SOUTHEAST OAHU, HAWAII

Diamond Head to Pearl Harbor

PRELIMINARY
REGIONAL SEDIMENT BUDGET

Prepared for

US Army Corps of Engineers

U.S. Army Corps of Engineers
Honolulu District,
and
State of Hawaii
Department of Land and Natural Resources
Office of Conservation and Coastal Lands

Prepared by

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EXECUTIVE SUMMARY

The preliminary sediment budget presented in this document summarizes existing knowledge of the sediment transport regime in the Diamond Head to Pearl Harbor (D2P) study area, along the south shore of O‘ahu. The information used to develop the preliminary sediment budget includes the following:

- Beach and nearshore profiles published in a variety of sources;
- Dredging records and other publicly available documents describing sediment sources and sinks;
- Shoreline change analyses performed by the University of Hawai‘i and extended in minor ways by Moffatt & Nichol;
- Recent wave and current modeling performed by the U.S. Army Corps of Engineers.

The sediment budget divides the D2P study area into six littoral cells. For all cells, the transport rates are small - generally less than 2,000 cubic yards per year. For some of the cells, particularly the Iroquois Point cell on the ‘Ewa side of Pearl Harbor, there may be a significant input of sediment from ongoing reef production. It is not known whether modern sand production by reefs is actually significant in the D2P study area – this is an important data gap, which can be filled through radiocarbon dating of beach sand.

Results for the six littoral cells include the following.

- **Diamond Head** is a slightly erosional cell. Transport rates in this cell are small – a few hundreds of cubic yards annually. There may be a small modern production of sand by the nearshore reef: this sand would be transported north into the Waikiki cell or offshore into deep water.
- The heavily engineered **Waikiki** cell is generally erosional at present, with sand moving from the beaches to the reef and further offshore. Between 1965 and 1985, beach nourishment at an average rate of approximately 10,000 cubic yards annually led to an accretion of the beach along the central and ‘Ewa portions of the Waikiki cell. However, this reversed between 1985 and 2005, when almost no beach nourishment took place. The 2006 nourishment at Kuhio Beach, if it is not an isolated event, may halt the ongoing erosion.
- The **Ala Moana** cell is similar in behavior to Waikiki. The beach at Magic Island is protected by three detached breakwaters, and is generally stable. The beach at Ala Moana Park is losing sand at a rate of about 1,000 cubic yards per year. While 30,000 cubic yards of sand was placed in 1976, this has since been lost offshore.
- The **Sand Island** cell contains little sand. Transport rates are low – a few hundreds of cubic yards annually.
- Similarly, the **Reef Runway** cell is almost entirely sand-starved. It is dominated by the Honolulu Reef Runway, which was constructed over the nearshore reef. Deep dredged channels at either side of the cell, and rip currents that are able to transport sand offshore, act as sinks for any sand that may be produced by the nearshore reef.
- The **Iroquois Point** cell, ‘Ewa of Pearl Harbor, contains a combination of erosional and accretional areas. Most of the south-facing shoreline of this cell, along ‘Ewa Beach, is slightly accretional. This may result from reef production or longshore sand transport from the ‘Ewa side. Keahi Point is extremely erosional, likely because of

loss into the dredged channel at Pearl Harbor: some of the 3,800 cubic yards lost annually from this part of the littoral cell is transported to the beach within Pearl Harbor, just south of Iroquois Lagoon.

The following investigations would reduce uncertainties associated with the preliminary regional sediment budget developed in this report.

- A regular program of aerial photography should be planned to allow ongoing erosion hazard mapping and monitoring of the sediment budget. A new flight every 5 years is recommended, with additional flights around significant events such as beach nourishment or other shoreline infrastructure, hurricanes, or tsunami. In particular, the effects of the 2006 nourishment of Kuhio Beach do not yet appear to have been captured through aerial photography.
- In the area from Diamond Head to Ala Moana, there appears to be significant movement of sand between the beaches and the reef. This sediment circulation is not well understood. Given the likely need for ongoing nourishment at Waikiki Beach, this should be investigated further through field work – including ongoing beach and nearshore profiling, wave/current measurements, and more detailed investigations of sand pockets on the reef – as well as through more detailed modeling analyses.
- The sand on the beach at Waikiki is largely imported from other areas. For the remainder of the D2P region, the sand was originally produced from the fringing reef system. It is not known whether modern production of sand is a significant contributor to the sediment budget in the area. This should be investigated, in the first instance through radiocarbon dating of beach sand.
- Sand sampling should be performed within Pearl Harbor and Honolulu Harbor, to determine the quality and volume of potential sand sources and to progress the present state of knowledge regarding sediment transport pathways.
- If significant sand from offshore sources is found in one or both of these harbors, the sediment transport pathways should be investigated further through field work – including wave and current data collection and possibly turbidity / sediment concentration measurements – and through more detailed modeling analyses.

Finally, the potential effects of climate change on the study area have not been addressed in the present RSM Plan. This should be incorporated into the planning process. Sea level rise, the potential effects of ocean acidification and reef degradation on sediment availability, and the potential for changes to the wave climate should all be considered.

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I. Introduction

This document provides a preliminary sediment budget analysis for the Southeast O‘ahu Region Regional Sediment Management Plan (RSM Plan), Diamond Head to Pearl Harbor (D2P) region.

II. Study Area Description

A. Overview

The D2P study area is located along the southern coast of O‘ahu (see Figure 1, with more detail in Figure 2). It stretches from Diamond Head in the east to Iroquois Point, including a portion of ‘Ewa Beach, in the west. The bathymetry is relatively shallow along most of this reach and the coastline is generally low-lying. The fringing reefs and southern exposure protect the coastline from the most energetic wave activity.

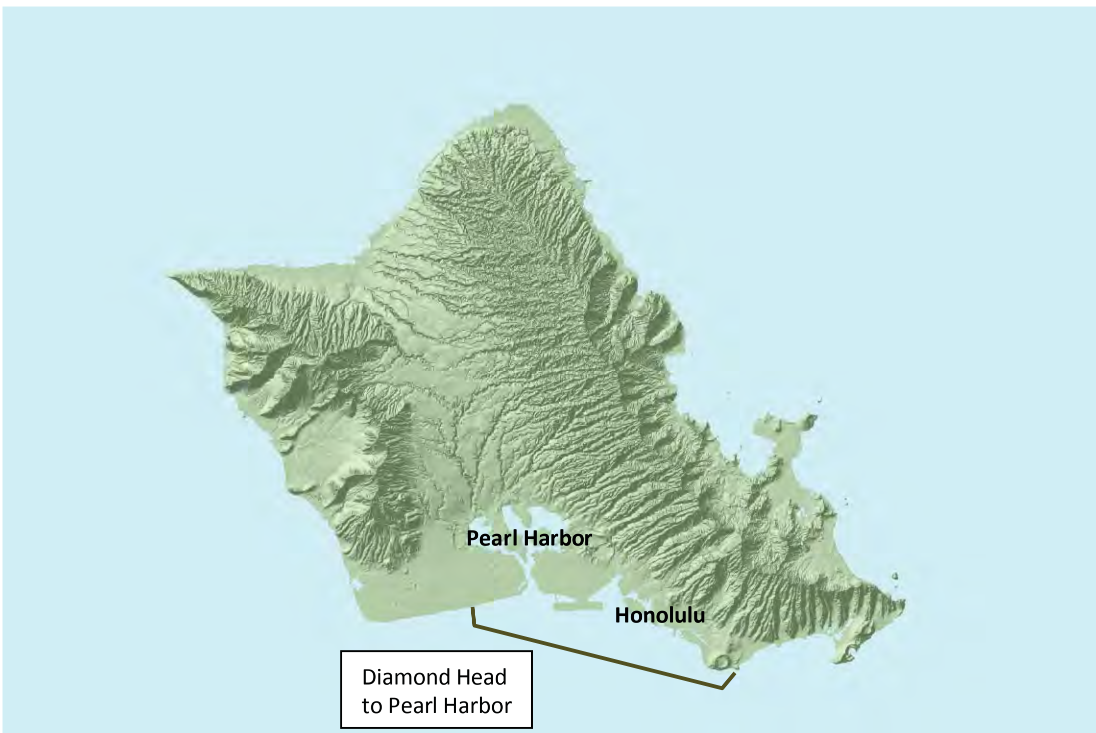


Figure 1. Diamond Head to Pearl Harbor (D2P) Study Area

The D2P region has been heavily modified. Between Waikiki and Sand Island, there are about nine groins, 1,500 lineal feet of submerged breakwater, and more than 2.5 miles of seawall and revetment (based on aerial images from Google Earth). For more details of the densely engineered Waikiki area, see Figure 14. The study area also includes four harbor entrances – Kewalo Basin, Ala Wai Yacht Harbor, Honolulu Harbor and Pearl Harbor. There are several channels of varying navigability in the Sand Island area, between the entrance of the Honolulu Harbor and the Honolulu Reef Runway.

For this sediment budget analysis, the study area has been divided into six littoral cells (Figure 3).

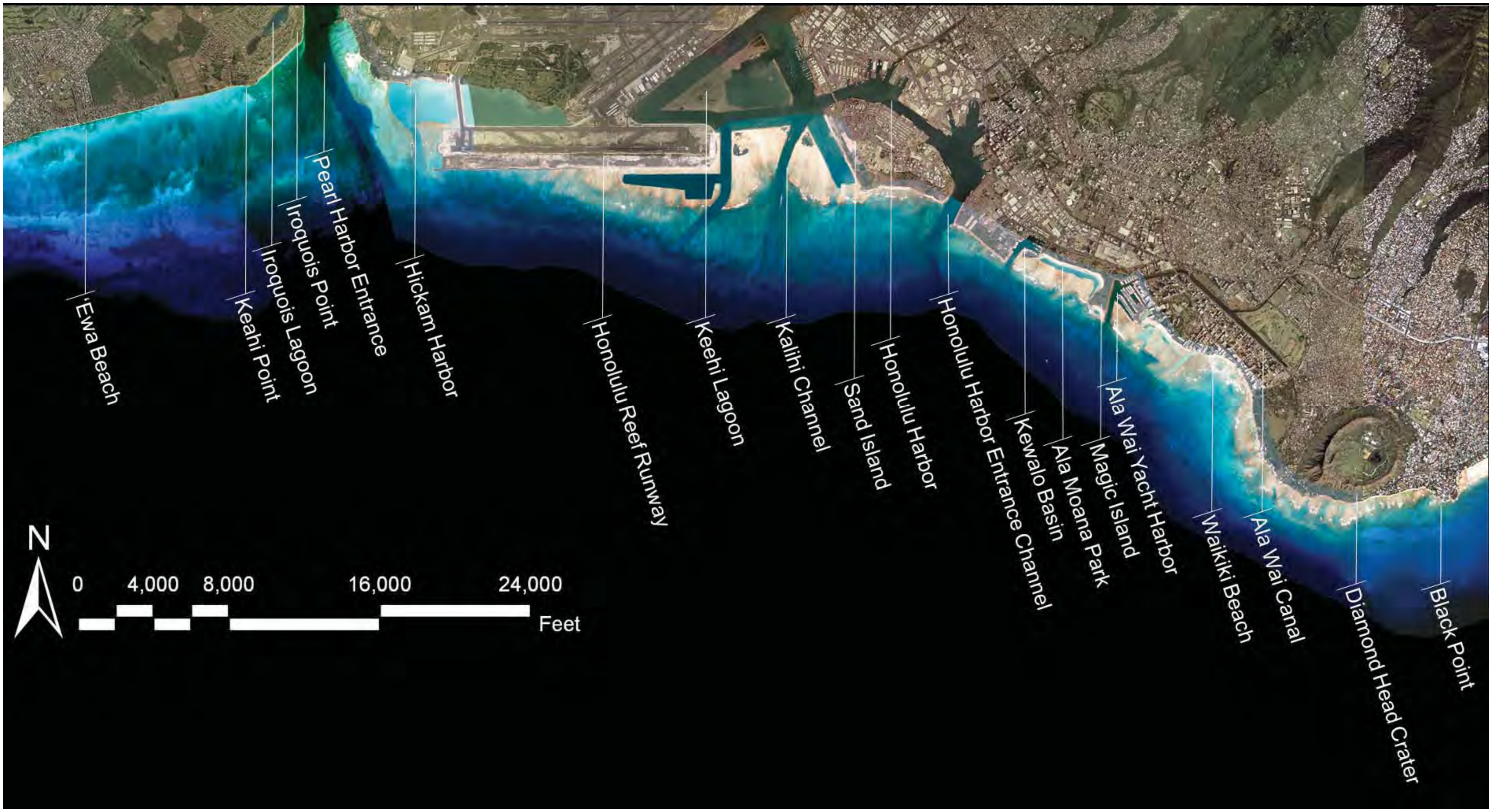


Figure 2. Diamond Head to Pearl Harbor (D2P) Region

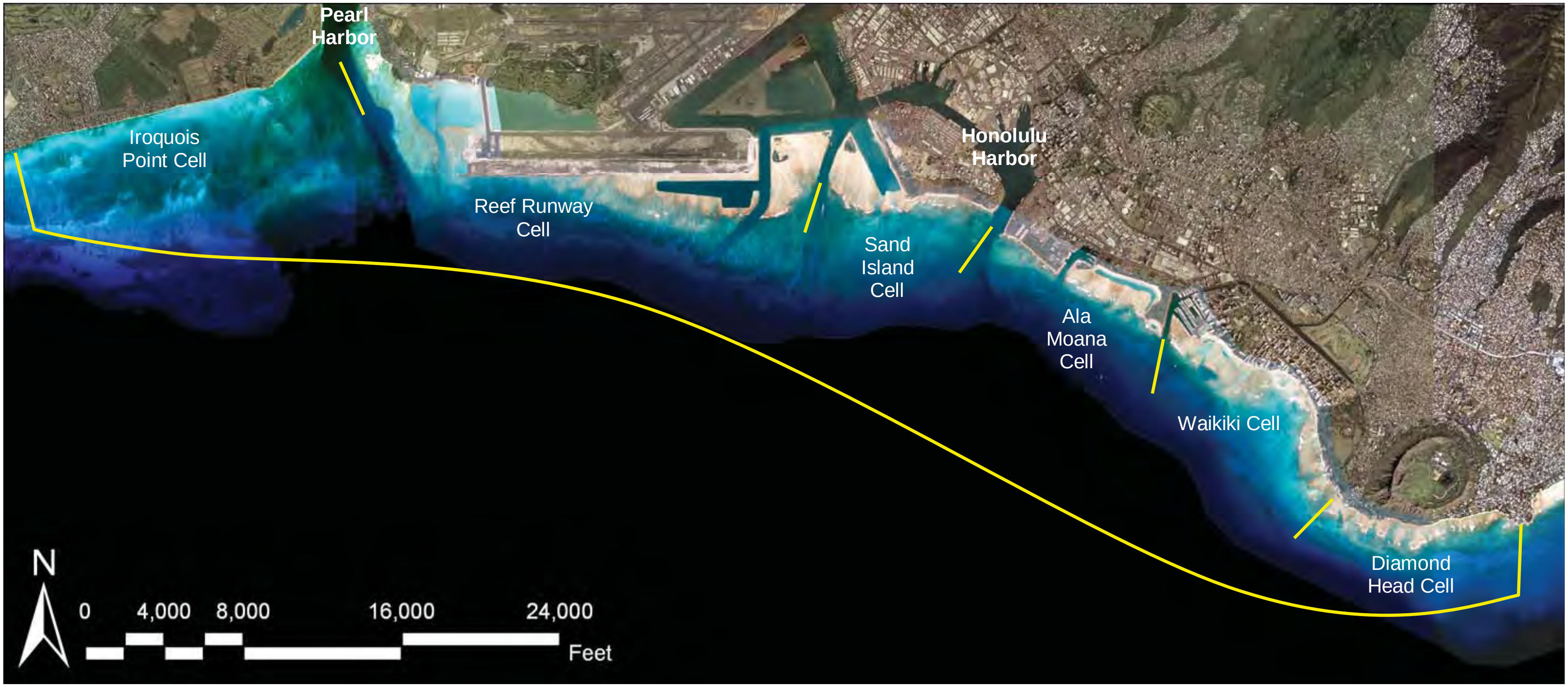


Figure 3. Diamond Head to Pearl Harbor (D2P) Littoral Cells

B. General Geomorphology

1. O‘ahu Island

O‘ahu is one of the older islands in Hawai‘i. It was formed by two major shield volcanoes, Waianae and Ko‘olau (Moberly 1963). The eroded remains of these shield volcanoes are visible in the general shape of the island.

As the volcanoes forming the Hawaiian Islands grow, their weight causes the underlying surface to bend, causing local variations in relative sea-level rise. In the westerly islands, including O‘ahu, the plate under the islands is flexing, causing uplift. As a result of this, O‘ahu has an uplift rate ranging between 0.3 and 0.6 mm/yr (Fletcher *et al* 2008).

2. Reefs

Coral reefs are found along much of the Hawaiian Island shorelines. Fringing reefs are the most common type in these waters. These reefs are formed on the fringing slopes of the shield volcanoes, after the volcanic activity has ceased, but before the land subsides (the atoll stage of island evolution); they are found on the shallow shelves of the islands.

The offshore shelf of O‘ahu is typical, in that it was created by reefal limestone units. O‘ahu’s shelf has a distinct offshore stair-step bathymetry, resulting from past sea-level standstills. The offshore shelf slopes gently seaward to a limestone drop-off at the end of the shelf (near the -60 or -70 ft contour). A second tier exists seaward of this drop, from approximately the -100 ft contour to the -150 ft contour. There is a second drop off and a third tier below the -150 ft contour (Fletcher *et al* 2008). It is along the first shelf that patches of coral and coralline algae growth occur, over a veneer of carbonate sand covering the underlying limestone. The second shelf is commonly covered with extensive fore-reef sediments.

The reef structure in the D2P region plays a significant role in the sediment budget by dissipating the incoming wave energy, stabilizing the toe of the beach, and providing a source of sand.

3. Study Area

A fringing reef parallels the coast along the entire study area, widening to the west. The same reef surface is reported to extend about the same distance inland, rising several feet above current sea level. The reef is intersected by several paleostream channels as well as channels dredged for navigation and to obtain fill materials.

Diamond Head is geologically young compared to O‘ahu as a whole: it was built by hydromagmatic explosions that ripped through 200,000 year old coral reefs and Ko‘olau basalt. The shoreline directly south of Diamond Head is accessible only by footpath. The beach is composed of calcareous sand mixed with terrigenous sediments (Fletcher, Grossman, and Gibbs 2002).

The Waikiki Beach area was, until the beginning of the 20^{th} century, a wetland and marsh holding only a narrow sandy strand at the shoreline. Early activities on the beach included sand mining in the early part of the 20^{th} century. Later, the marsh was drained, significant drainage, dredging, and upland fill projects were constructed, and imported sand was placed on the beach (Wiegel 2008). Further west, the reef has been destroyed to reclaim land at Magic Island, Sand Island, and for the Honolulu Reef Runway.

The Pearl Harbor embayment formed as the island sank approximately 360 m toward the end of the main shield building phase, drowning the river valleys that drained central O‘ahu (Fletcher and Feirstein 2009).

C. Coastal Processes

1. Tides

Hawai‘i shorelines are microtidal, with ranges much smaller than those observed over the west coast of the continental United States. Water level datums measured by NOAA at Honolulu Harbor and reported on their web site are given in Table 1 (NOAA 2009a).

Table 1: Tidal Datums at Honolulu Harbor (1983-2001 Epoch)

Datum	Value (feet, MLLW)
Highest Observed Water Level (2/14/1967)	3.39
Mean Higher High Water (MHHW)	1.90
Mean High Water (MHW)	1.44
Mean Sea Level (MSL)	0.82
Mean Tide Level (MTL)	0.80
Mean Low Water (MLW)	0.16
Mean Lower Low Water (MLLW)	0.00
Lowest Observed Water Level (4/30/1911)	-1.41

There are significant nonastronomical components to the water levels at the Hawaiian Islands. Extreme tide levels can occur due to large scale oceanic eddies that propagate through the islands. These eddies produce tide levels as much as 0.5 to 1 foot higher than normal for periods of up to several weeks.

During severe storm events, an additional increase in water level can result from storm surge due to reduced atmospheric pressure and wave setup due to the action of breaking waves on the reef. During hurricane conditions, an additional water level rise can occur due to wind stress.

2. Sea Levels

Based on measurements at Honolulu Harbor, the mean sea level in the study area has increased at an average rate of 1.50 ± 0.25 mm per year (5.9 ± 1.0 inches per century) between 1905 and 2006 (NOAA 2009b). This rate is less than the eustatic (global average) rate of sea level rise over the 20th century, and highlights the ongoing uplift experienced by O‘ahu.

The rate of global sea level rise appears to be accelerating in response to anthropomorphic climate change (Intergovernmental Panel on Climate Change 2007). For long-term planning it is important to consider a range of potential sea level rise scenarios (USACE 2009a).

3. Waves

The south shore of O‘ahu is sheltered from the predominant northeast tradewind-generated waves as well as from the winter North Pacific swell. Thus, wave activity at the shore is relatively mild except during the summer months, when the southern swell can produce moderately high surf conditions. The south shore is also exposed to infrequent Kona storms and to hurricane waves. One way of visualizing the offshore waves approaching the Hawaiian Islands is through the swell wave rose shown in Figure 4. This figure shows that the annual significant wave height for waves approaching O‘ahu from the south is approximately 2 meters or 6 feet.

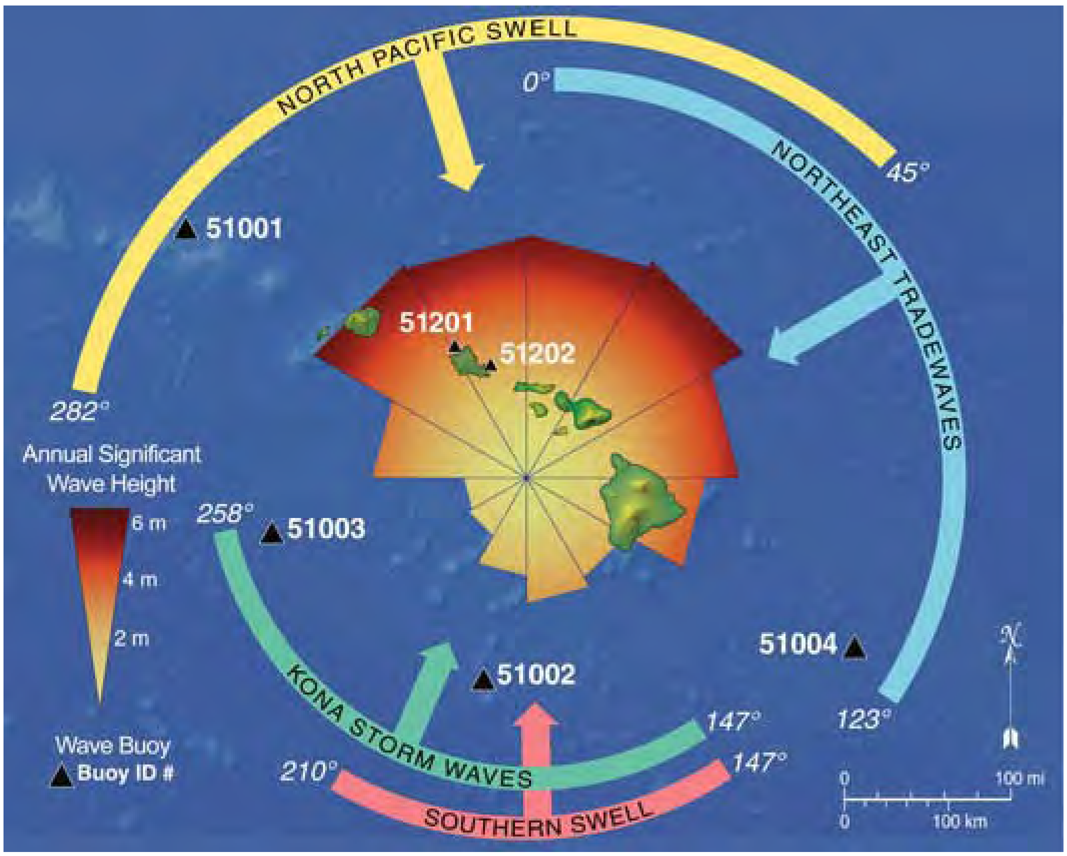


Figure 4. Dominant Wave Directions, Swell Wave Rose, and Monitoring Buoy Locations (Vitousek and Fletcher 2008)

The USACE Engineer Research and Development Center (ERDC) investigate wave transformation to shallow water in the study area using the STWAVE model (Tracy 2009; this document is attached as an appendix to the main RSM Plan). The study period for the modeling was three years: a low wave condition (1984), a medium wave condition (1992) and a high wave condition year (1994). The medium wave condition year also included Hurricane Iniki in September, 1992.

The model study was based on hindcast deepwater waves propagating to the north, with an average significant wave height of approximately 2 to 3 feet. This is consistent with Figure 4, which shows an annual maximum significant wave height slightly more than 6 feet (2 meters). Detailed model outputs (wave height, period, and direction throughout the period of record) were provided for a number of points near the shoreline of the study area. In most cases, these output points are at water depths of about 5 feet; some of the output points were at greater depths but still close to the shoreline.

Figure 5(a)-(f) shows the locations of the output points. The figures also show the model results in the form of wave roses for a subset of the output points (not all wave roses are shown to aid clarity). The period of record for these wave roses is the full 3 year modeling period: 1984, 1992, and 1994. The large wave rose in each figure, which is the same in all cases, illustrates the deepwater wave rose. In most but not all cases, the waves have dissipated energy breaking over the reef, and are oriented almost directly onshore. The average significant wave height near the shoreline ranges from less than 1 foot (0.3 m) (in sheltered areas such as Ala Moana Beach Park) to more than 3 feet (1 m) (locations immediately offshore of Diamond Head and Sand Island, where irregularities in the reef focus the waves).

Some exceptions to this general rule are as follows:

- Figure 5(a), Diamond Head Cell: Point DH3 – the wave height in this area is greater than the wave height offshore, most likely due to focusing by the irregular reef bathymetry.
- Figure 5(d), Sand Island Cell: Point SI1 – the waves in this area approach directly from the south, representing the general reef contours in the area, which do not parallel the present-day filled (and hardened) shoreline.
- Figure 5(f), Iroquois Point Cell, most points – the waves in this area tend to approach from a direction more to the south than directly onshore, which leads to a significant transport in the direction towards Pearl Harbor. However, the three wave roses on the west side (IP4 through IP6) are more variable and closer to directly onshore, indicating that the net transport is less in this area.

The wave roses illustrate a combination of southern swell and Kona storm waves. The study period also included Hurricane Iniki (September 1992). The largest hindcast deepwater wave height, which occurred during Hurricane Iniki, was approximately 26 feet. The hindcast deepwater waves during Hurricane Iniki approached from the southwest (this is normal for hurricane waves, which generally approach the study area from the southeast-through-southwest directions).

The largest wave height predicted at any of the output points was approximately 12 feet. However, wave heights of 10 feet or more were only predicted in a few locations, near hardened shorelines and in relatively deep water. Near beaches, the peak significant wave heights were typically less than twice the average significant wave heights, and no more than 4 feet. The wave directions during Hurricane Iniki were similar to normal wave directions.

The effects of hurricanes on beaches can be mixed. Hurricane Iwa, in November 1982, may have triggered sand delivery to Waikiki Beach (Miller 2002), while Hurricane Iniki was reported to cause erosion at Waikiki Beach but not at Ala Moana (Wiegel 2002). Hurricane waves can also cause significant damage to reefs.

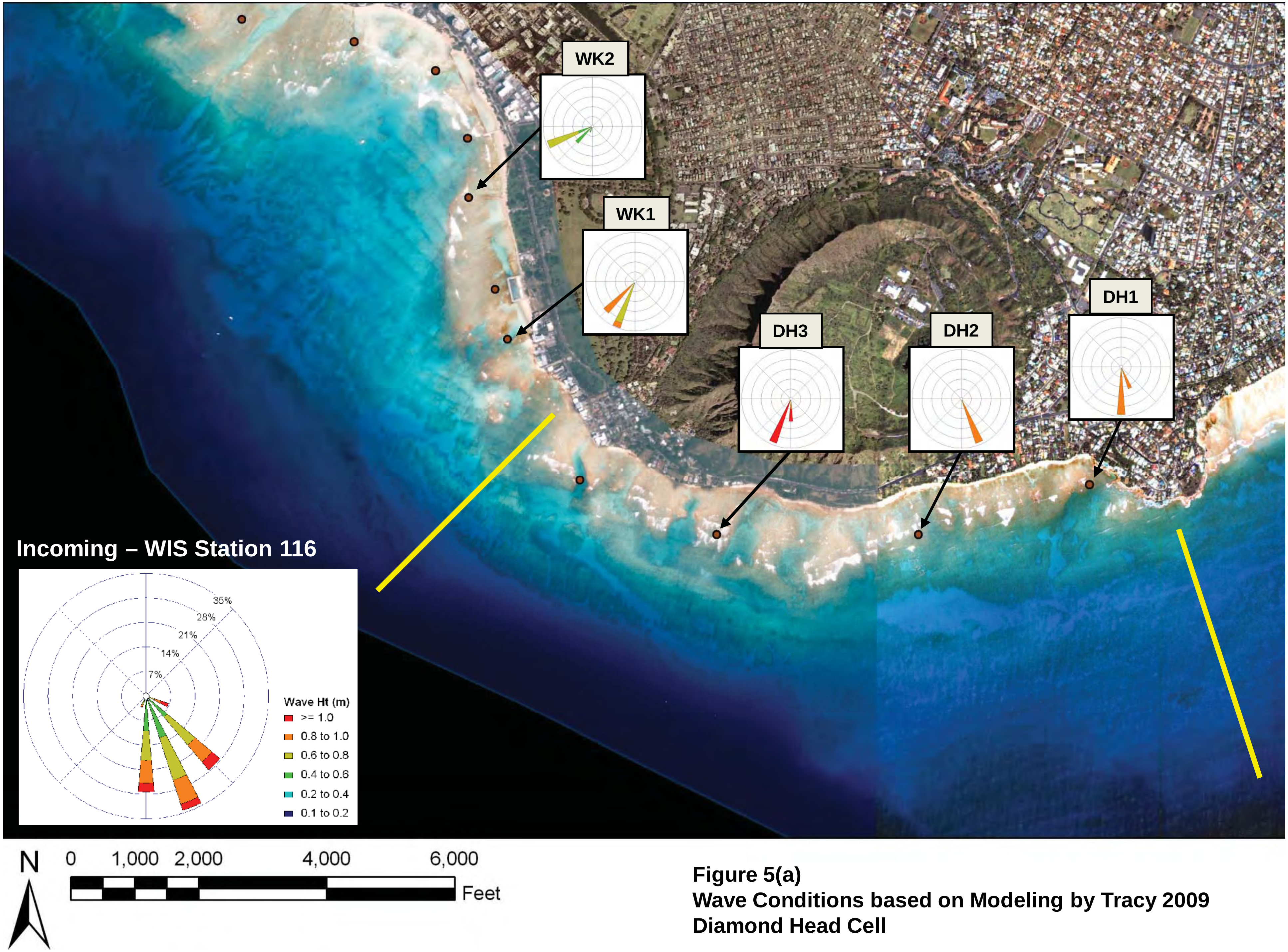


Figure 5(a)
Wave Conditions based on Modeling by Tracy 2009
Diamond Head Cell

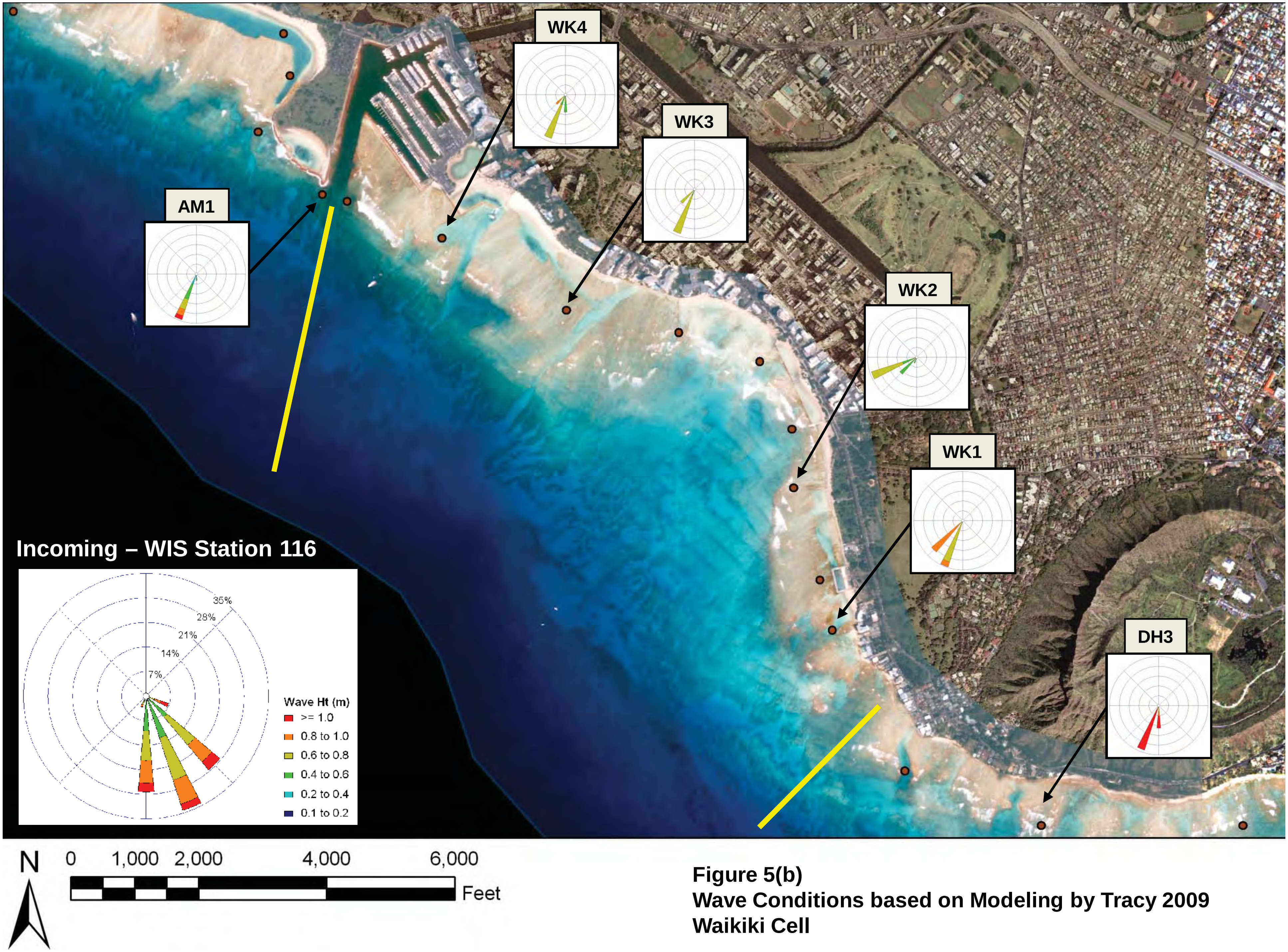


Figure 5(b)
Wave Conditions based on Modeling by Tracy 2009
Waikiki Cell

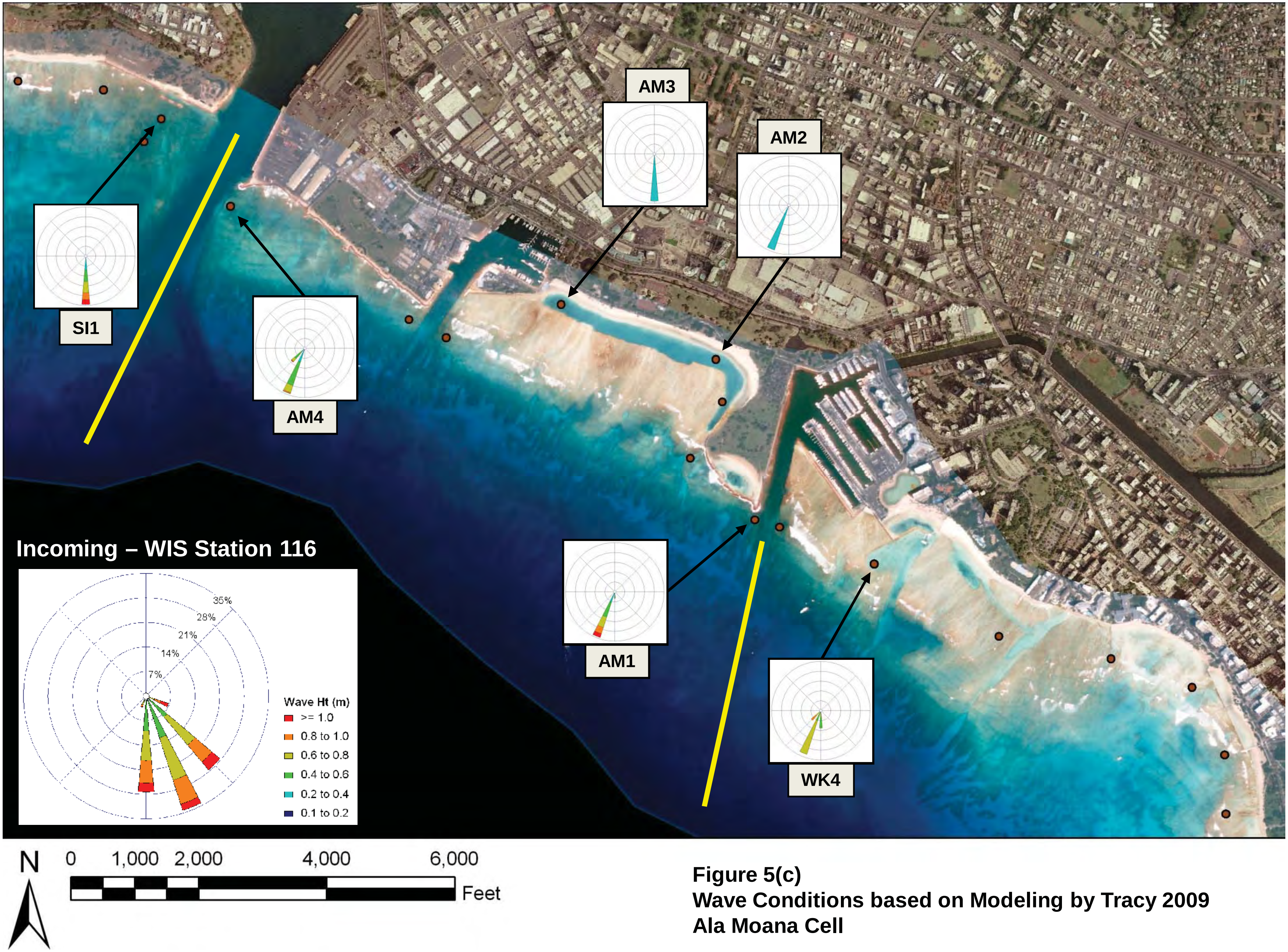


Figure 5(c)
Wave Conditions based on Modeling by Tracy 2009
Ala Moana Cell

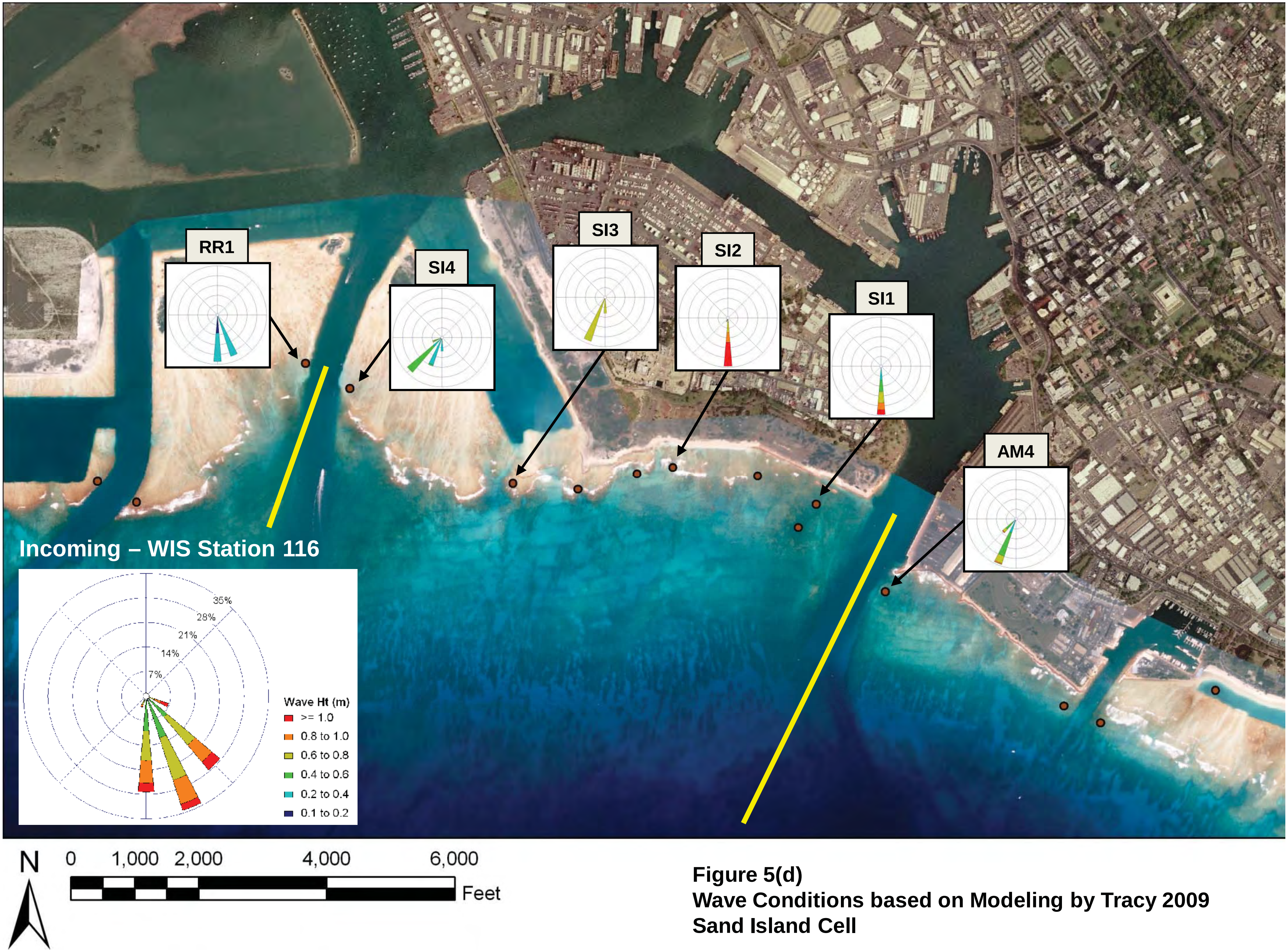


Figure 5(d)
Wave Conditions based on Modeling by Tracy 2009
Sand Island Cell

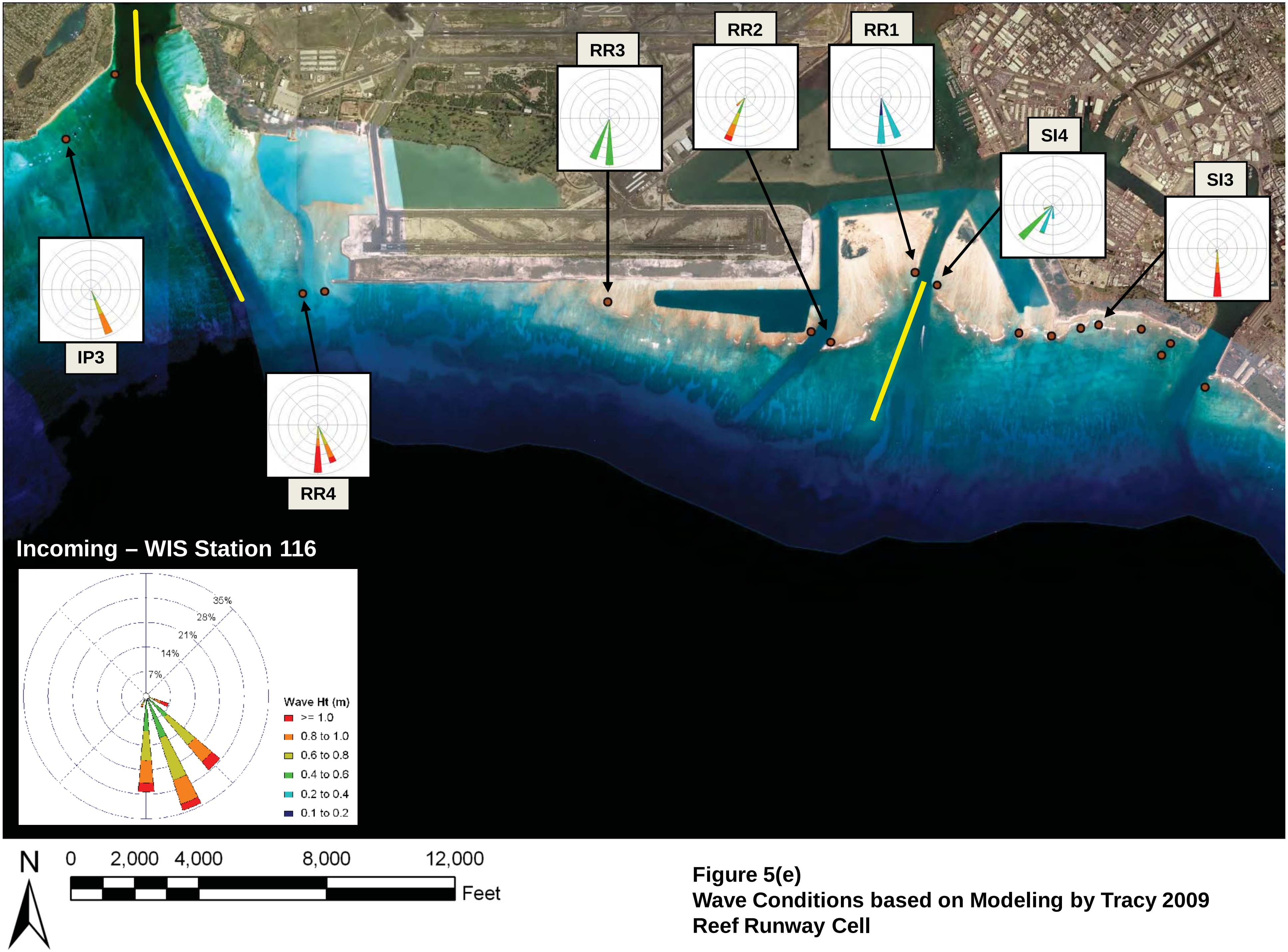


Figure 5(e)
Wave Conditions based on Modeling by Tracy 2009
Reef Runway Cell

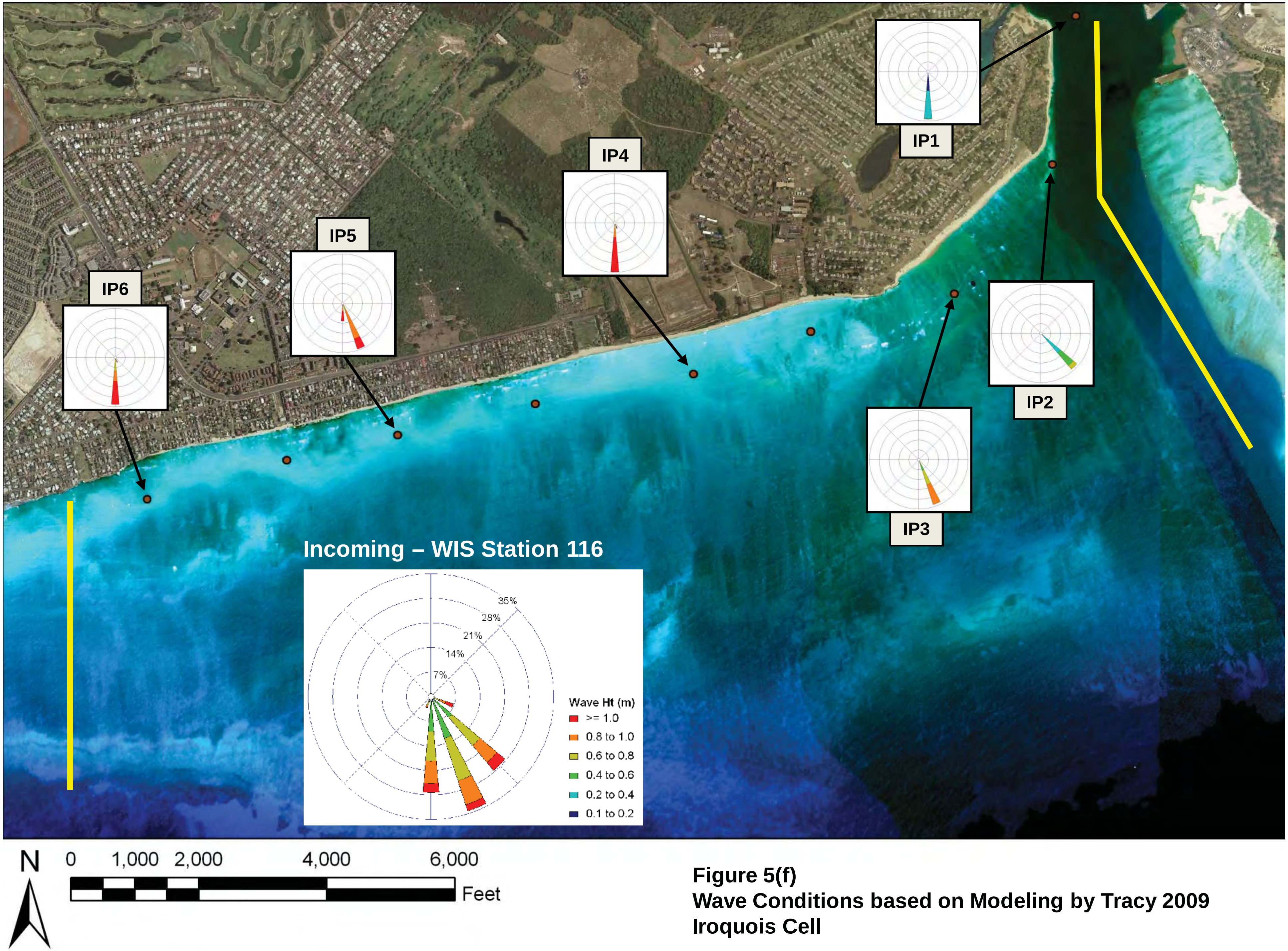


Figure 5(f)
Wave Conditions based on Modeling by Tracy 2009
Iroquois Cell

The last type of wave to be considered is tsunamis. These can approach from any direction and can create significant scour on reef fronts (Wiegel 2006). The 1960 Chile tsunami included a wave crest more than 4 feet above sea level and a trough approximately 6 feet below (Houston 1978) – low enough to uncover much of the reef surface in the study area. Although these waves can cause significant sediment transport, they do not occur frequently enough to be considered in the present sediment budget.

4. Currents

Sand is transported by waves (which mobilize the sand) and tidal or wave-generated currents (which transport the sand). As a result, water circulation is critical in understanding sediment transport.

Currents in the Waikiki area have been studied through a combination of numerical modeling efforts (Sea Engineering 2008a), dye studies (Eversole 2004), and field reviews of littoral drift as observed on the beach (USACE 1992). Relatively little information has been obtained for the western part of the D2P study area, particularly the Iroquois Point cell. However, recent modeling work by the USACE 2009b has provided insights into the behavior of currents in this western region. The modeling work is consistent with previous studies of the Waikiki area.

In the open ocean near the Hawaiian Islands, the tide wave is progressive: peak tidal currents are towards the SSW under the wave crest (high tide) and towards the NNE under the wave trough. Around the islands, the tide wave interacts with the island masses. The tide wave on the south side of O‘ahu approaches from the northeast, diffracts around the southeastern tip of the island and then Diamond Head, passes the south shore, and continues to the southwest (Noda and Associates 1991). The tidal current is important in deep water off the study area, where it is directed west (high tide) or east (low tide). However, it is much smaller than wave-driven currents in the breaker zone (where most sediment transport occurs), and is not considered to be statistically significant for the sediment budget.

Rip currents that carry sand offshore through reef channels and to deeper water are a significant factor in Hawaiian coastal erosion (Wang and Gerritsen 1995, Miller 2002). Rip currents result from water brought towards the shore by waves, which moves alongshore until it reaches a channel in the reef that allows it to move offshore, providing a hydrodynamic mass balance.

Figure 6(a) shows the model bathymetry developed by USACE 2009b, and Figure 6(b)-(k) shows snapshots of the wave-driven currents. The report detailing the model setup is provided as an appendix to the main RSM Plan. Two main wave conditions are illustrated: southern hemisphere swell and Kona storm waves. The offshore wave conditions were taken from a wave buoy (National Data Buoy Center 51203) at Kaumalapau, Lana‘i. The wave heights at this buoy location are representative of wave heights south of O‘ahu (Sea Engineering and Group 70 International 2008), although the buoy is sheltered from the east so waves at the buoy tend to be more westerly than would be representative of the project site. To investigate the effect of this, one run (with southern hemisphere swell) was repeated with the wave approach rotated by 30 degrees counterclockwise. The resulting currents differ in detail from the currents with no rotation, but the general pattern is the same. It is concluded that the results shown here are representative of actual conditions.

Figure 6(b) and Figure 6(c) represent the region from Diamond Head to the Honolulu Channel – that is, the Diamond Head, Waikiki, and Ala Moana littoral cells – during a period of southern hemisphere swell. (To give a good overview of the current patterns, this discussion shows the current patterns for areas larger than the individual littoral cells). Figure 6(b), on August 22 2007, represents a deepwater wave height of approximately 2 feet, while Figure 6(c), on August 24 2007, represents a 3-foot wave. Wave-driven currents along the south shore of the Diamond Head crater are generally weak and variable. However, along the west shore of Diamond Head, the wave-driven currents move strongly northward, towards Waikiki Beach. Two clockwise eddies can be identified along the Waikiki shoreline, with some offshore transport at the Fort DeRussy end. Another clockwise eddy is visible at Ala Moana Beach Park. The currents are relatively light in this area.

Figure 6(d) through Figure 6(f) represent the same region, but for a Kona storm. The deepwater wave height is approximately 6.2 feet for the first two figures, and drops slightly to 5 feet in Figure 6(f). The general pattern of currents is the same for the Kona storm as for the southern hemisphere swell. However, during the course of the storm, a strong offshore current is visible in the Waikiki cell. This current, which forms and reforms during this storm (as well as during a January 2009 storm, not shown) has the potential for moving sand offshore. Pockets of sand are visible on the fringing reef along the entire Ala Moana and Waikiki areas (USACE 2009c); it is not clear if these pockets are the result of local reef production of if they represent sand that has been transported from the beach.

The model bathymetry does not include structures such as the groins along Waikiki Beach, which have been associated with rip currents in the area (e.g., Miller 2002). These results suggest that the groins are not solely responsible for rip currents, and thus for the associated erosion. However, it is perfectly possible that the groins would modify the currents. The immediate conclusion that might be drawn from these figures, that sand eroded from Waikiki Beach will tend to collect offshore of Ala Moana Beach Park, may not be correct. However, it is likely that the sand is transported offshore during certain storm and wave conditions.

A second conclusion from the modeling results is that sand from the Ala Moana cell is unlikely to be deposited in the Honolulu Channel. This is supported by the observation that there is significant terrigenous and organic material found in the Honolulu Channel (Marine Advisers Inc. 1968). Figure 6(g), which shows the Honolulu Harbor and Sand Island region, focuses on this area. The currents in this region are relatively strong in places, particularly in shallow bathymetry over the reef. The pattern of currents in and around Honolulu Harbor and the Keehi Lagoon is rather complex and varies with wave conditions. This region is not discussed in detail, since there is little or no sand here. However, it appears that currents do move clockwise around Sand Island.

The last region to be considered here is from the Honolulu Reef Runway to the eastern portion of ‘Ewa Beach – including the entrance to Pearl Harbor and Iroquois Point. The currents in this area are shown in Figure 6(h) through Figure 6(l); the waves are the same as those in Figure 6(b) through Figure 6(f). Currents along the Reef Runway are strongly towards Diamond Head in this area.

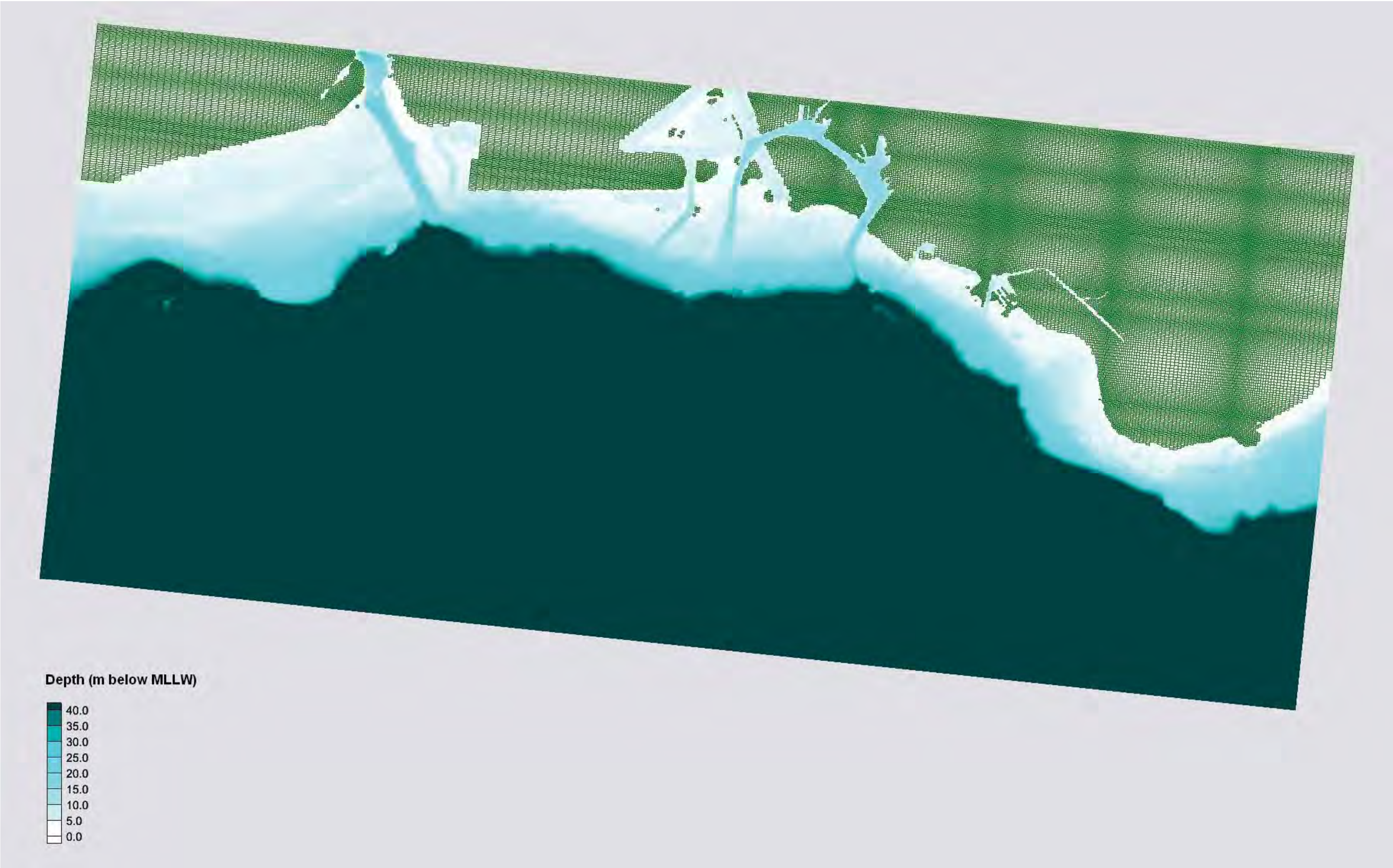


Figure 6(a)
Wave-Driven Currents based on Modeling by USACE 2009
SMS Model Domain

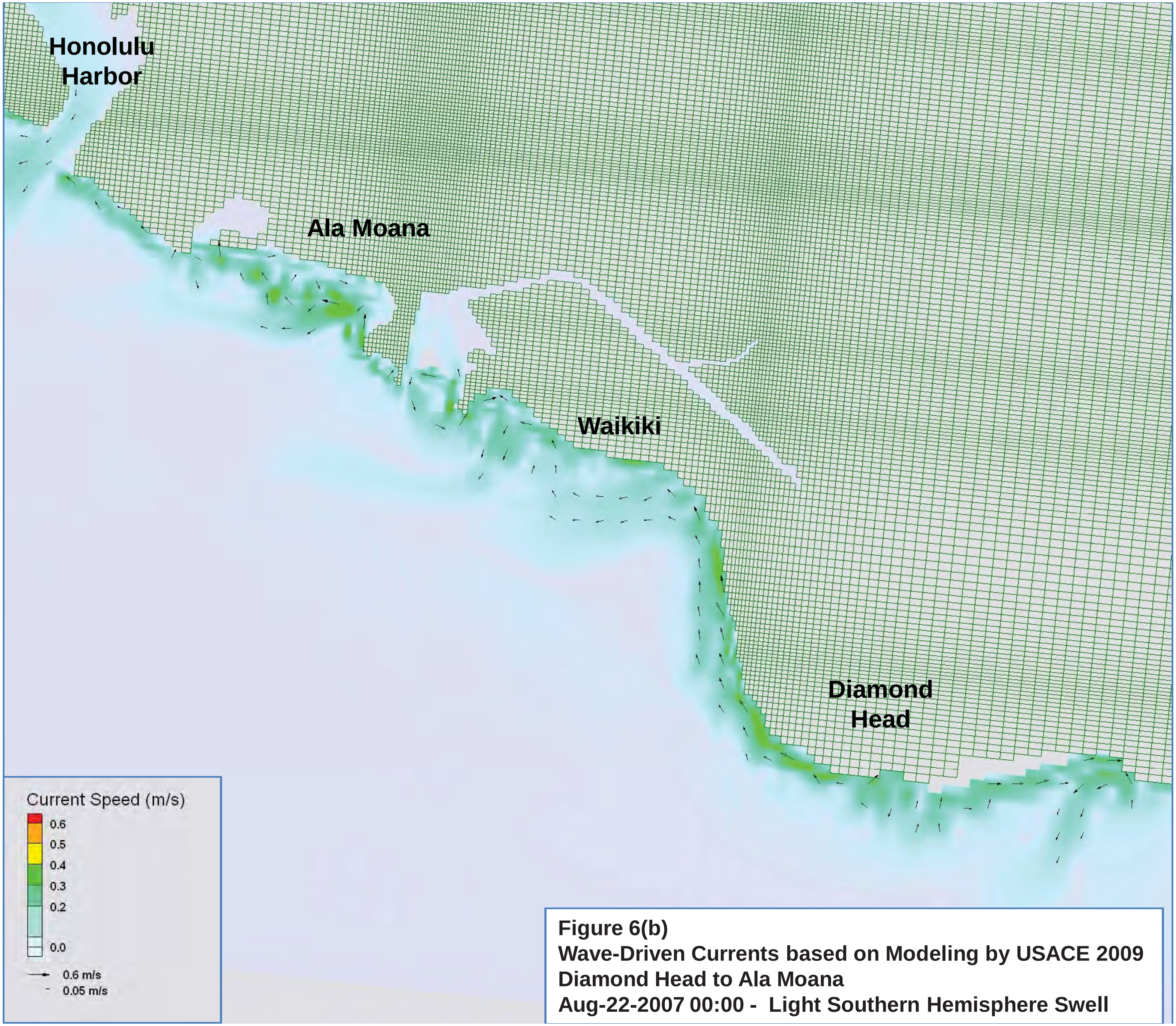


Figure 6(b)
Wave-Driven Currents based on Modeling by USACE 2009
Diamond Head to Ala Moana
Aug-22-2007 00:00 - Light Southern Hemisphere Swell

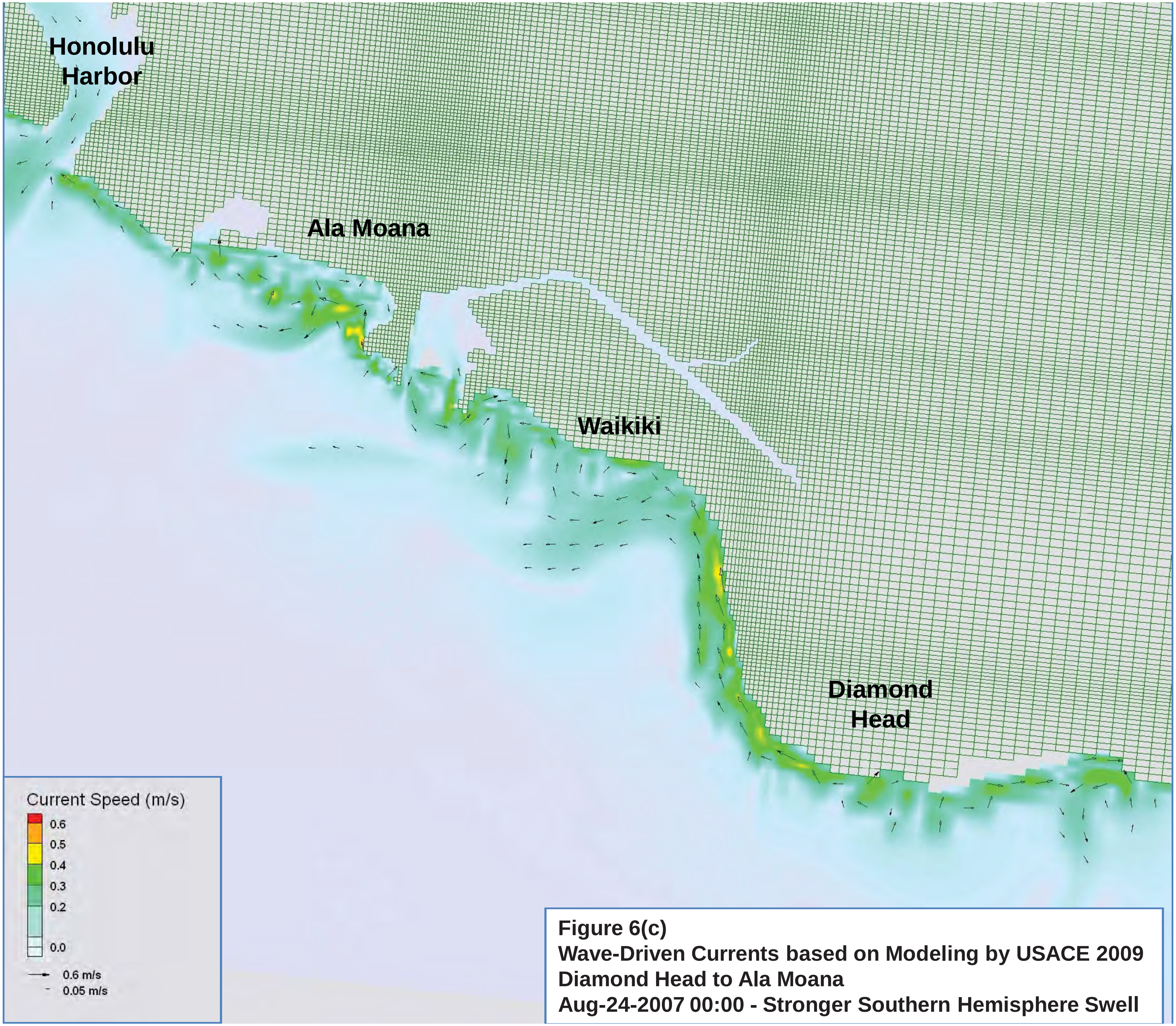


Figure 6(c)
Wave-Driven Currents based on Modeling by USACE 2009
Diamond Head to Ala Moana
Aug-24-2007 00:00 - Stronger Southern Hemisphere Swell

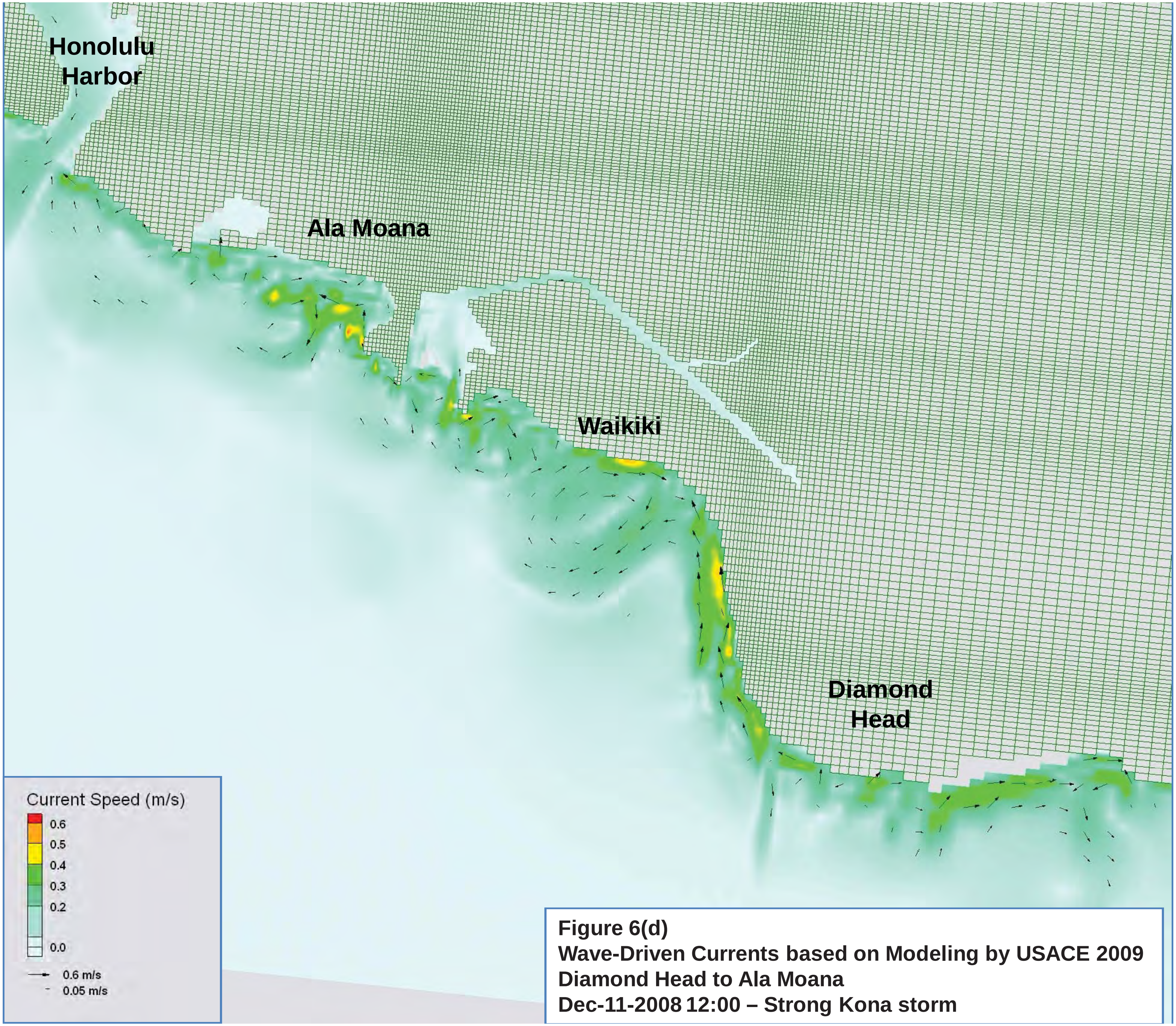


Figure 6(d)
Wave-Driven Currents based on Modeling by USACE 2009
Diamond Head to Ala Moana
Dec-11-2008 12:00 – Strong Kona storm

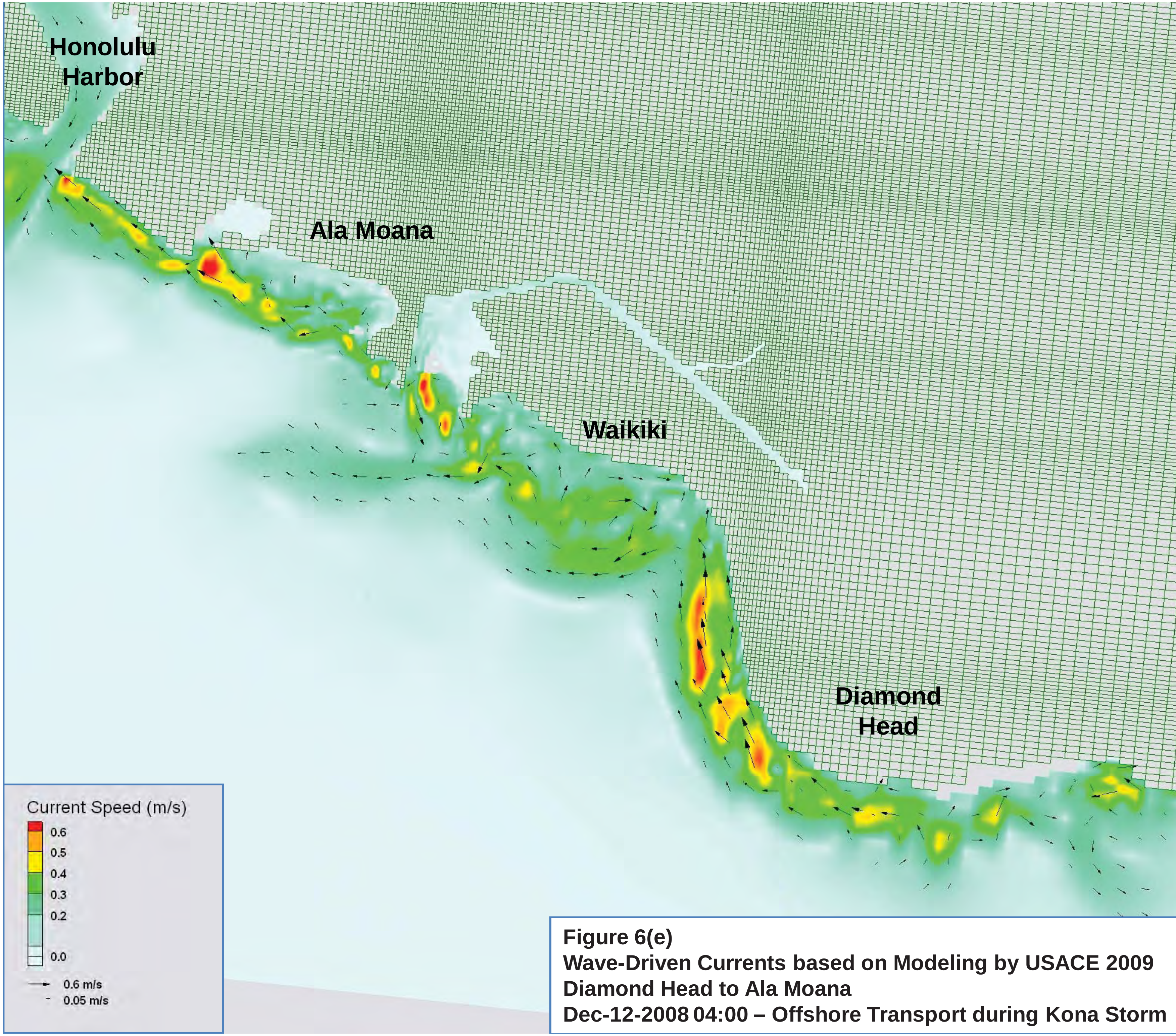


Figure 6(e)
Wave-Driven Currents based on Modeling by USACE 2009
Diamond Head to Ala Moana
Dec-12-2008 04:00 – Offshore Transport during Kona Storm

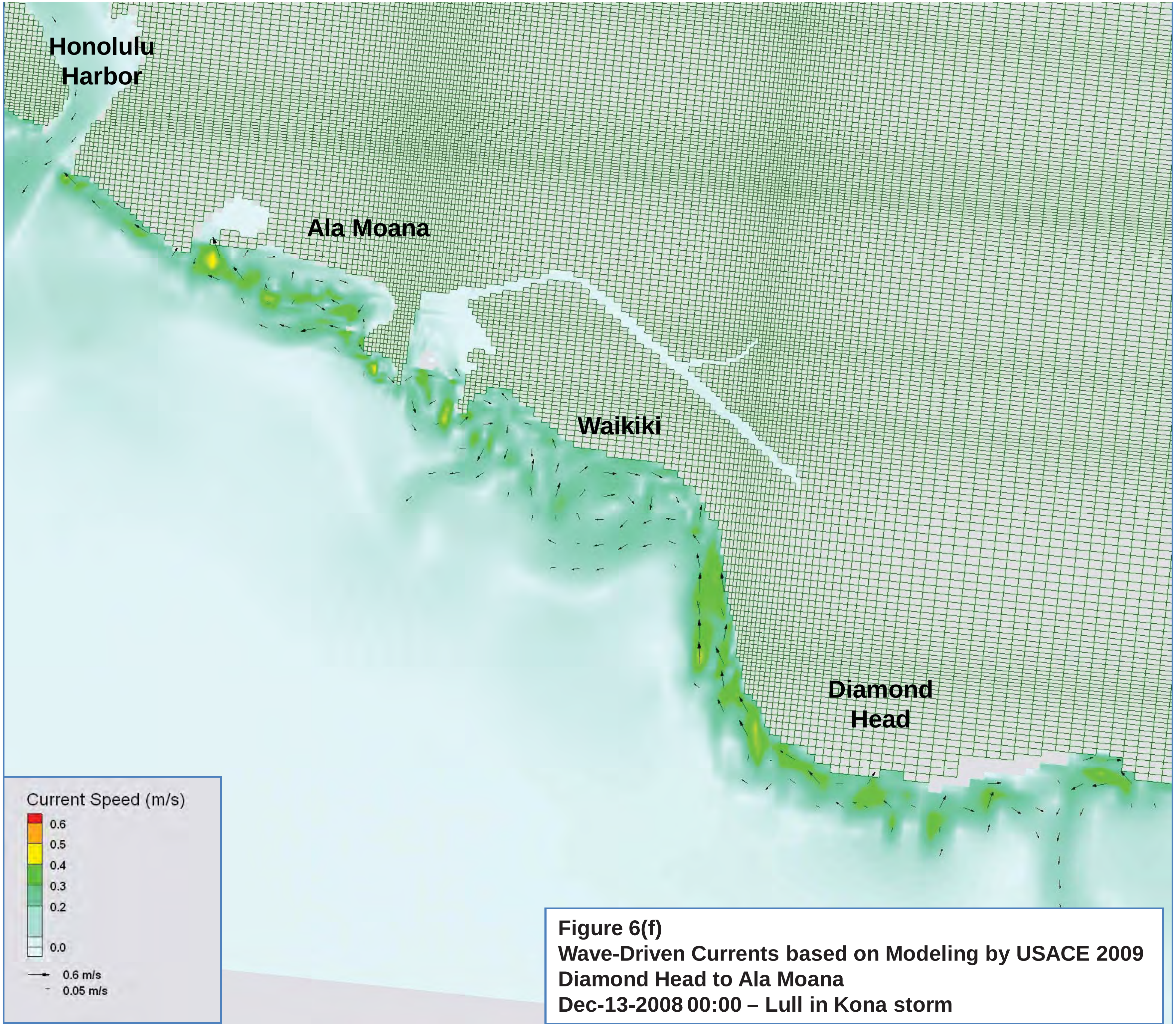


Figure 6(f)
Wave-Driven Currents based on Modeling by USACE 2009
Diamond Head to Ala Moana
Dec-13-2008 00:00 – Lull in Kona storm

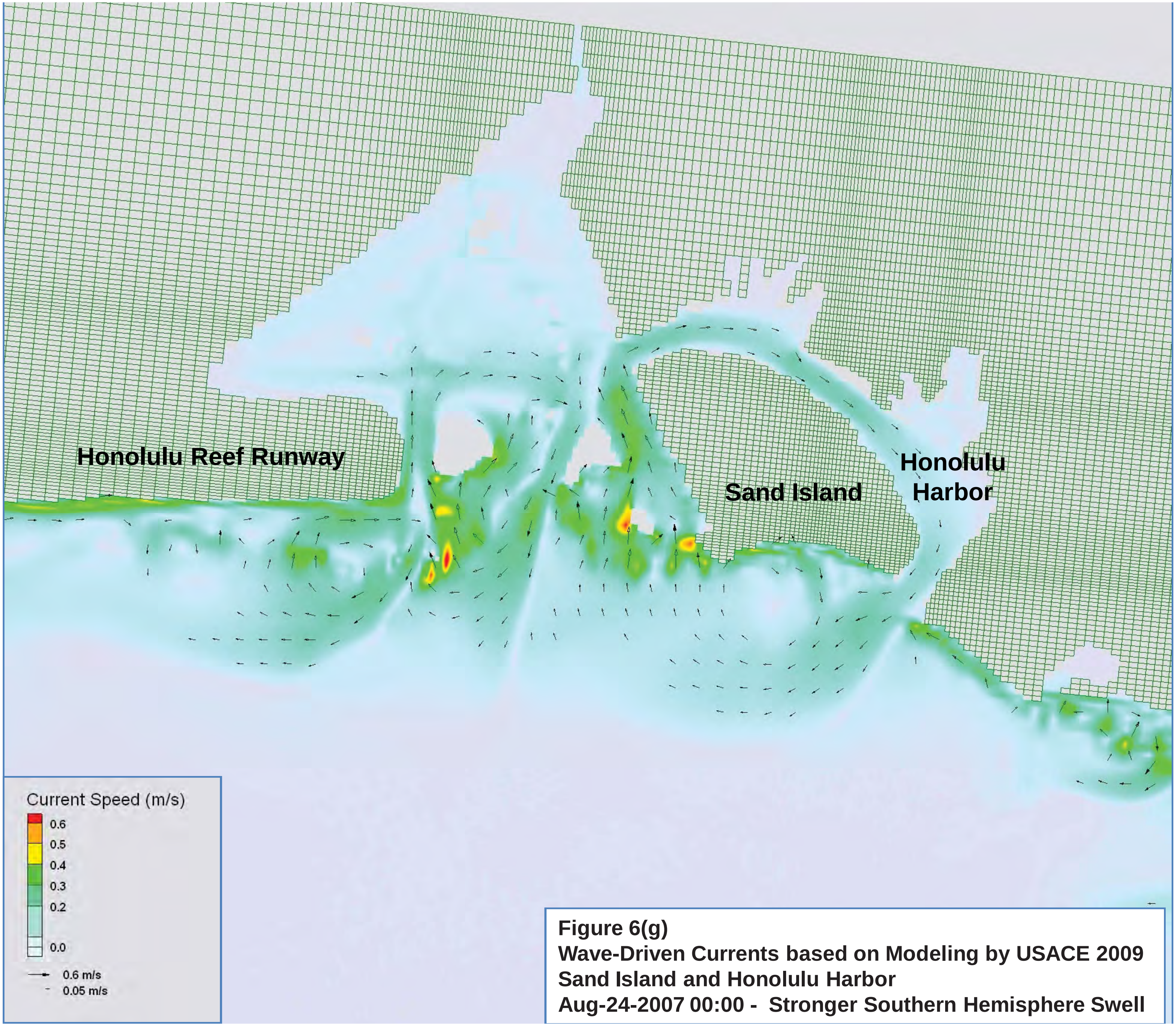


Figure 6(g)
Wave-Driven Currents based on Modeling by USACE 2009
Sand Island and Honolulu Harbor
Aug-24-2007 00:00 - Stronger Southern Hemisphere Swell

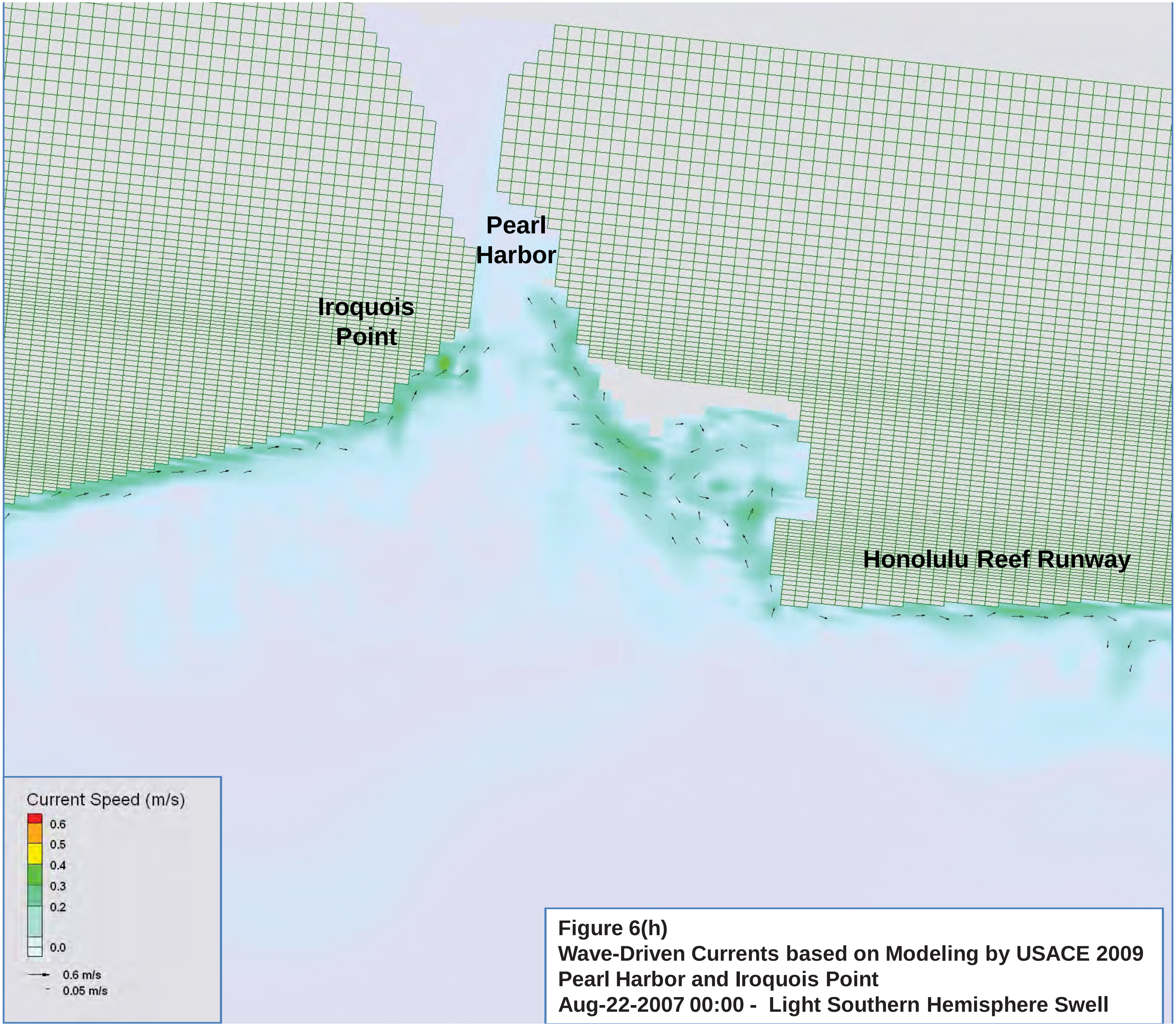


Figure 6(h)
Wave-Driven Currents based on Modeling by USACE 2009
Pearl Harbor and Iroquois Point
Aug-22-2007 00:00 - Light Southern Hemisphere Swell

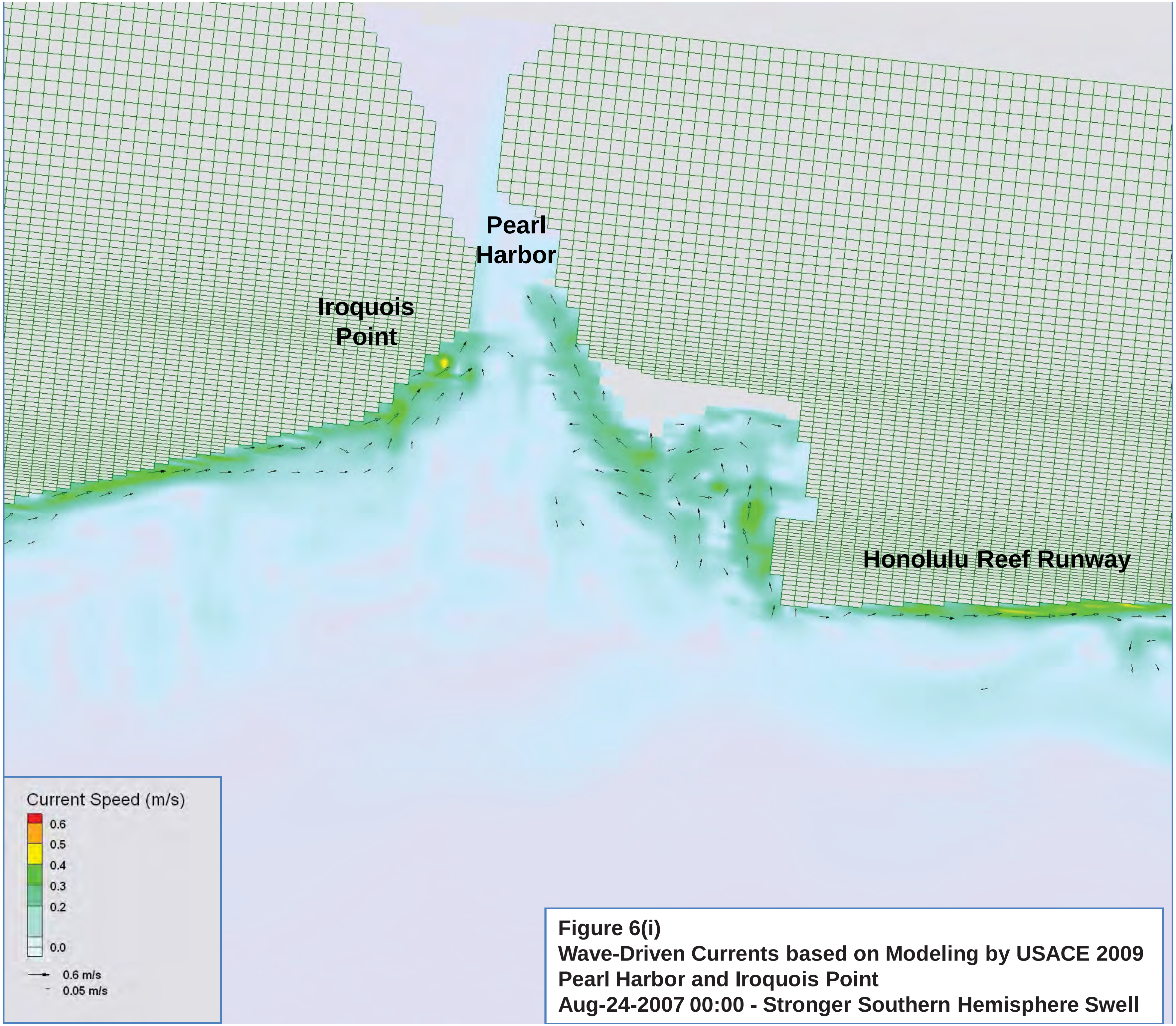


Figure 6(i)
Wave-Driven Currents based on Modeling by USACE 2009
Pearl Harbor and Iroquois Point
Aug-24-2007 00:00 - Stronger Southern Hemisphere Swell

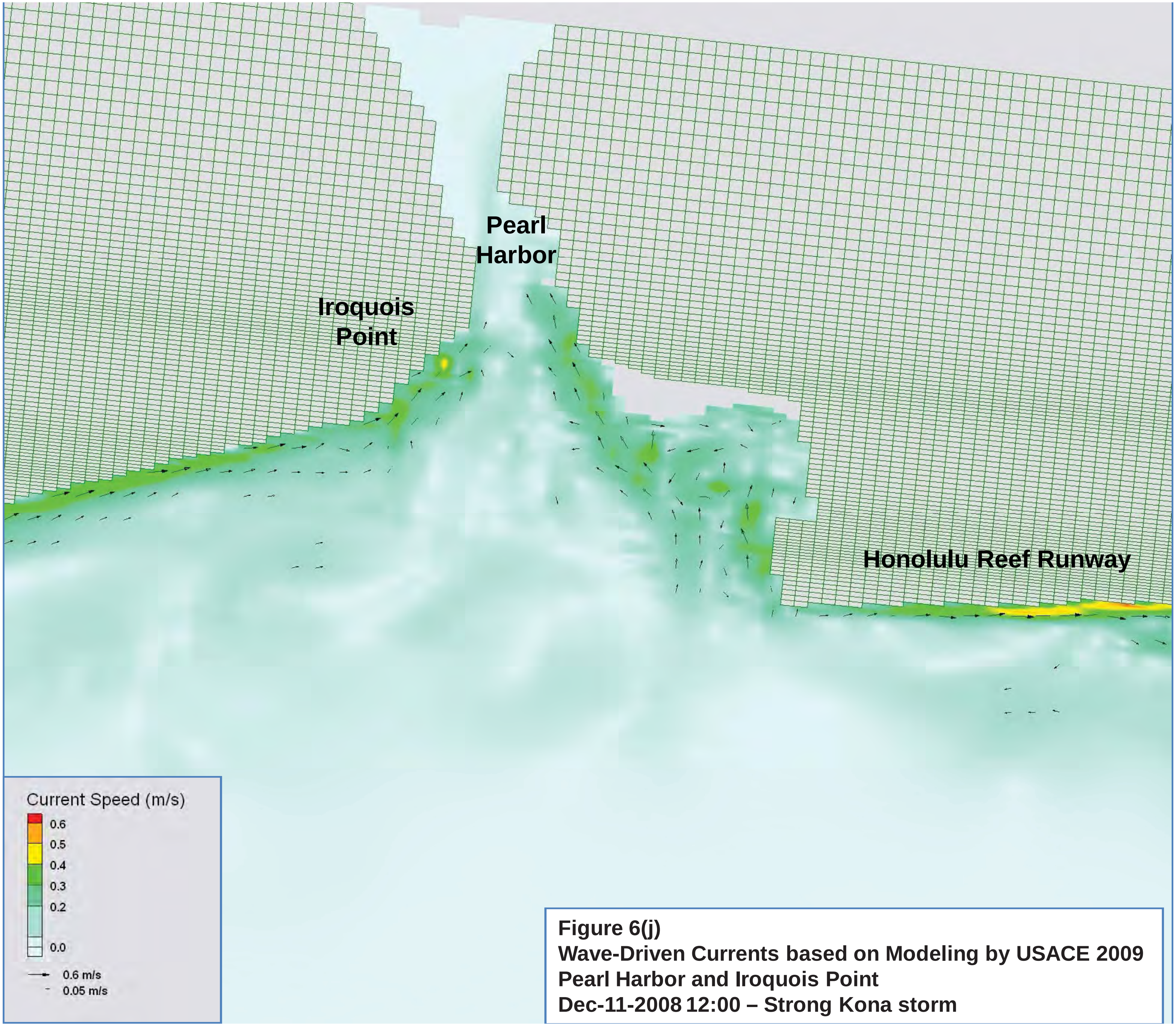


Figure 6(j)
Wave-Driven Currents based on Modeling by USACE 2009
Pearl Harbor and Iroquois Point
Dec-11-2008 12:00 – Strong Kona storm

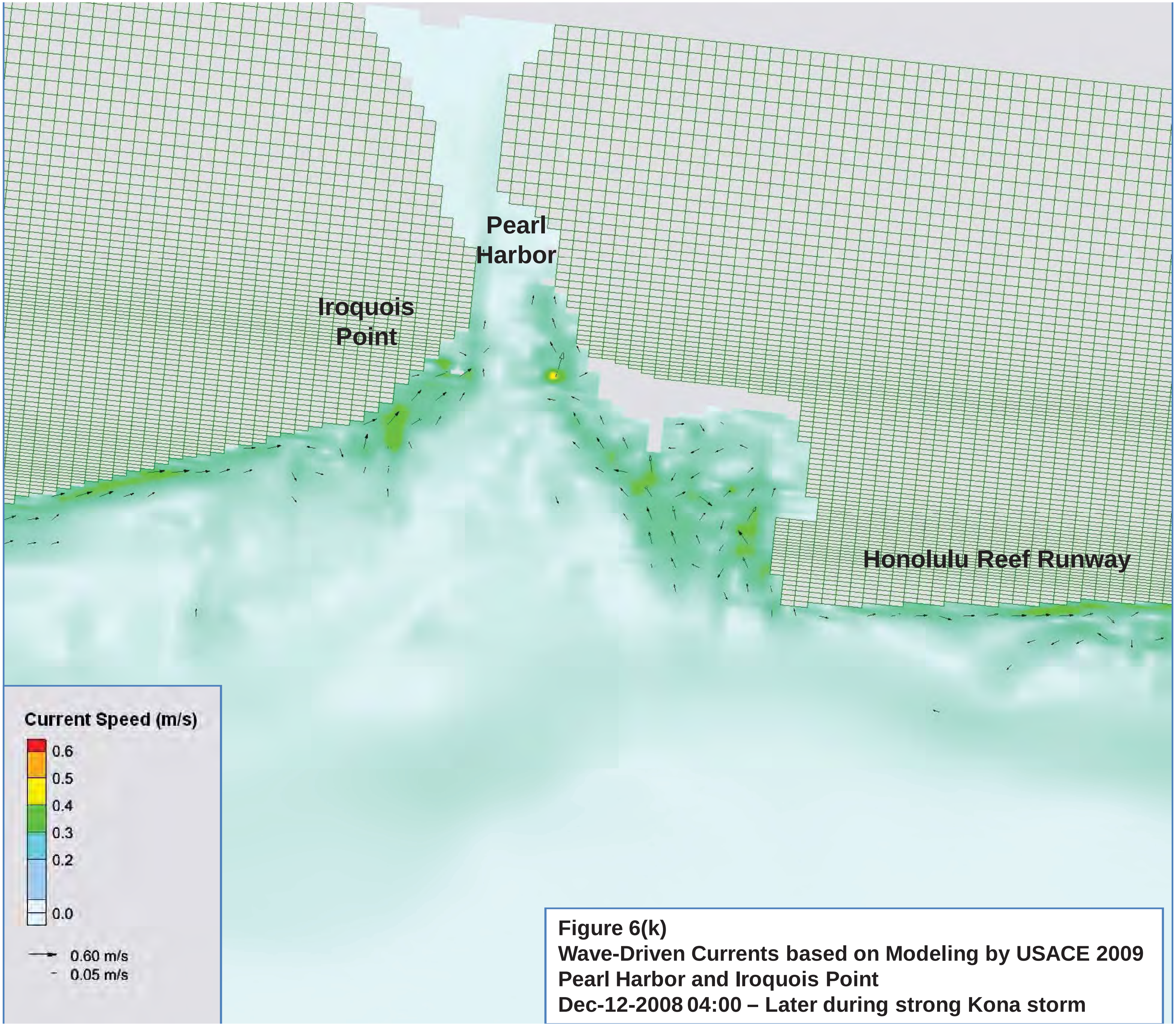


Figure 6(k)
Wave-Driven Currents based on Modeling by USACE 2009
Pearl Harbor and Iroquois Point
Dec-12-2008 04:00 – Later during strong Kona storm

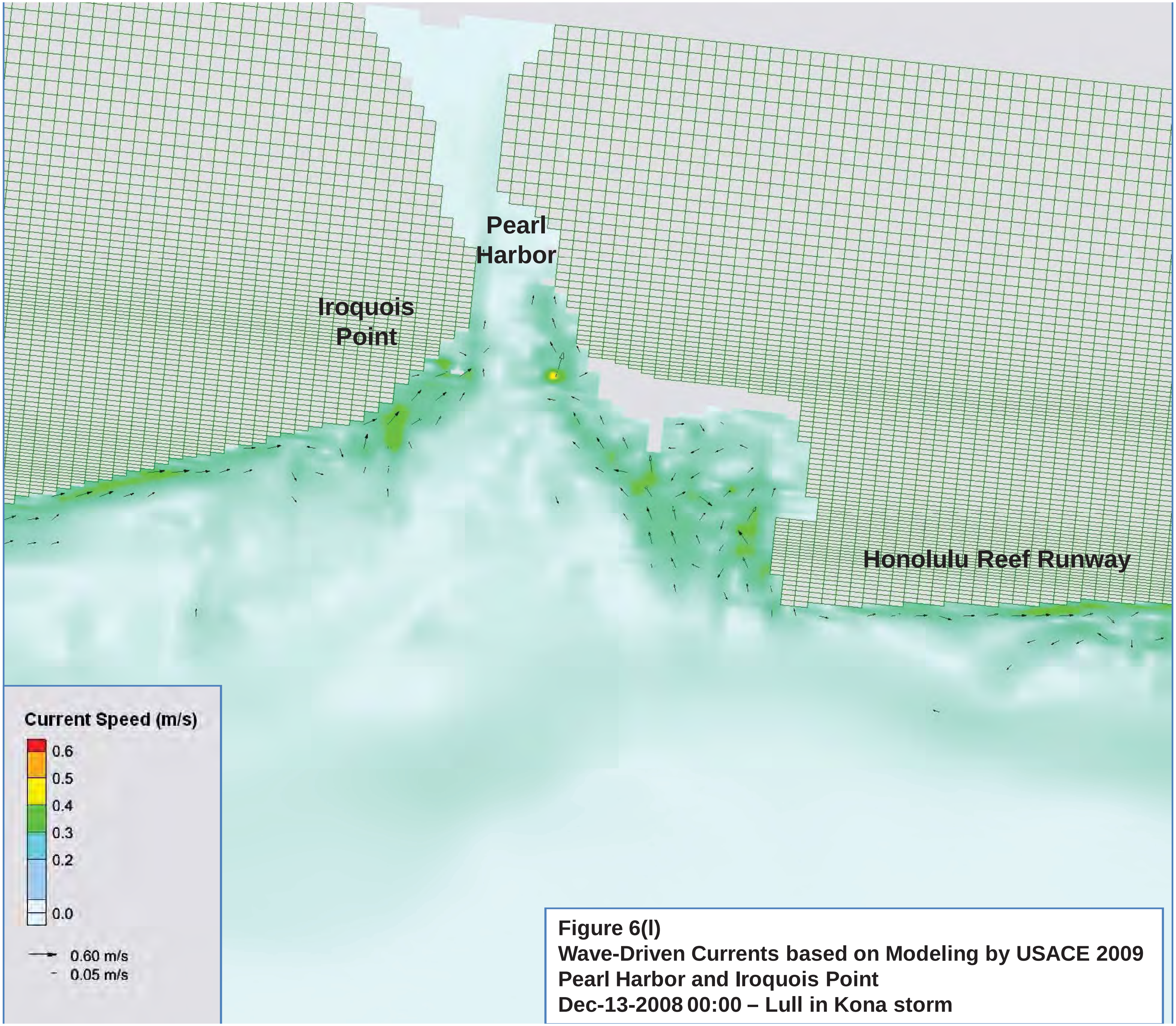


Figure 6(l)
Wave-Driven Currents based on Modeling by USACE 2009
Pearl Harbor and Iroquois Point
Dec-13-2008 00:00 – Lull in Kona storm

A rip current forms along the runway (it is visible in the southern hemisphere swell figures, and is further towards Diamond Head for the Kona storms). This rip current does not have a significant effect on sediment transport, since there is little or no sand along the shoreline of the Reef Runway. The currents in the lee of the runway are rather confused, but are eventually directed into Pearl Harbor.

On the ‘Ewa side, the wave-driven currents from Keahi Point around to Iroquois Point are consistently (and strongly) towards the Pearl Harbor entrance. Currents ‘Ewa of Keahi Point are generally towards Pearl Harbor, but are more variable and reversals do occur. Figure 6(k) shows a localized and weak reversal of the currents immediately west of Keahi Point. The change in strength and consistency of the currents at the point is responsible for the ongoing erosion in this area. Relatively sand appears to be present on the fringing reef ‘Ewa of Pearl Harbor (USACE 2010), which supports the conclusion that most of the currents and transport are into Pearl Harbor. Unfortunately, the dredging records of Pearl Harbor do not identify the quantity of beach sand versus fine material, which would help to quantify this component of the sediment transport.

D. Sediment Sources

The beaches in the study area are composed almost completely of calcareous grains of biochemical origin, the fragments of skeletal parts of certain marine invertebrate animals and algae. There is very little silicate material, which would be of terrigenous origin. Much of the sand in the Waikiki area results from beach nourishment and is of foreign origin (Gerritsen 1978), and beach nourishment has also occurred at Ala Moana Beach.

Locally generated calcareous sediment is ultimately from the fringing reefs surrounding O‘ahu. The unconsolidated sediment, which is available to build beach systems, is from two main sources:

- Biological and mechanical erosion of the coral reef framework;
- Direct sediment production upon the death of such organisms as *Halimeda* (a green macroalgae), mollusks, and foraminifera.

Harney and Fletcher 2003 estimated total unconsolidated sediment production over a 3,000 acre reef system at Kailua Bay, on the windward side of O‘ahu, to be approximately 5,200 cy/year. This is low compared to estimates of reef production in other areas, although it is likely to be higher than actually found in the study area, where the reefs are at shallower depths and are degraded in many cases. Modern sand production on Hawaiian reefs may be relatively low compared to 2,000 to 4,000 years ago, when the sea level was higher and the wave energy may have been lower (Rooney *et al*. 2004). Harney and Fletcher estimated that, of the sediment produced at Kailua Bay over the past 5,000 years, approximately 50% is now stored in the coastal plains, 20% in various reef channels and holes in Kailua Bay, 5% is now on the beaches, and the remaining 25% has been lost offshore and through natural processes of dissolution and abrasion. The 5,000 year period is that in which Kailua Bay has been inundated by postglacial sea level rise.

In an unmodified system, there would be an additional sand source as beaches retreat into coastal plains and dune fields in response to ongoing sea level rise. This would release stored sediment in these upland areas into the littoral system. In the present condition of the shoreline, which is armored in large part, this can no longer occur. These potential sources are currently not available to the littoral system.

III. Sediment Budget Methodology

A. Overview

The sediment budget presented in this report is, at best, semi-quantitative. Based on available information regarding reef productivity, shoreline accretion and erosion, the location of sand pockets on the nearshore fringing reef (USACE 2010) and the patterns of wave-driven currents, a balanced budget is presented. However, there are significant uncertainties in the different elements of the budget. Absolute sediment transport rates, including longshore transport and losses offshore and into the deep channels, have not been quantified individually: rather, they are selected precisely to balance the budget. Therefore, the actual numbers given should be used only as a guide to the orders of magnitude. However, the values are adequate for planning and evaluating potential sediment management and beach nourishment projects in the region.

Sections III.B and III.C below describe two elements that are commonly used in sediment budget analyses, but which were ultimately not useful in the present situation.

- Estimates of sediment transport rates based directly on the wave modeling by Tracy 2009 are dramatically higher than plausible – most likely because of the presence of the reef. Conventional sediment transport rates are actually potential rates, based on the assumption that a sandy bottom is present throughout the study reach: a more sophisticated sediment transport analysis would be needed to provide insight into the D2P region.
- Seasonal trends are common in beach dynamics, but based on measurements by the United States Geological Survey (USGS) 2001, no significant seasonal trends are observed in the D2P region. Therefore, it is not necessary to detrend the shoreline retreat data.

Since a sediment transport rate analysis was found not to be useful in this area, the sediment budget was developed based on volumetric changes over the past few decades. The timeframe for the analysis varies by littoral cell, based on the extent of recent human modifications.

- The volume of sediment released from beaches through erosion, and impounded in beaches and upland areas through accretion, was estimated based on the analysis of aerial photography prepared by the University of Hawai‘i (Hawai‘i Coastal Geology Group 2009). Minor additions and modifications were made for the present application, and retreat distances were converted to retreat volumes using with available measurements of the local beach profiles. This analysis is described in Section III.D.
- Historical beach nourishment volumes were largely taken from work by Wiegel, as described in Section III.E.
- The rate at which new calcareous sediment is produced by reefs is highly uncertain. The amount of the sediment that reaches the beach is even more uncertain. Section III.F describes the approach taken here to estimating the net rate of sediment production. However, the short-term importance of reef production is a significant data gap, as this is the only natural source for sand in the D2P region.
- The majority of loss mechanisms are included in the budget through balancing, rather than through independent estimation. Section III.G describes the mechanisms considered in a more or less explicit way.

With the volume changes established, the sediment transport pathways are developed based on the coastal processes described in Section II.C and on general morphological considerations. These sediment transport pathways, together with the balanced budgets, are described for each littoral cell in Section IV.

B. Potential Sediment Transport Rates

The rate of longshore sediment transport is often modeled as a function of such inputs as breaker wave height, period, approach direction, and sediment parameters. A typical model – far from the only one of its type – is known as the CERC Equation, which is based on the assumption that the longshore sediment transport rate is proportional to the longshore energy flux. It is expressed by Smith, Ebersole, and Wang 2004 as follows:

$$Q = \frac{K}{16\sqrt{\gamma}} \rho_w g^{3/2} H_{sb}{}^{5/2} \sin 2\alpha$$

where Q is the longshore sediment transport rate expressed as an immersed weight, K is an empirical coefficient, ρ_w is the density of water, g is the acceleration due to gravity, H_{sb} is the significant wave height at breaking, γ is the breaker index (often set equal to 0.78), and α is the angle between the breaking wave crests and the shoreline. The calibration coefficient K has been obtained for different conditions based on field measurements.

Models of this type produce potential transport rates – that is, the rate of sediment transport under the assumption that plentiful sediment is available throughout the breaker zone. This is not the case in the presence of a fringing reef, which introduces a hard bottom over much of the breaker zone (e.g., Eversole and Fletcher 2003). In addition, breaker dynamics are affected by the large bottom friction that results from the very rough reef surface (Hearn 1999). Therefore, it is likely that the straightforward application of standard potential transport rate equations to the D2P region will vastly overpredict the actual transport rates.

This turns out to be the case. As an example, the longshore sediment transport rate was calculated using the CERC equation for the Iroquois Point littoral cell, using the wave conditions predicted by Tracy 2009. The immersed weight was converted to a volume of sediment on the beach using a grain specific gravity of 2.4 (density of 2,400 kg/m^3) and a porosity of 2.4. With these parameters, the calculated longshore transport rates varied upwards of 400,000 cubic yards annually. This is a factor 100 more than the sediment transport rates estimated on the basis of volume changes. A much more sophisticated approach would be needed to make numerical modeling a useful quantitative tool in sediment budget analysis for this region.

C. Seasonal Trends

Seasonal trends in beach characteristics are common worldwide. Seasonal changes in wave energy can bring about onshore-offshore transport, with beaches typically becoming narrower during periods of high wave energy and recovering when the wave energy decreases. Seasonal changes in wave direction can bring about longshore transport, with different areas accreting and eroding at different seasons.

Moberly and Chamberlain 1964 identify seasonal trends on the beaches in O‘ahu, based on measurements between May 1962 and August 1963. For example, changes in the wave intensity on the windward side of the island as the trade winds and associated waves become stronger and weaker led to observable changes in the beach profiles on that coast. Countervailing trends were observed on the leeward side.

However, Moberly and Chamberlain do not describe specific seasonal trends for beaches on the south coast (including three locations within the study area: the Natatorium, Kuhio Beach, and Ewa Beach). Gibbs, Richmond, and Fletcher 2000 also do not mention seasonal trends for the south coast, while describing seasonality on the leeward and northern-windward coast. Subsequent bi-monthly beach profiles in the study area between October 2000 and May 2002 (Miller 2002, shown as volume changes in Norcross *et al* 2003) do not show any clear seasonal trends.

The analysis by Gibbs *et al*. was based on beach profiles measured by USGS between August 1994 and August 1999, including five locations on the south shore of O‘ahu (USGS 2001). Figure 7 shows how the area under the beach profiles varied by month during this period. The vertical scale on this axis has an arbitrary origin, so that the values for the different beaches are visible separately – it is not the case that Oneaula Beach Park has by far the greatest beach volume. No seasonal trend is visible on this chart.

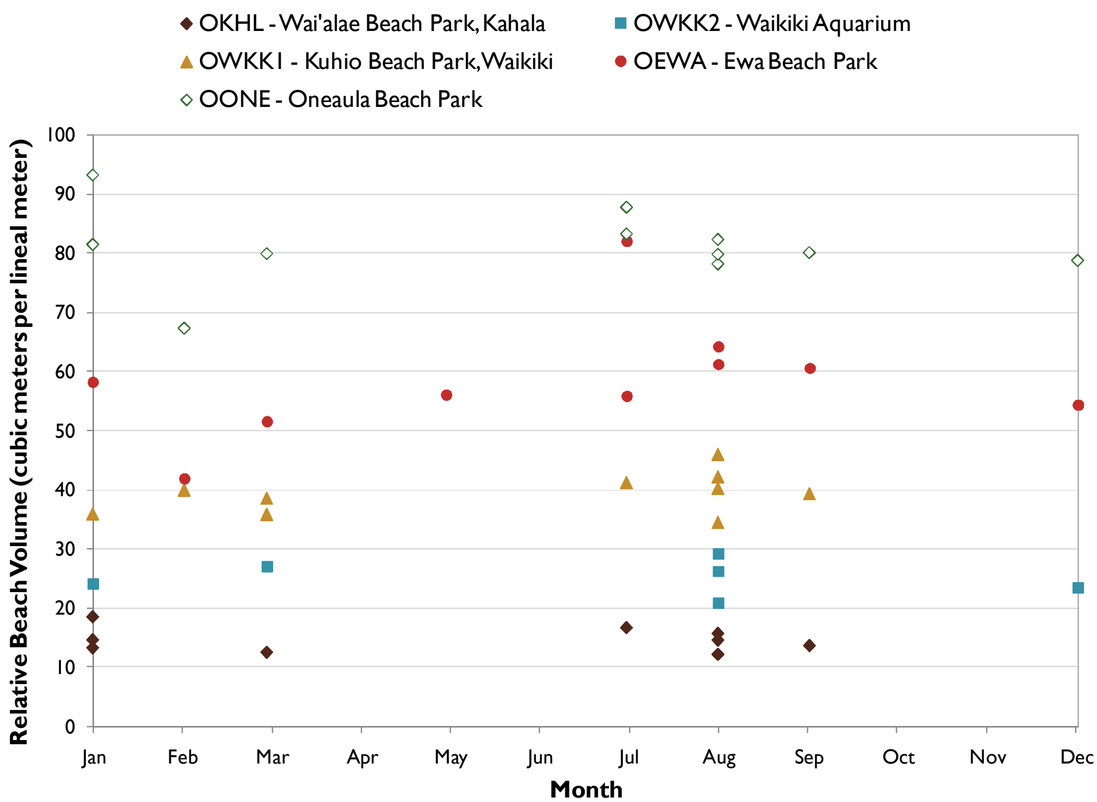


Figure 7. Relative beach volume, by month, for five beaches on the south shore of O‘ahu as measured by USGS between 1994 and 1999 (arbitrary y-axis origin)

It is concluded that seasonal trends in beach width may not be a significant factor for the D2P region, and this effect need not be corrected for in the analysis.

D. Beach Erosion and Accretion

Two main sources of information are used to evaluate beach erosion and accretion volumes.

The first source of information is a shoreline change analysis, which measures changes in land (mostly beach) area over time. This analysis is almost entirely based on the shoreline erosion mapping work prepared by the University of Hawai‘i (Hawai‘i Coastal Geology Group 2009; methods are described in Fletcher *et al.* 2003). The orthorectified historical photomosaics used in this work are available online at <http://www.soest.hawaii.edu/asp/coasts/oahu/mosaics.asp>; shoreline shapefiles and measured shoreline positions along each transect (spaced at 20 meters) were provided to M&N. M&N extended the shoreline on the ‘Ewa side of Pearl Harbor further inland, to capture an accretional area at Iroquois Point. M&N also performed a beach area analysis, calculating the changes in total beach area for individual littoral cells and some subcells (in contrast to the work by UH, which focused on retreat distances along the shoreline). The result of this work was an estimate of total beach area, relative to the latest (2005) vegetation line, for each set of aerial photomosaics.

The second source of information is the vertical extent of the active shoreline profile. M&N reviewed available data on shoreline profiles, which covered the Waikiki and Iroquois Point littoral cells (USGS 2001; Moberly 1964; Gerritsen 1978; Miller 2002; Sea Engineering 2008b). Figure 8 and Figure 9 give examples of the profiles.

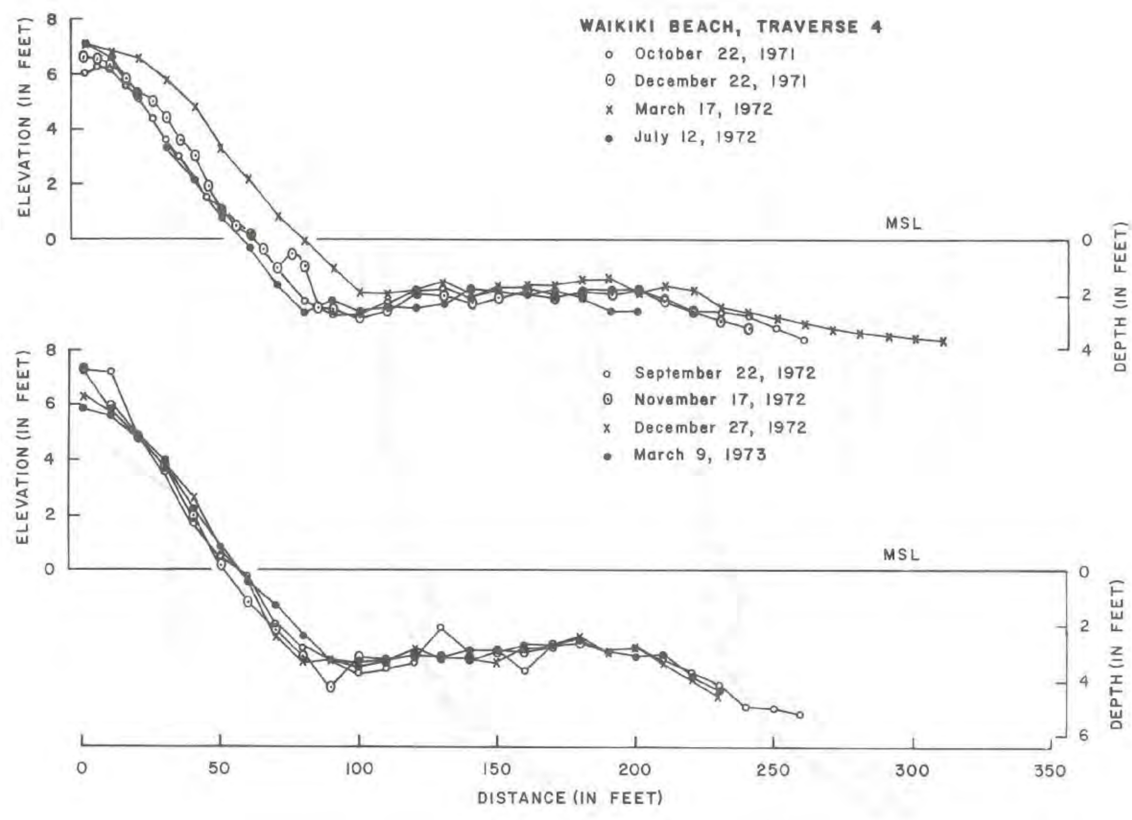
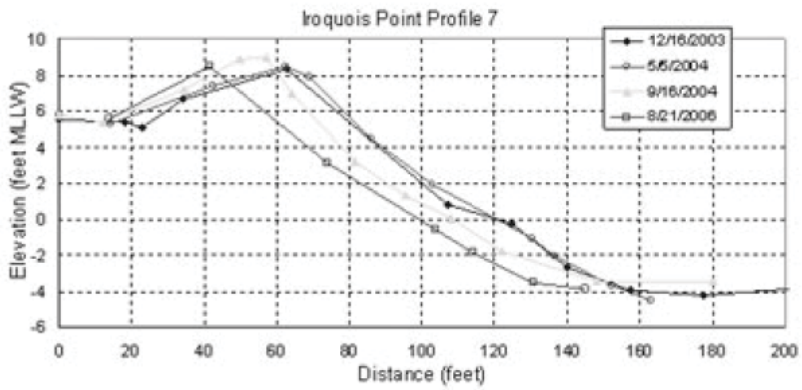


Figure 8. Illustrative beach profiles – Waikiki cell (Gerritsen 1978)



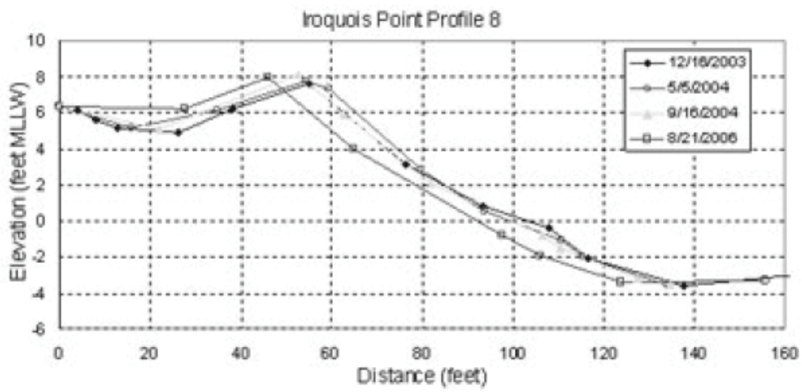


Figure 9. Illustrative beach profiles – Iroquois Point cell (Sea Engineering 2008b)

These profiles, and the other profiles from the study area, varied rather little in their vertical extents. Throughout the study area, the uppermost limit of the beach profile was in the region +6 feet to +10 feet MLLW. The higher values tended to be found in the Iroquois Point cell, and the beach in this case took the form of a higher beach berm with the upland area at +6 to +7 feet MLLW. The lowest limit of the active beach profile, where the sandy beach meets the reef, was in the region -4 feet to -5 feet MLLW.

Based on these and the other profiles considered, M&N determined that the typical active beach profile ranged from typically -5 feet MLLW to typically +7 feet MLLW – a vertical extent of 12 feet. If one square foot of beach is lost with an active profile depth of 12 feet, this corresponds to a loss of 12 cubic feet, or 12/27 = 0.44 cubic yards. Therefore, the beach area losses (or gains) were converted to volume losses (or gains) using a density of 0.44 cubic yards per square foot. The same conversion factor seems appropriate for the entire study area.

E. Historical Sand Placement

Table 2 provides an overview of the known sand placement activities, together with other significant coastal activities and events, in the Waikiki and Ala Moana cells. The table shows events since the early 1960s, based on Wiegel 2002 and Wiegel 2008. Earlier events are not shown because the sediment budget only considers the period after approximately 1964, when the work at Magic Island (which significantly changed the shoreline, and most likely littoral processes) was complete. No sand placement has been recorded in other littoral cells in the D2P study area.

Table 2: Significant Activities at Waikiki and Ala Moana Cells

Date	Activity	Volume (cy) where relevant	Cell	Comments
1962 to 1964	Magic Island constructed on 30 acres of reef flat.			
	Narrow channel dredged parallel to the northwest side of Magic Island, through the reef.			
	Stone seawall built along the Diamond Head side of Magic Island and the Ala Wai entrance channel to hold fill.			
	75-foot-long rubble mound spur jetty built at right angle to the stone seawall along the Ala Wai entrance channel.			
1963	Outrigger Canoe Club placed 1,660 cy of coral fill and 6,000 cy or sand from foundation excavation on Sans Souci Beach	7,660	Waikiki	
	Connecting channel dredged in reef at Outrigger Canoe Club			
	190-foot-long groin built ‘Ewa of the Outrigger Canoe Club			
3/24/1964	Alaska tsunami			
1968 to 1970	Fort DeRussy Beach 1,800 feet long constructed in front of seawall; 82,000 cubic yards of coral material dredged from reef (US Navy stockpile) and concrete debris as base; unwashed crushed coral sand used to cover the fill	98,000	Waikiki	assumes 2-feet of sand over 1800 feet, 120 feet wide, in addition to stated base quantity
1972	Kuhio Beach and (?) Queen's Surf Beach sand fill of 82,500 yards (quantity not certain)	82,500	Waikiki	
1975	Kuhio Beach sand fill of 9,500 yards	9,500	Waikiki	
1976	Fort DeRussy. Layer of sand 2 feet thick placed over the beach	15,900	Waikiki	
1976	Ala Moana Beach Park. 30,000 cubic yards of sand placed on eroded beach.	30,000	Ala Moana	
1978	Maintenance dredging of silt from Ala Wai canal			

Date	Activity	Volume (cy) where relevant	Cell	Comments
1981	Beach restoration (maintenance). Fort DeRussy	0	Waikiki	No import of sand; grooming and scarifying hardpan
1982	Hurricane Iwa		Waikiki	Additional sand brought inshore, per Miller (2002)
1987	Beach restoration (maintenance). Fort DeRussy	0	Waikiki	Not detailed; assumed no import as with earlier restoration.
1992	Hurricane Iniki			
1994	Beach restoration (maintenance), Fort DeRussy, and Hawaiian Village (Duke Kahanamoku Beach)	0	Waikiki	Not detailed; assumed no import as with earlier restoration.
2000	Kuhio Beach. 1,400 cubic yards of sand dredged from thin pocket in reef offshore and pumped through a pipeline to the beach	1,400	Waikiki	
2002	Sand moved by front-end loader in February from west end of Kaimana Beach (where it accumulated) to east end (from where it had eroded).			
2002	Maintenance dredging of site (and trash and debris) from Ala Wai Canal (185,801 cubic yards)			
2006	Kuhio Beach Nourishment; sand pumping to renourish beach and demonstrate the effects of offshore sand retrieved from the reef flat. 10,000 cubic yards of sand (8,155 according to Wiegel 2008) dredged and pumped to the beach; grading completed.	10,000	Waikiki	Not included in sediment budgets described below, to match most recent (2005) aerial photography
	Total volume, estimated (cubic yards)	**223,000**	**Waikiki**	
		30,000	**Ala Moana**	

Source: Wiegel 2002, 2008.

This sand placement is used as an additional source of sediment. It is noticeable that the rate of sand placement decreased dramatically after the placement of 30,000 cubic yards of sand at Ala Moana Beach Park in 1976. The sediment budget for the Waikiki and Ala Moana cells is divided into two periods – before and after the mid-1980s – to highlight the effects of this. (The budgets do not include the 2006 placement at Kuhio Beach: the most recent aerial photomosaic was in 2005, so for consistency the sediment budget analysis ended at this time).

F. Reef Production

The calcareous sand on Hawaiian beaches, in upland areas, and stored on reef tops or lost to deep water, is believed to result from reef production – either modern or paleoproduction. If modern production of calcareous sediment is a significant part of the sediment budget, this adds one more reason to protect and enhance Hawai'i's beach resources. However, the relative rates of modern and paleoproduction are not well known.

A relatively well-studied case is Kailua Bay on the windward side of O'ahu. Harney and Fletcher 2003 estimate sediment production to the littoral system at 0.53 (± 0.13) kg of carbonate sediment per square meter per year. This is divided into two main contributions:

- Frame erosion – that is, mechanical and biological breakage of the reef framework, which is produced by coral and encrusting coralline algae.
- Direct sediment production by the green alga *Halimeda*, branching coralline algae, mollusks, and benthic foraminifera.

Assuming an average carbonate grain density of 2,400 kg per cubic meter (Smith and Cheung 2002) and a porosity of 40 percent, this converts to a sediment production of 0.00037 (± 0.00013) cubic meters per square meter of reef per year, or 1.9 (± 0.7) cubic yards per acre per year. This is low compared to typical reef productivity, particularly in protected, leeward settings.

The reefs off O'ahu have been present for about 5,000 years, when the areas they now occupy were flooded. It appears that reef sediment productivity has decreased over the past few thousand years, due to increases in wave energy (Rooney *et al.* 2004). This is supported by observations that much of the sediment in Kailua Bay is relatively old – eleven out of 20 calibrated radiocarbon dates on skeletal constituents of sand were more than 1,000 years old. The older grains in this study were generally finer, supporting the notion that there is sand loss due to abrasion and possibly dissolution (Harney *et al.* 2000). An attempt to develop a long-term sediment budget – over the past 5,000 years – for this bay led to the conclusion that approximately 50% of the material has been lost offshore into deep water.

Studies of this type provide little firm information as to how reef inputs might contribute to the modern sediment budget in the D2P study area. First, the wave exposure of the study area – which is exposed to Kona storms but not to trade winds, in contradistinction to Kailua Bay – and the relative shallowness of the reef affects its biological structure and productivity. It is likely that reef productivity is lower on the south shore of O'ahu compared to the windward side (Fletcher, personal communication, 2009). The reef offshore of Waikiki likely has a particularly low productivity, because of the large amount of sand on the reef and historically poor water quality – due to natural causes (mud and debris delivered from stream mouths) as well as human activities.

Second, also because of differences in the wave exposure and the physical reef structure, it is likely that a different fraction of any sediment produced will reach the beach system compared to windward sites.

This preliminary sediment budget uses an approximate estimate of reef productivity, in order to highlight the potential importance of this contribution to the overall budget. For the Waikiki and Ala Moana cells, it is assumed that there the net productivity is insignificant because of the degraded nature of the reef. For other cells, the following assumptions are made.

- The reef productivity is taken to be 0.6 cubic yards of sediment per acre per year – one-half of the low end productivity estimated for Kailua Bay.
- Only the reef area above -25 feet MLLW is taken to contribute sediment to the beach system. There is a rapid drop-off in the reef top from about -25 to about -50 feet MLLW, and it is assumed that sediment produced in deeper waters is lost offshore.
- Finally, it is assumed that one-half of the sediment produced on the shallow part of the reef is available to the beach and one-half is lost offshore.

This gives net sediment productivity to the beach system between 100 cubic yards annually (the Diamond Head cell) up to 700 cubic yards annually (the Iroquois Point cell). These are nominal values, and are very low compared to the production rates that have been estimated elsewhere. However, as will be seen in Section IV, these nominal values of reef productivity are not insignificant compared to the overall volumes of sediment being transported in the system. It is important to determine whether modern reef productivity is, in fact, a significant contributor to the sediment budget in the study area.

G. Sand Loss Mechanisms

The preliminary sediment budget presented here assumes that any loss of sand is offshore; into the Pearl Harbor channel; into the dredged areas at the Diamond Head end of the Honolulu Reef Runway; or into Keehi Lagoon. The locations referred to here are illustrated in Figure 2 and Figure 28. In this preliminary sediment budget, these losses are used to balance the budget – they are not estimated independently. Additional modeling and analysis work would be valuable to confirm these general rates.

Sand loss mechanisms that are considered small, and therefore not included explicitly in the sediment budget, are as follows.

- **Sea level rise**. This is not strictly a sand loss mechanism. However, it must be considered in a sediment budget analysis, because the shoreline will retreat as the sea level rises unless additional sand is available to build the beach up.

  The nearshore profile for Hawaiian beaches is often stated to have a typical slope of 1 percent (e.g., Fletcher *et al.* 2008). This means that a sea level rise of 1 inch would cause the shoreline to retreat by 100 inches, or about 8 feet. However, this is not typical of the shorelines in the study area. These shorelines have a rather steep active profile – between 5 and 10 percent slope. Therefore, a sea level rise of 1 inch would cause the shoreline to retreat by, at most, 20 inches or less than 2 feet. Sea level rise in the study area is approximately 0.06 inches per year (NOAA 2009b), which corresponds to a horizontal retreat rate of up to 1.2 inches or 0.1 feet per year. This is very small compared with the typical rates of shoreline retreat in the study area. Therefore, the effects of sea level rise upon the near-term sediment budget are very small.

- **Beachrock**. Beachrock is formed by cementation of beach sand in the intertidal zone. Beachrock can consist of sand or gravel cemented by calcium carbonate – which in turn is formed from, and impounds, calcareous sediments. Relatively little beachrock is found in the study area. Furthermore, any beachrock would remain on the beach – and would not be removed from the beach volume. Therefore, its formation is not believed to be a significant component in coastal erosion in that area, and it may actually help to stabilize the beach in certain instances.
- **Abrasion and dissolution of calcareous sand grains**. This is believed to be important for calcareous beaches over the long-term (millennial scale). However, it has not been adequately quantified for use in a short-term sediment budget. Any uncertainties in this loss mechanism can be incorporated into the uncertainties in reef sediment production.
- **Sand mining** is an obvious mechanism for beach erosion. In the early 1900s, large quantities of sand were removed from Waikiki Beach. Large-scale sand mining is now prohibited: the few exceptions include clearing sand from stream mouths.

H. Climate Change

Over the longer term – possibly over a timescale as short as 50 years – the sediment budget could be affected by climate change. There are a number of contributing factors:

- The potential for increased sea level rise, possibly as much as 4 to 5 feet over the next century;
- The potential for changes in the wave climate;
- The potential for degradation to the reef structure (e.g., bleaching);
- The potential for increased dissolution of calcareous grains as the seas acidify.

These potential changes are not incorporated into the preliminary sediment budget given here, which describes the littoral system as in a steady state apart from changes in the rate of beach nourishment. The potential for these effects to change the sediment budget presented here should be addressed as this RSM Plan progresses and the science presents quantifiable changes.

IV. Littoral Cells

A. Overview

For this study, the Diamond Head to Pearl Harbor Region has been separated in to six littoral cells:

1. Diamond Head
2. Waikiki
3. Ala Moana
4. Sand Island
5. Reef Runway
6. Iroquois Point

These are shown in Figure 10.

This section goes through each littoral cell in turn. A general description of the cell is followed by an analysis of its sediment budget.

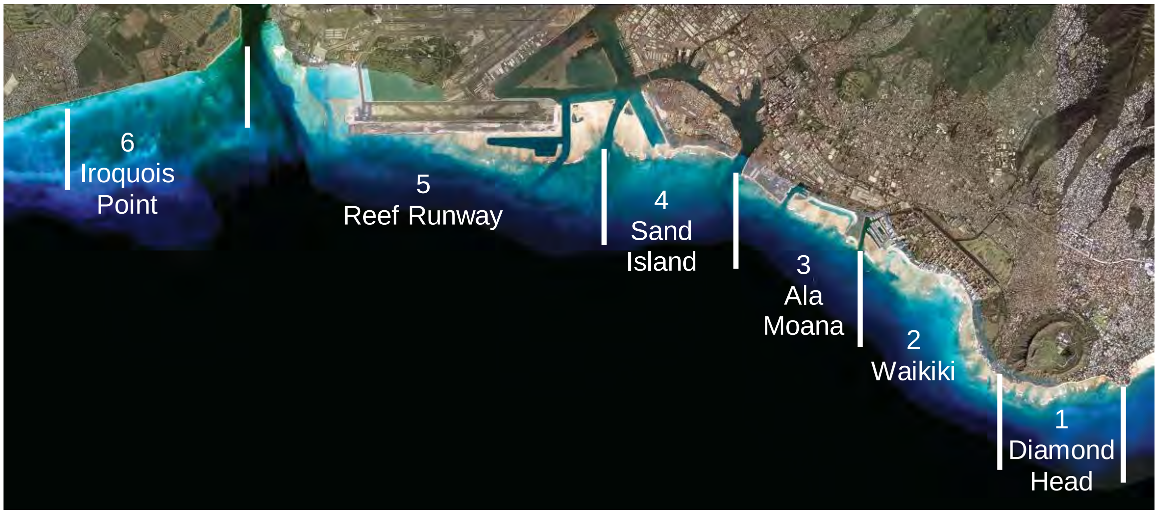


Figure 10. D2P Littoral Cells

B. Diamond Head Cell

The Diamond Head littoral cell consists of the region from Black Point to Coconut Avenue (where a rocky outcrop forms a partial barrier to littoral transport). The Diamond Head Crater and the fringing reef offshore of this region are clearly visible in Figure 11. Relief in this area is generally steep, with the beaches only accessible by footpath.

The shoreline in this area has been modified relatively little, with no recorded beach nourishment. Figure 12 shows how the beach volume within the Diamond Head cell has varied since 1958, based on aerial photography and beach profiles as described in Section III.D. A linear fit to the beach volume is also shown. This linear fit was developed using a weighted least squares approach similar to that used in the development of the Coastal Erosion Maps for the area (Hawai‘i Coastal Geology Group 2009). This linear fit corresponds to a loss of sediment from the beach of 400 cubic yards per year.

Reef production in the littoral cell is estimated at 100 cubic yards per year, based on the approach described in Section III.F. As described in that section, this is a very preliminary value.

Based on the current modeling results shown in Figure 6, Black Point appears to block sediment transport completely. A rip current transports sediment offshore at this end. However, sediment may be transported towards the Waikiki cell.

Figure 13 presents a preliminary sediment budget for the Diamond Head littoral cell, based on these considerations.

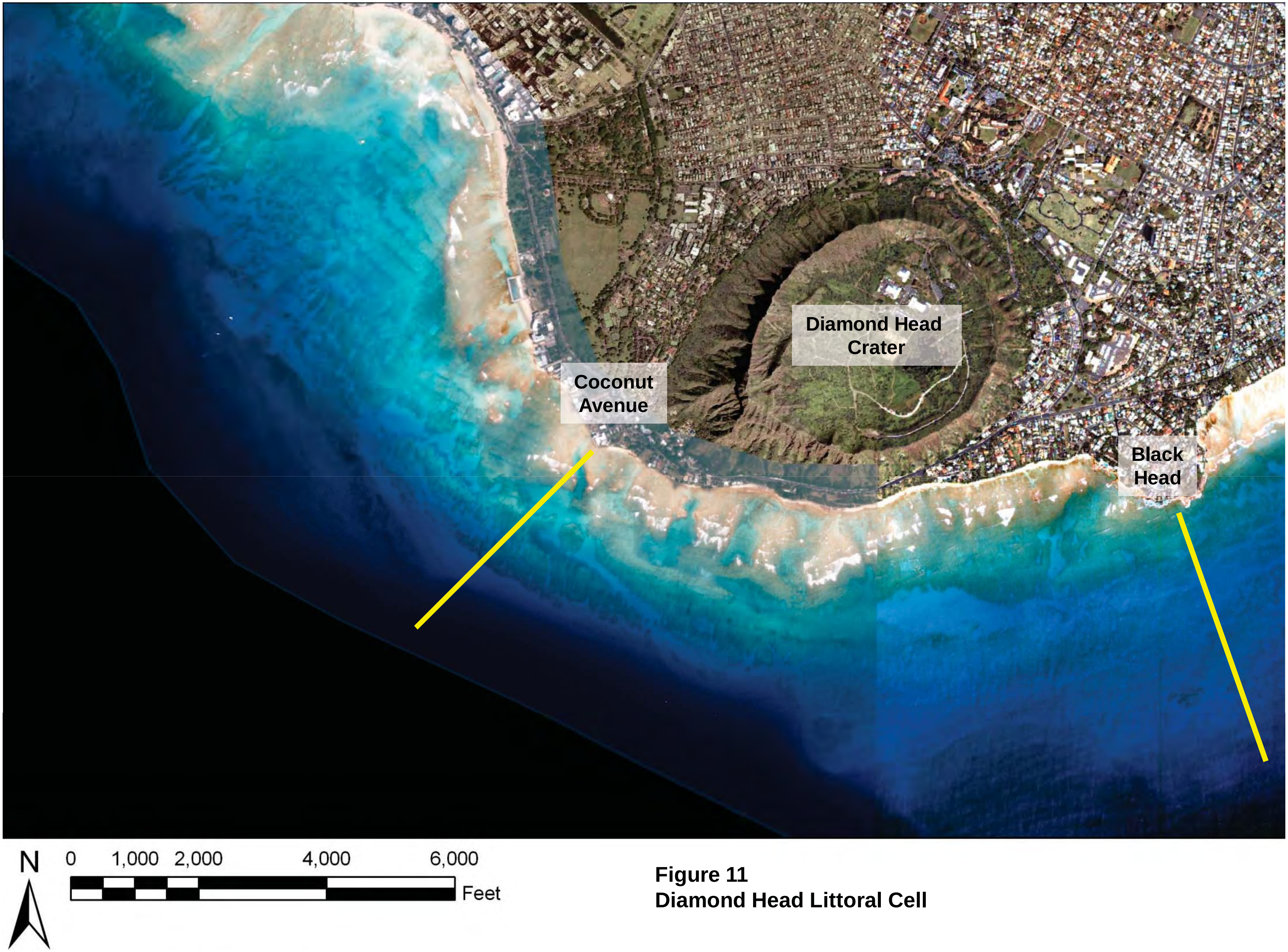


Figure 11
Diamond Head Littoral Cell

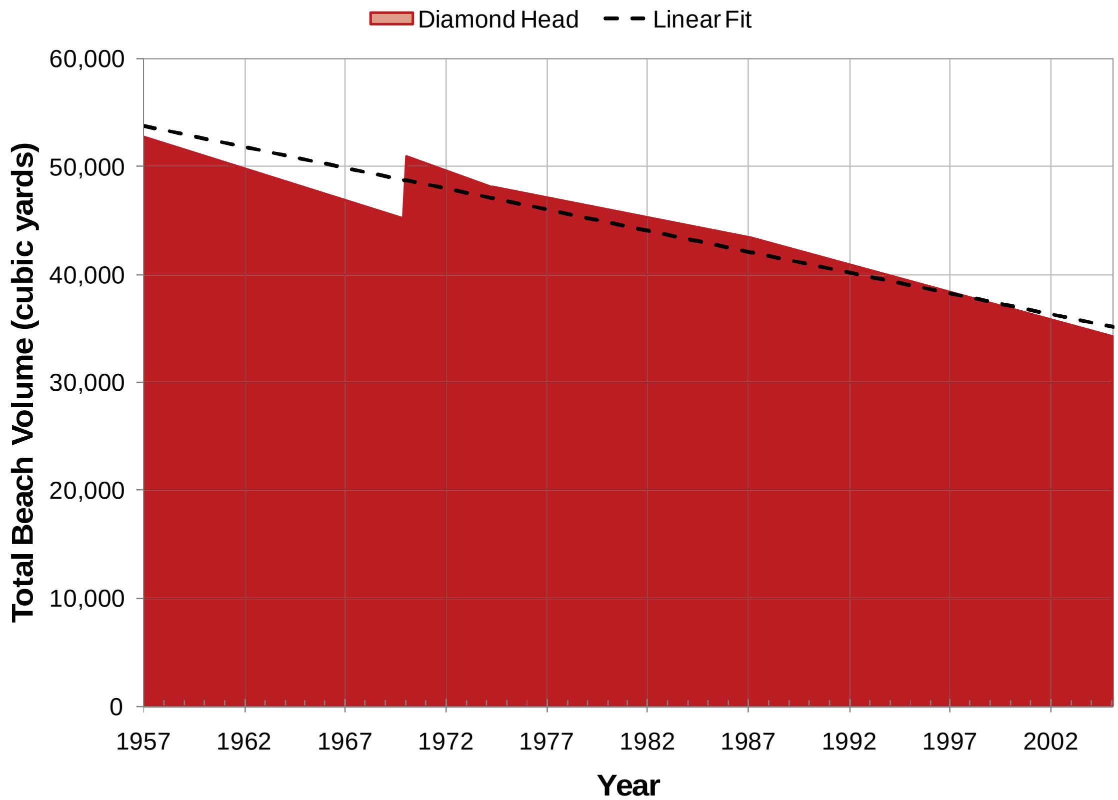


Figure 12. Beach Volumes at Diamond Head

C. Waikiki Cell

Waikiki Beach is a densely engineered littoral cell, with a variety of coastal structures, dredged and natural channels, and other structures. An overview of the littoral cell, including common names for beaches within Waikiki, is shown in Figure 14. The western limit of this cell is the entrance channel to the Ala Wai Yacht Harbor.

Figure 15 through Figure 19 illustrate some of the structures on this beach.

To highlight some of the behavior of this littoral cell, Figure 20 shows the beach volumes in four littoral subcells:

- Sans Souci Beach, south of the Natatorium;
- Queen’s Beach, which has a distinctive pattern of accretion and erosion;
- The central part of Waikiki, including Kapiolani Park Beach, Kuhio Beach, and the Royal Hawaiian Beach;
- The heavily nourished area of Halekulani Beach and Fort DeRussy Beach.

The time frame illustrated here is from 1968 to 2005. Magic Island, immediately ‘Ewa of the Ala Wai Yacht Harbor, was constructed in the early 1960s, so littoral processes might have been quite different at that time.

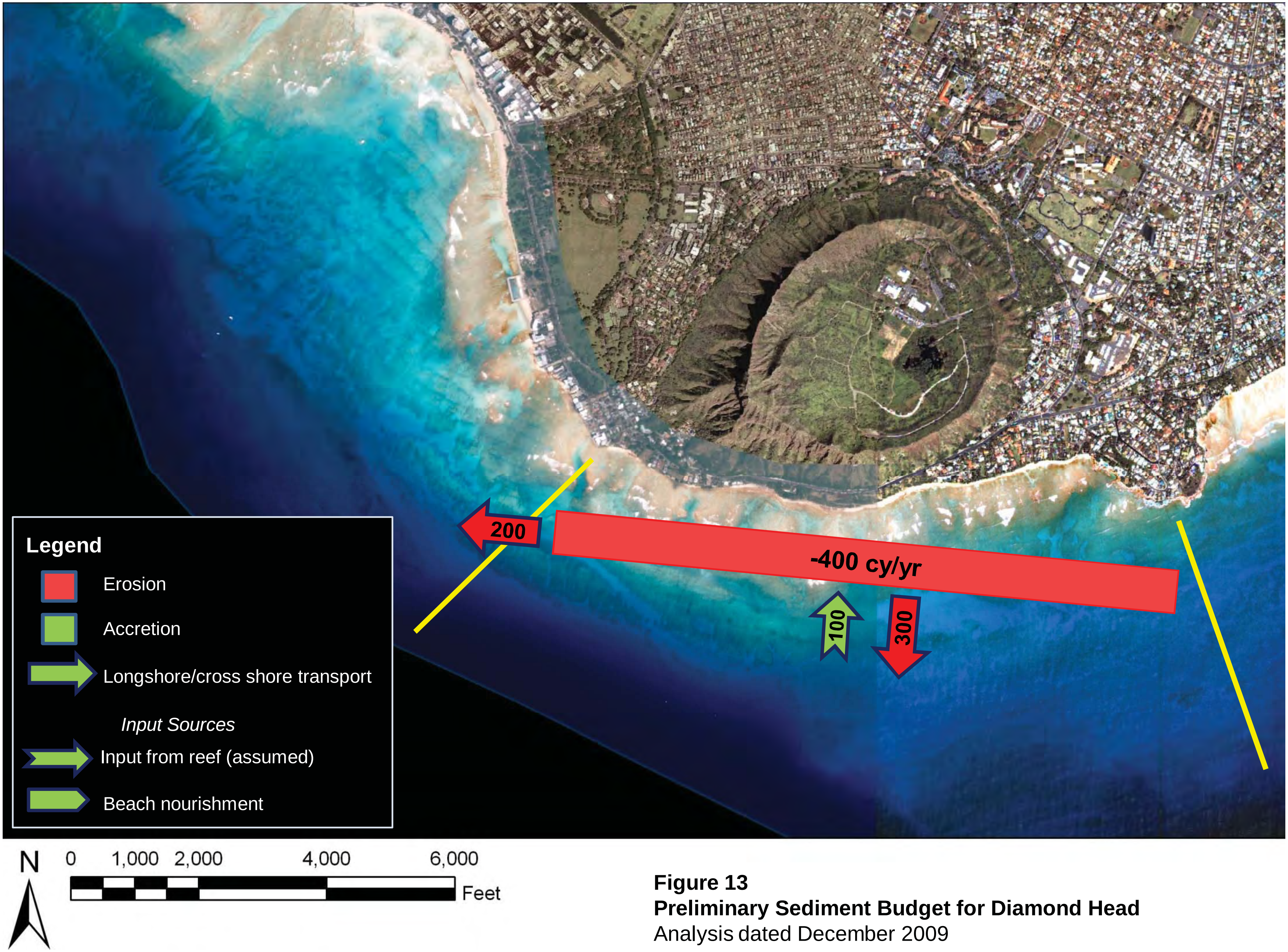


Figure 13
Preliminary Sediment Budget for Diamond Head
Analysis dated December 2009

The total quantity of sand in the littoral cell generally increased from 1968 until the mid-1980s, and then decreased more gradually. The broken line, labeled as “Linear Fit plus Nourishment”, is the best fit based on the assumption that the quantity of sand in the littoral cell decreases at a constant rate (similar to the linear fit shown for the Diamond Head cell), except that nourishment volumes are directly added to the total quantity of sand. The time frame shown here is until 2005 (the last available aerial photograph). Therefore, the 2006 nourishment of Kuhio Beach, which added nearly 10,000 cubic yards of sand, is not included here.

The “Linear Fit plus Nourishment” line increases more rapidly than the estimated volume based on aerial photography, but it also begins to decline sooner. This suggests that it takes two or three years for the beach to return to a natural profile after nourishment. For example, if the nourished beach had a higher crest elevation than a natural profile, it would have a relatively narrow width, but a higher volume per unit area of beach – so the photographic analysis would underestimate its volume.

The maximum sand volume shown in this figure was in late 1982, shortly after Hurricane Iwa arrived. This hurricane was observed to bring sand onshore. Without contradicting this assessment, Figure 20 suggests that some of the sand in question may have resulted from the then-recent beach nourishment events, and that the hurricane completed the natural process by which the beach profile readjusted to its natural state. Essentially, the hurricane appears to have liberated sand that had previously been stored in inactive areas at the top of the profile and placed it in to the active profile. Subsequent declines in beach volume result from the loss of sand offshore that was already occurring, but that had been masked by the beach nourishment. This analysis raises the question as to whether the sediment budget should explicitly consider nearshore sand storage, either as part of the beach system or as a separate reservoir.

Based on this linear fit, the loss of sand from the beaches in the absence of beach nourishment averages 4,000 cubic yards per year. Given that the rate of beach nourishment changed dramatically – to almost nothing between 1985 and 2005 – during the study period, the sediment budget is divided into two periods. In the first period, from 1965 to 1985, the beaches were nourished at a rate of approximately 10,000 cubic yards per year, and accreted at approximately 6,000 cubic yards per year. Between 1985 and 2005, when there was almost no nourishment, the beaches have eroded at an average 4,000 cubic yards per year.

As previously described, it is assumed the reef off Waikiki is sufficiently degraded that it produces an insignificant quantity of calcareous sediment. A small quantity of sand (200 cubic yards per year) is assumed to enter the system from the Diamond Head cell.

The Waikiki area experiences rip currents (Figure 6), which are assumed to transport the remaining sediment offshore. There is little dredging in the Ala Wai Yacht Harbor, so it is assumed that this is not a significant sink of sediment. (Large quantities of terrigenous sediments are dredged from the Ala Wai Canal, but this is not relevant to the beach sediment budget being constructed here).

Based on these considerations, Figure 21 presents a preliminary sediment budget for the Waikiki cell. This preliminary sediment budget does not attempt to quantify transport between subcells, which appears to be rather small based on fact that the beach widths for the different subcells do not generally change in unison. Two figures are shown, representing the periods 1965 to 1985 (in which a relatively large quantity of sand was placed on the beach) and 1985 to 2005 (in which very little beach nourishment occurred).

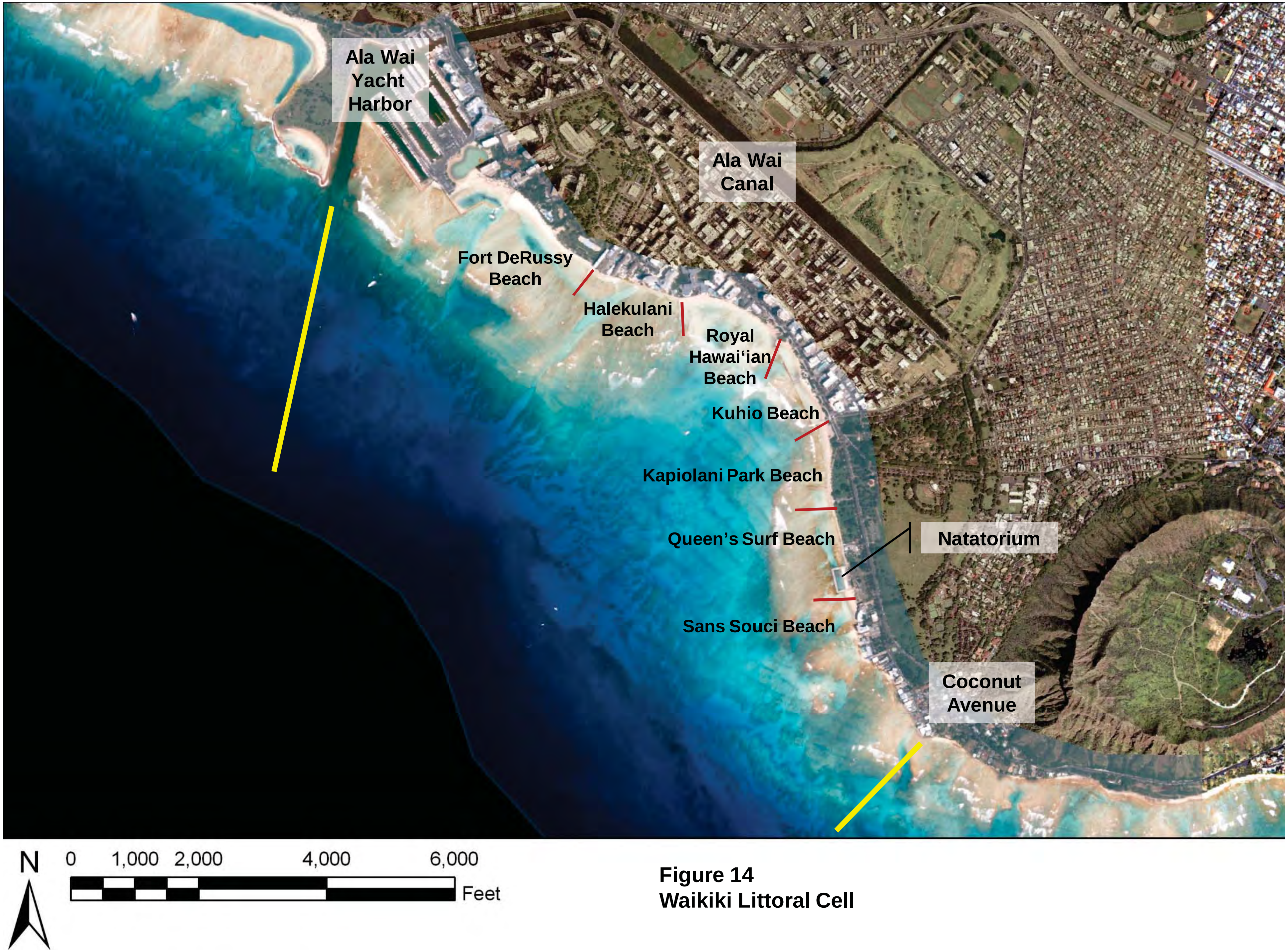


Figure 14
Waikiki Littoral Cell

Figure 15. West (‘Ewa) side of Natatorium structure.

Figure 16. View along shore fronting Kapiolani Beach Park north of the Natatorium, looking toward ‘Ewa.

Figure 17. Shore-parallel breakwater at Kuhio Beach, looking toward Diamond Head

Figure 18. Groin structures located on the Royal Hawaiian Beach

Figure 19. Concrete Seawall at the west ('Ewa) end of the Royal Hawaiian Beach

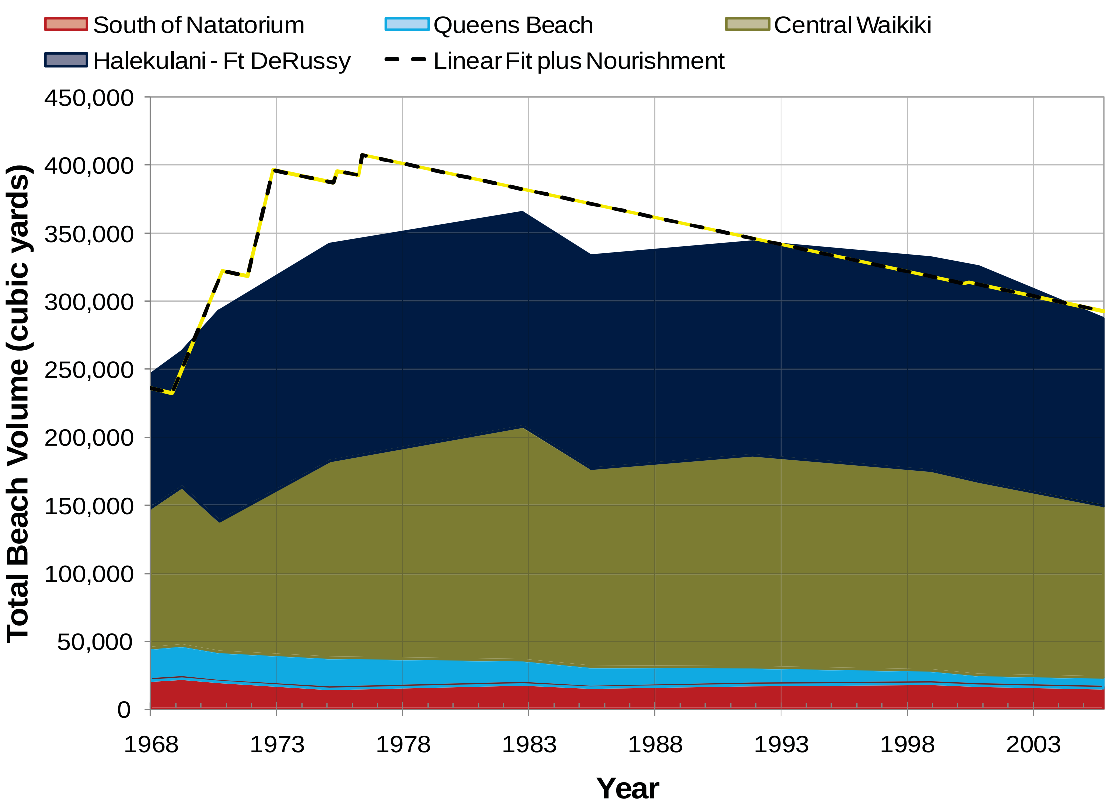


Figure 20. Beach Volumes at Waikiki

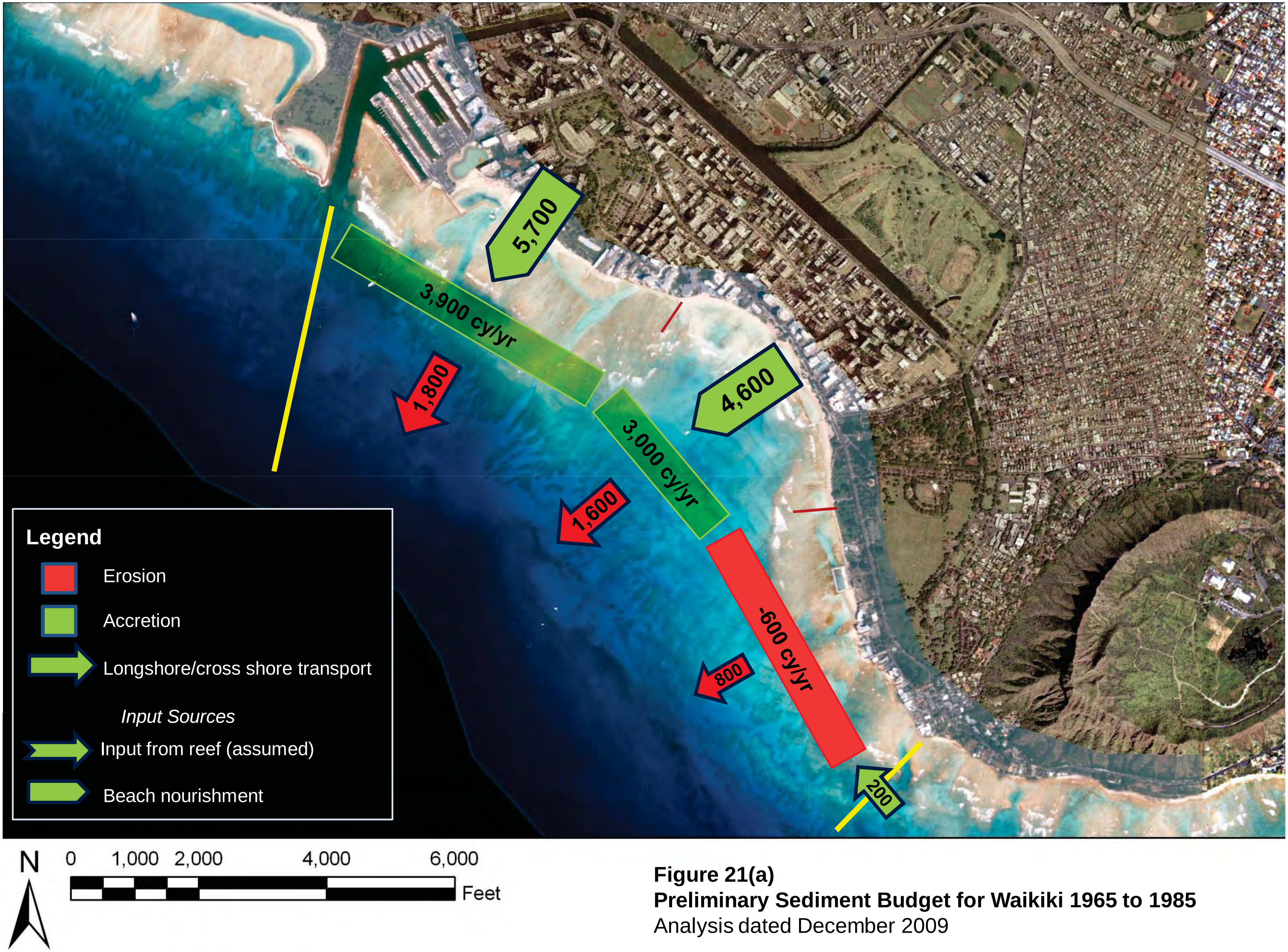


Figure 21(a)
Preliminary Sediment Budget for Waikiki 1965 to 1985
Analysis dated December 2009

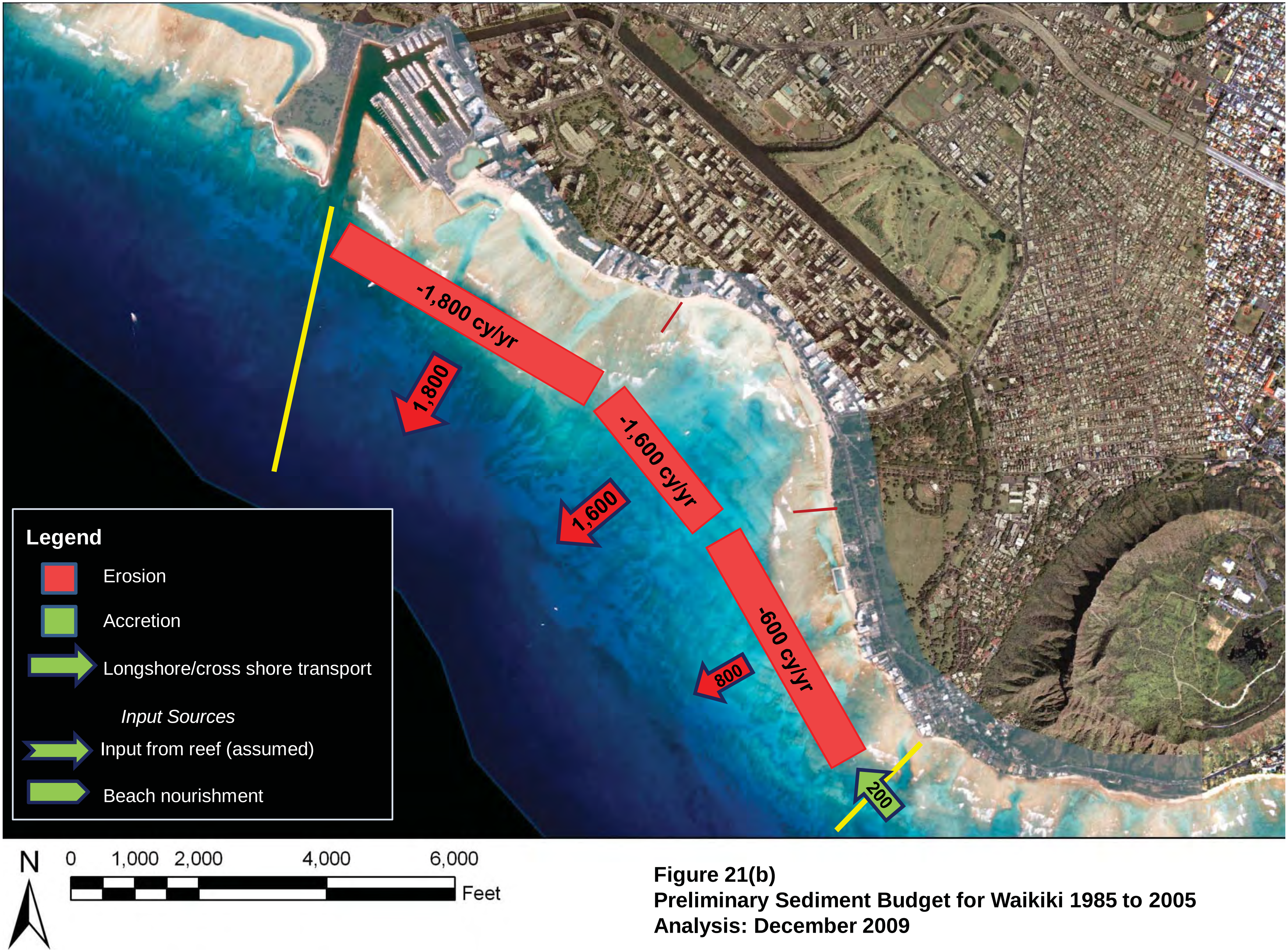


Figure 21(b)
Preliminary Sediment Budget for Waikiki 1985 to 2005
Analysis: December 2009

D. Ala Moana Cell

The Ala Moana Littoral Cell, shown in Figure 22, is delimited by the entrance to the Ala Wai Yacht Harbor on the Diamond Head side and the Honolulu Entrance to Honolulu Harbor on the ‘Ewa side.

The Ala Wai Yacht Harbor and Kewalo Basin are man-made harbors located on each end of Ala Moana Park. The Honolulu Channel has been dredged through the fringing reef to provide one of the entrances to Honolulu Harbor. Magic Island (actually a peninsula) is an artificially filled area, with a constructed beach protected by detached breakwaters.

The Ala Moana cell has similarities to Waikiki, in that it is a heavily modified cell with an artificially enhanced beach. One significant beach nourishment, 30,000 cubic yards at Ala Moana Beach Park in 1972, has occurred here since Magic Island was constructed in the early 1960s (Table 2).

Figure 23 shows how the beach volume at Ala Moana has varied over time. The beach at Magic Island has remained stable for 35 years, indicating the success of the detached breakwaters in protecting this pocket beach. In contrast, Ala Moana Beach Park has consistently lost sand. This loss could be offshore to deep water, or it could be to the dredged channel (once a navigation channel) directly offshore of the beach. The loss of sand from Ala Moana Beach has averaged 1,000 cubic yards annually.

As described previously, it is assumed that reef inputs of sediment to the system are insignificant for this cell. Additionally, the fact that little dredging has occurred in the Ala Wai Yacht Harbor or the Kewalo Basin suggests that these are not significant sinks of sediment. The modeling of wave-driven currents (Figure 6) and the admixture of terrigenous sediments in the Honolulu Channel (Marine Advisers Inc. 1968), both suggest that the navigation channels in the area do not act as sinks for the Ala Moana cell. This leads to the conclusion that the loss of sand is either offshore or into the dredged area offshore of the beach.

Figure 24(a) and (b) present a preliminary sediment budget for the Ala Moana cell based on these considerations. As with Waikiki, the sediment budget is divided into two periods (1965 to 1985, and 1985 to 2005) to represent changes in the intensity of beach nourishment activities.

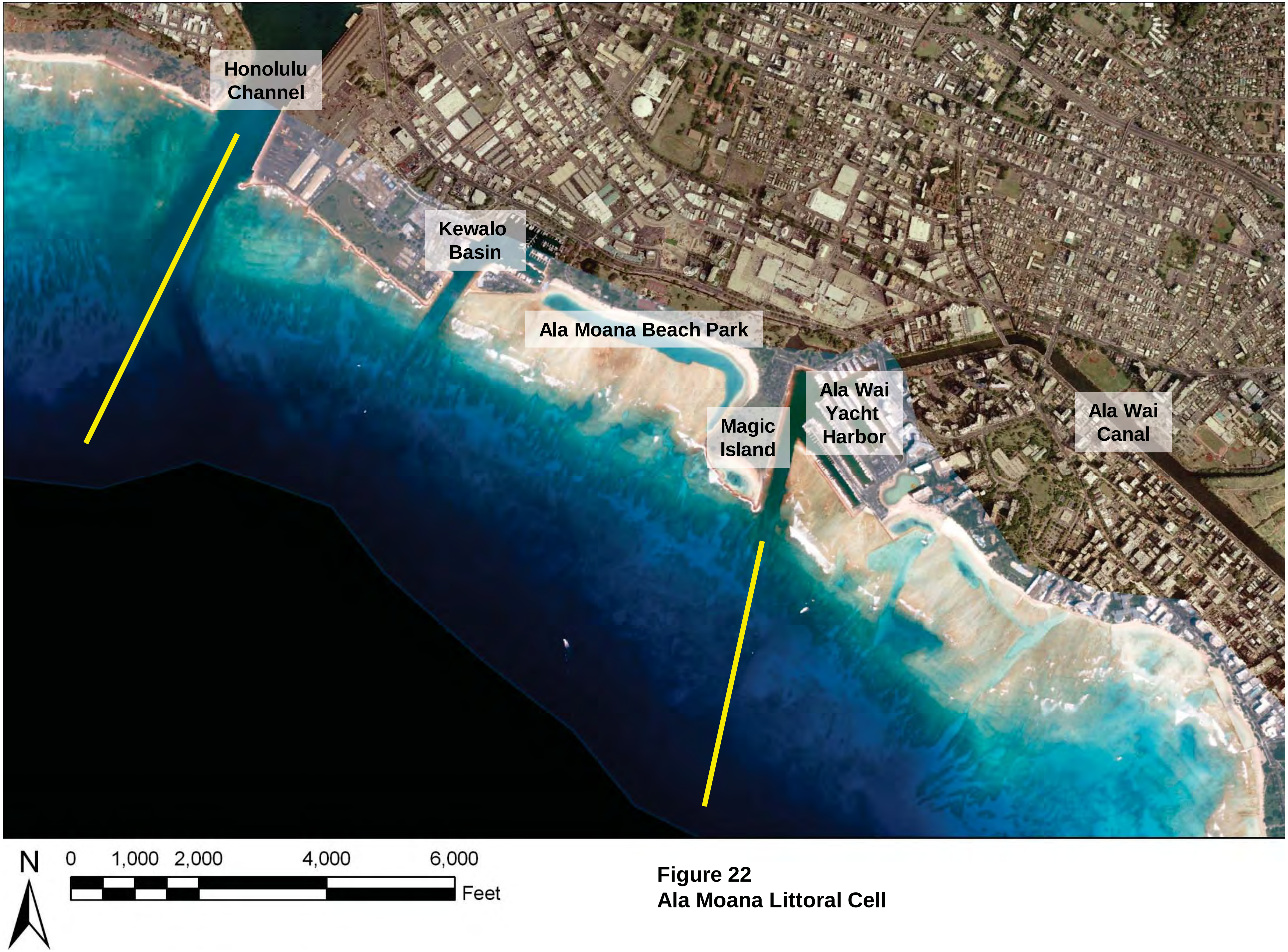


Figure 22
Ala Moana Littoral Cell

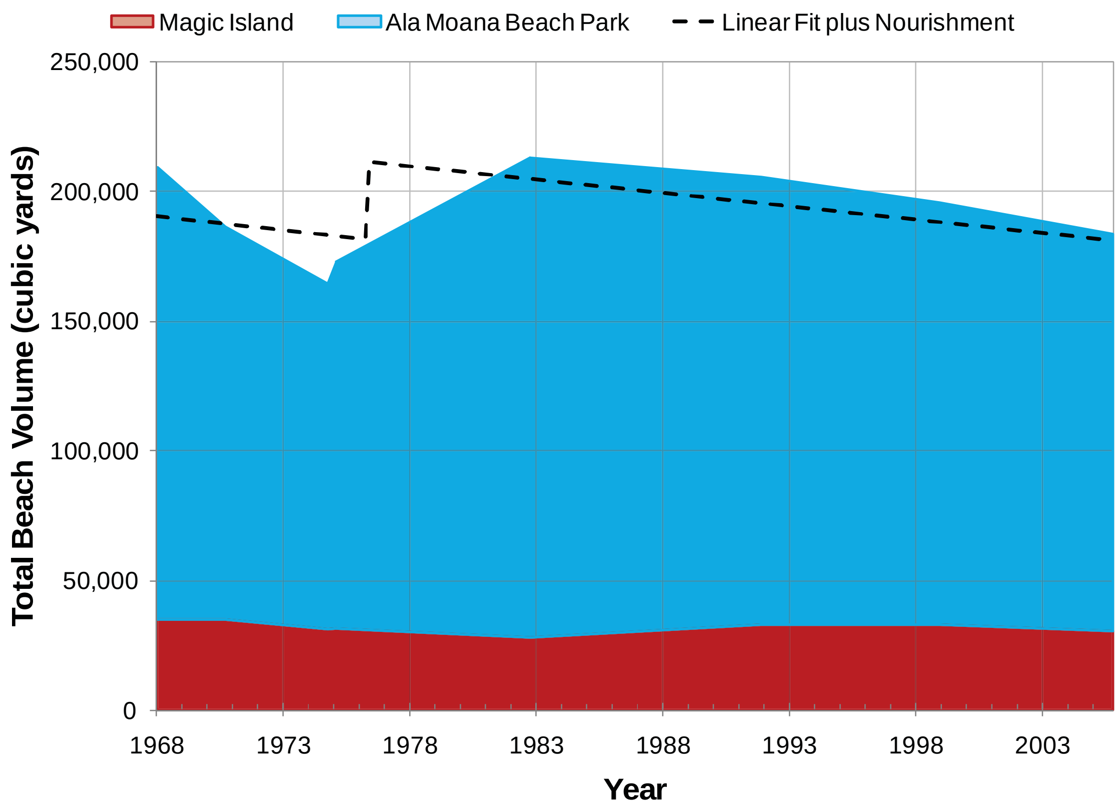


Figure 23. Beach Volumes at Ala Moana

E. Sand Island Cell

The Sand Island littoral cell is delimited by the Honolulu Channel of Honolulu Harbor on its Diamond Head side and the Kalihi Channel on the ‘Ewa side (Figure 25). These are two deep draft navigation channels. The shallower dredged channel immediately ‘Ewa of Sand Island was originally constructed as a seaplane lane.

Sand Island is an artificially filled island. The southern shore of this island has 2,000 feet of revetment and a pocket beach protected by three detached breakwaters on the Diamond Head side. Towards the ‘Ewa side of the south shore is a natural beach.

The erosion mapping only contains information on the ‘Ewa side beach – not enough aerial photographs are available to analyze the pocket beach towards the Diamond Head end of the south shore. However, based on the stability of the pocket beach at Magic Island, it seems reasonable to suppose this beach also would be stable.

Figure 26 shows that the beach volumes at Sand Island are gradually decreasing over time. The loss rate corresponds to 200 cubic yards annually.

Based on the approach described in Section III.F, reef sediment production in this cell is also estimated at 200 cubic yards annually.

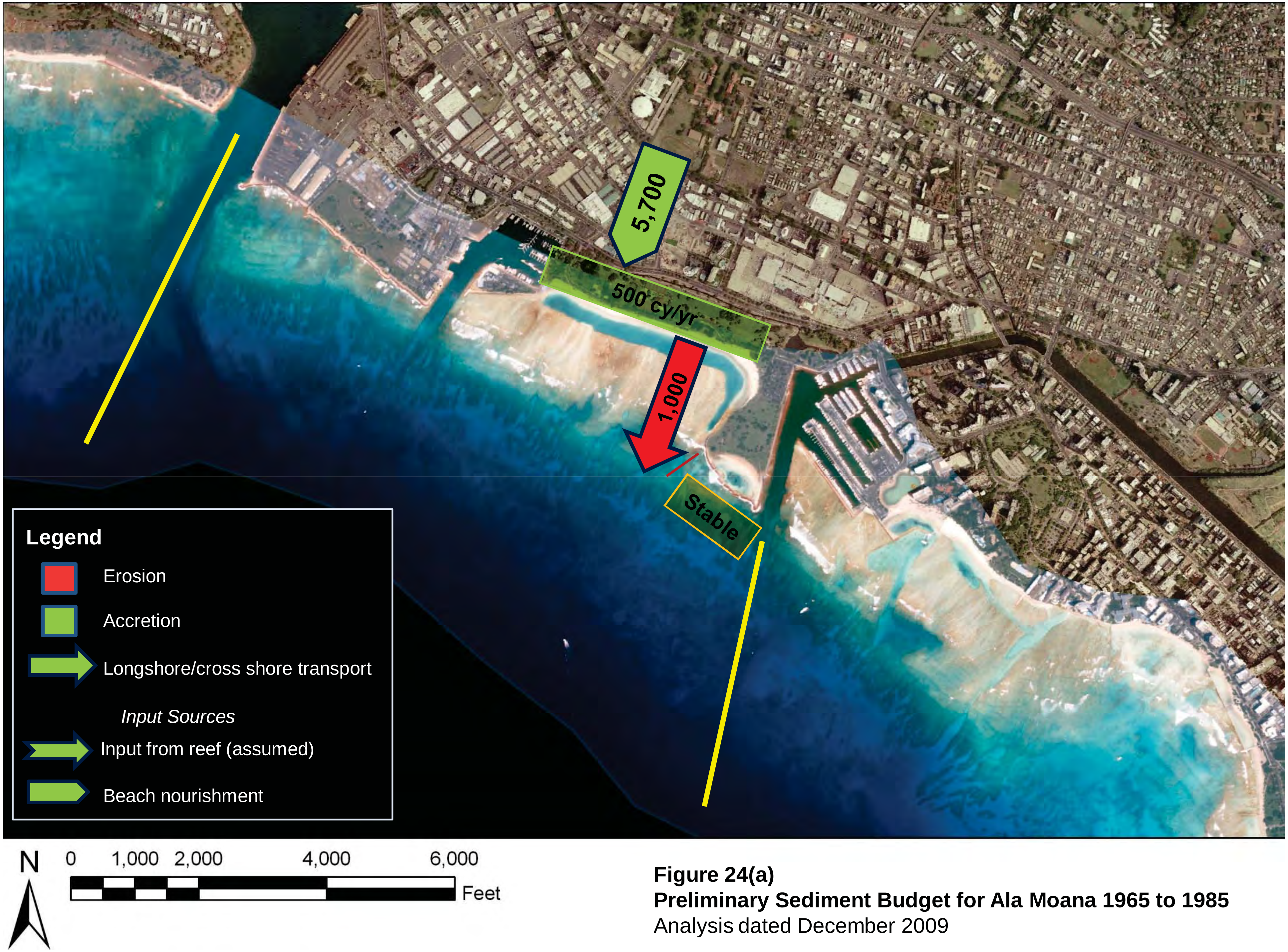


Figure 24(a)
Preliminary Sediment Budget for Ala Moana 1965 to 1985
Analysis dated December 2009

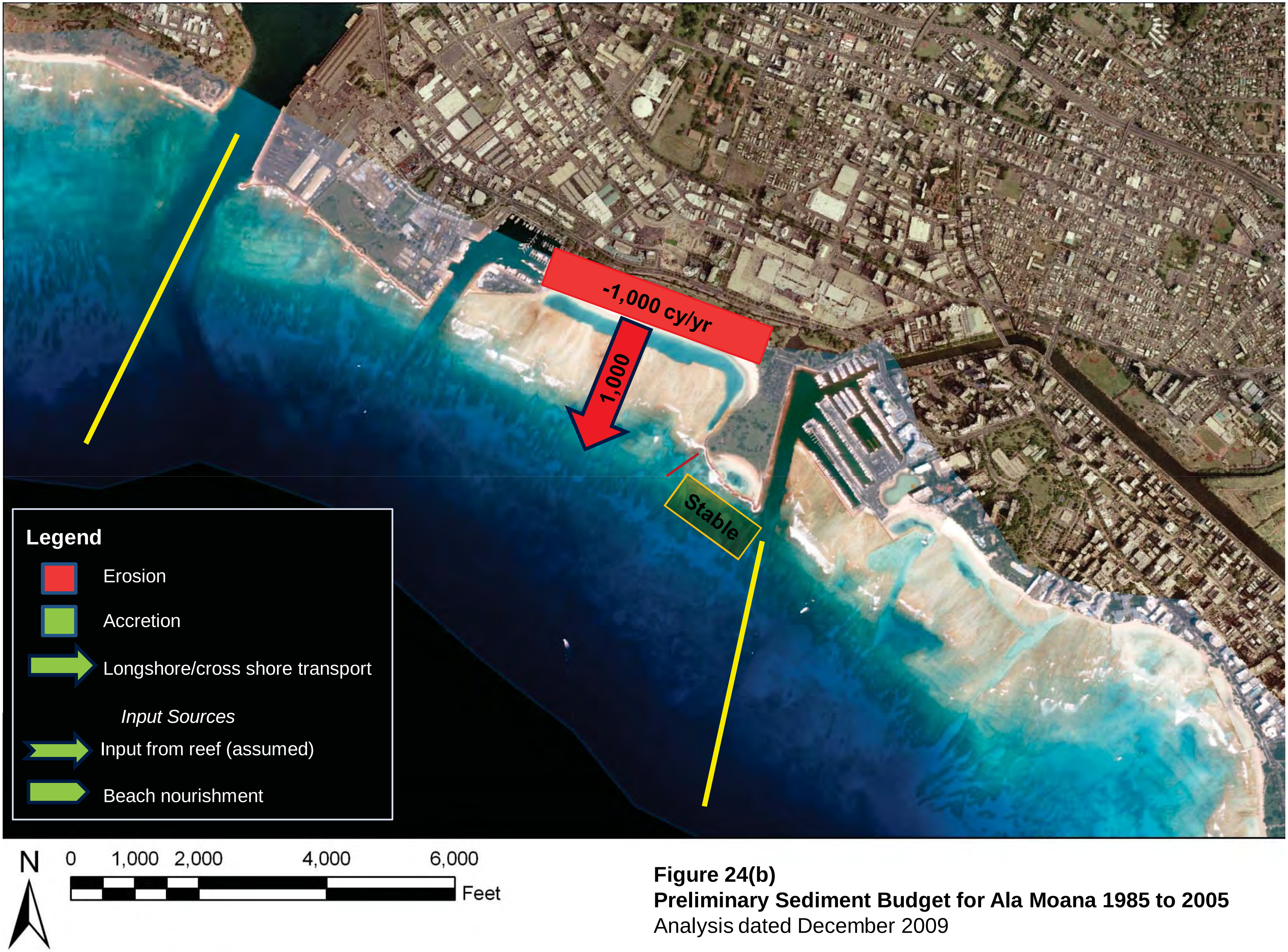


Figure 24(b)
Preliminary Sediment Budget for Ala Moana 1985 to 2005
Analysis dated December 2009

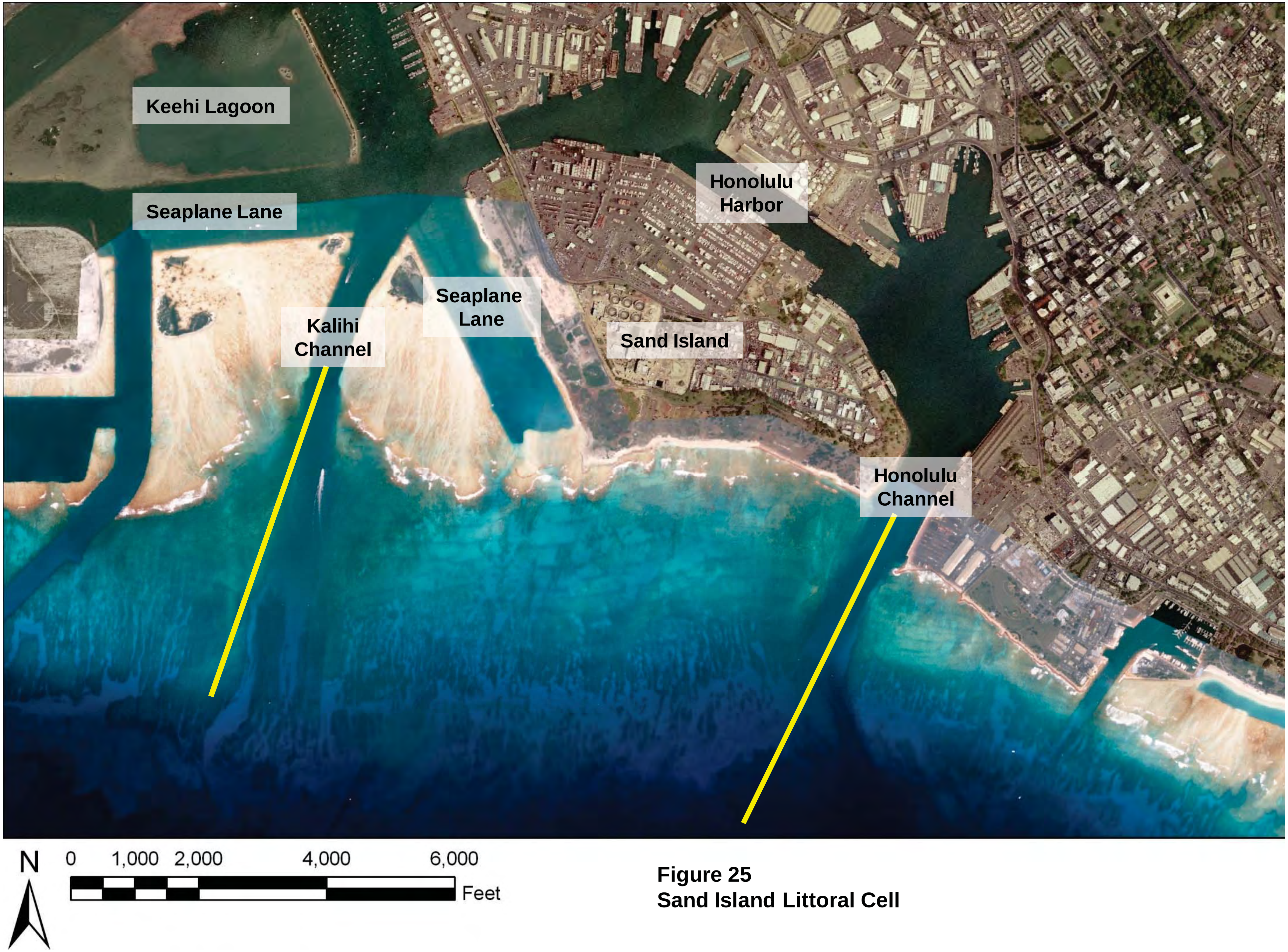


Figure 25
Sand Island Littoral Cell

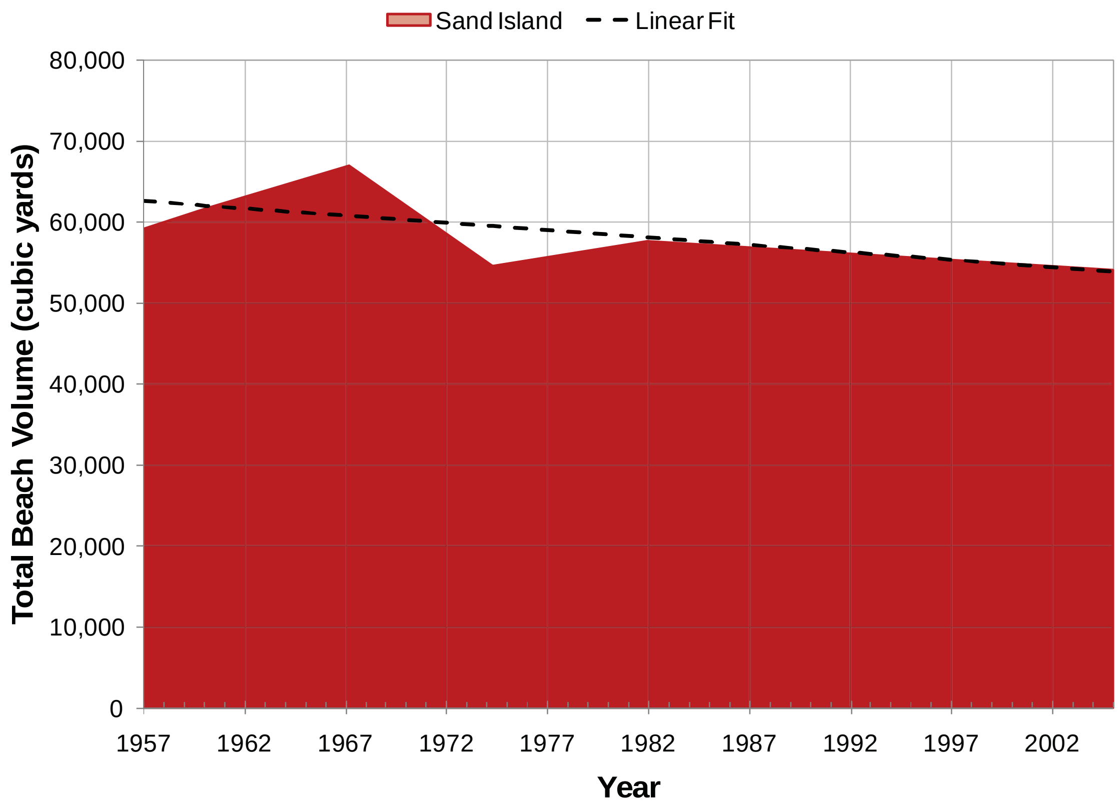


Figure 26. Beach Volumes at Sand Island

These two estimates lead to the conclusion that 400 cubic yards of sediment annually is released into the Sand Island littoral cell. This is a relatively small quantity. As with the Ala Moana cell, it is unlikely that any sediment is transported into the Honolulu Channel. The 400 cubic yards of sediment loss that balances the budget could be transported into Honolulu Harbor via the Kalihi Channel or into the seaplane lane immediately ‘Ewa of Sand Island – it is possible that beach quality sand could be found in the harbor as a result. The sand could also be transported offshore. Figure 27 illustrates this preliminary budget.

F. Reef Runway Cell

The Reef Runway cell is delimited by Kalihi Channel on its Diamond Head side, and the Pearl Harbor entrance channel on the ‘Ewa side.

Figure 28 illustrates this littoral cell (note the scale on this figure is smaller than for the other littoral cells). The Reef Runway Cell is another heavily modified area. The Honolulu Reef Runway is an artificially filled peninsula. The area of reef immediately southeast of the runway was dredged to provide construction access. The seaward shore of the runway is protected by 6-ton concrete armor units (dolosse).

Much of the remaining shoreline is protected by seawalls or by engineered or rubblemound revetment. The exception to this is a small area of sandy beach and sand bar on the ‘Ewa side of Hickam Harbor, at the entrance to Pearl Harbor. This appears to be a receiver location for sand brought in from offshore, although the quantity appears to be small. The beach is shown in Figure 29 and Figure 30.

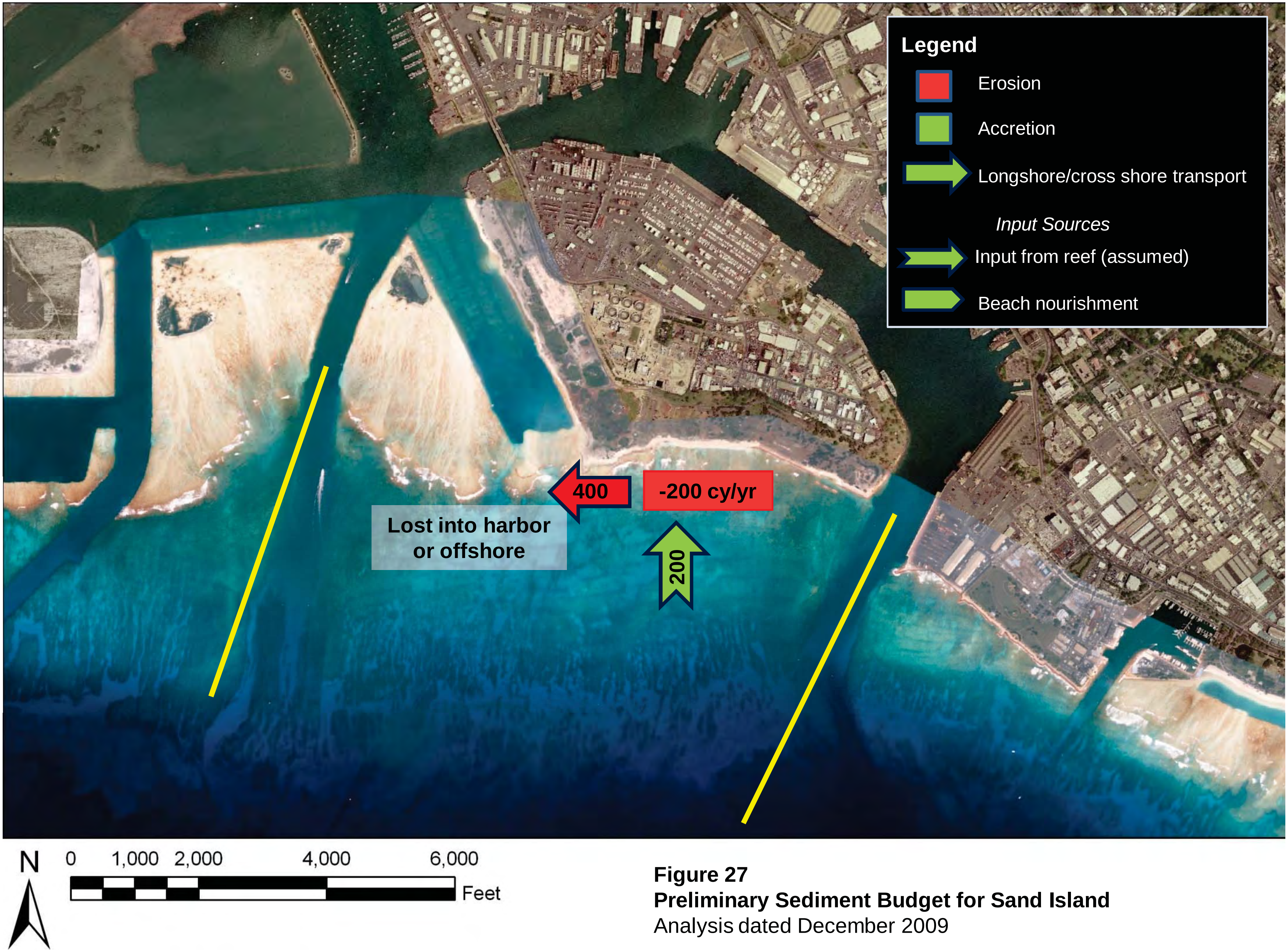


Figure 27
Preliminary Sediment Budget for Sand Island
Analysis dated December 2009

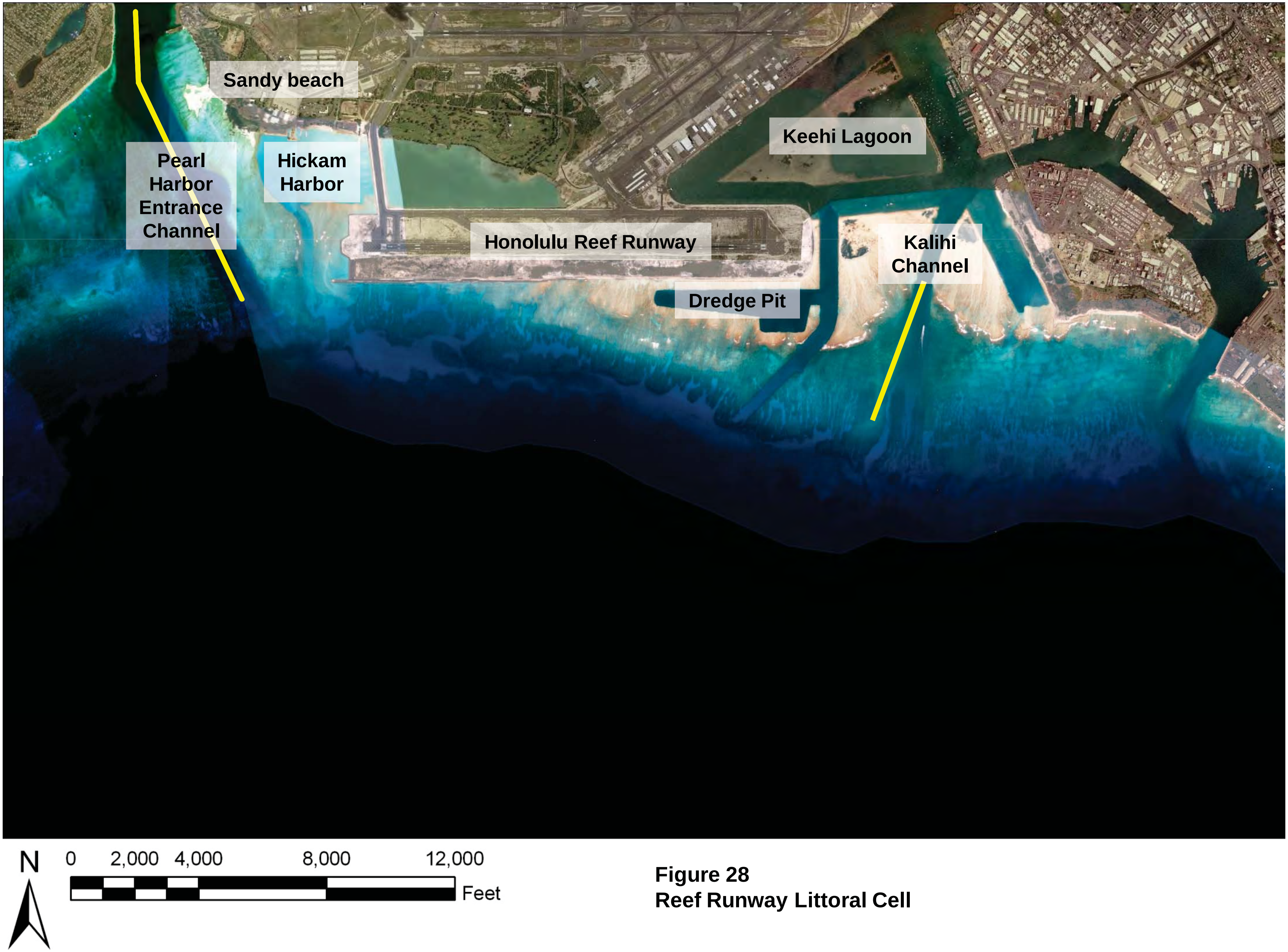


Figure 28
Reef Runway Littoral Cell

Figure 29. Sandy Beach at the Entrance to Pearl Harbor

Figure 30. Sand Bar at the Entrance to Pearl Harbor

With the exception of this beach area, there is almost no sand in the Reef Runway littoral cell. Any sediment that may be produced by the reef would be lost offshore, into one of the dredged areas, and possibly at this beach area. Figure 31 illustrates this assessment. Because of the small quantities of sand involved and the lack of information regarding transport rates, no attempt has been made to quantify the sand losses to the different areas.

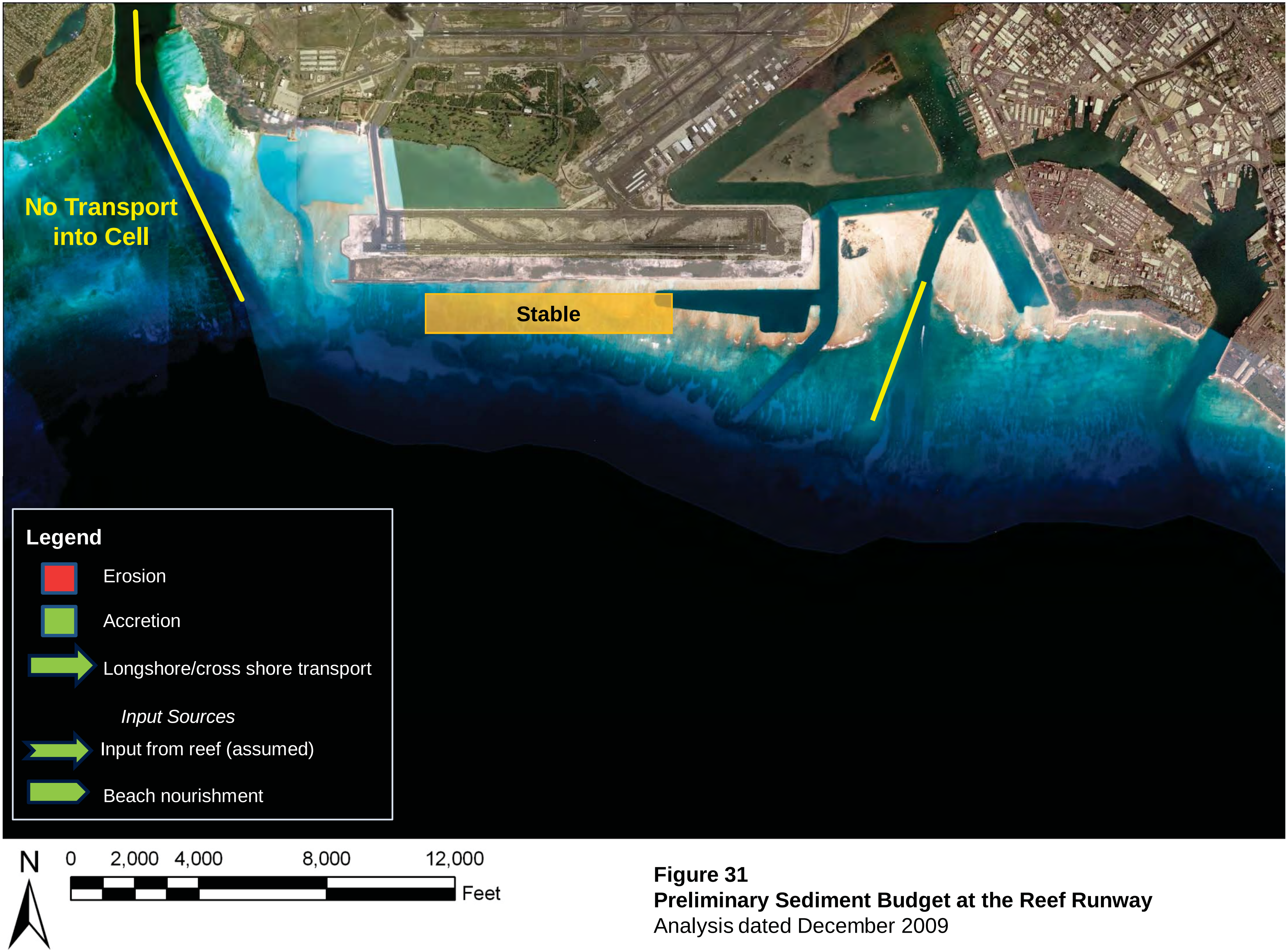


Figure 31
Preliminary Sediment Budget at the Reef Runway
Analysis dated December 2009

G. Iroquois Point Cell

The Iroquois Point Cell is delimited by the Pearl Harbor entrance and the rocky area west of ‘Ewa Beach Park. This area is illustrated in Figure 32. The discussion here considers the entrance to Pearl Harbor as far inland as the mouth of Iroquois Point Lagoon.

Over 75 percent of this area is hardened by seawalls and revetments (Hwang and Fletcher 1992), although most of the beach appears stable. A major exception is the beach in the vicinity of Keahi Point, where the erosion rate is as much as 5 feet annually. Permit applications are under way (Ford Housing LLC) to construct nine T-head groins and to nourish 4,200 feet of beach in this area (USACE 2009c).

Figure 33 clearly illustrates the ongoing erosion at Keahi Point. Based on the shoals drawn in the 1925 T-sheet, this was originally an accretional area. It is now the most heavily erosional site in the D2P study area. As described below, this may be associated with the deep dredged channel at Pearl Harbor.

The modeling of wave-driven currents (Figure 6) shows that the currents in this area are almost entirely directed into the Pearl Harbor entrance channel. There are occasional reversals on the ‘Ewa side of Keahi Point, which would exacerbate erosion in that area but which are consistent with the fact that the shoreline ‘Ewa of Keahi Point is generally stable.

A large fraction of the sand lost from the beach at Keahi Point appears to be accreting further into the Pearl Harbor channel, immediately south of the Iroquois Point Lagoon mouth. Figure 34 shows this area in 1950 and 2005. In 1950, this was a heavily industrialized shoreline, with no beach at all over a distance of nearly 1,000 feet. A beach has grown out over the past 55 years. The obvious conclusion is that the dredging of Pearl Harbor has led to capture of sand in the channel.

Figure 35 shows beach volumes in the Iroquois Point littoral cell. The volumes are divided into three areas.

- Along the ‘Ewa Beach portion of the cell, ‘Ewa of Keahi Point, the beach is slightly accretional.
- At Keahi Point – in the area that is the subject of a private application for beach stabilization – the shoreline is very erosional.
- Within the Pearl Harbor channel, the shoreline is accretional.

Two linear fits are shown: one including only the ‘Ewa Beach and Keahi Point portions of the cell, and a second linear fit including the entire cell. Based on the second linear fit, the cell as a whole is losing 1,000 cubic yards annually. However, the accretional area is gaining 1,600 cubic yards – the erosional area at Keahi Point is losing approximately 2,600 cubic yards of sediment each year.

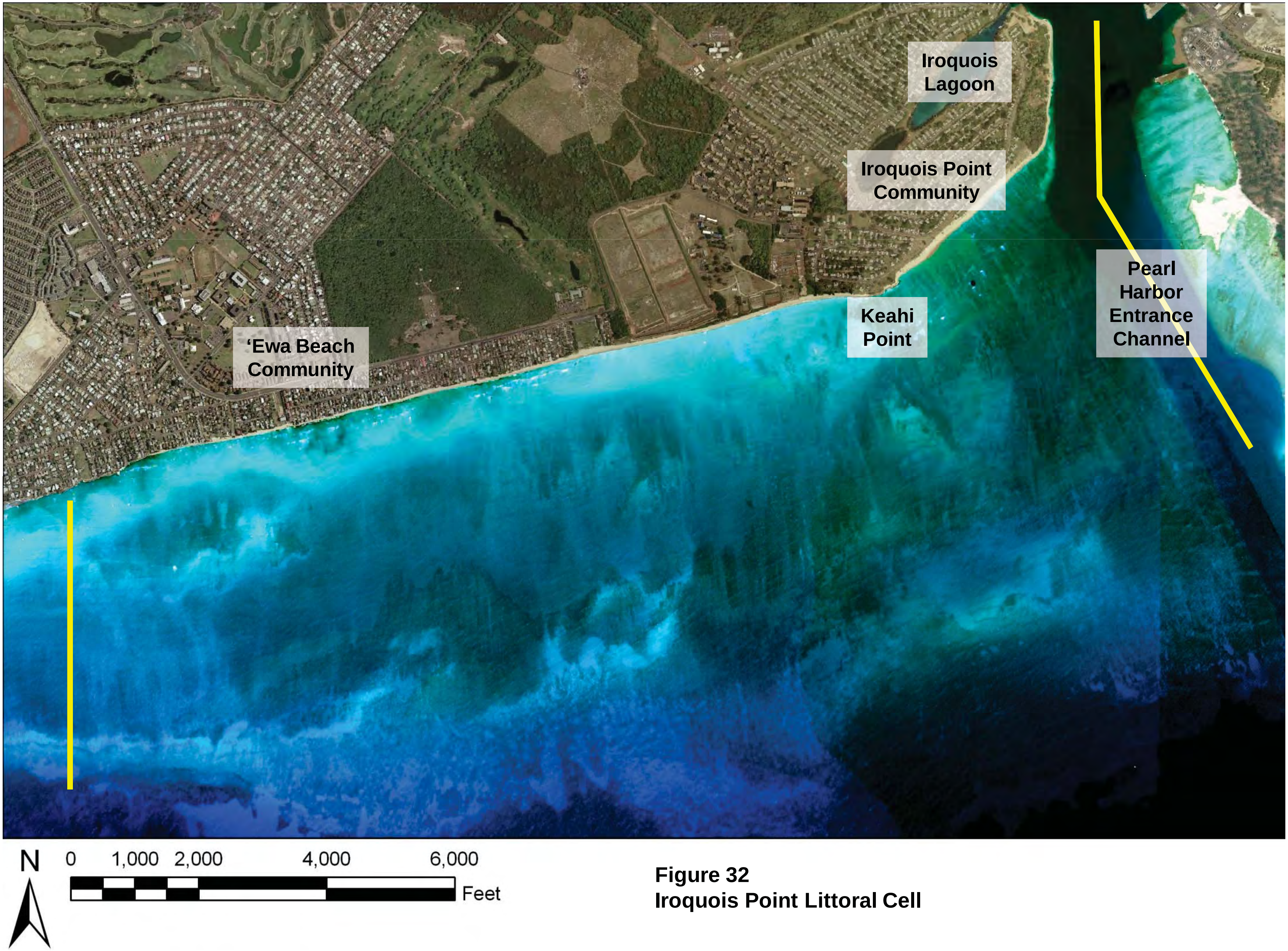


Figure 32
Iroquois Point Littoral Cell

Figure 33. Keahi Point in 1925, 1950, and 2005, with the 2005 low water mark

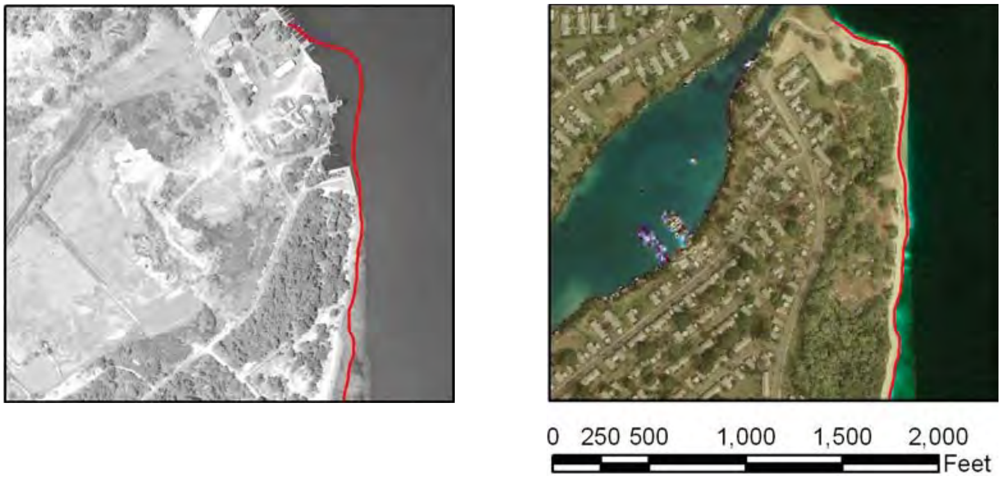


Figure 34. Shoreline south of Iroquois Lagoon in 1950 and 2005

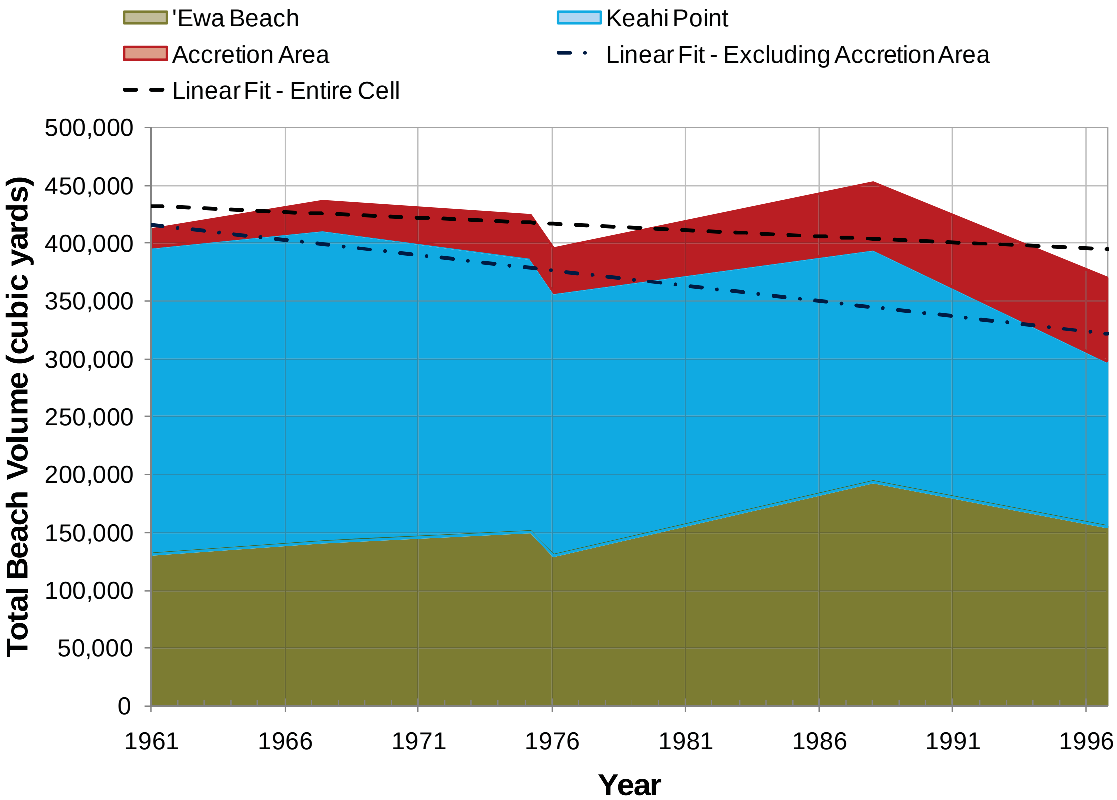


Figure 35. Beach Volumes at Iroquois Point

The originally accretional nature of Keahi Point, as well as the sand plains that make up the upland at ‘Ewa Beach within and also west of the D2P study area, support the concept that ongoing reef production may be important in this area. The estimated reef productivity, based on the approximate approach described in Section III.F, is 700 cubic yards annually. In addition, it is perfectly possible that additional sediment is entering this littoral cell from further west. These contributions to the sediment budget are being lost into the dredged Pearl Harbor entrance or offshore.

Two considerations suggest that a sizeable portion of this sand must be lost in the Pearl Harbor entrance channel, rather than offshore. First, there appears to be relatively little sand located in depressions on the nearshore reef (USACE 2010). Second, there is significant dredging from the entrance, as illustrated in Figure 36. Of the 47,800 cubic yards dredged from the channel in 2006, 22,800 cubic yards was from the accretional area immediately south of the Iroquois Lagoon mouth (second green rectangle in from the mouth). It has not been confirmed how much of this material is of calcareous, beach quality sand.

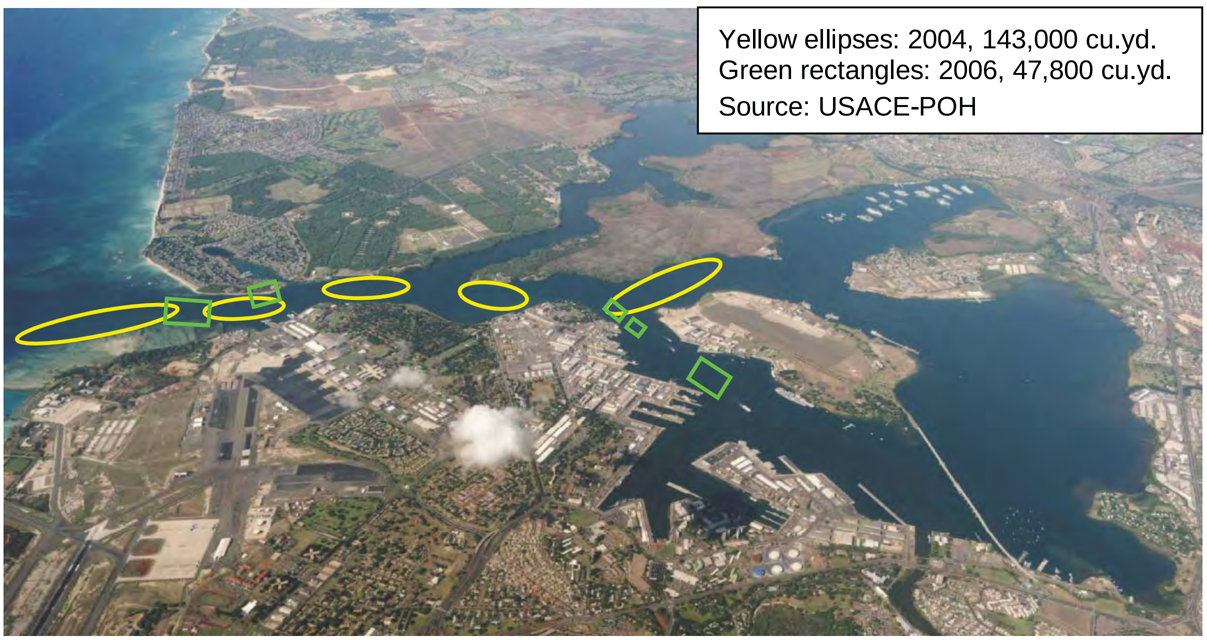


Figure 36. Recent entrance channel dredging locations at Pearl Harbor

Figure 37 presents a preliminary sediment budget based on these considerations. This budget does not show longshore transport from further west. It is possible that some of the accretion along the south shoreline is due to transport from the ‘Ewa side. This additional contribution, if present, would be balanced by additional losses into the Pearl Harbor channel and/or offshore. Additional study, including field assessments and modeling, would be needed to determine whether this is a significant component of the budget.

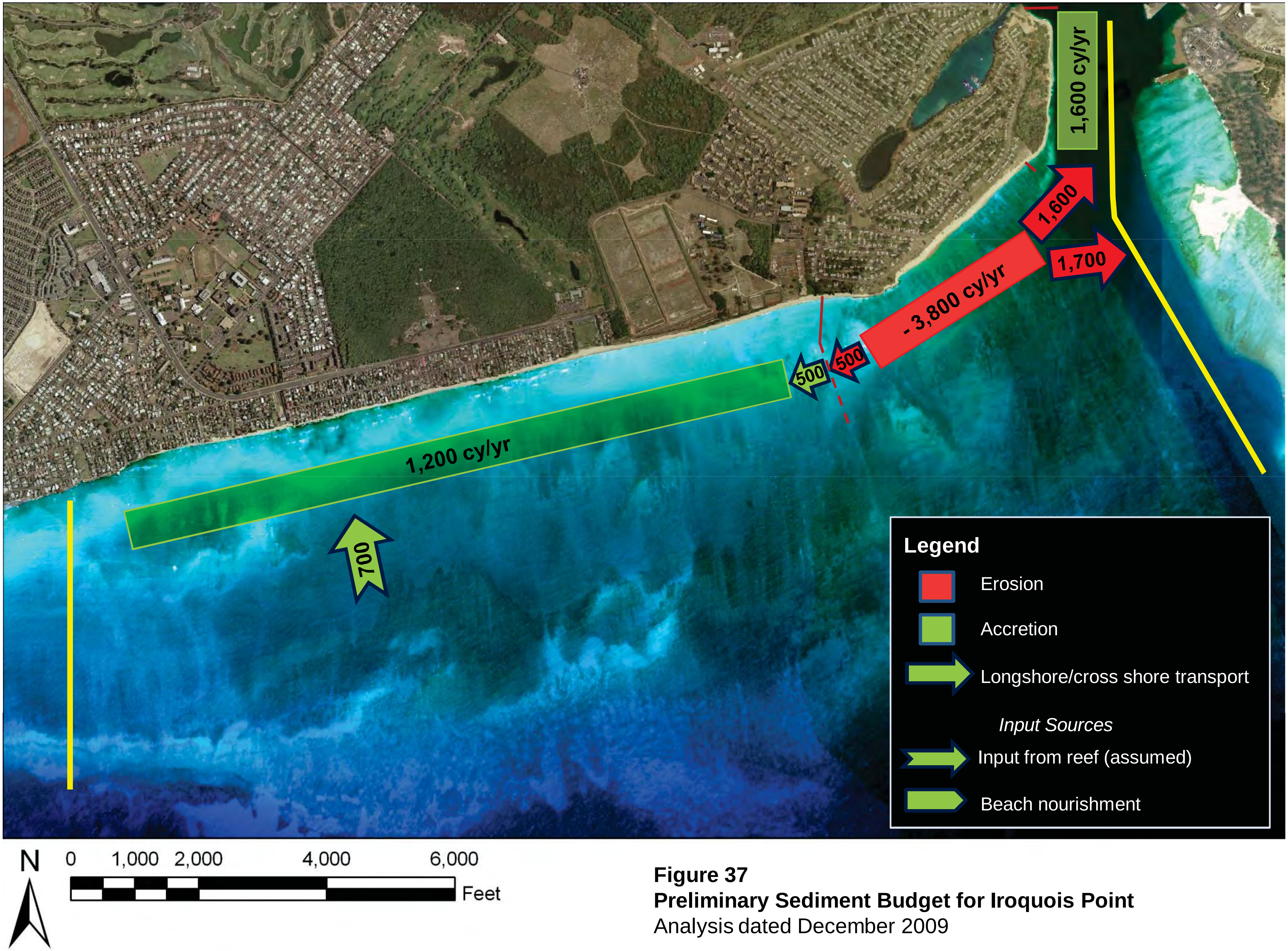


Figure 37
Preliminary Sediment Budget for Iroquois Point
Analysis dated December 2009

V. Conclusions

Results for the six littoral cells include the following.

- **Diamond Head** is a slightly erosional cell. Transport rates in this cell are small – a few hundreds of cubic yards annually. There may be a small modern production of sand by the nearshore reef: this sand would be transported north into the Waikiki cell or offshore into deep water.
- The heavily engineered **Waikiki** cell is generally erosional at present, with sand moving from the beaches to the reef and further offshore. Between 1965 and 1985, beach nourishment at an average rate of approximately 10,000 cubic yards annually led to an accretion of the beach along the central and ‘Ewa portions of the Waikiki cell. However, this reversed between 1985 and 2005, when almost no beach nourishment took place. The 2006 nourishment at Kuhio Beach, if it is not an isolated event, may halt the ongoing erosion.
- The **Ala Moana** cell is similar in behavior to Waikiki. The beach at Magic Island is protected by three detached breakwaters, and is generally stable. The beach at Ala Moana Park is losing sand at a rate of about 1,000 cubic yards per year. While 30,000 cubic yards of sand was placed in 1976, this has since been lost offshore.
- The **Sand Island** cell contains little sand. Transport rates are low – a few hundreds of cubic yards annually.
- Similarly, the **Reef Runway** cell is almost entirely sand-starved. It is dominated by the Honolulu Reef Runway, which was constructed over the nearshore reef. Deep dredged channels at either side of the cell, and rip currents that are able to transport sand offshore, act as sinks for any sand that may be produced by the nearshore reef.
- The **Iroquois Point** cell, ‘Ewa of Pearl Harbor, contains a combination of erosional and accretional areas. Most of the south-facing shoreline of this cell, along ‘Ewa Beach, is slightly accretional. This may result from reef production or longshore sand transport from the ‘Ewa side. Keahi Point is extremely erosional, likely because of loss into the dredged channel at Pearl Harbor: some of the 3,800 cubic yards lost annually from this part of the littoral cell is transported to the beach within Pearl Harbor, just south of Iroquois Lagoon.

VI. Recommendations

The preliminary sediment budget presented in this report is based on available information, including recent modeling work and analysis of aerial photography prepared for the USACE Honolulu District.

The following investigations would reduce uncertainties associated with the preliminary regional sediment budget developed in this report.

- A regular program of aerial photography should be planned to allow ongoing erosion hazard mapping and monitoring of the sediment budget. A new flight every 5 years is recommended, with additional flights around significant events such as beach nourishment or other shoreline infrastructure, hurricanes, or tsunami. In particular, the effects of the 2006 nourishment of Kuhio Beach do not yet appear to have been captured through aerial photography.

- In the area from Diamond Head to Ala Moana, there appears to be significant movement of sand between the beaches and the reef. This sediment circulation is not well understood. Given the likely need for ongoing nourishment at Waikiki Beach, this should be investigated further through field work – including ongoing beach and nearshore profiling, wave/current measurements, and more detailed investigations of sand pockets on the reef – as well as through more detailed modeling analyses.
- The sand on the beach at Waikiki is largely imported from other areas. For the remainder of the D2P region, the sand was originally produced from the fringing reef system. It is not known whether modern production of sand is a significant contributor to the sediment budget in the area. This should be investigated, in the first instance through radiocarbon dating of beach sand.
- Sand sampling should be performed within Pearl Harbor and Honolulu Harbor, to determine the quality and volume of potential sand sources and to progress the present state of knowledge regarding sediment transport pathways.
- If significant sand from offshore sources is found in one or both of these harbors, the sediment transport pathways should be investigated further through field work – including wave and current data collection and possibly turbidity / sediment concentration measurements – and through more detailed modeling analyses.
- Finally, the potential effects of climate change on the study area have not been addressed in the present RSM Plan. This should be incorporated into the planning process. Sea level rise, the potential effects of ocean acidification and reef degradation on sediment availability, and the potential for changes to the wave climate should all be considered.

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