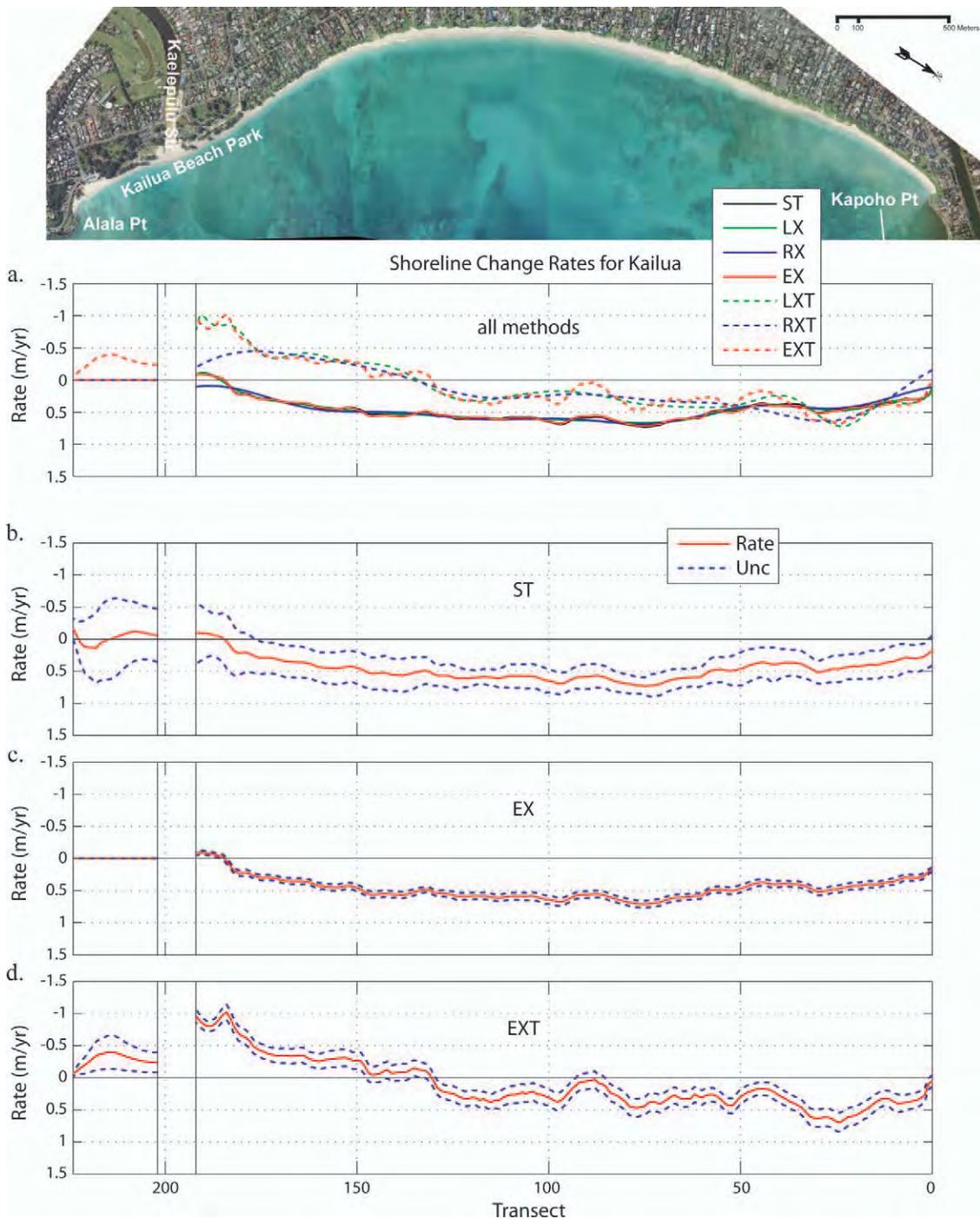


Figure 6. Shoreline change rates (m/y) at Kailua Beach, 1928–2005. Negative rates indicate annual erosion. (a) Rates from ST, PX, and PXT models (\pm uncertainties not shown). (b) ST rates with \pm uncertainties. (c) EX (lowest IC score among the PX models) rates with \pm uncertainties. (d) EXT (lowest IC score among the PXT models) rates with \pm uncertainties.

In the segment south of Kaelepulu Stream, the EX model shows no long-term change, in contrast to results from the ST model and previous studies. The selection of an EX model (based on IC scores) that shows no significant change may be interpreted two ways. One, the historical shorelines data for

this portion of beach is too highly variable (noisy) to calculate a statistically significant long-term trend. Or, two, this segment of beach is stable in the long term, and any erosion or accretion is episodic within the time frame of the study. The ST method (which always produces a model with rates) has

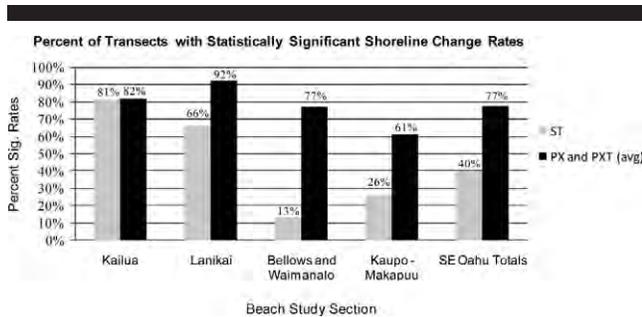


Figure 7. Percentage of transects with statistically significant shoreline change rates using the ST method and PX and PXT methods. Statistically significant rates are those with a \pm uncertainty that does not overlap a rate of 0 m/y.

higher rate uncertainties in this segment, further suggesting a highly variable data set. High uncertainty with the ST model results in insignificant rates (\pm uncertainties overlap 0 m/y) at all transects, essentially in agreement with the EX model results showing no long-term change.

EXT has the lowest IC score among the PXT models. In contrast to ST and EX, EXT estimates recent erosion at Kailua Beach Park with rates up to -1.0 ± 0.1 m/y. EXT also indicates that the extent of erosion may be spreading north from Kailua Beach Park toward central Kailua. Recent beach erosion (2006–2008) has cut a scarp and undermined trees in the beachfront dunes at Kailua Beach Park. Looking at the movement of historical shorelines in an individual transect plot from Kailua Beach Park, we see a previous episode of accretion from 1947 to 1967 and erosion from 1967 to 1978 (Figure 8). According to the EXT model, erosion rates at Kailua Beach Park have been accelerating since the late 1960s or early 1970s. Inspection of the shoreline data in the transect plots shows that the trend toward erosion probably began more recently, beginning with the 1988 or 1996 historical shoreline.

EXT results for Kailua Beach provide a warning of potential erosion hazards not indicated by the EX model. EXT results indicate recent accelerating erosion at 39% of transects (all in the south). EXT also shows recent decelerating accretion at 48% of transects (in the center area). These transects could become erosive if the trend of deceleration continues. Therefore, based on EXT results, the fitness of the littoral sediment budget along most of Kailua Beach (87% of transects) has recently deteriorated.

Lanikai

At Lanikai, 1229 m of beach were lost to erosion in the time span of this study (306 m at north Lanikai, 923 m at south Lanikai) (Figures 9a–9c). Present-day Lanikai Beach is bounded on both ends by extensive seawalls constructed in areas where the beach has been lost to erosion. Aerial photographs show the beach at north Lanikai was completely lost to erosion between 1975 and 1982 and has not returned. At south Lanikai, the shoreline advanced seaward between 1949 and 1975 forming an accretion point similar in size to the

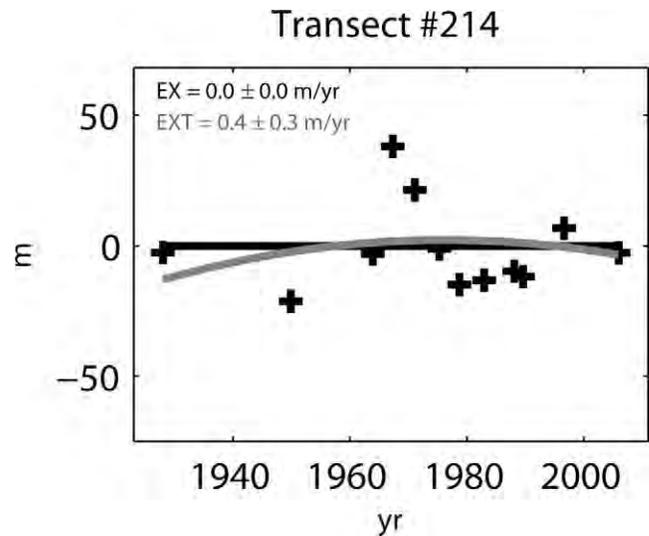


Figure 8. Individual transect plot (transect 214) from Kailua Beach Park showing the fit of the EX and EXT model. Note apparent previous episode of accretion (1949–1967) and erosion (1967–1978).

accretion point presently growing in the north-central portion of Lanikai Beach. Accretion ended and erosion took over in the late 1970s and much of the beach was lost by 1989. We

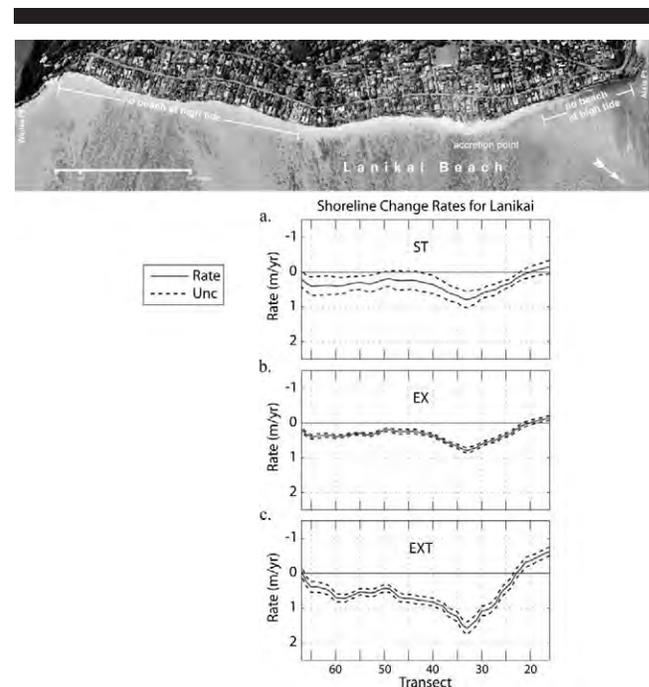


Figure 9. Shoreline change rates (m/y) at Lanikai Beach, 1911–2005. Negative rates indicate annual erosion. (a) ST rates with \pm uncertainties. (b) EX (lowest IC score among the PX models) rates with \pm uncertainties. (c) EXT (lowest IC score among the PXT models) rates with \pm uncertainties.

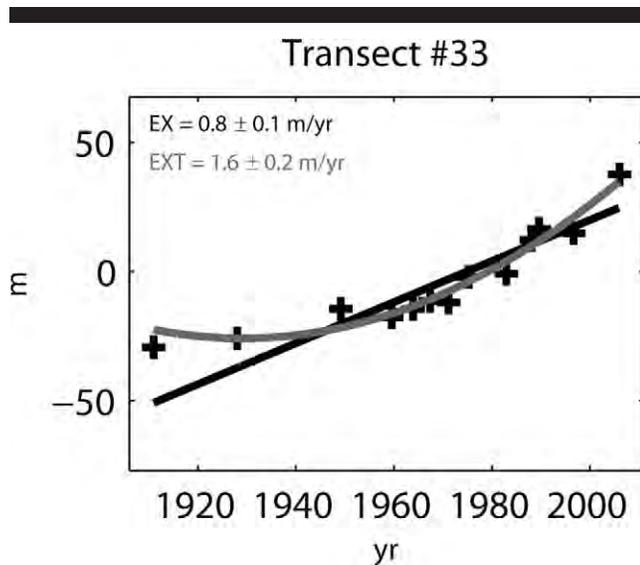


Figure 10. Individual transect plot (transect 33) from north-central Lanikai Beach. The EXT model results indicate accelerating accretion in this area beginning prior to 1949.

calculate shoreline change rates only for the remaining portion of Lanikai Beach.

At Lanikai, the EX model has the lowest IC score among the PX models. EX measures long-term accretion at all transects at Lanikai Beach, except for a small area of erosion at the northern end of the beach. EX calculates the highest accretion rates (up to 0.8 ± 0.1 m/y) aligned with the middle of the accretion point in the north central portion of the beach.

The EXT model has the lowest IC score among the PXT models at Lanikai Beach. Similar to EX, the EXT model calculates the highest accretion rates (up to 1.6 ± 0.2 m/y) at the center of the accretion point in north central Lanikai Beach. The EXT model indicates accelerating erosion at the north end of Lanikai Beach. Based on the EXT model, the central portion of Lanikai Beach began undergoing accelerating accretion prior to 1949 (Figure 10). The EXT model at the southernmost transects indicates that accretion is slowing in this area and may be turning to accelerating erosion. Recent beach profile surveys have shown that the extent of beach loss in south Lanikai continues to expand to the north. All of Lanikai Beach could eventually disappear if the pattern of encroaching beach loss continues.

Bellows and Waimanalo Beaches

At north Bellows (Figure 11), the northern end (690 m) of the beach was lost to erosion prior to 1996. Waves break against stone revetments at high tide in this area. At the remaining portion of north Bellows Beach (Wailea Point to Waimanalo Stream) and central Bellows Beach (Waimanalo Stream to Inaole Stream), the EX model has the lowest IC score among the PX models. At south Bellows and Waimanalo beaches (Inaole Stream to Kaiona Beach Park) (Figure 12), the LX model has the lowest IC score among the PX models.

The EX model indicates long-term erosion at nearly all

transects at north Bellows with the highest erosion rates at the northern end of the beach (up to -0.4 ± 0.1 m/y). The EX model at central Bellows indicates long-term erosion in the northern half of the beach study segment and long-term accretion in much of the southern half of the segment. At south Bellows and Waimanalo the LX model indicates long-term accretion in the northern half of this beach study segment and an area of long-term erosion (up to -0.4 ± 0.1 m/y) in the south at Kaiona Beach Park. Again, the alongshore pattern of shoreline change rates from PX models is similar to rates from the ST model. However, the PX models result in a higher percentage of transects with significant rates because the rate uncertainties are reduced compared with ST results.

EXT has the lowest IC scores among the PXT models in the three study segments at Bellows and Waimanalo beaches. In the northern end of Bellows Beach (area of beach loss) the EXT model indicates accelerating erosion throughout the time series of historical shorelines (Figure 13), with the highest rates at the north end of the beach adjacent to the revetments (up to -0.7 ± 0.2 m/y). The extent of recent erosion indicated by the EXT model in northern Bellows is similar to the extent of erosion indicated by the ST and EX models. Agreement among the three models in this area further supports the indication that the remaining beach at north Bellows is threatened by continued erosion and potential beach loss. The EXT model indicates accelerating accretion in the south of the north Bellows segment (against Waimanalo Stream jetty), suggesting that eroded sediment is being transported from the north end of the beach to the south and is accumulating against the jetty.

In the south Bellows and Waimanalo segment, the EXT model indicates a pattern of recent erosion that is significantly different than indicated by the ST and LX models over the long term. At the south end of Bellows Field Beach Park, the EXT model finds an area of recent erosion with rates up to -0.7 ± 0.1 m/y. Recent (1994–2007) biannual beach profile surveys near the middle of this erosive area (as modeled by EXT) do not indicate significant erosion in this area. The EXT model indicates recent accretion in the south of Waimanalo Beach near Waimanalo Bay Beach Park. Beach profile surveys (1994–2007) at Waimanalo Bay Beach Park have shown recent erosion, evidenced by a steep scarp in the beachfront dunes causing undermining of large trees on the dunes. The EXT models and beach surveys at south Bellows and Waimanalo provide a warning that this beach may be subject to episodic erosion even if the beach is relatively stable over the long term (as modeled by ST and LX).

The EXT models indicate recent accelerating erosion at 43% of transects and recent decelerating accretion at 14% of transects. Thus, the EXT models indicate deteriorating fitness of the littoral sediment budget at 57% of transects at Bellows and Waimanalo beaches. The areas of deteriorating fitness are in the northern portion of each of the three beach study segments, whereas the areas of improving fitness (43% of transects) are in the south of each study segment.

Kaupo and Makapuu Beaches

At Kaupo and Makapuu beaches the ST models and PX find a similar alongshore pattern of shoreline change for all

Southeast Oahu Shoreline Study

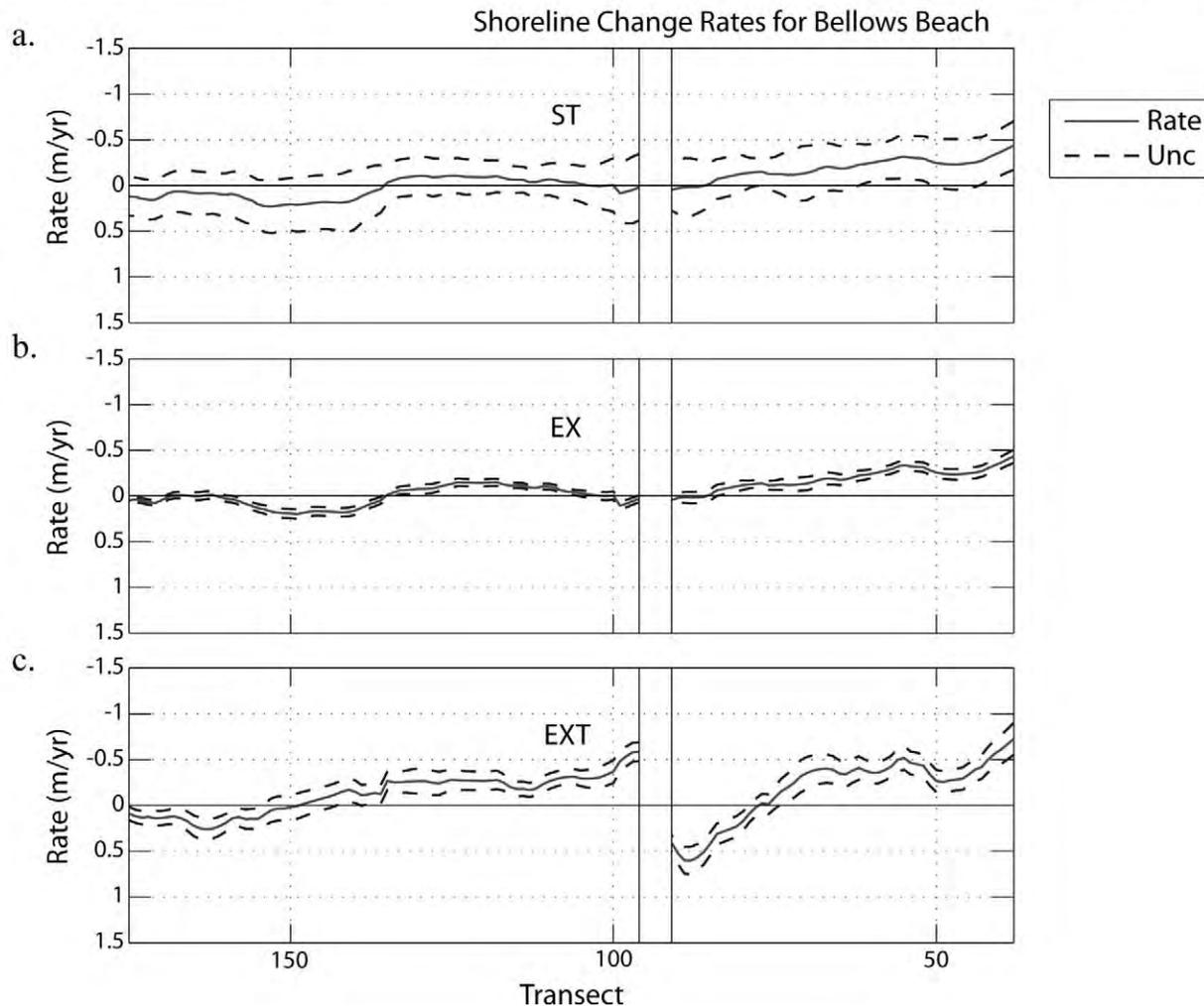


Figure 11. Shoreline change rates (m/y) at Bellows Beach, 1911–2005. Negative rates indicate annual erosion. (a) ST rates with \pm uncertainties. Note the high number of transects with insignificant rates (\pm rate uncertainties overlap 0 m/y) with ST at this beach. (b) EX (lowest IC score among the PX models) rates with \pm uncertainties. (c) EXT (lowest IC score among the PXT models) rates with \pm uncertainties.

beaches, except at Kaupo Beach Park (Figures 14a–14c). Other than at Kaupo Beach Park, the ST and PX models with the lowest IC scores estimate erosion rates under 0.3 m/y or find no significant change. The rate uncertainty is improved with PX models compared with ST models, resulting in significant rates at a greater percentage of transects. The PXT models with the lowest IC scores detect recent accretion or

find no significant change at all beaches, except Kaupo Beach Park.

At Kaupo Beach Park the RX model has the lowest IC score among the PX models. Here, the RX model finds long-term erosion (up to -1.7 ± 0.2 m/y) at the southern end of the beach and long-term accretion at the northern end of the beach (up to 1.2 ± 0.1 m/y). The LXT model, with the lowest

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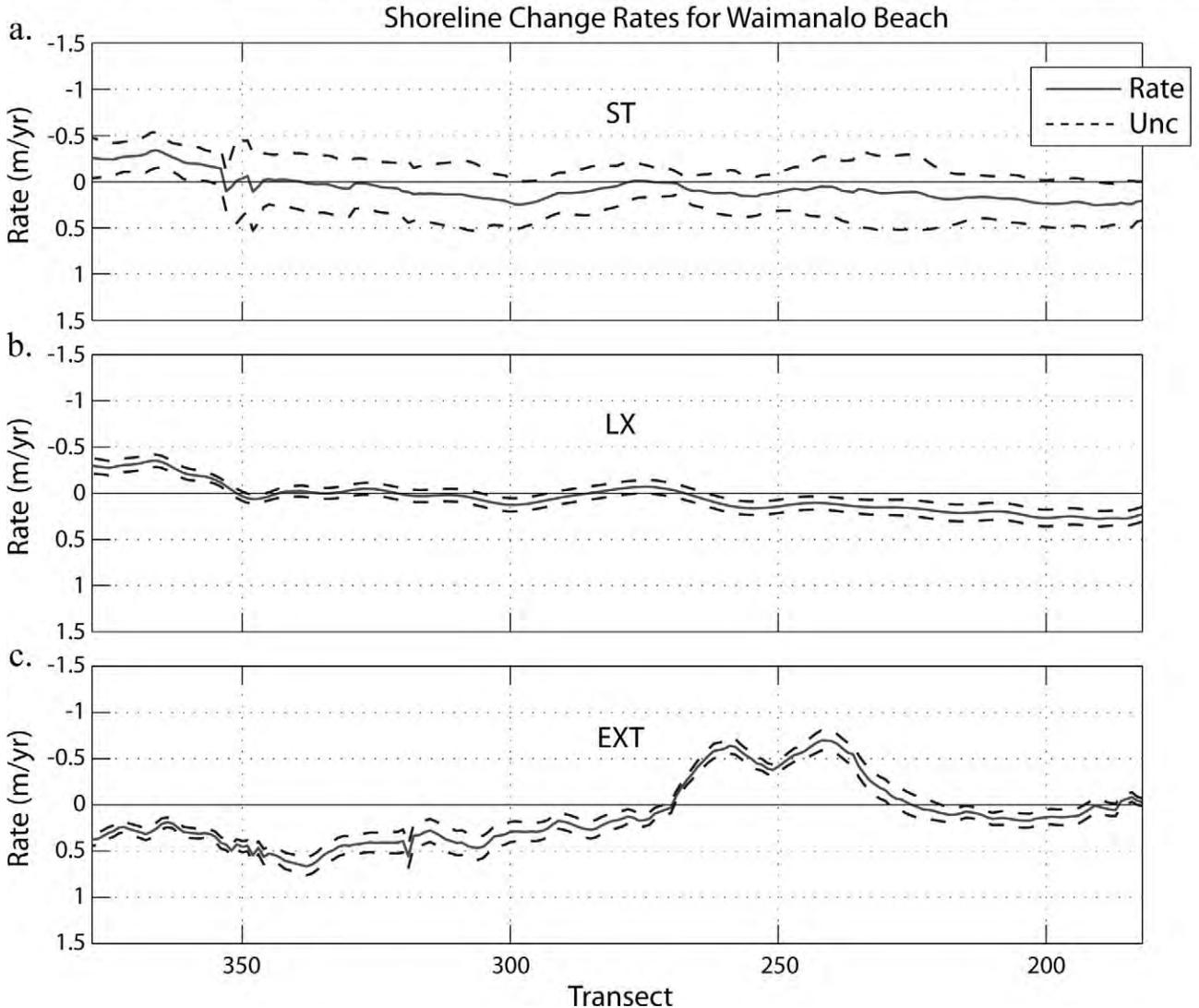


Figure 12. Shoreline change rates (m/y) at south Bellows and Waimanalo beaches, 1911–2005. Negative rates indicate annual erosion. (a) ST rates with \pm uncertainties. Note the high number of transects with insignificant rates (\pm rate uncertainties overlap 0 m/y) with ST at this beach. (b) LX (lowest IC score among the PX models) rates with \pm uncertainties. (c) EXT (lowest IC score among the PXT models) rates with \pm uncertainties.

IC score among the PXT models, indicates a pattern of shoreline change rates at this beach that is similar to the results of the RX model, with erosion in the south and accretion in the north. However, the results of the RX and LXT models do not agree with the results of the ST, EX, nor EXT models

at Kaupo Beach Park, bringing into question the validity of the RX and LXT models at this beach. Nonetheless, the results of the RX and LXT models here point out that Kaupo Beach Park should be monitored closely for future erosion hazards.

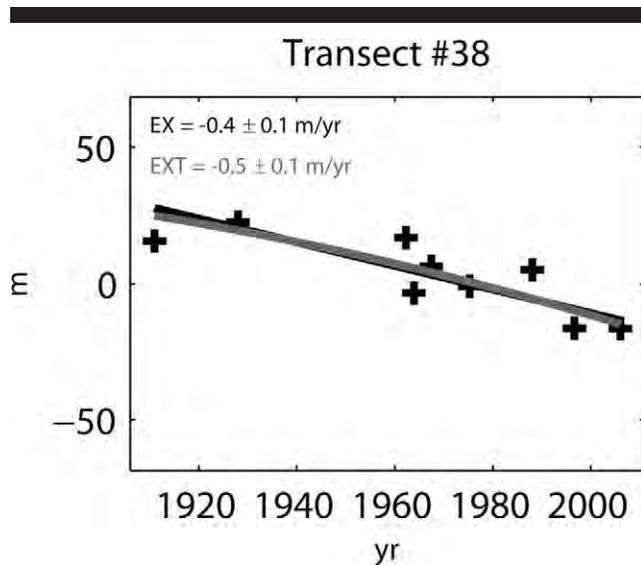


Figure 13. Individual transect plot (transect 38) from northern Bellows Beach. The EXT model results indicate accelerating erosion throughout the time series of historical shorelines in this area.

At Makapuu Beach the PX and PXT models indicating no significant change (rates = 0 m/y) have the lowest IC scores. The LX model (0 m/y) has the lowest IC score among the PX models. The LXT model reverts to the LX model (0 m/y and finds no acceleration) and has the lowest IC score among the PXT models. The ST model rates at Makapuu are statistically insignificant at all transects. Examination of the historical shorelines shows high variability in their position throughout the time span of the study (Figure 15). High seasonal variability is also recorded in beach profile surveys at Makapuu Beach. A lack of available shoreline data (six historical shorelines) for Makapuu may also be limiting our ability to calculate a long-term trend.

DISCUSSION

The EX model has the lowest IC score among the PX models in eight of fourteen beach segments in this study. The EXT model has the lowest IC score among the PXT models in 11 of 14 beach segments. EX and EXT may be calculating models with better fit to the data and fewer parameters because the alongshore polynomial model is composed of basis functions that are derived from the shoreline data itself. The other PX and PXT methods (LX, RX, LXT, RXT), which attempt to fit a series of predetermined mathematical basis functions to the data, often require a greater number of these basis functions (parameters) to produce a satisfactory fit to the data, resulting in higher IC scores. This may be especially true at beaches with one or more sudden sign changes in the shoreline change rates along the shore (e.g., erosion to accretion from one transect to the next). The LX and RX models may fit the shoreline data better where the rates vary smoothly alongshore (e.g., South Bellows and Waimanalo Beach).

Model parameters should be constrained by our knowledge

of the physics and/or limits of a system. For example, periodic phenomena such as tides and waves are best modeled using linear combinations of sine and cosine functions. The temporal dynamics of shoreline change are unknown. Because they are calculated from the beach data, eigenvectors (in EX and EXT) may provide a better description of the unknown dynamics of change at a beach than a model with predetermined basis functions (e.g., LX and RX).

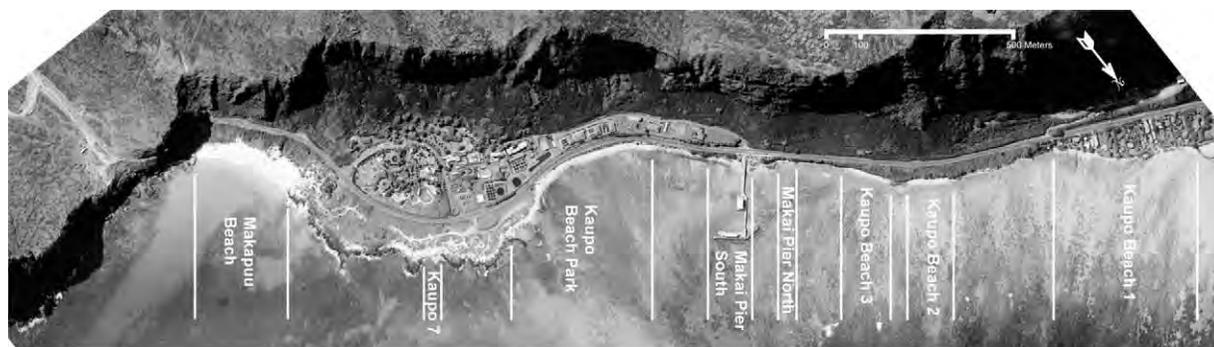
Whether the EX and EXT methods actually produce better shoreline change models at most beaches is an area of ongoing research. Further research could include comparison of predictions of the most recent shoreline(s) in truncated shoreline data sets by the various PX and PXT models, as in Genz *et al.* (2009). Updates to this study using modern shorelines (new aerial photography) are necessary to continue monitoring Oahu's beaches for changes in shoreline trends. New shoreline data may be used to test predictions of future shoreline positions made by the models in this study.

Inspection of the PXT models from this study in individual transect plots shows that the most recent trend of accelerating or decelerating rates, as indicated by these models, is often less than 50 years. In other words, the present rates (i.e., rates from the most recent shoreline time) from the PXT models are strongly influenced by the trend of the last several shorelines. Thus, the PXT models are better suited for describing the recent change at a beach and for showing how the rates may have changed throughout the time series of shorelines. The PX models, with a linear fit to the entire time series of shoreline data, provide a better characterization of the long-term change occurring at a beach.

In three of fourteen beach segments in this study, the model showing no change (0 m/y) had the lowest IC score among the PX models. IC's selection of a model showing no change may be interpreted two ways. One, the historical shoreline data are not adequately configured (not enough shorelines, too much positional uncertainty) to calculate statistically defensible shoreline change rates. Or, two, the beach is stable over the time span of the study. For the purpose of shoreline management, a model without rates provides statistically supported evidence that a beach has not changed significantly in the time span of the study. Thus, a result showing no significant change may be as valuable for erosion hazard planning as a model that indicates significant erosion or accretion.

Here we provide the rates and uncertainties from the PX and PXT model with the lowest IC score. However, the specific goals of an agency's coastal management plan may influence planners to choose another of the parsimonious PX or PXT models for erosion hazard planning. It is important that coastal scientists and coastal managers are clear on what question is being asked regarding shoreline change at a beach before reporting shoreline change results. Are we interested in long-term change or more recent change? Are we looking for the worst-case scenario or the most likely scenario? For example, an agency may determine that the most conservative or safest course is to select the model that calculates the highest erosion rates and predicts the greatest erosion hazard. Or, coastal planners may use results from several shoreline change rate calculation methods to present a range of

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Shoreline Change Rates for Kaupo and Makapuu Beaches

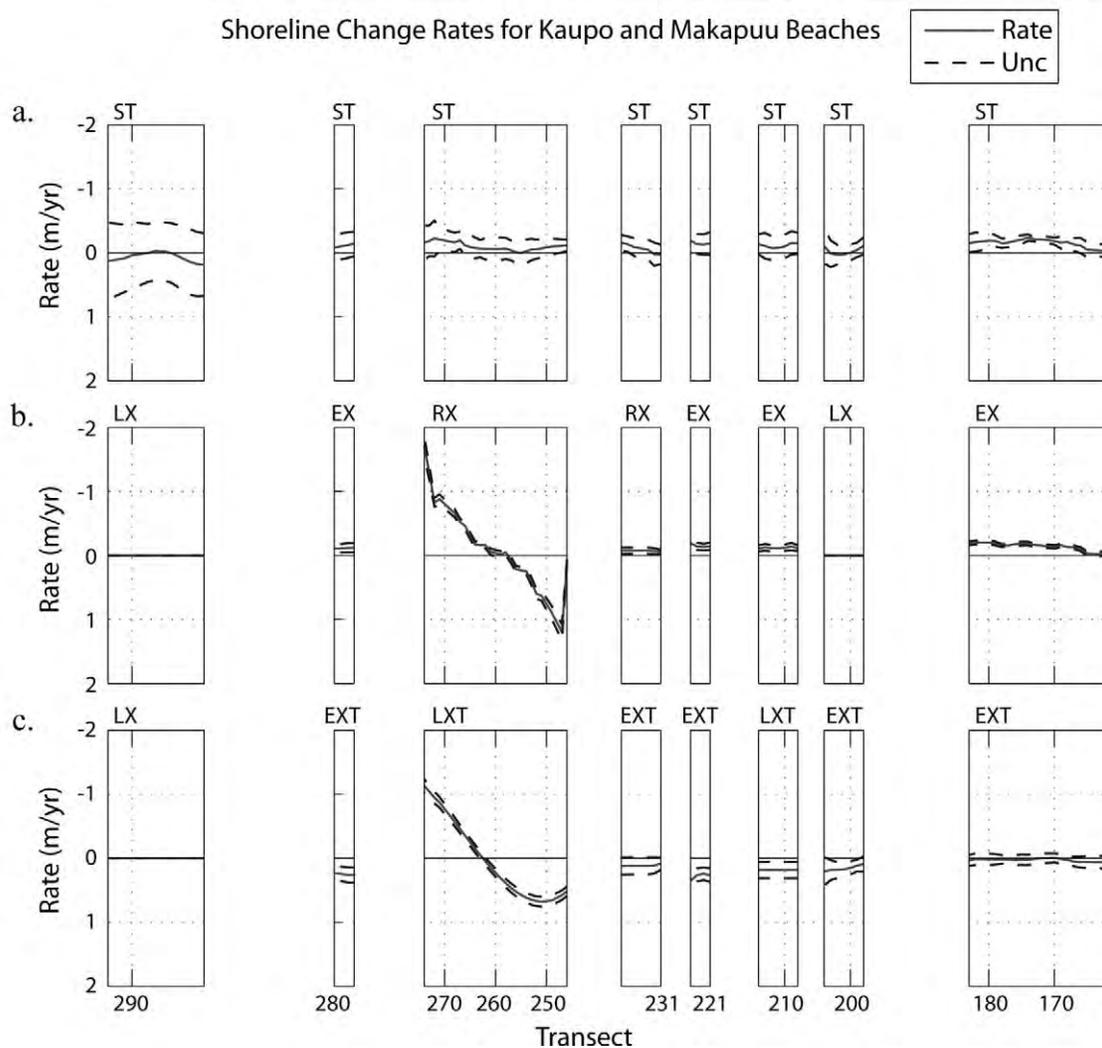


Figure 14. Shoreline change rates (m/y) at Kaupo and Makapuu beaches, 1911–2005. Negative rates indicate annual erosion. (a) ST rates with \pm uncertainties. (b) Rates and \pm uncertainties calculated by PXT model with lowest IC score in each study segment. (c) Rates and \pm uncertainties calculated by PXT model with lowest IC score in each study segment.

possible future shoreline change scenarios. Ultimately, the credibility of erosion rates and erosion hazard forecasts is improved if the results from various shoreline change rate calculation methods agree.

Time series of historical shorelines in this study span near-

ly 100 years. As discussed previously, the recent trend in PXT models often illustrates an erosion or accretion trend of the most recent shorelines (<50 years). Littoral processes along most Hawaiian beaches are driven primarily by waves from frequent easterly trade winds and powerful seasonal swells

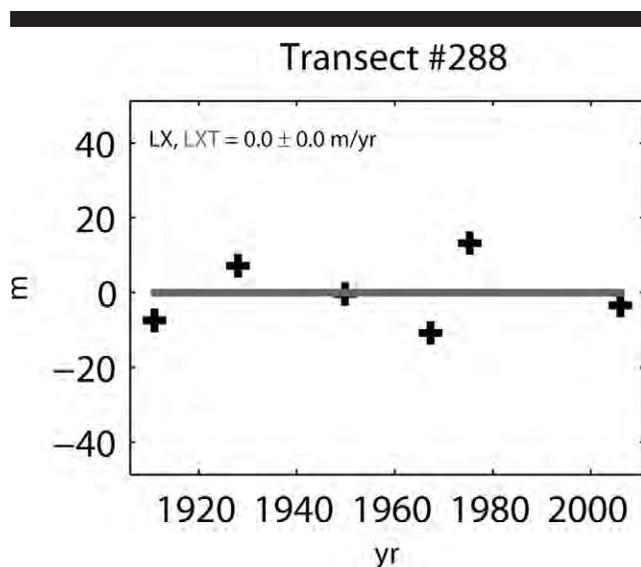


Figure 15. Individual transect plot (transect 288) from Makapuu Beach. The LX and LXT models (with the lowest IC scores among the PX and PXT models) find no significant change at Makapuu Beach, likely a result of the high temporal variability of the shoreline position here.

(Vitousek and Fletcher, 2008). It is possible that some PXT models are detecting shorter term (*e.g.*, decadal) fluctuations in shoreline position related to atmospheric variability (*e.g.*, ENSO, PDO, trade wind oscillations) at some beaches (Rooney *et al.*, 2003), as opposed to chronic, *i.e.*, long-term, shoreline change. An example of this may be the most recent episode of accelerated erosion as modeled by PXT at Kailua Beach Park. There we see at least one other prior episode of erosion and accretion in the movement of the historical shoreline positions. The PXT models (and the PX models) cannot identify multiple erosion and accretion events in a data set. Doing so would require fitting more complex models (*e.g.*, a sinusoid) to a limited shoreline data set, leading to overfitting of the data. In addition, the PXT models are limited by their inability to model the inevitable deceleration that should follow any period of accelerated shoreline change, such as seen at Kailua Beach Park. Theoretically, a rate that continues to accelerate into the future will eventually become unrealistically high. Therefore, the PXT models may not be appropriate for forecasting future shoreline positions in the long term (*e.g.*, 50 years) at most beaches.

Because the PXT methods can detect acceleration, these methods have the prospect of detecting accelerating shoreline change that should be expected with accelerating sea-level rise from global temperature increase (Church and White, 2006). We will attempt to investigate shoreline change due to sea-level rise in our continued studies of all the beaches in the Hawaiian Islands with the PX and PXT methods. Thus far, it appears shoreline change at Hawaii beaches is dominated by the dynamics of the local littoral sediment budget. If Hawaii beaches are changing because of sea-level rise, it appears difficult, at present, to detect this change signal in the background of typically noisy historical shoreline data.

CONCLUSIONS

The EX and EXT methods are the preferred methods for calculating shoreline change rates from historical shoreline data. The most parsimonious model is selected from a range of models utilizing IC. The EX and EXT models have the lowest IC scores among the PX and PXT models (with and without rate acceleration) at most southeast Oahu beaches.

The PX method, with a linear fit to the time series of historical shoreline positions, provides a better characterization of the change that has occurred throughout the time series of shorelines (*i.e.*, long-term). The PXT method, which is able to detect acceleration in the shoreline change rates, may provide additional information about recent change occurring at a beach and can show how the rates may have varied with time. Ability to detect accelerating shoreline change is an important advance because a beach may not change at a constant (linear) rate. The PXT models may identify potential erosion hazards not detected by the ST and PX models. Recent accelerated shoreline change detected by the PXT models provides additional valuable information that will help shoreline managers better plan for future erosion hazards.

The PX and PXT methods calculate shoreline change rates from an improved data set, compared with the ST method, by utilizing data from all shoreline transects on a beach. Therefore, the PX and PXT methods invariably calculate rates with lower uncertainties than the ST method. The result is a greater percentage of transects with significant rates and increased confidence in results from these models. Improved confidence in results from shoreline change studies will help shoreline managers to make better-informed decisions to protect against future erosion hazards.

In the time span of this study (1911–2005) nearly 2 km (1919 m) of beach were lost to erosion along the southeast Oahu shoreline, most notably at Lanikai and North Bellows. Calculating shoreline change rates with the PX methods indicates areas of significant long-term erosion at northern and central Bellows Beach and in the south of Waimanalo Beach. The PX methods indicate long-term accretion along most of Kailua Beach and Lanikai Beach. The PXT methods detect recent accelerating erosion at southern Kailua Beach, northern Bellows Beach, and at Kaupo Beach Park.

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APPENDIX G

**CMB REPORT 06-014: RESULTS OF OFFSHORE SAND INVESTIGATION
FOR THE SOUTHEAST OAHU REGIONAL SEDIMENT MANAGEMENT
DEMONSTRATION PROJECT, HAWAII, HONOLULU DISTRICT**

**GEOTECHNICAL AND STRUCTURES LABORATORY
ENGINEER RESEARCH AND DEVELOPMENT CENTER
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**US Army Corps
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Development Center

*Concrete and Materials Branch
Testing and Evaluation Program*

CMB Report 06-014: Results of Offshore Sand Investigation for the Southeast Oahu Regional Sediment Management Demonstration Project, Hawaii, Honolulu District

Joe G. Tom and Judy C. Tom

September 2006



CMB Report 06-014: Results of Offshore Sand Investigation for the Southeast Oahu Regional Sediment Management Demonstration Project, Hawaii, Honolulu District

Prepared For

US Army Engineer District, Honolulu

By Joe G. Tom and Judy C. Tom

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Preface

The work described in this report was authorized by the US Army Engineer District, Honolulu, (POH) for the Southeast Oahu Regional Sediment Management (SEO/RSM) Demonstration Project. The work was performed under MIPR No. W81HEM50275957, managed at the US Army Engineer Research and Development Center (ERDC), Vicksburg, MS. Mr. Joe G. Tom, ERDC, Geotechnical and Structures Laboratory (GSL), was the Principal Investigator. Mr. Tom and Ms. Judy C. Tom prepared this report. Drs. Philip G. Malone and Charles A. Weiss, Jr., GSL, consulted on the investigation.

Dr. W. Allen Roberson, Chief, Concrete and Materials Branch (CMB), monitored the investigation at ERDC, GSL, under the general supervision of Dr. Albert J. Bush, Chief, Engineering Systems and Materials Division, and Dr. David W. Pittman, Director, GSL.

1 Introduction

Background

The US Army Engineer Research and Development Center (ERDC) have the responsibility of quality assurance for construction materials on US Army Corps of Engineers projects. That responsibility includes the assurance that all construction materials meet the minimum requirements of the project specifications. The ERDC performs this function for the Districts through its Laboratories. The quality assurance responsibility also includes preliminary investigations of construction materials in preparation of the Materials Design Memorandum for the Districts. Construction materials include portland-cement concretes, asphalt concrete, soils, stones, joint materials, steel reinforcements, and other materials as requested.

This investigation is being conducted to determine the general movement of sediment offshore of Wailea Point (which is located in the central portion of the region).

Analysis of sediment grain size trends; Benthic sand samples will be collected around target SEO/RSM areas for grain size determination. Analysis of the resulting grain size distributions will reveal trends (i.e., coarse vs. fine) of long-term sediment erosion and deposition within adjacent areas of the sample regions. Sediment sampling will be carried out in two locations: (1) ~2.0 km² vicinity of Wailea Point. (250 samples) and (2) a smaller study on the shoreward opening of the Kailua sand channel (100 samples).

Sample spacing will be denser in areas of more specific interest, such as a 37.5 m spacing applied in the immediate vicinity of Wailea Point. changing to 75 m spacing in the off shore sand fields and 150 m spacing in the regions between sand fields. The resulting sediment transport vectors will have resolutions varying with sample spacing, such that vectors near shore will be plotted every 75 m and vectors in offshore sand fields will be plotted every 150 m. A final report containing all data, procedures, results, and interpretations from the grain size trend analysis will be

delivered. The approach and theory behind grain size trend analysis is published in McLaren and Bowles (1985), Goa and Collins (1992), Le Roux (1994), Hughes (2005).

Authorization

This work is authorized under US Army Engineer District, Honolulu, MIPR No. W81HEM50275957. Mr. Thomas D. Smith, CEPOH-EC-T, made the request for the offshore sediment sampling investigations.

Objective

The objective of this report is to provide specific results of tests and evaluations performed on the sand samples that are to be used in the sediment trend analysis.

Samples

The Concrete and Materials Branch (CMB) of the Geotechnical and Structures Laboratory, ERDC, received 224 samples of various beach sands taken from offshore of Wailea Point as shown on the maps in Appendix A. The samples were assigned CMB Serial Number 060166 supplemented with the POH sample number as shown in Appendix B, Table B1. The sand samples were collected by students from the University of Hawaii at Manoa under the direction of Mr. Christopher Bochiccho, Department of Geology and Geophysics, and Mr. Thomas D. Smith, CEPOH-EC-T, and sent to ERDC. Appendix B, Table B1 lists the initial mass determinations from the University of Hawaii and also the results determined from the as-received mass in their original bags and the oven-dry mass of each sample. Numerically, the samples are listed as 0 to 295, with many samples not sent to ERDC for analysis; those are indicated with a zero reading rather than a blank or deleted listing. Two samples, No. 76 and No. 144, were indicated as having been sent for analysis, however the samples were not found in the shipping containers. Another sample, No. 293, was indicated as having no sample sent for analysis; however, the sample numbered as 293 was found in the shipping containers and evaluated with the other samples.

Tests

The sand samples were tested and evaluated for particle size distribution with the current version of the following test methods or specifications:

- a. ASTM C 136, “Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates.”
- b. ASTM C 702, “Standard Practice for Reducing Samples of Aggregate to Testing Size.”

2 Evaluation

Sand Samples

The 224 samples of various beach sands (CMB Serial No. 060166) were evaluated in accordance with the standard test method, ASTM C 136. Each sample was removed from the zip-lock bag and surface-dried in a 100-degree F environmental room for approximately 24 hours to allow the wet dust material adhering to the interior of the bag to dry so that it could be easily removed without lost. The dry dust material was added back to the original sample and the entire sample was oven-dried to a constant mass. The larger samples of beach sand were reduced to testing size using a mechanical splitter in accordance with ASTM C 702.

The standard method requires the use of sieves designated in SI units and listed in units of millimeters and microns with an alternate listing in US inches. The SI sieves were converted to Phi, Φ , units as required by the Honolulu District personnel. The conversion on the sieve sizes are listed in Table 1 below. The nest of sieves started with -2.0-Phi down to 5.0-Phi sieve size in 0.5-Phi intervals. The nest of sieves included 15 individual sieves plus a collecting pan. Due to the large number of sieves, the analysis was divided into two operations, one set of sieves from -2.0-Phi to 2.0-Phi, and another set of sieves from 2.5-Phi to 5.0-Phi. Therefore, each sample or split portion was sieved twice, once in the larger sieves and then the material remaining in the collecting pan was placed in the second set of sieves and tested.

The material retained on each individual sieve was weighed and final mass recorded. The results were calculated as a percentage of the total sample sieved. All of the material from each sample was returned to the original bag and will be shipped back to Mr. Thomas D. Smith, CEPOH-EC-T, in Honolulu, Hawaii, upon completion of this investigation.

Table 1. Phi units with conversions to SI units and US equivalent units

Phi Units	Conversion to SI units	Standard Sieve Designation	Alternative US Designation
Φ	mm	mm / μm	No.
-2.0	4.00	4.00	No. 5
-1.5	2.83	2.80	No. 7
-1.0	2.00	2.00	No. 10
-0.5	1.41	1.40	No. 14
0.0	1.00	1.00	No. 18
0.5	0.707	710	No. 25
1.0	0.500	500	No. 35
1.5	0.354	355	No. 45
2.0	0.250	250	No. 60
2.5	0.177	180	No. 80
3.0	0.125	125	No. 120
3.5	0.088	90	No. 170
4.0	0.063	63	No. 230
4.5	0.044	45	No. 325
5.0	0.031	32	No. 450

3 Conclusions and Recommendations

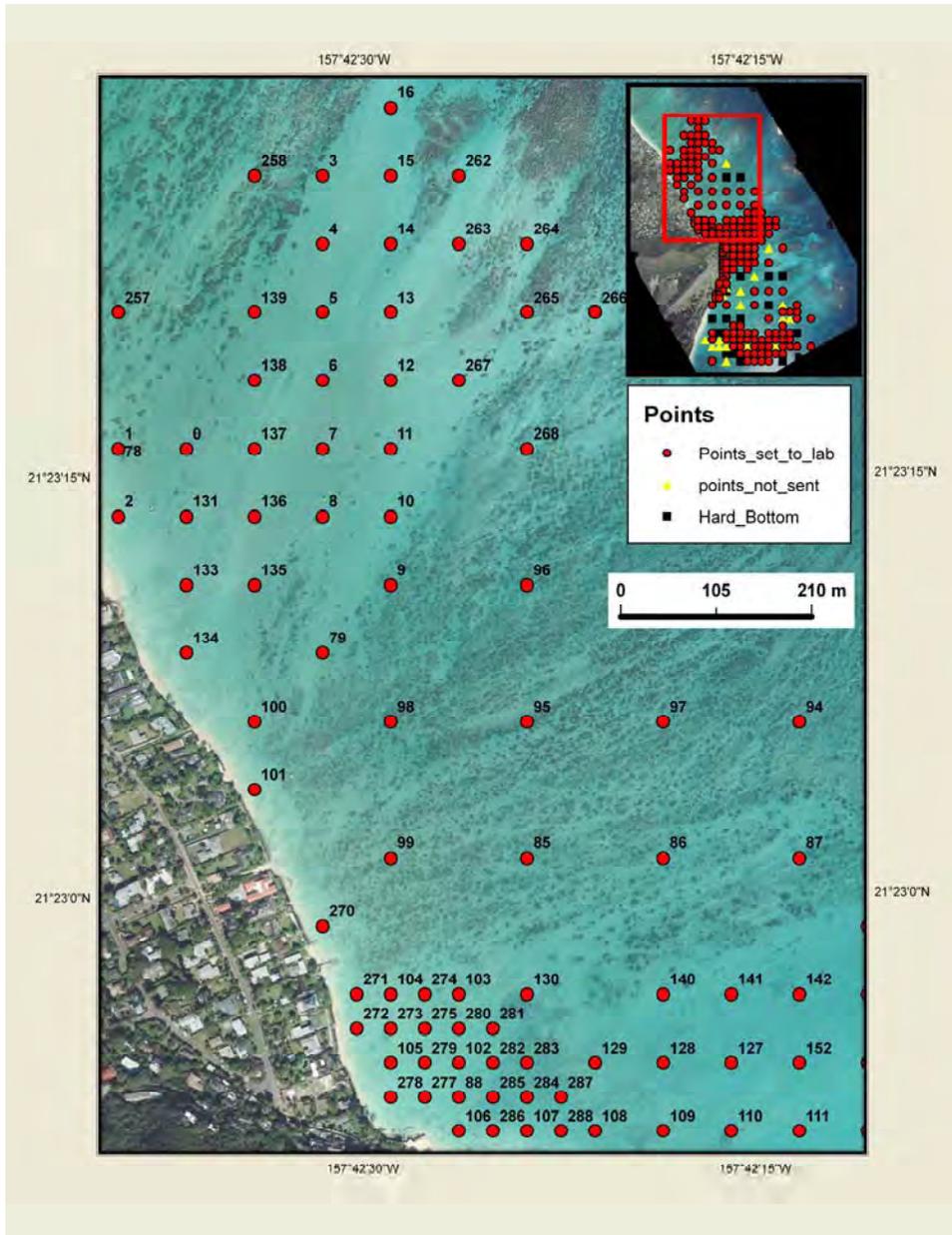
Sand Samples

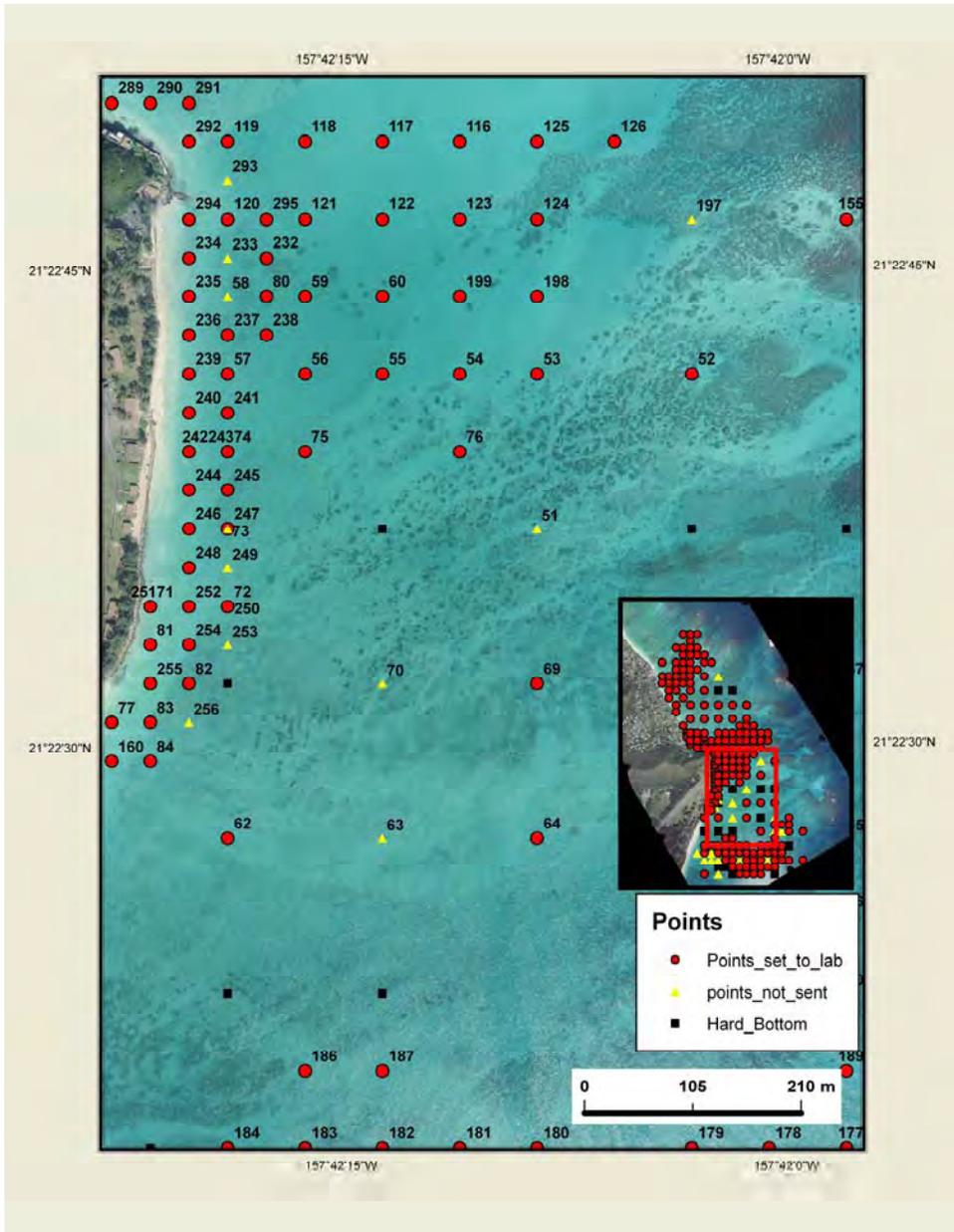
The 224 samples of beach sand (CMB Serial No. 060166) were tested and evaluated for particle size distribution in accordance with the project requirements. The sample results are provided as the results of the percentage of the total amount sieved per sieve size. The results are shown in graphic format to display the distribution of the particles sizes throughout the range of the sample as presented in Appendix C. The numerical results are provided in Appendix D.

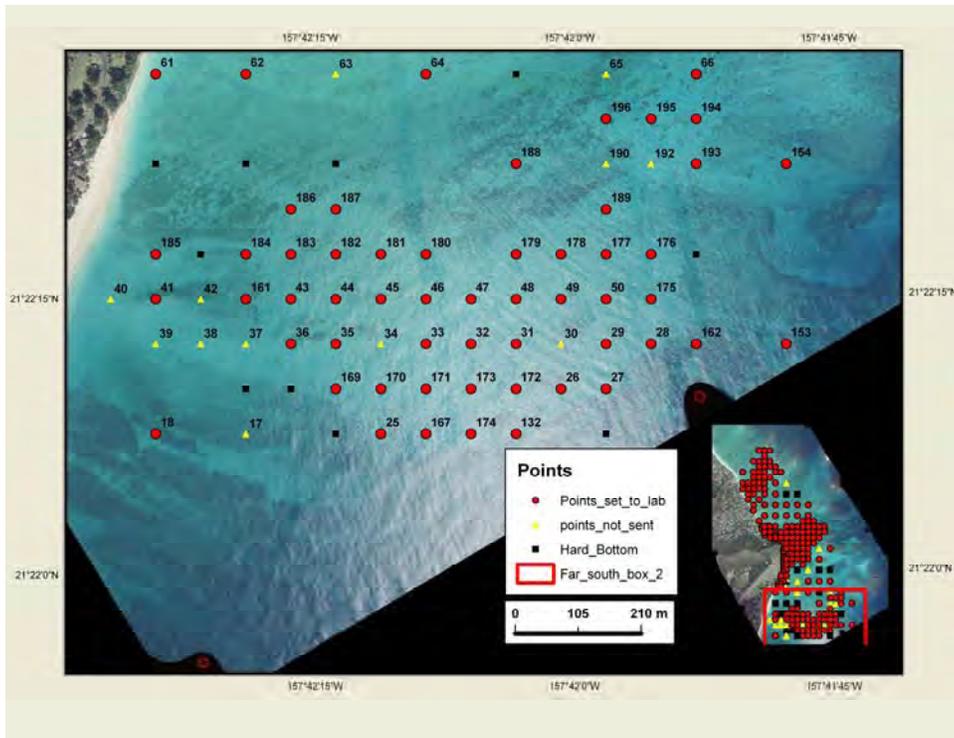
POH personnel indicated 225 samples were sent; however, only 224 samples were received. Sample numbers 76 and 144 were not received with the other samples. Sample number 293 was not listed as being sent; however, a sample identified as number 293 was received and analyzed. A total of 224 samples were received and analyzed for particle size distribution.

Appendix A

Maps of Sand Sample Locations







Appendix B

Sand Sample Identification and Masses

Table 2. Sand Samples, CMB Serial Number 060166				
CMB Serial Supplement No.	Field Identification	POH Mass, g	As-Received Mass in Bag, g	Oven-Dry Mass, g
0	0	615	586	432.0
1	1	538	511	376.10
2	2	630	626	450.2
3	3	452	441	309.40
4	4	604	583	423.4
5	5	650	606	452.2
6	6	568	545	435.5
7	7	716	617	501.9
8	8	705	646	489.1
9	9	625	562	381.90
10	10	672	685	478.7
11	11	747	695	522.7
12	12	780	718	511.5
13	13	611	553	421.3
14	14	768	709	534.2
15	15	584	557	399.90
16	16	589	523	416.0
17	No Sample	No Sample	0	0
18	18	708	715	521.1
19	No Sample	No Sample	0	0
20	No Sample	No Sample	0	0
21	No Sample	No Sample	0	0
22	No Sample	No Sample	0	0
23	No Sample	No Sample	0	0
24	No Sample	No Sample	0	0
25	25	759	758	580.0
26	26	645	646	509.8
27	27	836	846	649.5
28	28	504	504	425.6
29	29	605	622	477.5
30	No Sample	No Sample	0	0
31	31	601	591	415.3
32	32	643	642	448.7
33	33	632	635	436.2
34	No Sample	No Sample	0	0
35	35	566	566	406.3
36	36	558	558	400.4
37	No Sample	No Sample	0	0
38	No Sample	No Sample	0	0
39	No Sample	No Sample	0	0
40	No Sample	No Sample	0	0
41	41	553	558	426.4
42	No Sample	No Sample	0	0
43	43	498	499	444.8
CMB Serial	Field	POH Mass, g	As-Received	Oven-Dry

Supplement No.	Identification		Mass in Bag, g	Mass, g
44	44	814	785	539.9
45	45	574	576	460.8
46	46	479	478	411.8
47	47	560	555	400.5
48	48	639	625	438.2
49	49	563	562	434.0
50	50	753	732	533.0
51	No Sample	No Sample	0	0
52	52	598	542	410.1
53	53	481	419	322.74
54	54	577	548	359.91
55	55	646	613	476.6
56	56	529	503	374.43
57	57	627	597	459.3
58	No Sample	No Sample	0	0
59	59	554	521	343.28
60	60	530	518	364.77
61	61	650	649	470.9
62	62	769	723	501.1
63	No Sample	No Sample	0	0
64	64	553	552	388.24
65	No Sample	No Sample	0	0
66	66	709	642	454.6
67	67	946	880	624.9
68	68	479	334	306.37
69	No Sample	No Sample	0	0
70	No Sample	No Sample	0	0
71	71	848	800	592.7
72	72	513	427	315.3
73	No Sample	No Sample	0	0
74	74	443	402	278.15
75	75	779	686	469.6
76	76	430	Not Received	Not Received
77	77	1052	1020	743.8
78	78	1183	1082	886.1
79	79	1041	985	746.8
80	80	>2100	2529	1857.2
81	81	>2100	2461	1838.3
82	82	2065	1851	1371.9
83	83	1654	1592	1225.9
84	84	>2100	2327	1711.7
85	85	1560	1544	1126.5
86	86	>2100	2255	1437.7
87	87	>2100	1975	1469.6
88	88	1324	1205	873.8
CMB Serial Supplement	Field Identification	POH Mass, g	As-Received Mass in Bag, g	Oven-Dry Mass, g

No.				
89	89	1116	1050	776.7
90	90	>2100	2716	2137.5
91	91	>2100	1942	1294.2
92	92	888	835	605.4
93	93	1268	1177	880.5
94	94	>2100	2147	1620.9
95	95	>2100	2037	1665.9
96	96	2006	1882	1225.8
97	97	1413	1337	1032.5
98	98	1759	1575	1274.5
99	99	>2100	1840	1452.2
100	100	755	720	536.1
101	101	1774	1754	1233.3
102	102	555	506	368.02
103	103	644	610	473.3
104	104	477	468	315.88
105	105	610	556	398.90
106	106	687	671	501.5
107	107	616	588	424.6
108	108	729	712	509.5
109	109	503	484	332.49
110	110	561	548	377.64
111	111	620	616	430.7
112	112	605	591	412.1
113	113	651	638	452.2
114	114	577	519	366.41
115	115	478	471	306.62
116	116	567	543	381.01
117	117	551	531	363.26
118	118	624	589	414.8
119	119	624	561	398.80
120	120	605	567	410.3
121	121	435	402	280.01
122	122	607	602	402.6
123	123	560	524	389.19
124	124	639	570	444.2
125	125	521	490	349.93
126	126	583	534	348.16
127	127	603	545	386.73
128	128	520	480	368.42
129	129	442	399	298.89
130	130	604	551	371.51
131	131	718	641	484.1
132	132	480	456	324.24
133	133	713	609	485.5
CMB Serial Supplement No.	Field Identification	POH Mass, g	As-Received Mass in Bag, g	Oven-Dry Mass, g

134	134	520	505	380.99
135	135	650	606	469.2
136	136	622	577	490.7
137	137	720	656	505.0
138	138	665	565	456.0
139	139	487	433	339.82
140	140	783	734	524.7
141	141	514	487	365.02
142	142	547	508	348.48
143	143	566	522	371.96
144	144	558	Not Received	Not Received
145	145	532	462	352.46
146	146	528	512	354.39
147	147	666	647	492.9
148	148	561	549	430.7
149	149	604	567	409.6
150	150	639	619	443.2
151	151	582	557	390.11
152	152	561	521	376.17
153	153	1947	1887	1323.4
154	154	1056	989	714.2
155	155	1884	1796	1263.1
156	No Sample	No Sample	0	0
157	No Sample	No Sample	0	0
158	158	>2100	2016	1704.5
159	No Sample	No Sample	0	0
160	160	489	464	347.42
161	161	1254	1134	898.1
162	162	>2100	2386	1722.0
163	No Sample	No Sample	0	0
164	No Sample	No Sample	0	0
165	No Sample	No Sample	0	0
166	No Sample	No Sample	0	0
167	167	892	885	657.8
168	No Sample	No Sample	0	0
169	169	579	572	419.7
170	170	702	696	577.1
171	171	722	704	527
172	172	815	777	564.4
173	173	759	754	549.7
174	174	976	893	635.3
175	175	637	619	458.2
176	176	467	474	391.0
177	177	658	650	466.8
178	178	515	511	386.76
CMB Serial Supplement No.	Field Identification	POH Mass, g	As-Received Mass in Bag, g	Oven-Dry Mass, g
179	179	701	694	488.1

180	180	569	568	459.2
181	181	1103	1117	890.5
182	182	527	513	369.88
183	183	741	733	537.8
184	184	640	653	522.5
185	185	1011	1007	821.9
186	186	565	561	453.7
187	187	600	597	463.8
188	188	545	541	370.63
189	189	774	772	573.2
190	No Sample	No Sample	0	0
191	No Sample	No Sample	0	0
192	No Sample	No Sample	0	0
193	193	463	453	335.94
194	194	532	530	462.0
195	195	466	467	405.3
196	196	752	750	568.3
197	No Sample	No Sample	0	0
198	198	521	479	327.65
199	199	545	528	365.54
200	No Sample	No Sample	0	0
201	No Sample	No Sample	0	0
202	No Sample	No Sample	0	0
203	No Sample	No Sample	0	0
204	No Sample	No Sample	0	0
205	No Sample	No Sample	0	0
206	No Sample	No Sample	0	0
207	No Sample	No Sample	0	0
208	No Sample	No Sample	0	0
209	No Sample	No Sample	0	0
210	No Sample	No Sample	0	0
211	No Sample	No Sample	0	0
212	No Sample	No Sample	0	0
213	No Sample	No Sample	0	0
214	No Sample	No Sample	0	0
215	No Sample	No Sample	0	0
216	No Sample	No Sample	0	0
217	No Sample	No Sample	0	0
218	No Sample	No Sample	0	0
219	No Sample	No Sample	0	0
220	No Sample	No Sample	0	0
221	No Sample	No Sample	0	0
222	No Sample	No Sample	0	0
223	No Sample	No Sample	0	0
CMB Serial Supplement No.	Field Identification	POH Mass, g	As-Received Mass in Bag, g	Oven-Dry Mass, g
224	No Sample	No Sample	0	0
225	No Sample	No Sample	0	0

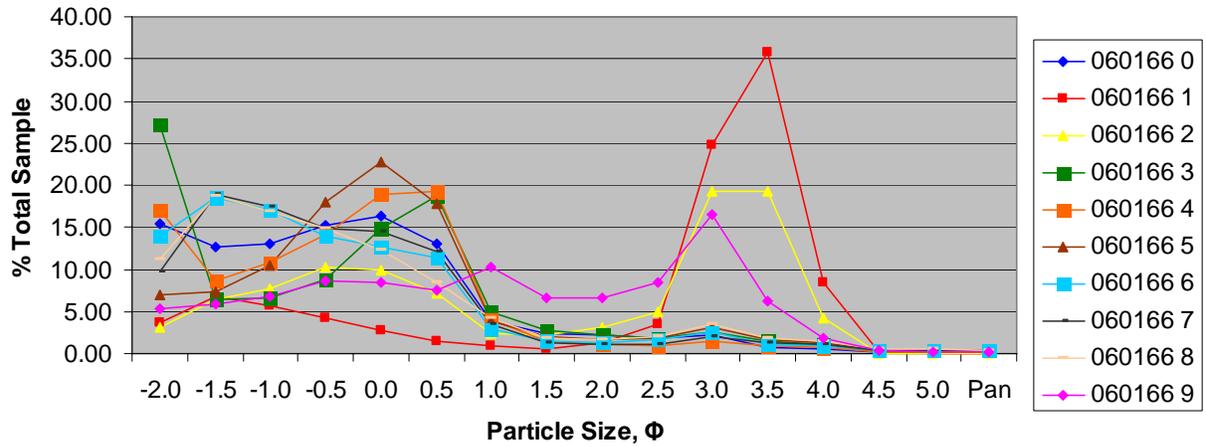
226	No Sample	No Sample	0	0
227	No Sample	No Sample	0	0
228	No Sample	No Sample	0	0
229	No Sample	No Sample	0	0
230	No Sample	No Sample	0	0
231	No Sample	No Sample	0	0
232	232	588	576	389.22
233	No Sample	No Sample	0	0
234	234	811	781	575.3
235	235	588	612	444.8
236	236	519	510	371.03
237	237	863	742	562.3
238	238	772	728	507.0
239	239	743	672	497.8
240	240	854	864	644.7
241	241	1087	1013	768.2
242	242	735	687	504.0
243	243	997	939	739.1
244	244	823	806	613.9
245	245	460	455	286.84
246	246	833	798	621.0
247	247	469	450	325.89
248	248	822	800	587.5
249	No Sample	No Sample	0	0
250	250	548	482	332.20
251	251	797	778	579.7
252	252	852	831	610.0
253	No Sample	No Sample	0	0
254	254	747	735	536.5
255	255	783	739	547.2
256	No Sample	No Sample	0	0
257	257	1100	1019	743.8
258	258	543	516	413.7
259	259	591	536	410.7
260	260	988	847	674.5
261	261	753	705	547.5
262	262	737	698	506.7
263	263	719	642	523.3
264	264	624	550	444.9
265	265	733	646	526.2
266	266	605	598	418.0
267	267	672	638	444.2
268	268	738	690	517.1
CMB Serial Supplement No.	Field Identification	POH Mass, g	As-Received Mass in Bag, g	Oven-Dry Mass, g
269	No Sample	No Sample	0	0
270	270	667	636	467.7
271	271	829	793	569.5

272	272	798	732	542.0
273	273	731	653	475.7
274	274	667	583	431.4
275	275	786	746	553.8
276	276	646	613	454.6
277	277	1005	1024	760.8
278	278	754	680	506.3
279	279	677	651	508.0
280	280	654	580	423.9
281	281	690	661	535.2
282	282	1113	1031	793.3
283	283	770	715	555.0
284	284	1240	1178	917.4
285	285	1058	995	779.1
286	286	662	661	502.6
287	287	580	554	408.1
288	288	915	872	645.4
289	289	882	873	653.6
290	290	518	509	349.36
291	291	612	580	414.5
292	292	802	801	606.1
293	293	Received	1034	740.9
294	294	680	675	498.2
295	295	774	746	533.3

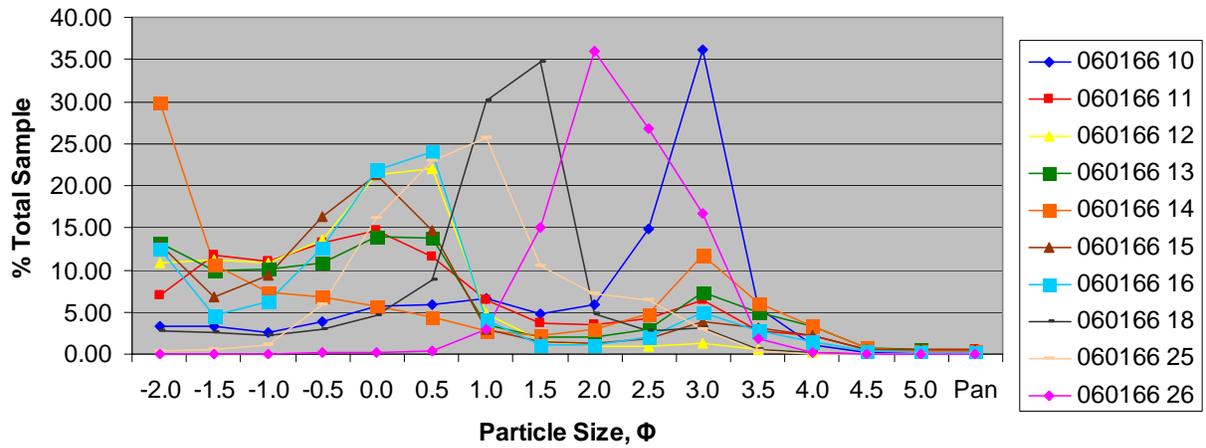
Appendix C

Sand Sample Graphic Results

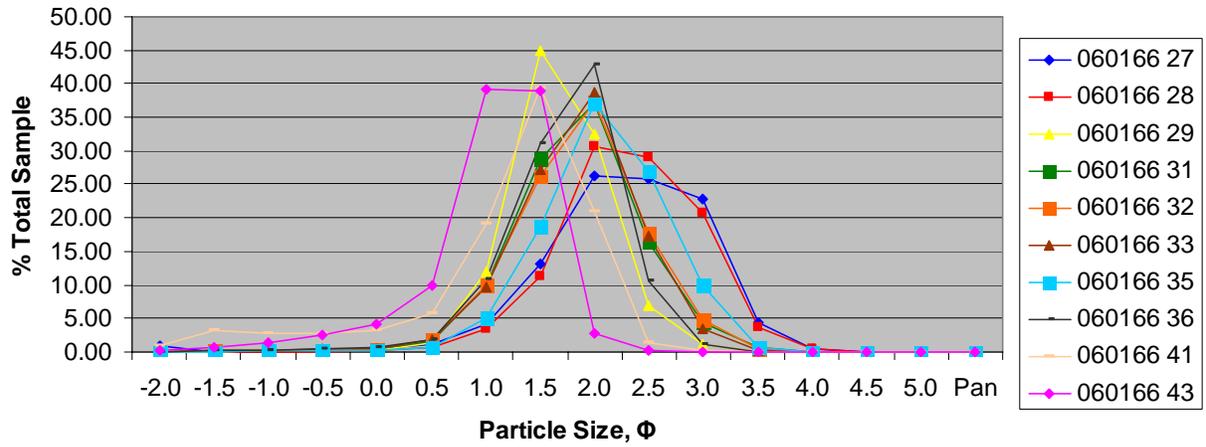
**Particle Size Distribution
Sample 0 to 9**



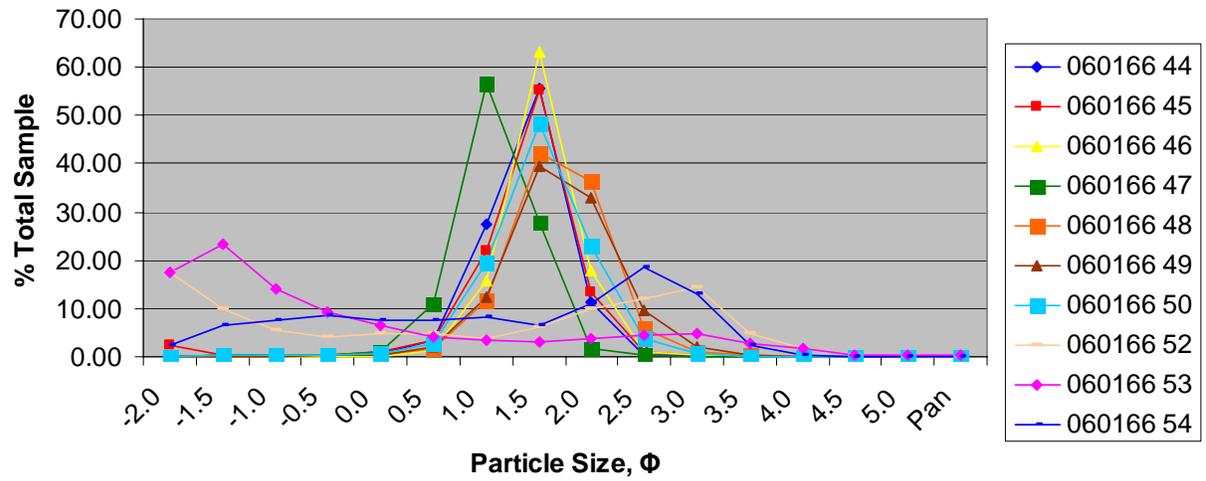
**Particle Size Distribution
Sample 10 to 26**



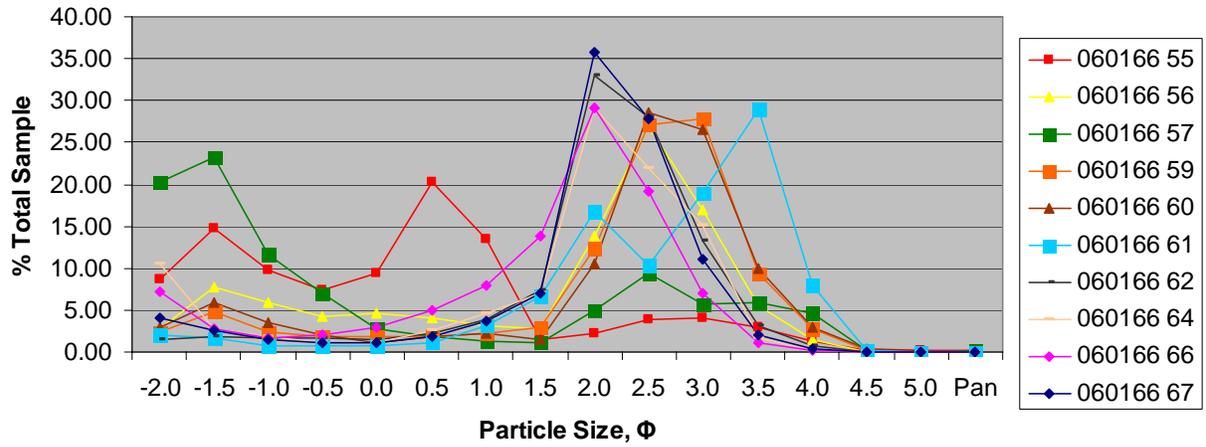
Particle Size Distribution Sample 27 to 43



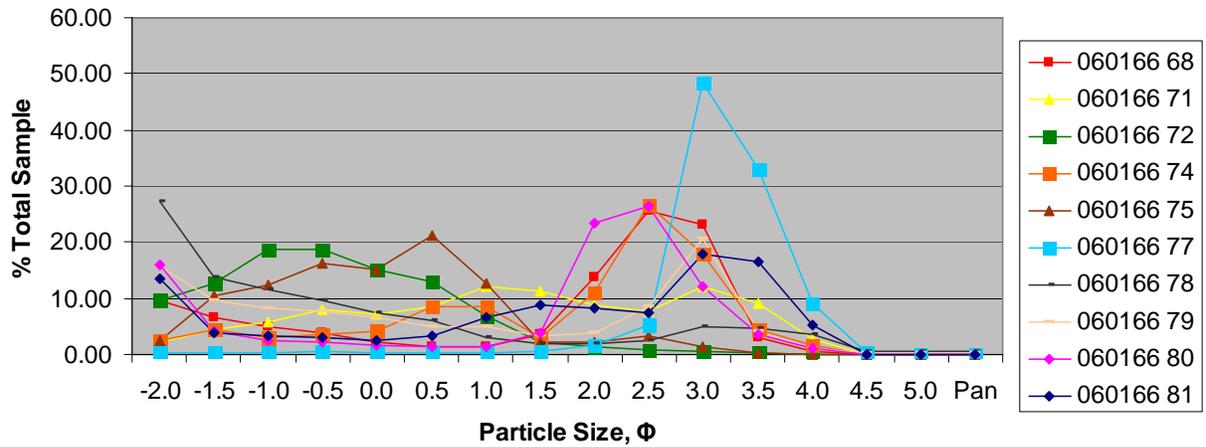
Particle Size Distribution Sample 44 to 54



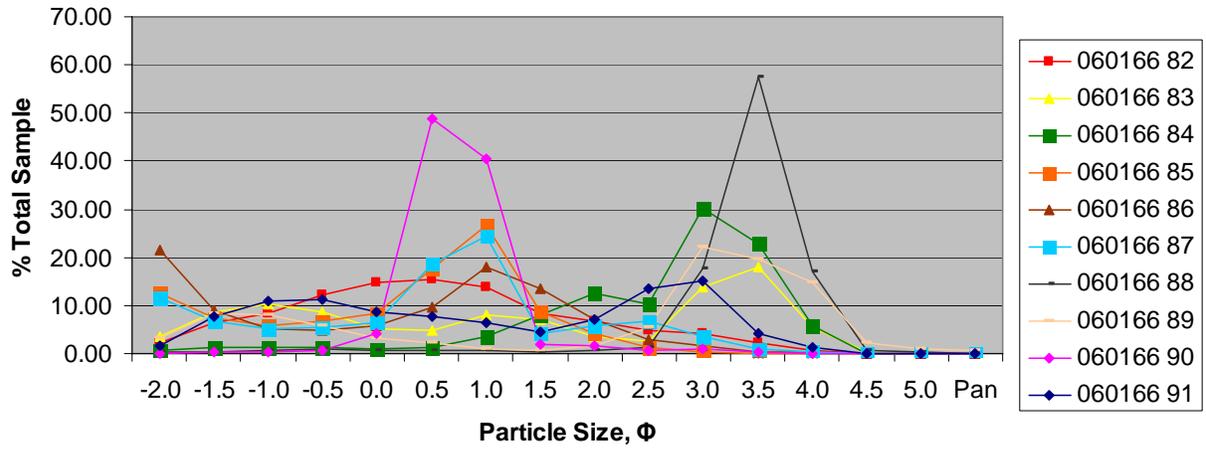
**Particle Size Distribution
Sample 55 to 67**



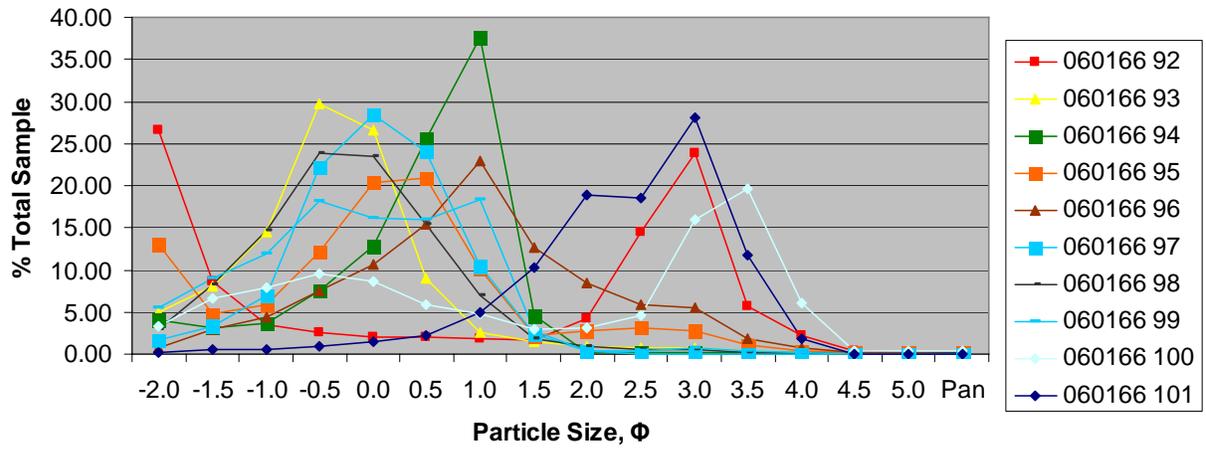
**Particle Size Distribution
Sample 68 to 81**



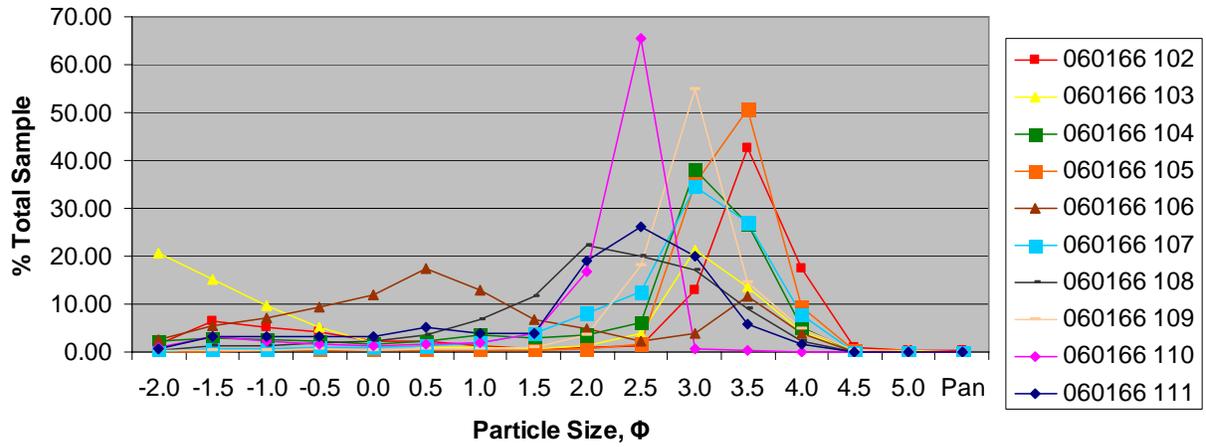
**Particle Size Distribution
Sample 82 to 91**



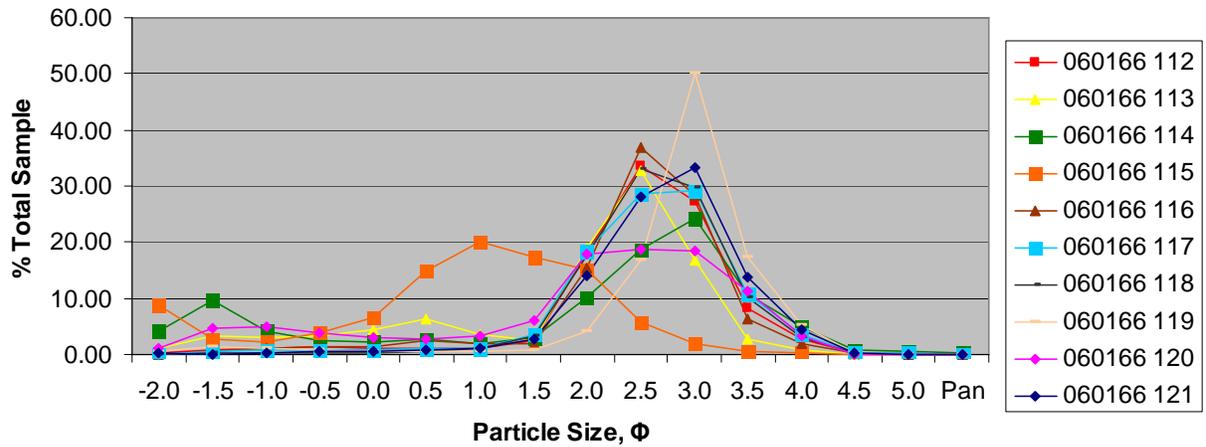
**Particle Size Distribution
Sample 92 to 101**



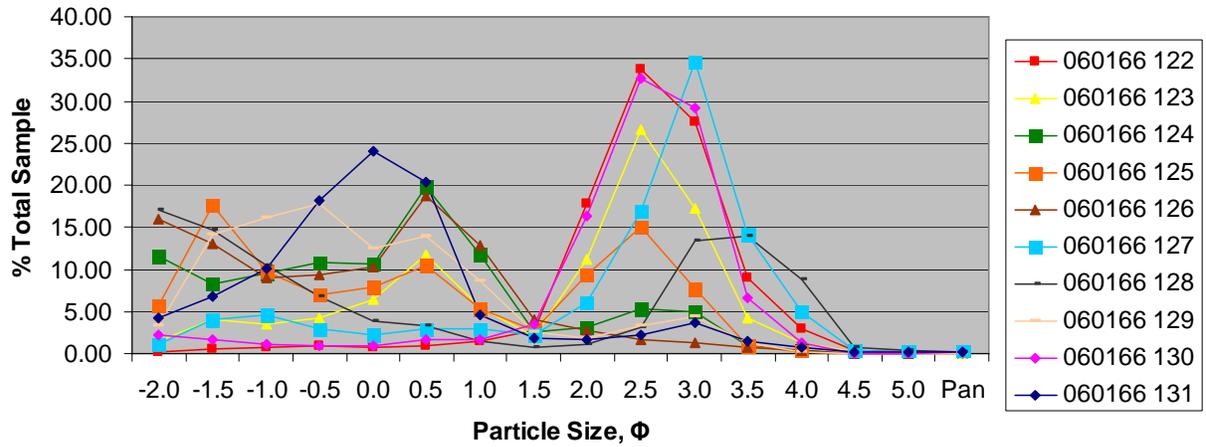
Particle Size Distribution Sample 102 to 111



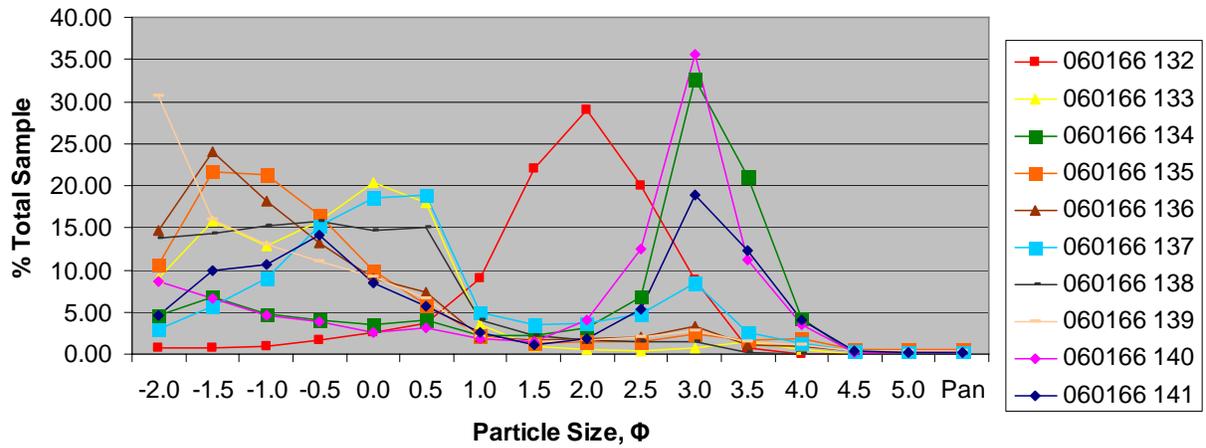
Particle Size Distribution Sample 112 to 121



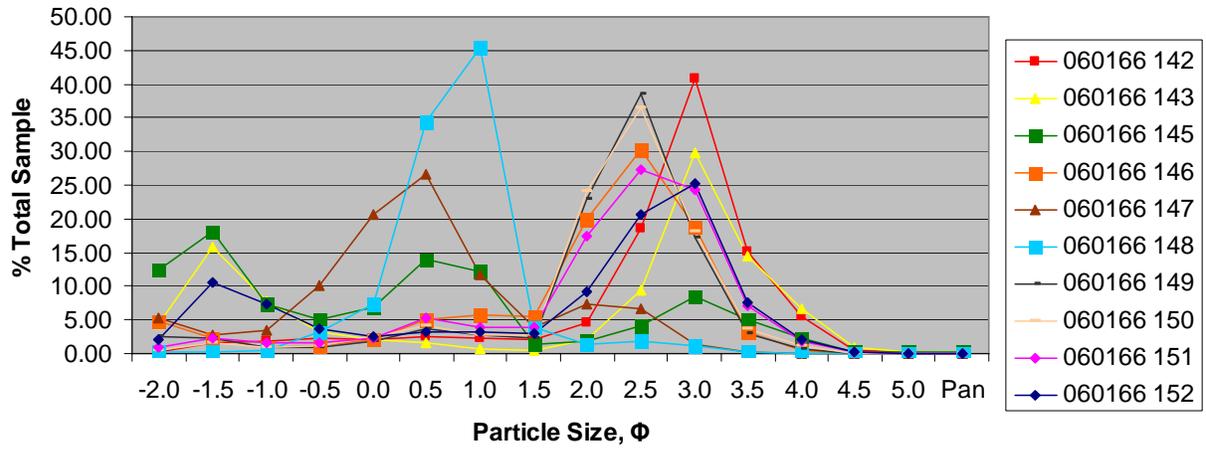
**Particle Size Distribution
Sample 122 to 131**



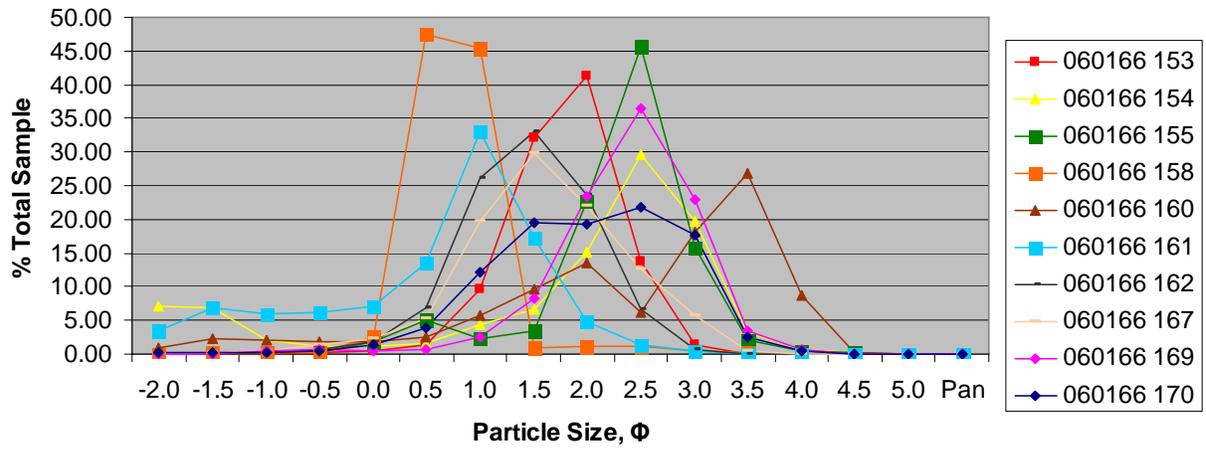
**Particle Size Distribution
Sample 132 to 141**



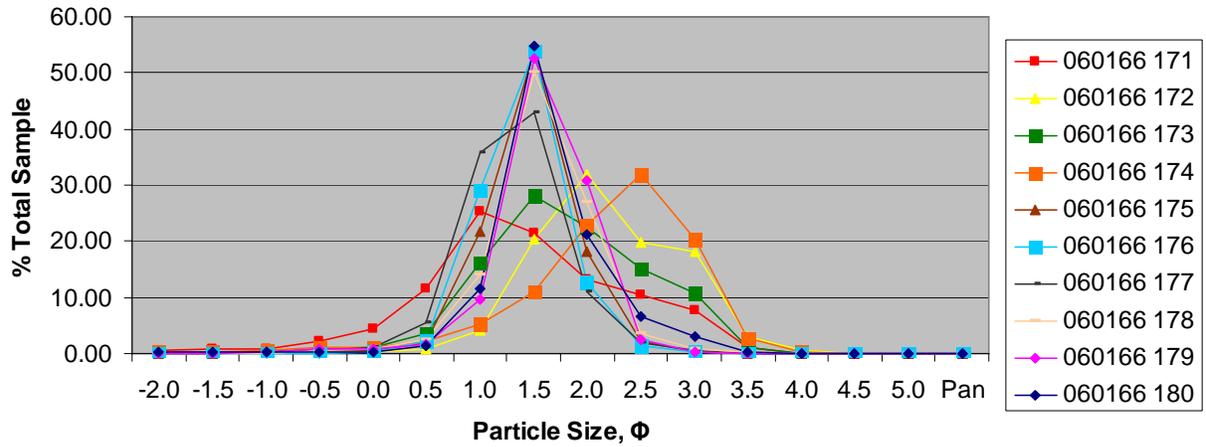
Particle Size Distribution Sample 142 to 152



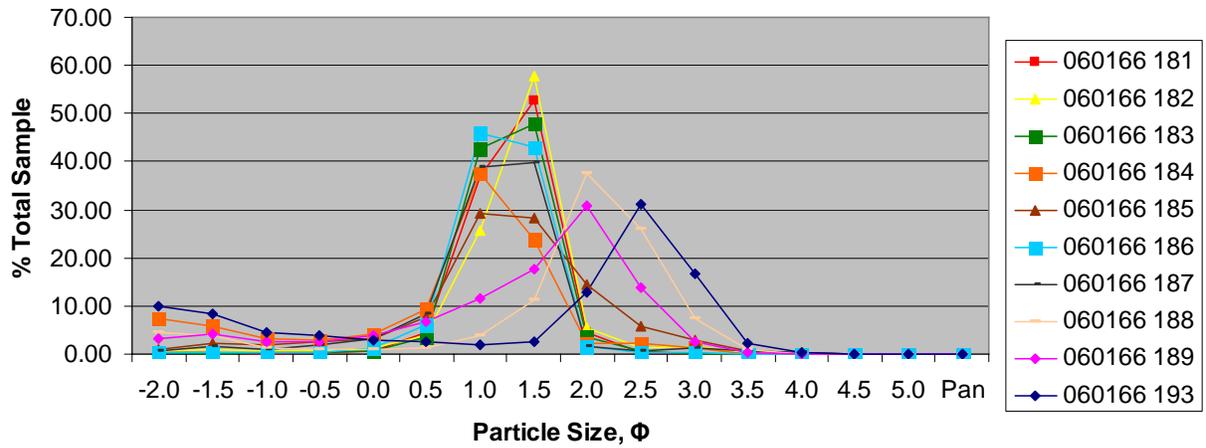
Particle Size Distribution Sample 153 to 170



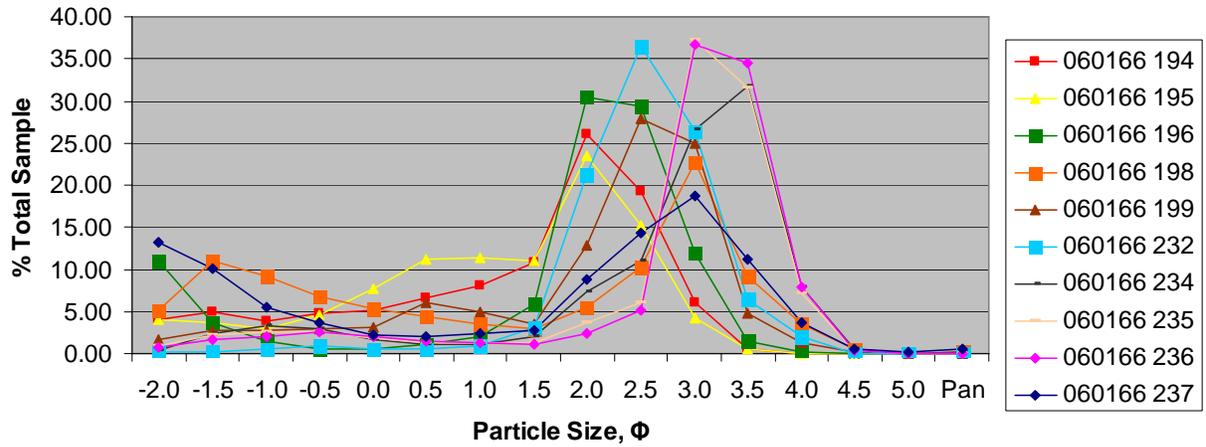
**Particle Size Distribution
Sample 171 to 180**



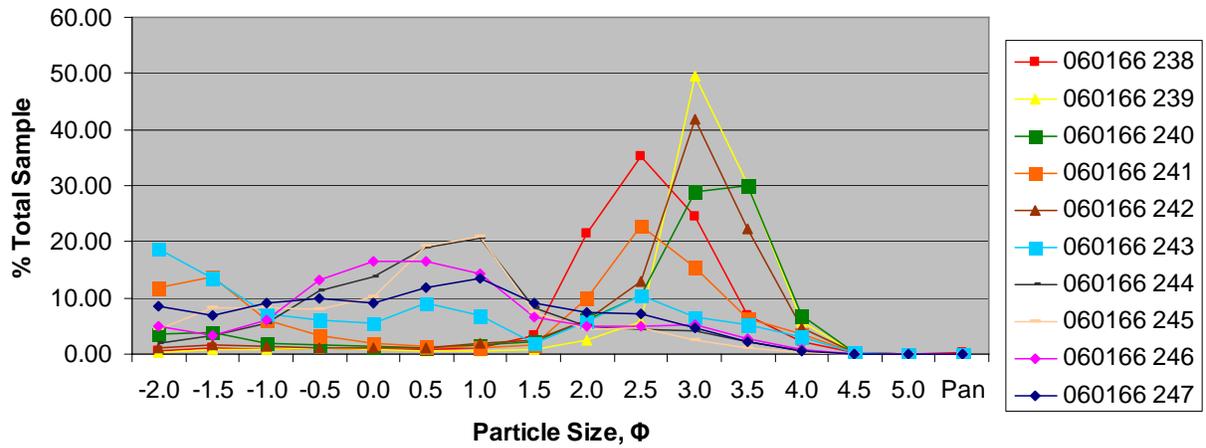
**Particle Size Distribution
Sample 181 to 193**



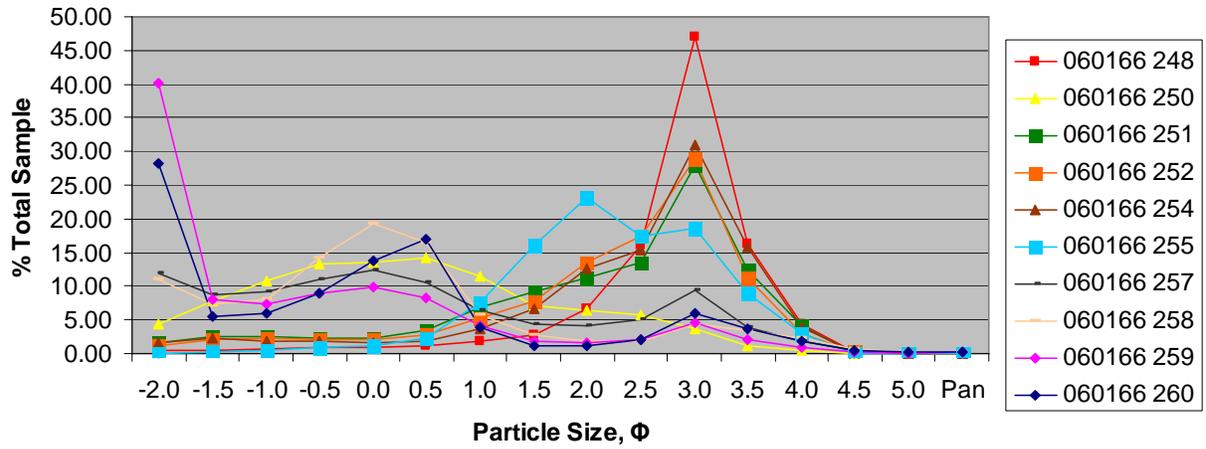
Particle Size Distribution Sample 194 to 237



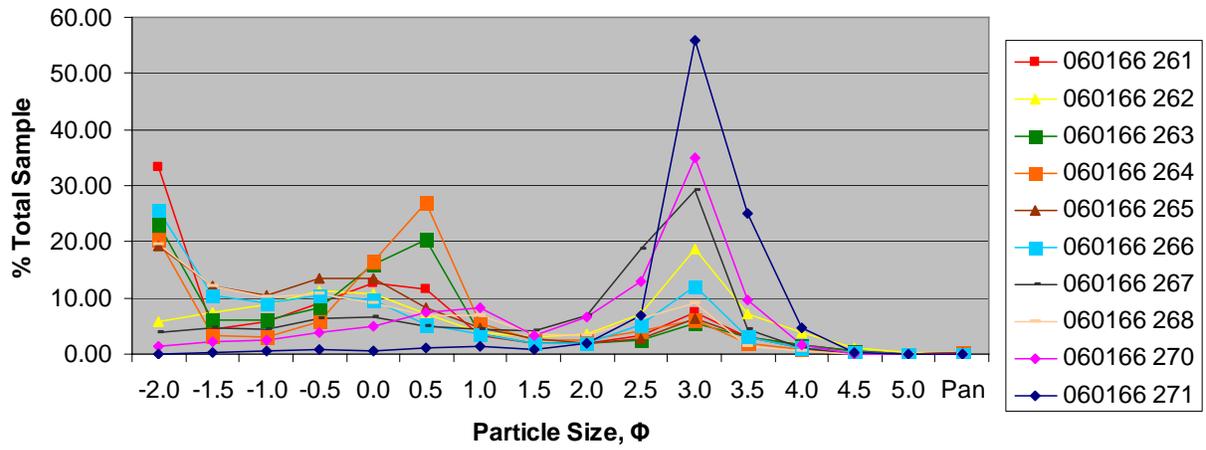
Particle Size Distribution Sample 238 to 247



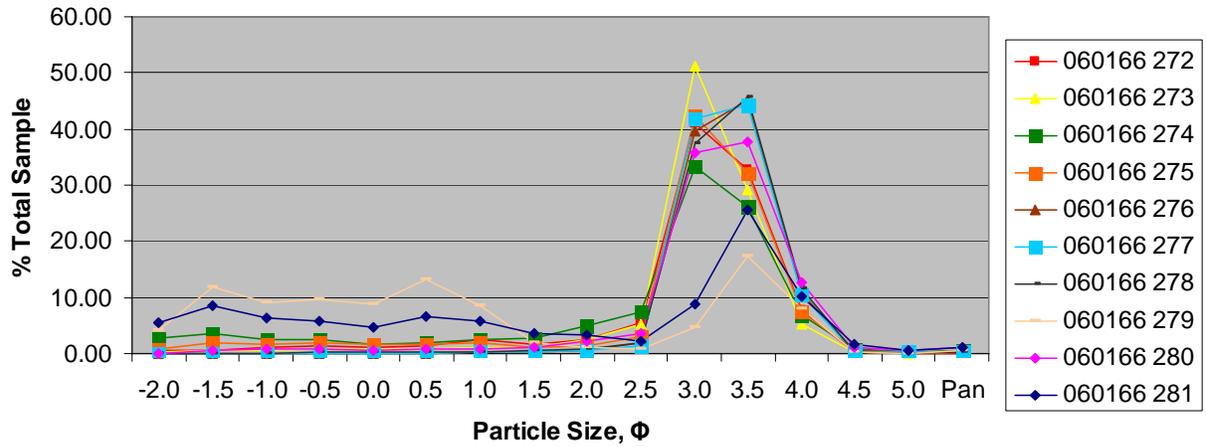
Particle Size Distribution Sample 248 to 260



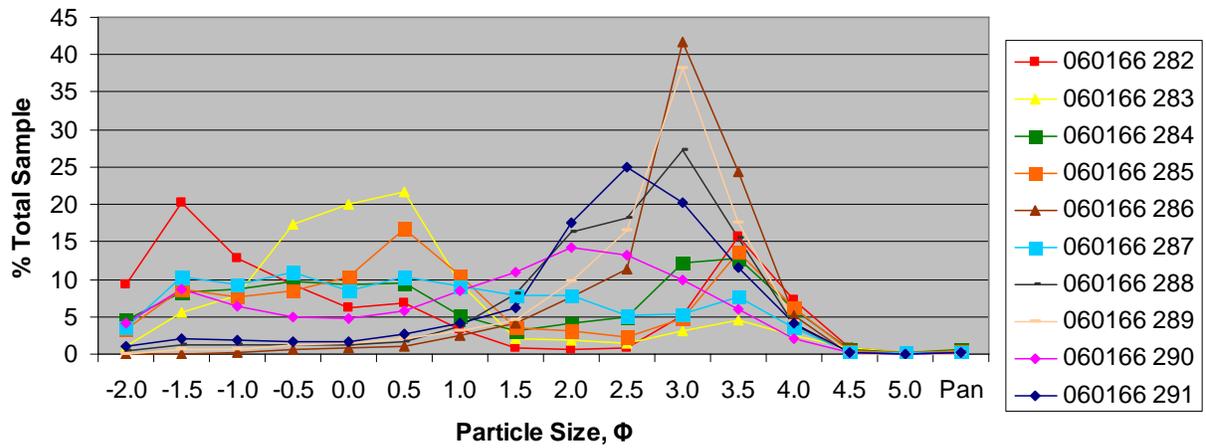
Particle Size Distribution Sample 261 to 271



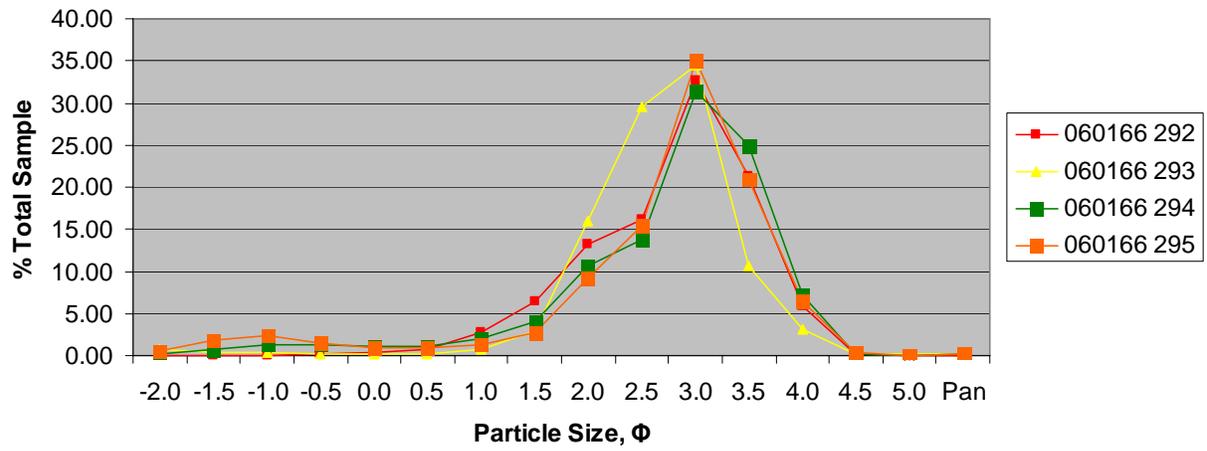
Particle Size Distribution Sample 272 to 281



Particle Size Distribution Sample 282 to 291



Particle Size Distribution Sample 292 to 295



Appendix D

Sand Sample Numerical Results

Table C1. Numerical Results of Particle Size Distribution for Samples 0 to 9

Particle Size, Φ	060166 0	060166 1	060166 2	060166 3	060166 4	060166 5	060166 6	060166 7	060166 8	060166 9
-2.0	15.41	3.65	3.16	27.07	17.02	7.02	13.94	9.68	11.14	5.41
-1.5	12.67	6.86	6.34	6.47	8.63	7.41	18.48	18.82	18.69	5.94
-1.0	12.96	5.72	7.76	6.62	10.82	10.45	17.00	17.39	16.85	6.76
-0.5	15.25	4.26	10.28	8.73	14.17	18.04	13.92	14.94	14.93	8.64
0.0	16.35	2.67	9.88	14.95	18.84	22.72	12.64	14.50	12.25	8.41
0.5	12.94	1.49	7.12	18.68	19.34	17.87	11.29	12.19	8.44	7.61
1.0	3.86	0.86	2.40	4.94	3.97	3.80	2.85	3.50	4.27	10.20
1.5	2.46	0.64	2.12	2.73	1.46	2.01	1.39	1.29	1.81	6.61
2.0	2.24	1.30	3.06	2.24	1.12	1.71	1.33	1.04	1.56	6.68
2.5	1.91	3.42	4.95	1.75	0.97	1.91	1.59	1.17	1.93	8.42
3.0	2.17	24.74	19.18	2.57	1.48	3.16	2.58	2.08	3.43	16.49
3.5	0.72	35.74	19.32	1.53	0.96	1.61	1.19	1.21	1.80	6.20
4.0	0.56	8.42	4.25	1.02	0.70	1.26	0.93	1.10	1.47	1.85
4.5	0.16	0.13	0.07	0.26	0.20	0.39	0.30	0.39	0.50	0.33
5.0	0.16	0.05	0.04	0.23	0.16	0.34	0.28	0.37	0.50	0.24
Pan	0.18	0.05	0.07	0.21	0.16	0.30	0.29	0.33	0.43	0.21
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C2. Numerical Results of Particle Size Distribution for Samples 10 to 26

Particle Size, ϕ	060166 10	060166 11	060166 12	060166 13	060166 14	060166 15	060166 16	060166 18	060166 25	060166 26
-2.0	3.28	7.02	10.76	13.23	29.96	12.94	12.50	2.71	0.29	0.00
-1.5	3.33	11.67	11.26	9.99	10.62	6.87	4.51	2.62	0.48	0.01
-1.0	2.60	11.08	10.75	10.16	7.29	9.32	6.23	2.20	1.10	0.02
-0.5	3.94	13.13	13.54	10.83	6.78	16.24	12.62	2.96	5.89	0.11
0.0	5.65	14.60	21.28	13.96	5.75	21.33	21.90	4.60	16.09	0.17
0.5	5.92	11.54	22.06	13.79	4.33	14.68	23.95	8.87	22.89	0.44
1.0	6.69	6.45	4.73	3.55	2.76	2.99	4.09	30.13	25.70	2.89
1.5	4.82	3.74	1.65	2.02	2.25	1.49	1.12	34.61	10.50	14.96
2.0	5.94	3.40	1.00	2.01	2.88	1.34	1.13	4.79	7.11	36.03
2.5	14.81	4.21	0.84	2.96	4.76	1.82	1.98	2.74	6.49	26.72
3.0	36.10	6.47	1.23	7.34	11.80	3.94	4.89	3.16	3.00	16.67
3.5	5.51	2.80	0.48	5.04	6.13	3.05	2.73	0.50	0.35	1.78
4.0	1.01	2.17	0.22	3.39	3.22	2.29	1.43	0.10	0.09	0.20
4.5	0.16	0.62	0.05	0.76	0.65	0.61	0.36	0.00	0.01	0.01
5.0	0.11	0.55	0.04	0.55	0.45	0.56	0.27	0.00	0.01	0.00
Pan	0.13	0.55	0.11	0.42	0.37	0.53	0.27	0.01	0.01	0.00
	100.0	100.0	100.0	100.0	100	100.0	100.0	100.0	100.0	100.0

Table C3. Numerical Results of Particle Size Distribution for Samples 27 to 43

Particle Size, ϕ	060166 27	060166 28	060166 29	060166 31	060166 32	060166 33	060166 35	060166 36	060166 41	060166 43
-2.0	0.90	0.00	0.00	0.00	0.03	0.05	0.05	0.05	0.95	0.18
-1.5	0.04	0.02	0.09	0.13	0.13	0.28	0.01	0.22	3.27	0.71
-1.0	0.10	0.04	0.18	0.20	0.24	0.29	0.15	0.31	2.75	1.31
-0.5	0.26	0.05	0.26	0.31	0.31	0.35	0.17	0.40	2.65	2.51
0.0	0.45	0.22	0.33	0.47	0.54	0.57	0.24	0.64	3.15	4.21
0.5	1.04	0.75	1.28	1.70	1.93	1.84	0.65	1.95	5.69	9.82
1.0	4.09	3.37	12.05	9.86	9.88	9.62	5.17	10.74	19.21	39.12
1.5	13.07	11.26	44.96	28.82	26.30	27.17	18.69	31.04	39.48	38.95
2.0	26.38	30.68	32.60	37.14	37.23	38.60	37.05	42.89	21.03	2.88
2.5	25.85	28.94	6.94	16.36	17.83	17.36	26.94	10.63	1.37	0.16
3.0	22.85	20.65	1.14	4.32	4.92	3.54	10.01	1.04	0.34	0.11
3.5	4.48	3.64	0.09	0.58	0.56	0.28	0.77	0.11	0.08	0.04
4.0	0.45	0.38	0.02	0.10	0.08	0.05	0.10	0.00	0.02	0.00
4.5	0.02	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.01	0.00
5.0	0.01	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Pan	0.01	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.01	0.00
	100.0	100.0	100.0	100.0	100.0	100.01	100.0	100.0	100.0	100.0

Table C4. Numerical Results of Particle Size Distribution for Samples 44 to 53

Particle Size, ϕ	060166 44	060166 45	060166 46	060166 47	060166 48	060166 49	060166 50	060166 51	060166 52	060166 53
-2.0	0.04	2.48	0.00	0.17	0.02	0.06	0.09	0.05	17.42	17.64
-1.5	0.32	0.42	0.01	0.29	0.16	0.14	0.29	0.01	9.88	23.24
-1.0	0.32	0.35	0.01	0.31	0.18	0.14	0.34	0.15	5.57	14.19
-0.5	0.34	0.42	0.03	0.37	0.19	0.22	0.39	0.17	4.27	9.31
0.0	0.55	0.91	0.15	1.14	0.42	0.51	0.69	0.24	4.89	6.52
0.5	3.41	3.37	1.21	10.98	1.69	2.01	2.84	0.65	4.70	4.21
1.0	27.53	22.03	15.82	56.61	11.66	12.27	19.45	5.17	3.71	3.50
1.5	55.55	55.27	63.15	27.83	42.16	39.61	48.47	18.69	6.01	2.95
2.0	11.34	13.26	17.94	1.88	36.32	32.86	23.05	37.05	10.01	3.94
2.5	0.34	0.93	1.20	0.36	5.93	9.70	3.69	26.94	11.90	4.39
3.0	0.21	0.43	0.43	0.05	1.02	2.08	0.59	10.01	14.43	4.97
3.5	0.05	0.10	0.06	0.00	0.20	0.31	0.09	0.77	4.94	2.79
4.0	0.01	0.02	0.00	0.00	0.03	0.05	0.02	0.10	1.74	1.68
4.5	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.25	0.30
5.0	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.18
Pan	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.13	0.20
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C5. Numerical Results of Particle Size Distribution for Samples 54 to 66

Particle Size, Φ	060166 54	060166 55	060166 56	060166 57	060166 59	060166 60	060166 61	060166 62	060166 64	060166 66
-2.0	2.28	8.72	2.72	20.28	2.31	2.87	2.03	1.54	10.42	7.24
-1.5	6.65	14.80	7.75	23.19	4.77	5.95	1.63	1.87	2.73	2.68
-1.0	7.59	9.72	5.84	11.55	2.48	3.47	0.80	1.58	1.85	1.70
-0.5	8.60	7.38	4.28	7.02	1.91	1.97	0.77	1.60	1.19	2.03
0.0	7.45	9.45	4.52	2.85	1.80	1.17	0.74	1.53	1.13	2.97
0.5	7.70	20.25	4.01	1.82	1.84	1.84	1.10	2.22	2.67	4.95
1.0	8.12	13.52	3.14	1.28	2.24	2.25	3.20	3.81	4.65	7.98
1.5	6.36	1.50	2.85	1.15	2.95	1.46	6.61	7.35	6.95	13.77
2.0	10.91	2.23	13.75	4.96	12.39	10.50	16.69	33.06	29.17	29.14
2.5	18.42	3.78	27.00	9.40	27.06	28.56	10.30	28.08	22.00	19.15
3.0	12.96	4.03	17.01	5.76	27.84	26.49	19.01	13.36	15.17	6.99
3.5	2.32	2.95	5.45	5.85	9.34	9.98	28.88	3.20	1.71	1.07
4.0	0.45	1.25	1.52	4.52	2.76	3.02	7.87	0.70	0.25	0.23
4.5	0.06	0.17	0.07	0.19	0.17	0.31	0.24	0.04	0.05	0.04
5.0	0.04	0.11	0.04	0.09	0.07	0.11	0.07	0.02	0.02	0.02
Pan	0.08	0.14	0.05	0.10	0.07	0.07	0.04	0.04	0.04	0.04
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C6. Numerical Results of Particle Size Distribution for Samples 67 to 80

Particle Size, ϕ	060166 67	060166 68	060166 71	060166 72	060166 74	060166 75	060166 77	060166 78	060166 79	060166 80
-2.0	4.14	9.74	2.31	9.66	2.56	2.36	0.18	27.35	15.59	16.05
-1.5	2.65	6.50	4.35	12.60	4.38	10.57	0.30	13.75	9.64	4.02
-1.0	1.40	4.98	5.90	18.64	3.09	12.25	0.21	11.52	8.25	2.61
-0.5	1.04	3.85	8.02	18.66	3.53	16.36	0.43	9.65	7.80	2.22
0.0	1.07	2.16	7.20	15.03	4.14	15.07	0.29	7.44	6.61	1.62
0.5	1.92	1.45	8.61	12.93	8.57	21.11	0.21	6.01	5.09	1.26
1.0	3.60	1.49	12.00	6.96	8.61	12.78	0.27	3.13	4.82	1.49
1.5	6.93	3.65	11.25	2.31	3.11	2.31	0.45	1.99	3.33	3.84
2.0	35.85	13.66	8.79	1.29	11.08	2.17	1.62	2.01	3.79	23.46
2.5	27.86	25.71	7.71	0.85	26.76	3.21	5.36	2.42	8.48	26.39
3.0	11.09	22.99	12.00	0.53	17.91	1.28	48.38	5.09	20.76	11.99
3.5	1.95	3.11	9.19	0.26	4.50	0.29	33.02	4.70	4.01	3.65
4.0	0.40	0.50	2.62	0.13	1.62	0.10	9.08	3.51	1.12	1.19
4.5	0.05	0.07	0.03	0.03	0.04	0.02	0.18	0.52	0.21	0.07
5.0	0.02	0.06	0.00	0.02	0.03	0.02	0.01	0.43	0.21	0.05
Pan	0.04	0.08	0.02	0.10	0.06	0.10	0.01	0.49	0.29	0.07
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C7. Numerical Results of Particle Size Distribution for Samples 81 to 90

Particle Size, ϕ	060166 81	060166 82	060166 83	060166 84	060166 85	060166 86	060166 87	060166 88	060166 89	060166 90
-2.0	13.39	2.17	3.52	0.67	12.64	21.37	11.52	0.23	3.27	0.09
-1.5	3.72	6.36	8.75	1.42	7.34	9.10	6.59	0.44	8.38	0.19
-1.0	3.23	8.32	10.20	1.26	5.92	5.28	5.18	0.68	8.15	0.38
-0.5	2.89	12.26	8.58	1.23	6.68	4.82	5.44	1.06	5.76	0.65
0.0	2.49	14.66	5.03	0.99	8.35	5.62	6.49	0.76	3.10	4.09
0.5	3.32	15.41	4.76	1.34	17.64	9.71	18.50	0.65	2.13	48.79
1.0	6.52	13.85	7.97	3.48	26.51	17.99	24.28	0.54	0.98	40.33
1.5	8.72	8.34	7.16	8.01	8.72	13.55	4.32	0.46	0.61	2.05
2.0	8.34	6.64	3.62	12.45	4.19	7.13	5.84	0.76	1.65	1.45
2.5	7.54	4.94	2.65	10.32	1.18	3.03	6.74	1.13	5.55	0.79
3.0	17.96	4.33	13.83	30.09	0.46	1.57	3.50	17.57	22.11	0.84
3.5	16.46	2.09	18.06	22.65	0.15	0.40	0.82	57.46	19.63	0.24
4.0	5.25	0.52	5.61	5.89	0.08	0.18	0.44	17.15	14.90	0.08
4.5	0.12	0.03	0.17	0.12	0.03	0.06	0.10	0.67	2.22	0.01
5.0	0.02	0.02	0.05	0.03	0.03	0.06	0.08	0.27	1.09	0.00
Pan	0.04	0.05	0.04	0.04	0.09	0.13	0.14	0.16	0.49	0.00
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C8. Numerical Results of Particle Size Distribution for Samples 91 to 100

Particle Size, Φ	060166 91	060166 92	060166 93	060166 94	060166 95	060166 96	060166 97	060166 98	060166 99	060166 100
-2.0	1.62	26.52	5.04	3.97	13.01	0.69	1.64	2.97	5.57	3.25
-1.5	7.67	8.54	8.07	3.11	4.84	2.85	3.23	8.27	8.92	6.57
-1.0	10.78	3.56	14.51	3.75	5.93	4.33	7.03	14.62	11.89	7.89
-0.5	11.23	2.57	29.74	7.53	12.06	7.46	22.16	23.79	18.22	9.63
0.0	8.77	2.04	26.62	12.84	20.29	10.71	28.45	23.46	16.16	8.70
0.5	7.64	2.11	8.97	25.59	20.93	15.43	23.95	15.44	15.99	5.93
1.0	6.33	1.85	2.66	37.64	10.11	22.91	10.55	6.98	18.38	4.74
1.5	4.34	1.69	1.43	4.60	2.20	12.69	2.37	1.84	2.69	2.85
2.0	7.19	4.13	0.87	0.22	2.76	8.48	0.31	0.86	0.42	3.08
2.5	13.37	14.51	0.66	0.19	3.07	5.83	0.08	0.49	0.40	4.54
3.0	15.24	23.93	0.72	0.27	2.84	5.59	0.06	0.60	0.68	16.00
3.5	4.30	5.67	0.35	0.13	1.09	1.82	0.04	0.24	0.41	19.64
4.0	1.16	2.12	0.17	0.06	0.44	0.73	0.03	0.15	0.13	6.08
4.5	0.13	0.35	0.04	0.02	0.10	0.18	0.01	0.05	0.02	0.41
5.0	0.09	0.20	0.05	0.02	0.11	0.16	0.01	0.07	0.02	0.30
Pan	0.13	0.20	0.10	0.05	0.23	0.14	0.06	0.16	0.08	0.37
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C9. Numerical Results of Particle Size Distribution for Samples 101 to 110

Particle Size, ϕ	060166 101	060166 102	060166 103	060166 104	060166 105	060166 106	060166 107	060166 108	060166 109	060166 110
-2.0	0.20	1.49	20.79	2.13	0.02	2.62	0.11	0.46	0.43	0.94
-1.5	0.46	6.53	15.25	3.00	0.10	5.64	0.49	1.32	0.31	3.15
-1.0	0.49	5.25	9.69	2.60	0.19	7.17	0.56	1.38	0.31	2.27
-0.5	0.92	4.06	5.15	2.25	0.25	9.24	0.87	1.86	0.50	1.73
0.0	1.40	2.26	1.86	1.67	0.26	11.81	0.92	2.19	0.47	1.39
0.5	2.16	2.11	0.97	2.22	0.31	17.45	1.29	3.55	0.53	1.72
1.0	4.94	1.21	0.85	3.47	0.43	12.90	2.08	6.65	0.66	1.94
1.5	10.35	0.59	0.73	2.85	0.45	6.62	3.74	11.72	0.84	3.74
2.0	18.82	0.83	1.43	3.41	0.72	4.70	8.06	22.10	3.55	16.67
2.5	18.58	1.37	3.79	6.17	1.65	2.32	12.44	20.05	18.02	65.62
3.0	28.03	12.75	21.27	37.99	35.27	3.96	34.46	17.19	54.98	0.62
3.5	11.75	42.58	13.47	26.79	50.51	11.70	27.10	9.09	14.36	0.19
4.0	1.83	17.39	4.16	5.25	9.47	3.72	7.65	2.36	4.74	0.03
4.5	0.03	0.94	0.26	0.10	0.25	0.06	0.15	0.04	0.17	0.00
5.0	0.02	0.39	0.17	0.04	0.07	0.04	0.05	0.01	0.07	0.00
Pan	0.03	0.26	0.16	0.06	0.06	0.06	0.04	0.03	0.05	0.00
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C9. Numerical Results of Particle Size Distribution for Samples 111 to 120

Particle Size, ϕ	060166 111	060166 112	060166 113	060166 114	060166 115	060166 116	060166 117	060166 118	060166 119	060166 120
-2.0	0.68	0.24	1.10	4.19	8.94	0.09	0.06	0.04	0.58	1.19
-1.5	3.24	0.89	3.42	9.66	2.68	0.64	0.48	0.15	1.33	4.78
-1.0	3.19	1.07	2.92	4.02	2.22	1.06	0.69	0.33	1.15	4.98
-0.5	3.38	1.44	3.27	2.35	3.80	1.31	0.75	0.35	0.75	3.98
0.0	3.38	1.22	4.30	2.19	6.47	1.41	0.92	0.30	0.45	3.04
0.5	5.15	1.20	6.44	2.68	14.97	2.41	1.19	0.52	0.44	2.70
1.0	3.90	1.14	3.67	1.99	20.05	1.85	1.19	1.17	0.53	3.41
1.5	3.90	2.38	2.52	2.92	17.41	2.06	3.47	3.31	0.90	6.11
2.0	19.07	18.15	19.10	10.18	15.08	15.52	18.49	17.74	4.01	17.82
2.5	26.28	33.59	32.88	18.58	5.69	36.99	28.72	33.00	16.88	18.62
3.0	20.03	27.19	16.81	24.14	1.87	28.22	29.15	29.61	50.21	18.52
3.5	5.96	8.12	2.67	10.65	0.53	6.24	10.64	10.12	17.27	11.36
4.0	1.65	2.79	0.74	4.93	0.20	1.82	3.56	3.05	5.26	3.33
4.5	0.12	0.34	0.08	0.79	0.03	0.21	0.41	0.17	0.14	0.08
5.0	0.04	0.16	0.04	0.44	0.03	0.09	0.18	0.07	0.06	0.04
Pan	0.03	0.07	0.03	0.31	0.04	0.08	0.09	0.06	0.05	0.06
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C10. Numerical Results of Particle Size Distribution for Samples 121 to 130

Particle Size, ϕ	060166 121	060166 122	060166 123	060166 124	060166 125	060166 126	060166 127	060166 128	060166 129	060166 130
-2.0	0.14	0.25	1.50	11.47	5.68	15.89	1.02	17.14	3.38	2.21
-1.5	0.00	0.53	4.00	8.34	17.57	13.01	4.08	14.66	14.05	1.66
-1.0	0.18	0.82	3.51	9.50	9.70	9.08	4.63	10.54	16.17	1.12
-0.5	0.53	0.98	4.31	10.85	6.90	9.34	2.99	6.74	17.82	0.96
0.0	0.64	0.80	6.43	10.73	7.86	10.19	2.24	3.79	12.44	0.95
0.5	0.69	0.89	11.67	19.86	10.51	18.66	2.97	3.33	13.86	1.57
1.0	1.06	1.45	5.55	11.81	5.33	12.85	2.87	1.55	8.65	1.71
1.5	2.70	2.67	2.05	2.59	2.83	4.12	2.16	0.68	2.60	3.45
2.0	14.17	17.88	11.25	3.18	9.43	2.72	6.06	1.11	1.85	16.39
2.5	28.02	33.73	26.59	5.23	15.11	1.60	16.80	3.07	3.23	32.60
3.0	33.35	27.45	17.24	4.96	7.72	1.23	34.62	13.33	4.34	29.15
3.5	13.76	9.01	4.24	0.98	0.99	0.68	14.12	13.95	1.23	6.64
4.0	4.47	2.97	1.34	0.29	0.21	0.38	4.88	8.76	0.27	1.36
4.5	0.16	0.36	0.18	0.06	0.05	0.07	0.34	0.75	0.02	0.07
5.0	0.06	0.14	0.07	0.04	0.03	0.06	0.13	0.37	0.02	0.05
Pan	0.07	0.07	0.07	0.10	0.08	0.11	0.10	0.22	0.07	0.10
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C11. Numerical Results of Particle Size Distribution for Samples 131 to 140

Particle Size, ϕ	060166 131	060166 132	060166 133	060166 134	060166 135	060166 136	060166 137	060166 138	060166 139	060166 140
-2.0	4.20	0.80	9.01	4.55	10.68	14.64	2.93	13.71	30.73	8.66
-1.5	6.71	0.76	15.70	6.82	21.62	24.01	5.61	14.39	15.89	6.65
-1.0	10.08	0.93	12.76	4.79	21.29	18.17	8.90	15.14	12.96	4.58
-0.5	18.21	1.72	15.82	3.95	16.54	13.21	15.18	15.79	10.97	3.78
0.0	24.00	2.58	20.39	3.55	9.87	8.93	18.62	14.69	9.25	2.65
0.5	20.29	3.67	17.97	3.97	5.89	7.28	18.91	15.06	6.68	3.19
1.0	4.54	8.97	3.43	2.19	2.25	2.01	4.87	3.97	2.10	1.85
1.5	1.92	22.08	0.94	2.28	1.35	1.64	3.50	2.20	1.51	1.45
2.0	1.72	28.95	0.52	3.12	1.41	1.88	3.60	1.61	1.74	3.95
2.5	2.19	20.05	0.36	6.85	1.42	2.10	4.68	1.43	1.93	12.47
3.0	3.63	8.78	0.78	32.63	2.41	3.32	8.39	1.53	2.81	35.51
3.5	1.39	0.67	1.53	21.03	1.68	1.12	2.63	0.22	1.40	11.28
4.0	0.72	0.06	0.58	4.18	1.88	0.89	1.35	0.08	1.14	3.52
4.5	0.13	0.00	0.02	0.05	0.57	0.28	0.32	0.03	0.32	0.24
5.0	0.11	0.00	0.02	0.02	0.55	0.25	0.26	0.04	0.28	0.12
Pan	0.18	0.00	0.16	0.03	0.60	0.27	0.24	0.09	0.29	0.12
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C12. Numerical Results of Particle Size Distribution for Samples 141 to 151

Particle Size, ϕ	060166 141	060166 142	060166 143	060166 145	060166 146	060166 147	060166 148	060166 149	060166 150	060166 151
-2.0	4.63	0.24	4.34	12.35	4.83	5.29	0.23	2.52	0.51	0.96
-1.5	9.94	1.56	15.81	18.16	2.25	2.64	0.17	2.28	1.57	2.31
-1.0	10.58	1.90	7.79	7.28	0.81	3.47	0.52	0.89	0.93	1.62
-0.5	14.07	2.35	3.21	4.99	1.10	10.02	3.29	0.94	1.17	1.57
0.0	8.41	1.98	2.09	6.95	1.95	20.64	7.30	1.73	2.45	2.38
0.5	5.60	2.48	1.52	14.08	5.12	26.50	34.47	3.76	4.17	5.17
1.0	2.64	2.34	0.78	12.15	5.64	11.80	45.49	2.79	2.77	3.83
1.5	1.18	1.99	0.55	1.29	5.40	3.86	3.89	2.38	2.74	3.87
2.0	1.89	4.54	2.11	1.75	20.01	7.28	1.37	22.89	24.07	17.54
2.5	5.26	18.53	9.50	4.15	30.17	6.74	1.73	38.61	36.54	27.29
3.0	18.88	40.72	29.77	8.58	18.72	1.49	1.06	17.31	18.06	24.33
3.5	12.28	15.13	14.45	5.14	3.30	0.14	0.27	2.99	3.78	7.05
4.0	4.07	5.56	6.73	2.36	0.50	0.05	0.11	0.73	1.06	1.81
4.5	0.33	0.45	0.81	0.33	0.07	0.02	0.02	0.08	0.09	0.13
5.0	0.12	0.13	0.34	0.20	0.06	0.02	0.03	0.05	0.05	0.07
Pan	0.12	0.09	0.20	0.23	0.07	0.03	0.03	0.05	0.03	0.07
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C13. Numerical Results of Particle Size Distribution for Samples 152 to 169

Particle Size, ϕ	060166 152	060166 153	060166 154	060166 155	060166 158	060166 160	060166 161	060166 162	060166 167	060166 169
-2.0	1.98	0.00	7.21	0.03	0.02	0.96	3.47	0.07	0.07	0.00
-1.5	10.52	0.00	6.86	0.11	0.15	2.27	6.85	0.25	0.12	0.06
-1.0	7.33	0.00	2.12	0.14	0.17	1.97	5.90	0.32	0.35	0.38
-0.5	3.66	0.27	1.20	0.28	0.28	1.82	6.30	0.67	1.30	0.65
0.0	2.43	0.36	1.14	1.88	2.59	1.77	7.09	1.79	2.30	0.57
0.5	3.13	1.30	1.70	4.99	47.47	2.46	13.42	6.81	5.23	0.72
1.0	3.10	9.52	4.30	2.30	45.47	5.65	33.00	26.06	19.66	2.51
1.5	3.05	32.00	6.74	3.35	0.82	9.56	17.21	33.10	29.89	8.34
2.0	9.12	41.19	15.08	22.82	1.22	13.47	4.88	23.54	22.04	23.29
2.5	20.56	13.76	29.61	45.64	1.08	6.09	1.40	6.60	12.60	36.37
3.0	25.15	1.46	19.78	15.77	0.50	18.05	0.36	0.74	5.83	22.87
3.5	7.47	0.07	3.17	1.99	0.15	26.93	0.09	0.04	0.53	3.54
4.0	2.17	0.04	0.79	0.49	0.06	8.75	0.02	0.01	0.07	0.66
4.5	0.21	0.02	0.18	0.12	0.03	0.21	0.01	0.00	0.01	0.03
5.0	0.03	0.00	0.03	0.02	0.00	0.01	0.00	0.00	0.00	0.00
Pan	0.08	0.02	0.10	0.08	0.00	0.03	0.01	0.02	0.00	0.01
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C14. Numerical Results of Particle Size Distribution for Samples 170 to 179

Particle Size, ϕ	060166 170	060166 171	060166 172	060166 173	060166 174	060166 175	060166 176	060166 177	060166 178	060166 179
-2.0	0.22	0.53	0.04	0.12	0.18	0.00	0.01	0.07	0.05	0.01
-1.5	0.28	0.96	0.03	0.08	0.25	0.00	0.00	0.07	0.11	0.09
-1.0	0.26	0.86	0.15	0.34	0.65	0.19	0.01	0.20	0.12	0.34
-0.5	0.56	2.12	0.24	0.85	1.01	0.65	0.09	0.63	0.54	0.77
0.0	1.46	4.50	0.37	1.19	1.11	0.66	0.39	1.23	0.91	0.80
0.5	3.93	11.62	0.84	3.55	2.10	1.83	2.23	5.61	2.48	1.75
1.0	12.26	25.37	4.19	16.22	5.36	21.72	29.04	35.77	13.93	9.67
1.5	19.41	21.49	20.47	28.01	10.98	54.00	54.08	42.99	50.03	52.70
2.0	19.38	13.25	31.99	22.51	22.81	18.25	12.55	11.03	26.97	30.84
2.5	21.81	10.33	19.91	15.22	31.86	2.30	1.31	1.84	3.71	2.60
3.0	17.59	7.82	18.28	10.61	20.35	0.36	0.28	0.47	0.89	0.36
3.5	2.41	1.02	3.01	1.16	2.88	0.04	0.02	0.07	0.19	0.07
4.0	0.39	0.13	0.47	0.12	0.41	0.00	0.00	0.01	0.04	0.01
4.5	0.02	0.01	0.03	0.01	0.04	0.00	0.00	0.00	0.02	0.00
5.0	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00
Pan	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C15. Numerical Results of Particle Size Distribution for Samples 180 to 189

Particle Size, ϕ	060166 180	060166 181	060166 182	060166 183	060166 184	060166 185	060166 186	060166 187	060166 188	060166 189
-2.0	0.14	0.18	0.76	0.44	7.54	1.06	0.19	0.68	4.47	3.10
-1.5	0.40	0.20	1.01	0.15	5.72	2.22	0.32	1.56	3.86	4.15
-1.0	0.22	0.10	0.67	0.18	3.31	1.89	0.23	1.02	1.43	2.51
-0.5	0.24	0.20	0.75	0.23	2.86	2.42	0.41	1.83	0.93	2.70
0.0	0.41	0.59	1.15	0.57	4.03	3.35	1.29	3.26	0.81	3.86
0.5	1.30	4.39	3.72	3.68	9.37	7.72	6.25	8.43	1.32	6.60
1.0	11.48	36.87	25.57	42.68	37.42	29.14	45.97	38.92	3.74	11.70
1.5	54.64	52.57	57.81	47.78	23.73	28.14	43.06	39.73	11.39	17.75
2.0	21.17	4.57	5.57	3.65	2.30	14.50	1.68	1.72	37.44	30.67
2.5	6.73	0.17	1.22	0.51	2.36	5.64	0.20	0.60	26.14	13.95
3.0	2.97	0.13	1.49	0.10	1.19	3.01	0.30	1.31	7.29	2.66
3.5	0.30	0.03	0.23	0.02	0.14	0.66	0.07	0.65	1.01	0.28
4.0	0.02	0.00	0.03	0.01	0.04	0.24	0.02	0.22	0.14	0.05
4.5	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.04	0.02	0.00
5.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Pan	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.01
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C16. Numerical Results of Particle Size Distribution for Samples 193 to 236

Particle Size, Φ	060166 193	060166 194	060166 195	060166 196	060166 198	060166 199	060166 232	060166 234	060166 235	060166 236
-2.0	10.08	3.97	3.99	10.97	5.07	1.74	0.27	0.43	0.96	0.79
-1.5	8.26	4.91	3.68	3.68	10.96	2.72	0.26	2.38	2.19	1.72
-1.0	4.43	3.93	2.95	1.53	9.10	2.83	0.61	3.26	2.53	2.04
-0.5	3.88	4.74	4.65	0.60	6.85	2.96	0.84	2.98	2.57	2.52
0.0	2.86	5.13	7.65	0.56	5.32	3.16	0.55	1.67	1.80	2.11
0.5	2.51	6.58	11.16	1.05	4.41	6.13	0.52	1.17	1.35	1.46
1.0	2.05	8.02	11.43	2.07	3.54	4.93	0.90	1.13	1.20	1.25
1.5	2.44	10.80	10.93	5.94	2.90	3.56	3.19	2.00	1.30	1.04
2.0	12.91	26.08	23.42	30.40	5.48	12.78	21.31	7.30	3.67	2.46
2.5	31.20	19.18	15.25	29.40	10.24	27.90	36.54	10.94	5.97	5.12
3.0	16.72	6.10	4.30	12.01	22.72	25.02	26.43	26.60	37.25	36.75
3.5	2.20	0.48	0.49	1.51	9.26	4.68	6.45	31.67	31.51	34.44
4.0	0.38	0.09	0.09	0.23	3.43	1.31	2.03	7.82	7.17	7.92
4.5	0.06	0.01	0.01	0.02	0.51	0.21	0.03	0.47	0.40	0.29
5.0	0.00	0.00	0.00	0.01	0.09	0.02	0.02	0.07	0.07	0.06
Pan	0.02	0.00	0.00	0.00	0.11	0.06	0.06	0.12	0.07	0.05
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C17. Numerical Results of Particle Size Distribution for Samples 237 to 246

Particle Size, ϕ	060166 237	060166 238	060166 239	060166 240	060166 241	060166 242	060166 243	060166 244	060166 245	060166 246
-2.0	13.29	0.48	0.30	3.52	11.96	1.11	18.58	1.94	4.51	4.86
-1.5	10.04	1.12	0.83	3.96	13.86	1.76	13.46	3.35	8.16	3.22
-1.0	5.51	0.76	0.91	1.91	5.96	1.26	7.04	5.37	8.12	6.09
-0.5	3.76	1.01	1.00	1.62	3.36	1.14	5.95	11.37	7.99	13.21
0.0	2.24	0.90	0.80	1.32	1.90	1.10	5.60	13.68	10.28	16.53
0.5	1.97	0.82	0.64	1.23	1.42	1.16	9.19	19.08	19.14	16.50
1.0	2.41	1.09	0.68	1.63	1.23	1.93	6.88	20.64	21.05	14.27
1.5	2.80	3.17	0.76	2.15	1.68	2.60	1.79	8.36	7.41	6.72
2.0	8.88	21.46	2.39	5.96	9.93	6.00	5.71	5.00	4.52	4.94
2.5	14.31	35.30	5.75	10.50	22.95	12.80	10.47	4.29	4.70	4.82
3.0	18.73	24.38	49.44	28.79	15.47	41.96	6.71	4.20	2.56	5.34
3.5	11.21	6.78	30.23	30.08	6.38	22.19	5.21	2.12	1.13	2.79
4.0	3.59	2.28	5.91	6.93	3.45	4.79	3.00	0.57	0.35	0.69
4.5	0.50	0.19	0.28	0.29	0.31	0.15	0.23	0.01	0.01	0.01
5.0	0.17	0.10	0.03	0.06	0.04	0.03	0.04	0.00	0.02	0.00
Pan	0.59	0.15	0.04	0.05	0.11	0.02	0.13	0.00	0.03	0.01
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C18. Numerical Results of Particle Size Distribution for Samples 247 to 259

Particle Size, Φ	060166 247	060166 248	060166 250	060166 251	060166 252	060166 254	060166 255	060166 257	060166 258	060166 259
-2.0	8.63	0.49	4.43	1.51	1.07	1.62	0.04	11.99	11.09	40.11
-1.5	6.83	0.49	7.90	2.48	2.17	2.18	0.29	8.73	7.42	7.92
-1.0	9.13	0.66	10.72	2.41	2.34	1.91	0.36	9.24	8.06	7.32
-0.5	9.99	0.90	13.22	2.26	2.11	1.74	0.86	10.98	14.25	8.94
0.0	9.12	1.02	13.57	2.32	2.05	1.53	1.13	12.49	19.22	9.95
0.5	11.70	1.17	14.15	3.50	2.75	1.75	2.29	10.59	16.54	8.20
1.0	13.50	1.89	11.40	6.91	5.18	3.76	7.47	6.34	5.73	4.05
1.5	9.14	2.77	7.21	9.17	7.76	6.69	16.07	4.39	2.69	1.74
2.0	7.40	6.74	6.40	11.21	13.63	12.65	23.24	4.23	1.93	1.63
2.5	7.17	15.98	5.78	13.54	17.47	15.34	17.40	4.97	1.88	2.02
3.0	4.55	47.04	3.57	28.05	28.91	30.94	18.64	9.36	4.42	4.54
3.5	2.07	16.33	1.24	12.33	11.33	15.76	9.03	3.97	3.39	2.06
4.0	0.65	4.39	0.35	4.18	3.06	3.82	3.09	1.78	2.26	0.99
4.5	0.06	0.13	0.02	0.09	0.12	0.21	0.07	0.51	0.68	0.31
5.0	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.13	0.12	0.06
Pan	0.06	0.00	0.06	0.01	0.03	0.06	0.01	0.30	0.31	0.15
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C19. Numerical Results of Particle Size Distribution for Samples 260 to 270

Particle Size, Φ	060166 260	060166 261	060166 262	060166 263	060166 264	060166 265	060166 266	060166 267	060166 268	060166 270
-2.0	28.31	33.17	5.69	23.00	20.23	19.18	25.50	3.98	19.62	1.51
-1.5	5.41	4.45	7.47	5.93	3.30	12.05	10.46	4.72	12.10	2.16
-1.0	5.92	5.86	8.72	5.95	3.03	10.39	8.96	4.41	10.29	2.46
-0.5	9.03	9.12	11.37	8.12	5.78	13.60	10.48	6.41	10.65	3.88
0.0	13.83	12.54	10.86	15.90	16.65	13.60	9.75	6.49	9.18	4.99
0.5	16.87	11.69	7.26	20.36	27.02	8.14	5.32	4.85	6.88	7.42
1.0	3.79	3.27	3.99	3.56	5.52	4.80	3.67	4.31	6.77	8.20
1.5	1.26	1.87	2.96	1.91	2.56	2.73	1.99	4.13	3.50	3.36
2.0	1.25	1.90	3.50	1.79	2.59	1.85	2.06	6.93	3.23	6.63
2.5	2.00	3.20	7.15	2.37	4.10	2.73	5.12	18.80	6.38	12.96
3.0	6.05	7.40	18.61	5.43	6.04	6.22	12.16	29.14	9.17	34.99
3.5	3.70	3.13	7.16	3.09	1.79	2.95	3.14	4.45	1.46	9.53
4.0	1.76	1.54	3.78	1.78	0.86	1.23	0.97	1.08	0.49	1.67
4.5	0.42	0.50	0.99	0.54	0.30	0.31	0.24	0.11	0.12	0.13
5.0	0.16	0.10	0.17	0.11	0.05	0.04	0.06	0.09	0.04	0.05
Pan	0.23	0.26	0.34	0.16	0.18	0.18	0.12	0.10	0.11	0.06
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C20. Numerical Results of Particle Size Distribution for Samples 271 to 280

Particle Size, ϕ	060166 271	060166 272	060166 273	060166 274	060166 275	060166 276	060166 277	060166 278	060166 279	060166 280
-2.0	0.04	0.46	0.22	2.71	0.71	0.00	0.01	0.02	4.16	0.06
-1.5	0.22	0.54	0.47	3.55	1.81	0.04	0.02	0.08	11.91	0.56
-1.0	0.51	0.97	0.58	2.59	1.62	0.05	0.04	0.12	9.20	0.76
-0.5	0.74	1.47	0.85	2.40	1.98	0.07	0.07	0.21	9.62	0.90
0.0	0.68	1.21	0.71	1.78	1.62	0.11	0.09	0.23	8.83	0.67
0.5	1.00	1.44	0.77	1.83	1.73	0.11	0.11	0.22	13.28	0.70
1.0	1.36	2.46	1.20	2.46	2.00	0.18	0.17	0.37	8.44	0.89
1.5	0.80	1.74	1.21	2.69	1.23	0.24	0.23	0.50	1.86	1.15
2.0	1.97	2.45	2.35	4.82	1.34	0.65	0.54	0.90	1.10	2.08
2.5	6.95	5.51	5.25	7.33	2.89	1.95	1.50	1.98	0.78	3.47
3.0	55.77	40.99	51.20	33.28	42.35	39.70	41.93	37.45	4.60	35.80
3.5	24.91	32.67	29.24	26.07	32.20	45.15	44.23	45.59	17.22	37.62
4.0	4.67	7.58	5.36	6.90	7.49	10.84	10.35	11.61	8.00	12.72
4.5	0.25	0.33	0.26	0.81	0.62	0.48	0.36	0.41	0.39	1.12
5.0	0.05	0.08	0.09	0.29	0.15	0.15	0.14	0.11	0.13	0.42
Pan	0.07	0.11	0.25	0.48	0.26	0.27	0.19	0.18	0.46	1.09
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C21. Numerical Results of Particle Size Distribution for Samples 281 to 290

Particle Size, ϕ	060166 281	060166 282	060166 283	060166 284	060166 285	060166 286	060166 287	060166 288	060166 289	060166 290
-2.0	5.53	9.25	1.07	4.54	3.28	0.05	3.58	0.48	0.09	4.16
-1.5	8.61	20.29	5.57	8.29	8.76	0.04	10.32	1.17	0.52	8.66
-1.0	6.24	12.78	7.91	8.64	7.62	0.2	9.27	1.15	0.669	6.31
-0.5	5.73	9.29	17.24	9.78	8.49	0.67	10.86	1.33	1.21	4.99
0.0	4.76	6.29	20.08	9.33	10.25	0.77	8.54	1.23	1.38	4.66
0.5	6.71	6.77	21.64	9.41	16.63	1.08	10.26	1.71	2.04	5.74
1.0	5.67	3.38	9.45	5.13	10.61	2.4	9.09	3.65	3.17	8.56
1.5	3.46	0.8	2.13	3.13	3.43	4.21	7.87	8.1	4.53	10.85
2.0	3.2	0.71	1.81	4.16	3.16	7.73	7.9	16.21	9.67	14.25
2.5	2.13	0.77	1.38	5.01	2.36	11.36	5.11	18.07	16.46	13.21
3.0	8.85	5.21	3	12.19	4.8	41.8	5.31	27.19	38.24	9.89
3.5	25.64	15.72	4.51	12.74	13.55	24.31	7.61	15.43	17.59	6.07
4.0	10.21	7.26	2.52	6.05	6.12	5.25	3.57	3.89	4.32	2.11
4.5	1.56	0.79	0.74	0.66	0.37	0.09	0.28	0.17	0.08	0.21
5.0	0.49	0.22	0.23	0.22	0.15	0.01	0.17	0.05	0.02	0.08
Pan	1.21	0.48	0.7	0.72	0.42	0.03	0.24	0.14	0.03	0.26
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C22. Numerical Results of Particle Size Distribution for Samples 291 to 295

Particle Size, ϕ	060166 291	060166 292	060166 293	060166 294	060166 295
-2.0	1.05	0.02	0.75	0.23	0.60
-1.5	2.00	0.07	0.29	0.82	1.92
-1.0	1.79	0.09	0.28	1.23	2.36
-0.5	1.72	0.20	0.25	1.26	1.53
0.0	1.70	0.33	0.22	1.01	0.95
0.5	2.71	0.74	0.24	1.09	0.89
1.0	4.11	2.75	0.65	1.95	1.33
1.5	6.12	6.47	2.87	4.06	2.78
2.0	17.56	13.12	16.01	10.71	9.20
2.5	25.01	16.19	29.60	13.70	15.38
3.0	20.16	32.74	34.58	31.33	35.03
3.5	11.57	21.20	10.67	24.95	20.93
4.0	4.06	5.85	3.16	7.24	6.51
4.5	0.19	0.12	0.18	0.24	0.32
5.0	0.10	0.08	0.11	0.08	0.08
Pan	0.15	0.05	0.16	0.11	0.18
	100.0	100.0	100.0	100.0	100.0

APPENDIX H

**REGIONAL SEDIMENT MANAGEMENT BULLETIN
VOL 4, WINTER/SPRING 2006**

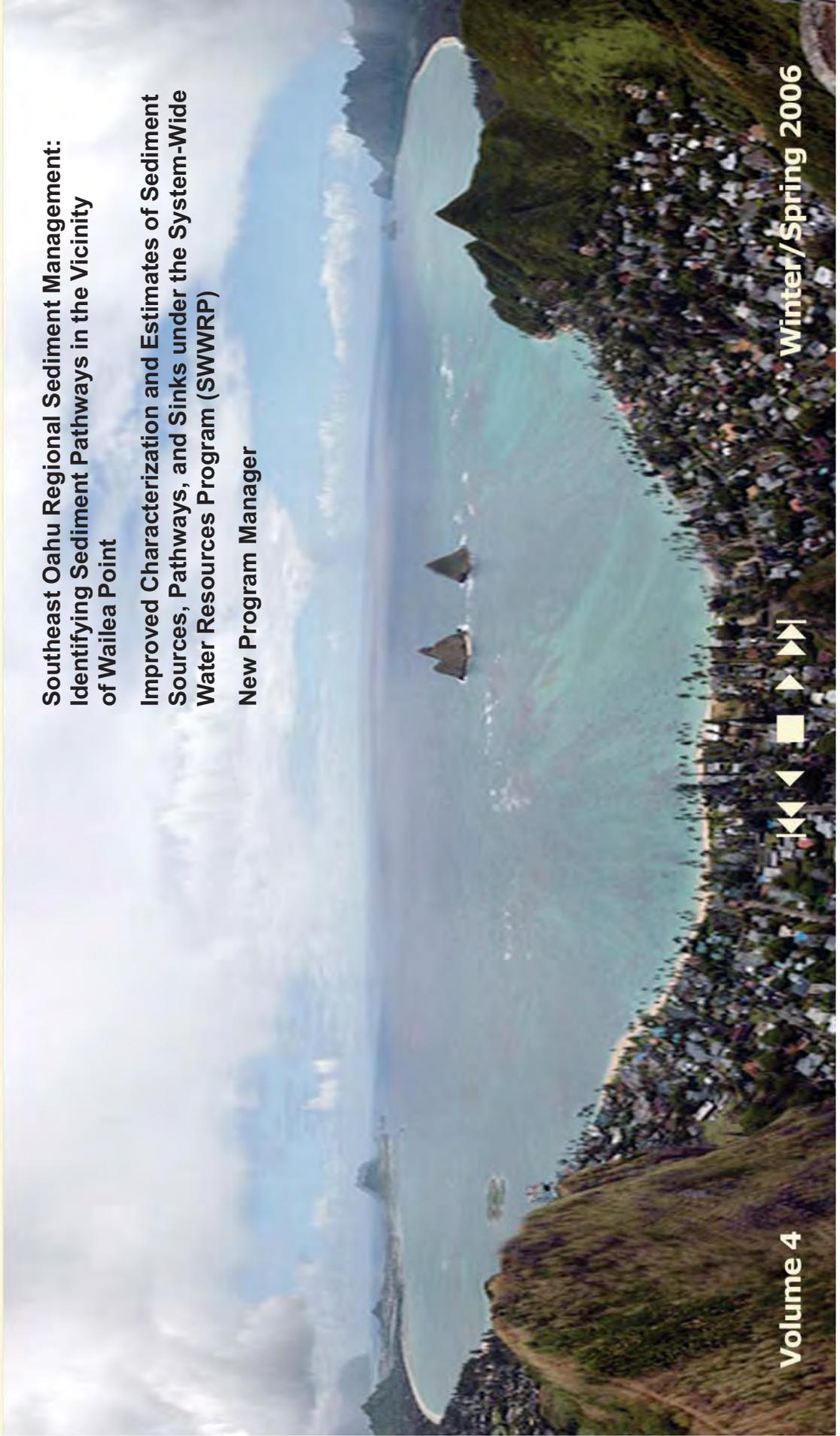


Regional Sediment Management

**Southeast Oahu Regional Sediment Management:
Identifying Sediment Pathways in the Vicinity
of Wailea Point**

**Improved Characterization and Estimates of Sediment
Sources, Pathways, and Sinks under the System-Wide
Water Resources Program (SWWRP)**

New Program Manager



Southwest Oahu Regional Sediment Management: Identifying Sediment Pathways in the Vicinity of Wailea Point

by *Thomas D. Smith and Jessica R. Hays, U.S. Army Engineer District, Honolulu*

Initial regional sediment management efforts in Hawaii have been focused along the southeast O'ahu (Hawaiian for the gathering place) coast. The Southeast O'ahu Regional Sediment Management (SEO/RSM) study area extends along approximately 12 miles of shoreline from Mokapu (taboo) Point to the north and Mokapu'u (hilltop) to the south. Towns within the region include Kailua (whole in the sea), Lanikai (sky and sea) and Waimanalo (sweet water). Military installations within the area are Marine Corps Base Hawaii and Bellow Air Force Station (AFS). The region experiences prevailing trade winds from the northeast, associated trade showers, and locally generated wind waves. A broad shallow nearshore reef extends along the length of the region. The reef is nominally 2,000 feet wide and has an average depth of about 4 feet. Small offshore islets such as Manana (buoyant), Kaohikaipu (hold back breaking waves), Na Mokulua (calmed, two adjacent islands), Popoi'a, and Mokolea (filled with water) Rock are scattered throughout the reef flat.

Generally, wide sand beaches are a rare sight in Hawaii, but within the SEO region there are a number of long stretches of pristine kahaone (sandy beach). These areas include numerous State of Hawaii-owned beach parks and portions of Bellow AFS. Beach sand in the region primarily comprises calcium carbonate grains derived

from shells, corals, and other aquatic organisms. Basalt from the eroding island mountains can also be found in sand samples taken within the active beach profile. At the northern limit of the region, significant quantities of olivine are also present along the upper reaches of the beach.

This is not to say the region does not have erosion and sediment management issues. At Ka'elepulu (hollow and wet) stream mouth, sand from the adjacent shorelines accumulates and blocks the flow of water from Enchanted Lake upstream. The existing sediment management practice is to periodically excavate the sand from the mouth of the stream and place it along the adjacent streambanks. Not only does this practice take the material out of the active profile, strong trade winds blow the sand mauka (toward the mountain) and out of the system. On either side of Waialae (happy water) Point, coastal structures have been constructed such as seawalls, groins, revetments and jetties. Beaches in these areas (including portions of both Lanikai and Bellow AFS) are narrow to nonexistent. At the southern end of the region, the shoreline is eroding and currently within a few feet of Kalanianna'ole Highway along Kaupo (a variety of native banana) and Kaiona (sea mite) beaches. The highway is a major transit route and provides the only access to much of the windward O'ahu coastal margin. The scarcity

of beach quality sand and environmental concerns in Hawaii limit the opportunities for beach nourishment. A major goal of the SEO/RSM study is to quantify the movement of sand offshore of Wailea (happy waters) Point. The point is located in the central portion of the region and divides the town of Lanikai to the north and Bellows AFS to the south. At the present, the portion of Lanikai beach located adjacent to Wailea Point is awash at high tide and a continuous series of seawalls has been built to protect oceanfront singe-family homes. Further to the north, the beach widens significantly until one reaches Alala (a variety of sweet potato) Point. Beyond Alala Point, the beaches of Kailua are from 100 feet to 200 feet wide and the oceanfront houses are set back up to 300 feet from the mean high water shoreline.

Similarly, south of the point the shoreline has been armored through construction of a revetment along approximately 2,000 feet of the Bellows AFS shoreline. A 50-foot-long groin has been constructed at the point which retains a small pocket beach in front of an officer's beach cottage rental unit. Jetties have also been constructed at the mouth of Waimanalo stream in an attempt to keep the mouth of the stream from being plugged by the influx of sand from adjacent beaches. In order to quantify sediment transport in the vicinity of Wailea Point, the SEO/RMS study strives to incorporate multiple assessment techniques to attain an understanding of the regional coastal processes at work, assess anthropogenic impacts to the system and develop a sediment budget for the area and ultimately the entire region.

In pursuit of a regional sediment budget for SEO, wave, current, and sediment data have been collected, a wave transformation model has been coupled to a water circulation model, and a historical shoreline change analysis is underway. Field data collection was conducted for a one month period in the fall of 2005. Data collection consisted of deployment of Acoustic Doppler Current Profilers (ADCP) and currents) and Acoustic Doppler Velocimeters (ADV) gauges and the tracking of drogues following their release at various locations within Kailua and Waimanalo bays.

Instrument locations are shown in Figure 1. Deployment was on 9 Aug 2005 and retrieval was on 14 Sep 2005. Each gauge successfully collected a minimum of one month of time series data.

The ADCP gauges were RD Instruments 1,200 kilohertz Workhorse, bottom mounted facing upward with the sensor head approximately 0.4 meters off the bottom. Figure 2 shows the custom built

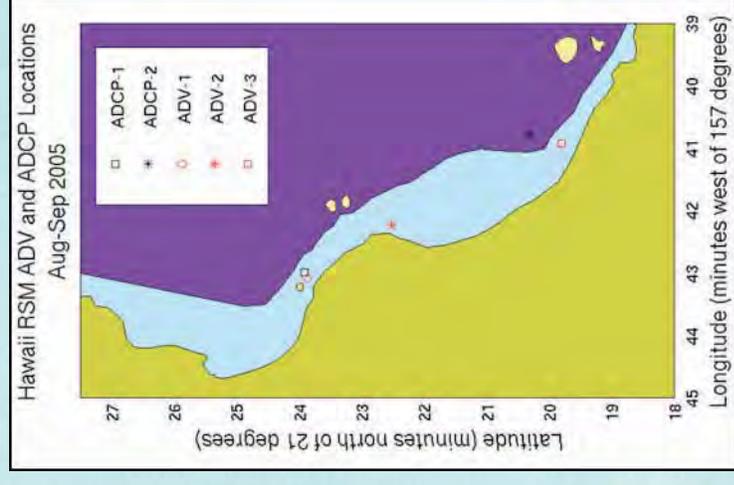


Figure 1. ADCP and ADV locations.



Figure 2. ADCP in frame (left) and close-up of transducer head with biofouling (right).

mount that was held to the bottom with about 80 pounds of lead weight. These gauges have four acoustic transducers for measuring currents and a pressure sensor, from which horizontal and vertical current profiles were computed at 0.2-meter vertical spacing. These units sampled at 2 kilohertz for directional wave measurements. Each hourly wave burst was approximately 34 minutes long, starting at the top of each hour, and consisted of 4,096 points. There is a 0.44-meter blanking distance from the transducer head, and with a 0.2-meter bin width, this makes the first sample 0.72 meter past the transducer, or about



Figure 3. Hydra ADV in frame (left) and closer view of the biofouled sensor head (right).

1.12 meters off the bottom. Current profiles were collected every 10 minutes from a 200-point average. The three ADV gauges were the Sontek's Hydra model that sample a single point current velocity (U, V, and W) and contained an external pressure sensor. The instrument frame and ADV transducer are shown in Figure 3 (after gauge retrieval). The sample volume for the current measurement is approximately 1 to 2 centimeters in size and about 0.17 meters from the center transducer. This unit uses three beams to determine the three current components.

Four inexpensive current drogues (drifters) were designed and built at the USACE Coastal and Hydraulics Laboratory (CHL) Field Research Facility (FRF) that used Global Positioning System (GPS) tracking and radio telemetry for positioning. They were constructed with off-the-shelf plumbing supplies (PVC pipe, vertical risers, rubber unions, hose clamps), Garmin Geko GPS



Figure 4. GPC current drogue with traditional drifter (grapefruit) and Hawaiian drifter (coconut). Drifter floats just below the surface.

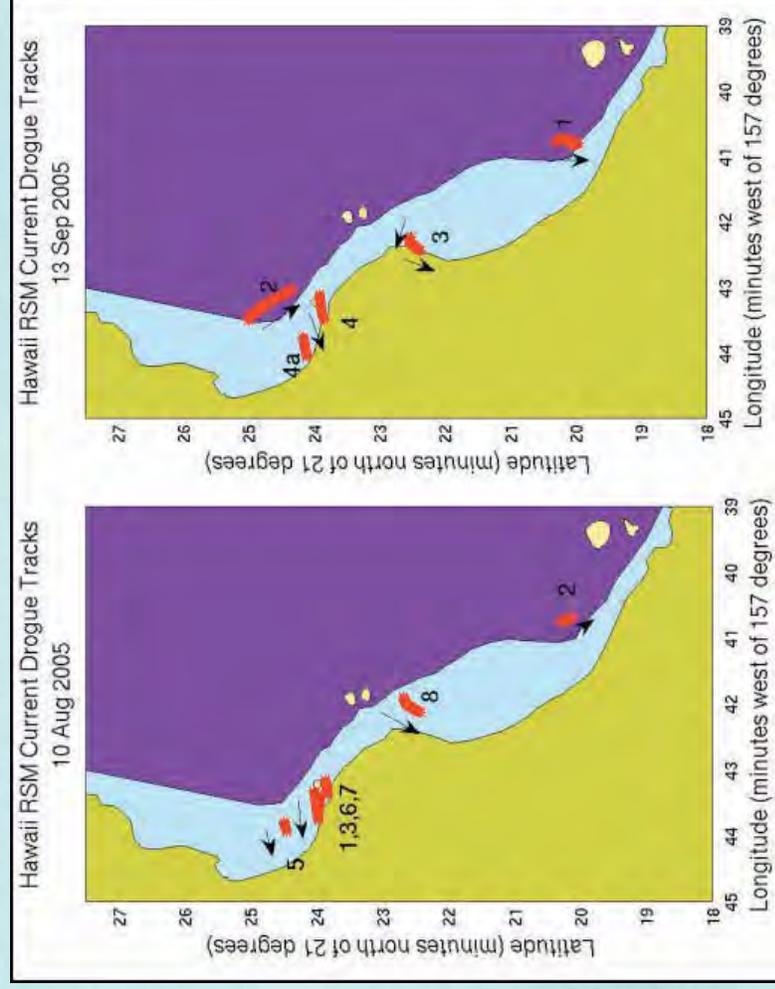


Figure 5. Drogue tracks with track number for 10 August (left) and 13 September (right).

receivers, and MaxStream (model XStream-PKG-R) radio modems (Figure 4). The sails had about a 1-meter cross section. The lower vertical PVC pipe (submerged) contained the modem and batteries, the upper horizontal pipe contained the GPS receiver and radio antennas. A National Electrical Manufacturers Association (NEMA) GPS data string was transmitted once per second and the Garmin Fround Control Points (GCP) unit internally recorded positions every 30 seconds. These GPS units are Wide Area Augmentation System

(WAAS) enabled and have a horizontal accuracy of about 3 meters. The radio tracking required line of sight, and it was not possible to simultaneously receive drifters signals in the Kailua and Waimanalo bays.

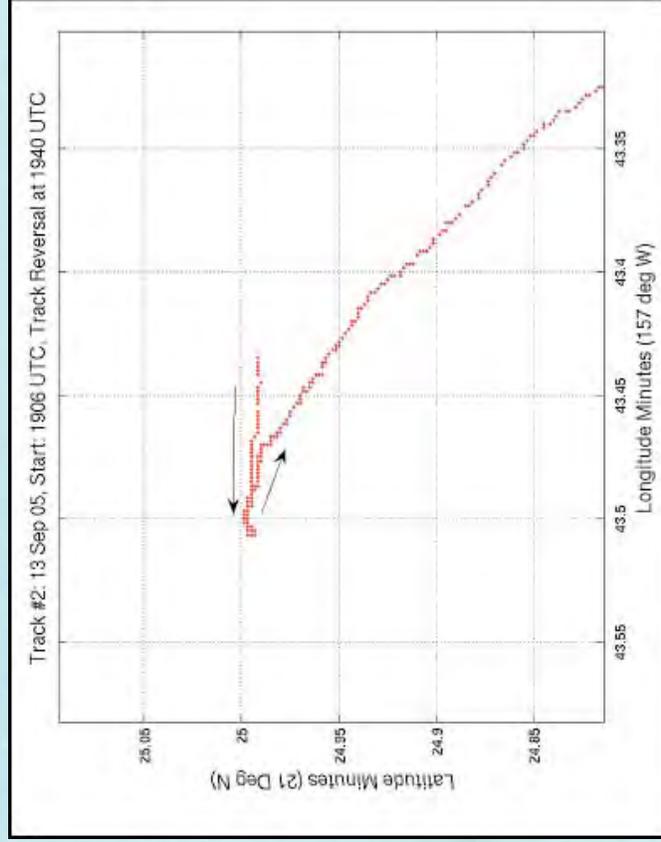


Figure 6. Drouge track reversal on 13 September.

Drouge tracks with track numbers are shown in Figure 5. Some drogues were deployed in the vicinity of the ADV and ADCP gauges for intercomparison. An interesting reversal of drogue No. 2 was observed shortly after deployment on 13 Sep (Figure 6), starting off on a nearly due west track and then turning back to a southeast trajectory.

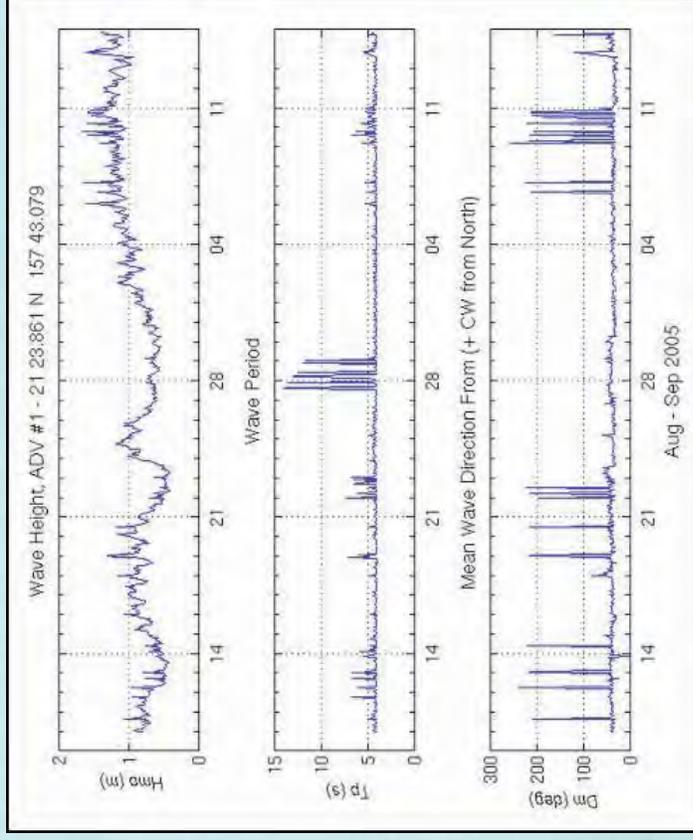


Figure 7. Wave height, period, and direction for ADCP No. 1.

Figure 7 is a plot wave height (Hmo), peak period (Tp), and mean direction (Dm) for ADV No. 1. Figure 8 compares Hmo for the three ADVs and shows ADV No. 3 as having the smallest wave heights. Current directions for ADV No. 2 appear to be mainly north or south which may be due to placing the gauge between coral heads that restricts flows to those directions.

The field data is being utilized to calibrate and verify the results of ongoing wave transformation and water circulation modeling. Bathymetric data used in the generation of model grids were derived from various sources. National

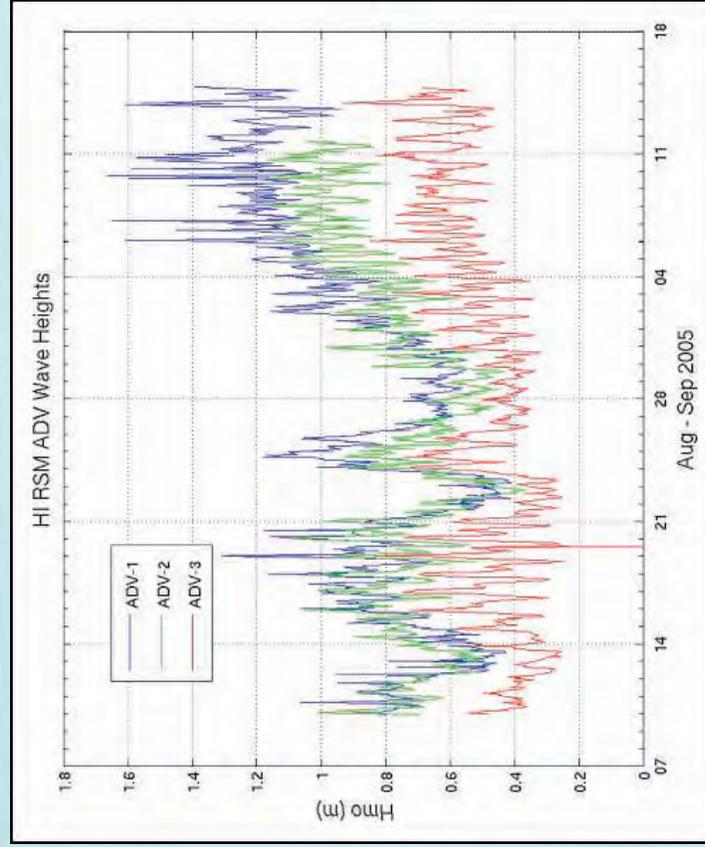


Figure 8. Wave height (H_{mo}) comparison of the three ADVs.

Geophysical Data Center data sets including ETOPO2 and GEODAS were used in the deep ocean while National Oceanic and Atmospheric Administration (NOAA) digital nautical charts and SHOAL were used for intermediate and nearshore waters, respectively. Grid element size for the circulation model ranged from 75 miles to 80 feet. Bathymetric data were interpolated onto the circulation model grid and hand-edited to ensure accuracy.

Tidal constituents from an established database were used to force the model boundary water levels as well as

hindcast winds procured from Ocean Weather, Inc. Tide levels generated by the model compared favorably to NOAA tide gauge data from Kaneohe (bamboo god) Bay and Honolulu (calm bay) Harbor. Wave transformation modeling was conducted over a grid incorporating the SEO region as well as additional area both longshore and makai (oceanward). A directional wave gauge (University of Hawaii/Coastal Data Information Program (CDIP) gauge 098) has been operational at the boundary of the grid from August 2000 to the present and has provided valuable boundary conditions for use in model calibration/verification with nearshore field gauge data acquired as

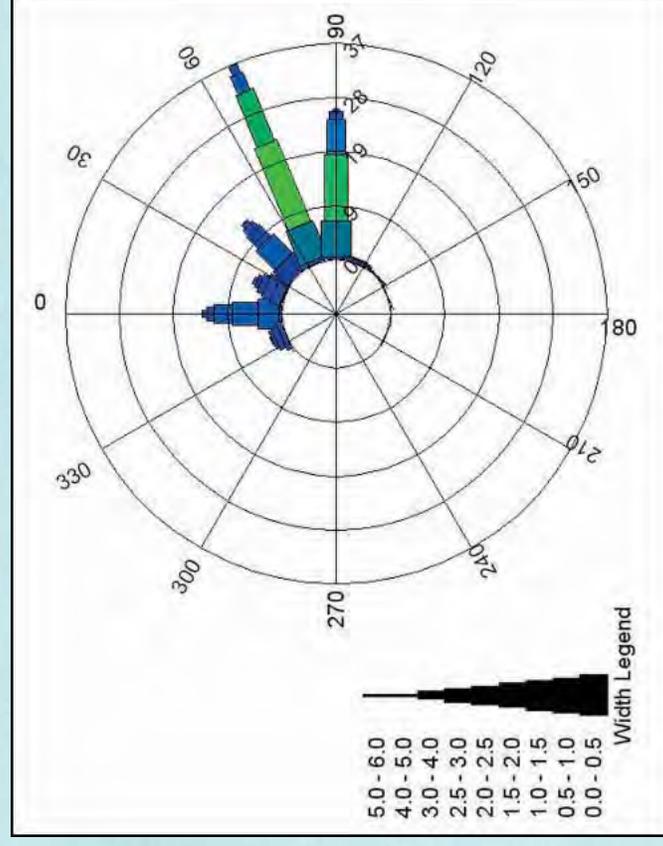


Figure 9. Wave rose for UH/CDIP buoy in RSM demo area.

previously described. As shown in Figure 9, waves recorded by the University of Hawaii gauge were generally from the northeast quadrant and ranged in height from 0.5 to 1.5 meters. Wave periods were on the order of 6 to 16 seconds. Currently, the wave transformation and water circulation modeling is being refined based upon comparison to the field data. Once calibrated, the models will be used to hindcast the wave/wind/tide induced water circulation within the SEO/RSM study area for the year 2004.

The historical shoreline change analysis being conducted for SEO/RSM by the University of Hawaii consists of determining the rate of shoreline change at 20-meter intervals alongshore over the period of early 20th century to 2005. NOAA "T" sheets dating from the early 20th century are being orthorectified using modern GPS ground control and used in comparison with four to eight orthorectified aerial photographs from the post-World War II era to determine a long-term rate of shoreline change. Reweighted weighted least median of squares linear regression technique is being used to determine the long-term trend of historical change. This technique eliminates outlier points from the linear regression and combines measurement and positional uncertainties with regression uncertainties in calculating the standard deviation of the trend.

New aerial photographs from 2005 with a scale of 1:8400 digitally scanned at 10 microns will be acquired for the study. These aerials will cover a coastal strip approxi-

mately 800 to 1,000 meters wide centered on the shoreline. Stereo-photogrammetry using orthorectified pairs of photos, with GPS ground control, will be used to create coastal digital terrain models (DTMs). These DTMs will be digitally combined with offshore SHOALS data (where such data exist) to create a seamless topographic/bathymetric DEM for the region. Historical photography and "T" sheets will be orthorectified using the 2005 DEM so that all derived shoreline data are based on orthorectified positions, thus minimizing positional errors. Root mean square positional error of final orthorectified photographs is typically about 1 to 2 meters. Using topographic field profiles to measure beach and dune volume shoreline change rates can be converted to rates of sand volume change over time. Along with historical shoreline change data presented at a 20-meter interval along the entire region a sediment budget for the period of study (approximately 80 years) will be produced.

Sediment Trend Analysis (STA) is a technique that derives patterns of net sediment transport from relative changes in grain-size distributions of aquatic sediments. STA also determines the dynamic behavior or stability (i.e., erosion, dynamic equilibrium, accretion or deposition) of the sediments. Sediment Trend Analysis is used to derive the following information:

- Grain size characteristics of surficial sediment encompassing the entire area of study
- Sediment sources and sinks
- Zones of influence of sediment sources

- Sediment transport pathways
- Sediment stability (i.e., erosion, accretion, dynamic equilibrium, etc.)
- Links between intertidal or beach areas and offshore sediments

For the SEO/RSM study, STA will be utilized as another means to identify sediment pathways in the vicinity of Wailea Point. Sediment sampling is to consist of acquisition of 250 grab samples by the University of Hawaii, analysis of the sediment samples by the CHL and the ultimate use of STA methodology by the University of Hawaii to qualitatively describe how sand moves around and offshore of Wailea Point.

Comparison and correlation of the field data, numerical model results, historical shoreline change analysis, and STA will unlock the mystery of sediment transport within the Wailea Point subregion of the SO/RSM study area. Given an accurate understanding of sediment transport and coastal processes in and around Wailea Point, stakeholders and decision-makers will be able to forge realistic goals in the management of beach resources along the Lanikai and Bellows Air Force Stations shorelines. With a regional sediment management plan in hand, the remaining question will be “Loa’a One? (Got Sand?)”.

Loa’a One? (Got Sand?)

APPENDIX I

**KAILUA BEACH/KAELEPULU STREAM INFORMATION
MEETING MINUTES AND NEWSPAPER ARTICLES**

MEMORANDUM For Record

SUBJECT: Recap of September 18, 2008 meeting on Kailua Beach Erosion

1) Attendees:

- USACE Honolulu District – Jessica Podoski (EC-T), Farley Watanabe (EC-R)
- Representative Cynthia Thielen (Kailua/Kaneohe Bay)
- Congresswoman Hirono's Office – Josh Wisch
- University of Hawaii Coastal Geology Dept. – Chip Fletcher, Ph.D.
- UH Sea Grant – Darren Lerner
- DLNR Office of Conservation of Coastal Lands – Dolan Eversole, Chris Conger (Sea Grant Extension Agents)
- DOH Clean Water Branch – Alec Wong
- City & County of Honolulu:
 - Dept. of Design/Construction – Terry Hildebrand, Clifford Lau
 - Dept. of Parks/Recreation – Wilfred Ho
 - Dept. of Facilities Maintenance – Tyler Sugihara, Craig Nishimura, Les Chang
 - Dept of Pubic Safety – Kevin Allen (Lifeguard Captain)

2) Discussion focused primarily on regulatory issues that will affect backpassing of sand from Kaelepulu Stream mouth to the eroded area adjacent to the boat ramp (below high water mark) on a regular basis in an effort to address worsening erosion problem. USACE (Watanabe) noted that a Statewide Programmatic General Permit from USACE is effective until 2010 and that DOH Clean Water Branch has the responsibility to enforce the Clean Water Act under this permit (i.e., USACE is not posing a regulatory barrier to backpassing material).

3) Group agreed to draft a Memorandum of Understanding between DLNR/USACE/DOH to outline issues of placing sand at the boat ramp (logistics, monitoring, etc.) and to ensure that all parties have agreed beforehand on procedures in the event that a complaint is registered with DOH following placement. (This occurred during the last attempt at backpassing and stopped sand placement due to suggestion of water quality impairment). Other action considered was to request an emergency declaration from the Governor to get things moving more quickly; however, it is uncertain whether this would exempt enforcement of Clean Water Act.

4) Following drafting and preliminary review of the MOU, group suggests another meeting to be attended by Department/Division heads so that agreement may be approved and forwarded for legal review. Date given for follow-up meeting was approximately 30 days (o/a 20 Oct 08). A follow up meeting to discuss long-term erosion solutions will also be scheduled.

5) For additional information, please see summary provided by meeting organizer (attached) or contact Thomas Smith (438-0581)/Jessica Podoski (438-1680) of Civil Works Technical Branch or Farley Watanabe (438-7701) of Regulatory Branch.

/s/

JESSICA H. PODOSKI, P.E
Coastal Engineer

Podoski, Jessica H POH

From: Dolan.Eversole@hawaii.gov
Sent: Thursday, September 18, 2008 5:32 PM
To: Dolan.Eversole@hawaii.gov
Cc: alec.wong@doh.hawaii.gov; Chris.L.Conger@hawaii.gov; Ikehara, Carolyn T; Mayeda, Craig S.; fletcher@soest.hawaii.edu; Podoski, Jessica H POH; kallen@honolulu.gov; Laurence.K.Lau@hawaii.gov; Chang, Lester K C; repthielen@capitol.hawaii.gov; Sam.J.Lemmo@hawaii.gov; Smith, Thomas D POH; Ho, Wilfred M.Y.; joshua.wisch@mail.house.gov; tsugihara@honolulu.gov; Rep. Cynthia Thielen; Watanabe, Farley K POH; thildebrand@honolulu.gov; lemer@hawaii.edu
Subject: Recap September 18 meeting on Kailua Beach park

I want to thank you all for coming to today's special meeting on the Kailua Beach erosion. I feel we made some progress today in understanding what needs to be done to place beach sand at the erosion site near the boat ramp. As a follow up to the discussion here is a brief summary:

1. The need to supplement with boat ramp area with sand is clear. The best available source is to backpass sand from the Kaelepulu stream either from the stream mouth clearing directly or from the dried stockpiled dune sand and along the banks of the stream (preferred).
2. The erosion occurring at Kailua Beach appears to be worsening and may have crossed a threshold becoming a chronic rather than episodic erosion problem. The erosion may be attributed to a lack of sediment in the system that may be partially alleviated by altering the current sand management practices at the Kaelepulu stream mouth so sand is mechanically redistributed back to the southern portion of the beach park near the boat ramp.
3. The erosion appears to spreading in either direction from the stream mouth and has required the removal of trees as well and the relocation of the lifeguard tower several times.
4. The DLNR and Army Corps of Engineers each have the discretion to allow the sand backpassing under periodic stream maintenance and this would not require a permit to backpass sand to the south.
5. The Department of Health, Clean Water Branch (DOH) is responsible for enforcing Federal and state water quality standards. Due to this fiduciary responsibility to uphold the Federal Clean Water Act the DOH is compelled to enforce if there is a violation of the state water quality standards.
6. It is not clear if the DOH has the discretion to determine at what level and to what degree exceeding the water quality standards constitutes an "violation"
7. The City and County Parks does not want to proceed with a project to bypass sand until there is some assurance they will not be in violation of the DOH's rules.
8. Need to weigh the risk of utilizing sand from stream area vs. impact of no action.
9. Conducting a conceptual feasibility study and project benefit vs. risk analysis may help illustrate the risk of no action.
10. As part of any future action to backpass sand Dolan will assist the City with development of a water quality monitoring plan to address potential concerns of water quality impacts related to the backpassing of sand. Initial estimates for regular water quality monitoring by qualified contractors are on the order \$1000 per event.

Future Action Items (with timeline).

1. (Week 1) Dolan Eversole will draft a draft MOU between the DLNR/ CORPS/DOH to outline the issues and how we might all agree to move forward with the project so the sand can be placed below the highwater mark without constituting a violation.
2. (Week 2-3) Upon completion of the draft MOU Dolan will send out for review and comments to this committee.
3. (Week 4) Once the initial comments and concerns have been reviewed another administrative meeting (with each Department/Division head) will be held to discuss the issues raised in the initial review and find expedited solutions.
4. (Week 5-?) Final MOU goes out for legal council review. The MOU will need to be reviewed by the City Corp

Council and the State Attorney General office and may take up to 60-90 days in total.

Other (Interim) Alternatives:

1. Governor's emergency declaration may not supersede Federal Water quality laws.
2. City might be able to proceed with sand placement with understanding of risk of DOH investigation if a complaint is generated. Need to discuss with DOH administration to obtain understanding of investigation and enforcement procedures.
3. Need to weigh the risk of utilizing sand from stream area vs. impact of no action.

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University of Hawaii Sea Grant College Program
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(808) 587-0321
(808) 587-0322 fax

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Posted on: Monday, September 8, 2008

PROBLEM UNSOLVED

Kailua's sandy shore fading

 [Photo gallery: Kailua Beach Erosion Worsening](#)

By **Eloise Aguiar**
Advertiser Staff Writer

KAILUA — Erosion at Kailua Beach has reached startling proportions, revealing a 60-foot-long sand trap installed 30 years ago at its southernmost end and buried until recently, and raising concern that the problem could work its way north along the entire beach if something isn't done.

The shore at the end of Kailua Bay, where a boat ramp juts out into the sea, is gone. In its place is a sheer dropoff to a narrow beach lined with a "sand grabber" placed there in the 1970s with the intention of catching and holding sand in place.

It was government's response to the problem and it seemed to work, until recently.

The boat ramp is also taking a hit where water is undermining its left edge, exposing its boulder foundation and causing parts of the asphalt surface to collapse.

About 100 feet of sandy shore from the dropoff out to sea is no longer there. For hundreds of feet along the shore, the roots of ironwood trees are exposed and several ironwood trees have had to be removed for safety reasons.

People thought the sand grabber was working but there was always seasonal movement of the sand, said Raul Fallau, who has lived in Kailua for 50 years and seen it go through many changes. Eventually the sand grabber was totally covered and beachgoers forgot it was there.

"As time went on it started eroding but it would always come back. But this time it isn't coming back," Fallau said. "They brought in sand and tried to fill it up, but you can't compete with Mother Nature."



The "sand grabber" extending from Kailua Beach's small boat launch ramp was installed 30 years ago to stave off erosion and has been covered by sand for so long that most beachgoers forgot it was there. Now, the sea has reached beyond the grabber's concrete blocks and eaten away the beach, leaving a 5-foot dropoff.

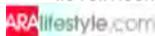
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But leaving the beach as it is could be dangerous to tourists and kids, said Steven and Carol Ann Inouye, who heard about the problem and were at the beach launch ramp recently to see the damage for themselves.

"I was surprised to see the tiles (of the sand grabber) and the erosion," Steven Inouye said. He had thought the sand grabber, a sort of wall made up of concrete tile blocks, was recently installed. "I don't think the tiles will stop big water from taking the sand."

The beach is part of the city's Kailua Beach Park. But the ocean and up to the high-water mark are the jurisdiction of the state.

The city has asked the state for recommendations about the sand grabber and whether to remove it or repair it, said Lester Chang, director of the city Department of Parks and Recreation. Chang said he's not sure that the sand grabber really worked but is deferring to the state because his department has no expertise on the issue.

When the erosion began, the city moved sand piling up at Kaelepulu Stream to the boat ramp area. However, the state Department of Health halted that, saying the sand, once moved, could not be allowed to come into contact with ocean water.

Kailua isn't the only beach that is eroding, Chang said. Areas in Hau'ula and Hale'iwa are experiencing similar problems. Over the years and at other beaches, he said, he's noticed that sand comes and goes — but what's happening at Kailua is different.

"Usually most of it comes back, but this last two years it seems like it's taking one step forward and three backward," he said.

At a workshop last week hosted by the Army Corps of Engineers on the broader subject of coastal sediment transport, Kailua's erosion problem was raised, said Joseph Bonfiglio, spokesman for the Army Corps.

"The workshop participants agreed on the need to form a focus group with all agencies involved to further discuss issues and alternatives to sediment management at the Kaelepulu Stream mouth," Bonfiglio said in an e-mail.

Chip Fletcher, a University of Hawai'i professor who is conducting a study of the historical shoreline changes of every beach on O'ahu, said the group needs to help develop best management practices for clearing sand from the stream mouth.

Fletcher said the erosion is chronic and creeping north but a plan to manage sand clearing might stem that progress.

"The longer we wait, the longer the erosion will work its way north and affect the entire beach," he said.

Reach Eloise Aguiar at eaguiar@honoluluadvertiser.com.

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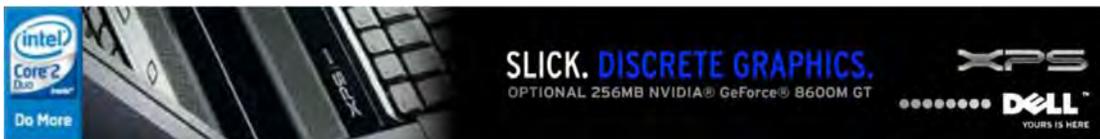
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Ocean Watch

Friday, December 26, 2008

Lesson on why Hawaii's sandy beaches change

When I moved to Hawaii in 1983, I took an oceanography class at UH-Manoa from the chairman of the Oceanography Department, E.D. Stroup.

His fine lectures answered my questions about the ocean so precisely, I even remember where I was sitting when I learned certain facts.

I was front and center the day Stroup explained why Hawaii's sand beaches often change dramatically from season to season. Sand beaches are sediment in motion, changing with the size and direction of waves. Big waves move sand seaward, making beaches narrow. Small waves move sand shoreward, making beaches wide. This phenomenon is called longshore transport.

I'm reminded of that lecture often lately as I read and listen to laments about Kailua Beach. The formerly wide, white beach, the best in Hawaii in many opinions, is going away. The big-wave-little-wave thing isn't working.

There are several possible reasons for this. Some experts think a sea level rise due to global warming might be causing this unusual and, perhaps, permanent erosion. But no one knows for sure that the rate of erosion on Kailua Beach is increasing. This could be one of those natural spikes that happen occasionally, and the beach will eventually fix itself.

Or not. We have man-made structures along the beach that are themselves slowly changing. One is Kaelepulu Stream, a canal that once emptied into the bay but is now sand-choked and stagnant.

Whether the stream ever flowed much naturally is hard to say since it has such a long history of human manipulation.

Enchanted Lake was once a 190-acre body of water called Kaelepulu Pond, a thriving fishpond supporting mullet and other aquatic species. About 90 acres of marshland surrounded this clear pond.

Ancient Hawaiians diverted water in this wetland area for taro farming. Later, sugar planters dammed Kaelepulu Stream, filled the pond and then pumped 2 million gallons of water from it daily to irrigate fields. After the sugar industry left, developers in the 1960s drained water from much of the marsh, filled it with soil and built the community we now call Enchanted Lake.

Over the years, silt from yards, pollution from streets and sand from Kailua Beach collected in the pond and stream. Now these once deep, clear bodies of water are shallow and murky.

Since the stream has too much sand and the beach not enough, it seems logical to dredge the stream, dump the sand back into the ocean and let the waves sort it out. But since the sand in the stream possibly contains pollutants, when workers dredge its mouth, they pile the sand in the beach park. Then wind and rain gradually deposit it back in the stream.

Nature gets away with flushing polluted water and sand into Kailua Bay during storms like we had last week, and we can see the gloomy results: brown water, bobbing trash and warning signs about contaminated water.

Besides the clogged stream, some Lanikai houses and a boat ramp also interfere with the shoreline's natural currents.

State officials are working on solutions to restore the beach, but there are no easy answers.

When Stroup explained beaches in motion, he made one point perfectly clearly: Mess with longshore transport and you'll pay a price.

In this case the price is dear.

Marine biologist Susan Scott writes the newspaper column, "Ocean Watch", for the Honolulu Star-Bulletin, www.starbulletin.com

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Kailua stream nearly overflows canal

Heavy rain frequently causes blockages of Kaelepulu Stream, an area resident says

[STORY SUMMARY](#) | [READ THE FULL STORY](#)

Firefighters opened the mouth of Kaelepulu Stream at Kailua Beach yesterday after waters rose to hazardous levels, a Fire Department spokesman said.

Firefighters with rubber boots and shovels dug a trench in the sand to allow the stream to drain into Kailua Bay.

Lifelong Kailua resident Bob Thurston, who lives on Kawailoa Road a few lanes from Buzz's, thanked the firefighters yesterday for opening a channel through the sand that had built up across the mouth of the stream into Kailua Bay.

But he said he would rather the city open the stream mouth before heavy rain.

— *Leila Fujimori*

[FULL STORY >>](#)

By *Leila Fujimori*

POSTED: 01:30 a.m. HST, Jan 03, 2009

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A fire crew checking Kaelepulu Stream in Kailua after heavy rainfall Thursday night discovered the waters had risen to a dangerously high level yesterday.

Water was beginning to lap over the canal wall onto the parking lot behind Buzz's Original Steakhouse, located across from Kailua Beach Park, Battalion Chief Lionel Camara said at the scene.

Honolulu Fire Department crews opened the mouth of the stream after getting approval from the city Facilities Maintenance and Emergency Management departments.

Firefighters wearing rubber boots and armed with shovels dug a trench about 50 feet long and 3 feet wide, working from noon to 2 p.m. and monitoring the flow until 3 p.m.

The water gushed through the narrow trench into the ocean.

Lifelong Kailua resident Bob Thurston, who lives on Kawailoa Road a few lanes from Buzz's, thanked the firefighters yesterday for opening a channel through the sand that had built up across the mouth of the stream into Kailua Bay.

"All it takes is heavy rains, and the stream starts to overflow back into the neighborhood," Thurston said.

He complained that the city, despite prior flood warnings, failed in the past to open the stream mouth before heavy rain, which led to flooding.

Leslie Muirhead, manager at Buzz's, said the stream "does fill up fast."

"The last big rain, the Friday after Thanksgiving, it flooded the parking lot," she said.

By 3 p.m. the water level in the canal had visibly dropped by about a foot, leaving a wet watermark on the concrete pilings that hold up the bridge running over the stream.

"We frequently drive throughout the communities looking for any unusual situations ... and also to see what the roads and streets look like," said fire Capt. Terry Seelig, adding they are familiar with the flooding problems in the area.

The city also opened the stream mouth Nov. 22 after heavy rain. The storm runoff prompted warning signs at Kailua Beach due to contaminated water.

In December 2007 there were a couple of instances of flooding in the area, and firefighters used portable pumps to move water from lanes on Kawailoa Road.

Camara said that the city's heavy equipment was standing by in case firefighters were unable to accomplish the job. He said it takes some time to haul out the equipment.

The relatively narrow trench will eventually widen by eroding through the sandbar and

FOILING A FLOOD
Firefighters open the mouth of Kaelepulu Stream to lower dangerously high water levels.



CINDY ELLEN RUSSELL / CRUSSELL@STARBULLETIN.COM
 Honolulu Fire Department personnel from Companies 18 (Kailua) and 19 (Aiea) cleared the channel at Kailua Beach Park yesterday morning to prevent flooding. Firefighters noticed the water level beginning to breach the embankment of Kaelepulu Stream and decided to clear the channel. The city also opened the stream mouth Nov. 22 after heavy rain.

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Star Bulletin

mobile edition

Monday, January 12, 2009



JAMM AQUINO /

JAQUINO@STARBULLETIN.COM

Chip Fletcher, professor of geology and geophysics at the University of Hawaii at Manoa, described yesterday the erosion that has exposed the hollow-tile bricks, known as "sandgrabbers," at Kailua Beach.

KAILUA'S SAND SLIPPING AWAY

Saving Kailua Beach

The rapid erosion of one of Oahu's most popular beaches spurs multiagency action

STORY SUMMARY | [READ THE FULL STORY](#)

The city, state and federal government are taking steps that could eventually counteract the erosion of Kailua Beach.

The Army Corps of Engineers, the state Department of Land and Natural Resources and the state Department of Health are working together to get needed permits and clearances to allow sand from Kaelepulu Stream to be used to replenish the rapidly disappearing beach. A public meeting was held last summer.

The state also hired a consultant to examine the problem and come up with options by 2010.

Beach users say something needs to be done soon.

"In the last two to three years, the shoreline has dramatically eroded," said Chip Fletcher, a professor in the Geology and Geophysics Department at the University of Hawaii at Manoa.

[By Robert Shikina](#)

.....

FULL STORY >>

[By Robert Shikina](#)

POSTED: 01:30 a.m. HST, Jan 11, 2009

Kailua resident David Brezel, 89, has been swimming daily at Kailua Beach for the past seven years.

Until recently, he entered the water near the boat ramp near the entrance to Lanikai.

Now, exposed cinder blocks stick out where sand used to be, forcing a detour in his routine. He now starts his twice-daily swim on the Kaneohe side of Kaelepulu Stream.

"The waves are smashing onto (the blocks), and it's dangerous, and I can't go swim there anymore," said Brezel, a retired eye doctor. "I like to swim there."

It's just one sign of erosion that's eating away Kailua Beach, which in 1998 was ranked as America's best beach.

Now, erosion has created a drop of about 6 feet before patrons can reach the sandy beach. Roots and pipes extend out of the sandy wall into midair.

The city recently removed 10 ironwood trees because they were being undermined by erosion, said city spokesman Bill Brennan. More trees might also be removed.

Some trees had fallen over because of the loss of beach, said Will Ho, the Windward District manager for the city's parks.

Charles "Chip" Fletcher, a professor in the Geology and Geophysics department at the University of Hawaii at Manoa, said erosion at Kailua has made it difficult to walk across the beach during high tide.

"It's a beach park, for god sakes," he said. "It's severe. It's been unrelenting for the last two years. It's approaching three years now."

The exposed cinder blocks, he said, are "sandgrabbers" built about three decades ago. They were meant to hold sand on the beach.

Now crumbling, the blocks are held together by corroded iron rebar.

Fletcher, a coastal erosion expert, said Kailua Beach had been growing for decades, but the southern portion started to erode the past 10 to 20 years. The erosion near the boat ramp has accelerated in the past two to three years and is now washing away the beach at a rate of 1 to 3 feet a year, he said.

The cause remains elusive.

There are a number of factors from a change in wind patterns to high surf that can lead to erosion, he said.

Fletcher thinks one culprit could be sand going into the mouth of Kaelepulu Stream.

The city regularly dredges the stream, but cannot use sand from the canal to replenish the beach because of federal clean-water requirements.

At the same time, the city dredges only a narrow portion of the stream, Fletcher said. While a heavy runoff could push the sand in Kaelepulu Stream back into the ocean, a dike upstream diverts some of the water to another canal in Kailua, Fletcher said.

The dike was built in the 1980s after flooding damaged the Coconut Grove neighborhood in Kailua.

The state Department of Health is seeking permission to allow the city to use sand recovered from the stream mouth for replenishing the beach.

"The redepositing of the dredged sand from the stream, it can be done, but there are permits, certifications and clearances needed from different agencies," said Joanna Seto, engineering section supervisor of the Health Department's clean-water branch.

Dolan Eversole, a state coastal geologist, said erosion has been increasing around the state, not just at Kailua Beach.

"In the last five years, there seems to be a sudden shift to erosion. Many of the beaches that were formerly stable like Kailua are now beginning to erode," he said.

Factors in the erosion could be locking up of sand by human activity, such as building structures, or the rising sea level, he said.

The state has recently hired a consultant for \$45,000 to create a Kailua Beach management plan to provide options for dealing with erosion that has been damaging the beach, said Eversole, who is on loan to the state land department from the University of Hawaii Sea Grant program.

A company called Plan Pacific will create recommendations for management strategies by 2010. The plan will look at erosion, beach management and land use.

"We're hoping that this will be the first of many more strategic beach management plans for the state," Eversole said.

There will be public meetings and workshops with the consultant to solicit concerns from the public .

Meanwhile, state officials still don't know why Kailua Beach's sand is slipping away.

It's unlikely that restoring the sand from the stream mouth will solve the erosion problem, but it could help, Eversole said. "It's the first thing to try."

APPENDIX J

RSM WORKSHOP #4 ATTENDEE LIST AND MINUTES

Hawaii Regional Sediment Management
Southeast Oahu Demonstration Project
Workshop #4

Workshop date: August 27, 2008

Workshop minutes (list of attendees is attached)

Welcome and Introductions (Tom Smith and Sam Lemmo)

Tom Smith welcomed the workshop participants to the fourth and final workshop. He introduced Sam Lemmo, who explained that southeast Oahu is a unique area and an understanding of the sedimentation of the region is needed to understand shoreline change, sand budget, and sand sources, and to develop economical solutions. Mr. Lemmo described the three previous workshops.

Southeast Oahu Regional Sediment Management Overview (Tom Smith)

Tom Smith continued by providing an overview of the SEO/RSM and the topics that would be covered in the workshop. The RSM is an integrated approach from mountains to sea and from Mokapu Peninsula to Makapuu Point. The final products of the SEO/RSM are shoreline change maps, sediment budget, modeling, GIS, demonstration projects, and an RSM plan. He mentioned the potential demonstration projects at Kaupo, Kaiona, Bellows, Lanikai, and Kaelepulu Stream and provided photos of those shorelines.

Field Investigations

Wave and Current Data Collection (Jessica Podoski)

Jessica Podoski presented a description of the data collection program undertaken by the USACE in August and September of 2005. Five weeks of data were collected using three ADVs, 2 ADCPs, and drogues. The CDIP wave buoy was used to determine the input conditions. Wave and current results were presented.

Shoreline Change Analysis (Brad Romine)

Brad Romine presented his results of the shoreline change analysis. He explained that he used historical aerial photographs, using the beach toe as the SCRF (shoreline change reference feature). The shoreline was divided into 20 meter intervals and the change along the SCRF was measured. The data was analyzed using the EX model and the EXT model, which includes acceleration. He explained how to interpret the results. Tom Smith asked which method would be better to use in developing a sediment budget. Mr. Romine explained that EX is better for

identifying the long-term trend, while the EXT is better as showing more recent trends. The areas covered by this work are Kailua, Lanikai, Waimanalo, Kaiona, Kaupo, and Makapuu.

Offshore Sand Sources and Sediment Trend Analysis (Chris Bochicchio)

Chris Bochicchio briefly presented his findings on sediment sources from Kailua Bay through Waimanalo Bay, showing locations and estimated volumes. The largest volume of sand is found in the Kailua sand channel. There were also karst deposits and sand fields throughout the study area.

He continued with a discussion of sediment trend analysis (STA). He explained how sediment size distributions could be interpreted to provide direction and intensity of sediment transport. He presented a color contour plot showing the shoreline change at Bellows and Lanikai. He pointed out that erosion in the location of the Bellows revetments preceded accretion at Lanikai by several years, and then following revetment construction at Bellows, Lanikai experienced erosion. The figure also showed how trends in the shoreline change could be tracked alongshore with time. He also presented a time series plot of weekly average wind direction which showed that the tradewinds have a tendency to oscillate between northeast and east over several years (or longer).

Numerical Modeling Results

Water Circulation and Wave Transformation (Jessica Podoski)

Jessica Podoski presented the water circulation modeling results that were performed using ADCIRC. The currents in the SEO region, modeled under tide and tradewind conditions, are not very strong, and along Lanikai, the currents are typically toward the north. A gyre was found in Kailua Bay. Animations were shown.

She continued with the wave modeling results from STWAVE. The input conditions were wave heights measured by the CDIP wave buoy for 2000 through 2004. The model results were compared with the data collected during the 2005 field experiment. The model included bottom friction as an input, and this value was iterated to determine which value produced the best data fit. A value of $n = 0.2$ (Manning's n) gave good correlation with the measured data, and this was a big improvement over $n=0$. It was also important to include tide in the model. Comparison with the JONSWAP friction coefficient produced similar results.

Regional Sediment Budget (Tom Smith)

Tom Smith presented his sediment budgets for SEO. The calculations were based on the shoreline change analyses presented by the UH Coastal Geology Group and wave modeling results produced by the USACE. He began his analyses at the northern extent of Kailua Beach and worked southward to Makapuu Point.

Mr. Smith pointed out sand sources, sinks, and the limits of littoral cells, which all played roles in the sediment budget. He asked for a discussion of his assumptions as he presented the analyses. In general, there were questions about how much sand, if any, moves around Alala Point between Kailua Bay and Lanikai, and around Wailea Point between Bellows AFS and Lanikai.

SEO/Regional Sediment Management Focus Areas

Kaupo and Kaiona Beaches (Tom Smith)

Tom Smith presented Kaupo Beach as having unstable shoreline along Kalanianaʻole Highway. DOT installed piles in 2006 to mitigate the erosion threat against the road. This stretch of beach is not believed to be able to hold a beach without structures, so Mr. Smith declared that there was nothing USACE could do at that site.

He continued with Kaiona Beach, which still has a generally sandy shoreline. Some of the properties south of Kaiona Beach Park contain seawalls and north of the beach park, the beach has eroded close to the road. He did not see much potential for a demonstration project at this location.

Kaelepulu Stream (Chip Fletcher)

Dr. Fletcher discussed the situation at Kailua Beach Park, including the erosion on the north side of the boat ramp and the sand buildup in the Kaelepulu Stream mouth.

The City is considering removing the sand grabbers, which have become exposed over the past two years. There is concern whether this would threaten the parking lot inshore. If so, should the parking lot and Ironwood trees be sacrificed to allow the natural progression of the shoreline to occur? He presented that the erosion trend was moving northward.

Will Ho of the C&C Dept. of Parks and Recreation reported that the City's plan for managing the Kaelepulu Stream mouth was to clear it monthly and the sand is piled on the banks adjacent to the stream. The stream mouth fills back in within a few days. State Dept. of Health regulations prohibit placing the sand at any other location on the beach. A heavy rain event might flush the sand back into the littoral system; however, there may not be enough flow, due to re-routing of water out Kawainui Stream. He also noted that the sand is finer than when he was a kid and that the sand has migrated inshore up the stream.

Dr. Fletcher reported on a sand field containing 50,000 to 100,000 cubic yards of sand that is not within the littoral zone and could be mined for beach nourishment.

Ideas that were discussed were removal of the boat ramp, new Best Management Practices, and a focus group to address the stream mouth.

DLNR is conducting a Kailua dune and beach management plan study. Scope of work includes study of sand processes, vegetation, etc.

Tom Smith offered that possibility of their 1135 authority, which would provide the first \$100,000 to study the situation. A representative from Congresswoman Hirono's office offered their assistance.

Bellows AFS (David Smith)

David Smith presented three conceptual plans for shoreline restoration at Bellows AFS. The first involved nourishing the beach by following the last stable shoreline (1987) with a minimum dry beach width of 30 feet. The second concept involved nourishing only in front of the revetments, as the southern portion of the shoreline did not need nourishing. This concept required significantly less sand. The third concept showed the effect of removing the revetment and the subsequent equilibrium shoreline location. At this location, there were several buildings that would be threatened by erosion.

Lanikai Beach (David Smith)

David Smith presented two conceptual plans for shoreline restoration at Lanikai Beach. The first concept involved nourishing the beach without the use of structures. This concept produced a 30-foot dry beach width. The second concept involved building tuned T-head groins and nourishing between the groins to produce a more stable beach. This concept produced arc-shaped beach cells with a desired minimum width of 30 feet.

Estimated costs were presented, with Concept 1 requiring renourishment every 8 to 9 years. This greatly increases the cost over 50 years. The 50 year cost for Concept 1 was estimated to be \$109,000,000 versus the estimated \$42,000,000 for Concept 2.

A question was asked regarding the ability to walk along the beach without obstruction. Dr. Smith replied that the dry beach area was one foot higher than the groin crest elevation. This would produce a continuous walking area with a minimum width of 30 feet, expanding to approximately 100 feet near the groins. Another question was asked regarding the effects of turbidity if the beach was nourished with offshore sand. Dr. Smith replied that the sand mined from the reef flat would likely not cause turbidity problems because the sand is already in a dynamic environment and fines would have been already removed from the sand. Additionally, matching the source sand to the native sand alleviates such concerns.

Tom Smith continued by introducing the Lanikai Beach Restoration Pilot Project. This would involve design of a two-groin system with beach nourishment. The groins would be made of a "soft" material such as a geotextile filled with sand and would be considered temporary. The project site would be centered at the beach access across from Pokole Way.

Future Work (Tom Smith)

Tom Smith presented a list of future work that builds upon the SEO/RSM. Work included investigating sand mining from Kaelepulu Stream, the Lanikai Beach Restoration Pilot Project, review of the SEO sediment budget, updating of the RSM plan, and preliminary development of a Maui RSM plan.

The participants were thanked and the workshop was adjourned.

Workshop #4 List of Attendees
August 27, 2008

FIRST NAME	LAST NAME	ORGANIZATION
Darin	Aihara	U.S. Army Corps of Engineers – intern
Laurie	Baron	
Gail	Baron	
Christopher	Bohicchio	University of Hawaii
Ned	Dewey	The Mills Group
Dianne	Drigot	Marine Corps Base Hawaii
Derek	Esibill	Kailua Intermediate School
Charles (Chip)	Fletcher	University of Hawaii
Peter C.	Galloway	U.S. Army Corps of Engineers – Regulatory Branch
Justin A.	Goo	U.S. Army Corps of Engineers – intern
Lynn	Graybeal	Earth Tech AECOM
Jarrett	Hara	U.S. Army Corps of Engineers – Civil Works Tech Branch
Terry	Hildebrand	Design and Construction City of Honolulu
Wilfred	Ho	City and County of Honolulu
Jamie	Ho	State of Hawaii, Department of Transportation
Sam	Lemmo	State of Hawaii, Department of Land and Natural Resources
Jennifer	Lutz	Earth Tech AECOM
Chadman	Maio	City and County of Honolulu
Frederick	Millen	Hickam Air Force Base
Sharon	Nekoba	Department of Land and Natural Resources
Jessica H.	Podoski	U.S. Army Corps of Engineers – Civil Works Tech Branch
Bradley	Romine	UH Coastal Geology Program
Thomas	Smith	U.S. Army Corps of Engineers – Civil Works Tech Branch
David	Smith	Sea Engineering
Kenneth	Tseutsch	Department of Transportation
Randall	Wakumoto	C&C of Honolulu, Dept. of Environmental Services
Jason	Wische	Representative for Congresswoman Mazie Hirono
Michael F.	Wong	U.S. Army Corps of Engineers – Civil Works Tech Branch