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Waikiki: Historical Analysis of an Engineered Shoreline

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ABSTRACT

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Short-term and long-term shoreline change at Waikiki Beach, Hawaii, is analyzed to enhance resource management. Bi-monthly beach profiles reveal short-term variations of the shoreline. Increased wave heights from south swells between May and October often correspond to beach volume increase, while short-period wind waves predominating between November and April correspond to volume losses. A total mean volume of 167,000 m^3 is estimated for Waikiki Beach, with an uncertainty of 15 to 40%. A net volume loss of approximately 5,200 m^3 is found between October 2000 and May 2002. The Royal Hawaiian littoral cell accounts for 93% of the loss. Historical aerial photographs and NOAA T-sheets establish a 76-year shoreline history (1925–2001). The shoreline has migrated a mean distance of 12 m seaward over this period, reflecting a high level of human intervention. Likewise, average beach width has increased by 32% since 1951. Four of seven littoral cells, however, are characterized by recent erosion at a mean erosion rate of 0.3 $\pm$ 0.1 m/yr. Of the remaining three littoral cells, two have experienced long-term accretion and one has exhibited stability. A relationship between beach width and corresponding sand volume change, established from beach profile data, is applied to historical shoreline changes to establish a history of sand volume fluctuations. Early volume fluctuations are traced to beach nourishment, typically with subsequent beach loss. Volume gains are documented across the entire shoreline between 1975 and 1985. Widespread chronic erosion characterizes the years after 1985. Despite past beach nourishment, a sediment budget for Waikiki reveals a sand volume deficit of at least 77,000 m^3 for the time period between 1951 and 2001, owing to permanent offshore losses.

ADDITIONAL INDEX WORDS: *Waikiki Beach, nourishment, sediment budget, beach erosion, shoreline rate-of-change, photogrammetry, Hawaii.*

INTRODUCTION

Purpose and Goals

The Hawaiian place name, Waikiki, translates to 'spouting waters'. The image that embodies the old Waikiki consists of taro fields and fishponds, meandering streams and coconut groves, as well as the fabled continuous, sandy beach. Today's Waikiki is dramatically different. The former wetland has developed into a commercial center of Honolulu backed by continually expanding high-rise construction. The beach is largely a product of human efforts at building a tropical visitor destination with larger subaerial surface areas, sand volume, and longshore extension than originally allotted by nature. The engineered beach was created by placement of natural sands and sand-like materials from other locations in addition to groins, seawalls, and other constructed features to stabilize the sand. Despite these efforts, today major segments of the shoreline have little to no sand at high tide and few will disagree that the beach is in a degraded state.

Waikiki is an 'economic engine' for the State of Hawaii. The urban corridor generates 44% of $11.4 billion originating from annual tourism expenditures in Hawaii and is responsible for 140,000 jobs (LENT, 2002). Directly and indirectly, the thriving economy of Waikiki is dependant on the recreational, environmental, and aesthetic appeal of the sand beach. For that reason, it is important to understand the history of erosion problems in Waikiki to plan for the future. This study was initiated at the request of the State of Hawaii to document past and present beach changes in order to enhance resource management. It was realized that a monitoring program designed to quantify shoreline change would be necessary to provide a basis for planning the execution of any major restoration. Here, we integrate approximately 2 years of modern beach profile fluctuations with a 50-year sand volume history to describe beach dynamics on a littoral cell basis for the Waikiki shoreline.

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Figure 1. Waikiki Beach in 1927. The Royal Hawaiian Groin was one of 11 groins built along the beach between 1927 and 1930. It was reported to be the only groin successful in maintaining sand. However, downdrift starvation was caused to Halekulani Beach to the west. Note the wide beach fronting The Royal Hawaiian and Moana Hotels. The rest of the shoreline is without beach.

Historical Overview

The Wetland Years

Waikiki was the center of government and culture for the Hawaiian people. The land where streams met the ocean was hailed as a place of great spirit, or mana, for Hawaiians. The natural springs provided irrigation for the taro crop. Fishponds were created in both fresh and brackish waters as an ancient form of aquaculture providing food for the chiefs (GRANT, 1996; BERRY and LEE, 2000). Approaching the twentieth century, much of the Polynesian lifestyle began to wane under the pressure of growing tourism. In the late 1800s, the first developments meant to attract visitors began to emerge, including hotels. It is reported that the first marine structures—i.e. seawalls, groins, and piers—began appearing along the beach during this period (CRANE, 1972). By 1906, the President of the Board of Health of the Territory of Hawaii, Lucius Pinkham, was endorsing full development of the Waikiki district. Pinkham declared the wetland of the district "deleterious to public health—is low covered and partly covered with water—is not drained at all—is incapable of effectual drainage and—is in an unsanitary and dangerous condition" (LUM and COX, 1991). Intending to improve conditions, Pinkham proposed to create a canal through the district that would drain and divert streams away from Waikiki. The material dredged from the canal could then be used to fill the wetland.

The Development Years

During the 1910s, seawalls were recognized as a problem. Several reports indicated beach loss relating to the use of seawalls to delineate seaward boundaries or to protect property from coastal erosion (U.S. ARMY CORPS OF ENGINEERS, 1992). A fragmented shoreline resulted, much like today. The Board of Harbor Commissioners of the Territory of Hawaii responded in 1917 by prohibiting the practice of building seawalls along the shoreline, but the prohibition was largely ignored. Consequently, it is reported that seawalls were in place along most of Waikiki Beach by 1920 (U.S. ARMY CORPS OF ENGINEERS, 1992). In general, the 1920s brought growing concern about beach erosion in Waikiki. A 1927 report by the Engineering Association of Hawaii pinpointed seawalls as the primary cause of erosion in Waikiki. The report concluded that beach nourishment and groins could be used to rebuild the beach (GERRITSEN, 1978; U.S. ARMY CORPS OF ENGINEERS, 1992). During the same time period, plans were underway to turn Waikiki district wetlands into an urban community. Construction commenced in 1922.

The Construction Years

In 1927, the Territorial Legislature authorized Act 273 allowing the Board of Harbor Commissioners to rebuild the eroded beach at Waikiki (NAKAMURA, 1979). By 1930, the Board of Harbor Commissioners reported on construction progress, which included 11 groins along a portion of the shoreline (Figure 1) (U.S. ARMY CORPS OF ENGINEERS, 1992). During the depression years between the 1930s and World War II, there was a general lack of interest in beach restoration. Thereafter, the post-WWII boom period and the introduction of air passenger service to Hawaii brought renewed interest in beach improvements over the decades of the 1950s and 1960s. Additionally, when Hawaii claimed statehood in 1959 and mass tourism was initiated with rapid jet service from the mainland, restoration once again became a priority. A formal application for a cooperative study regarding beach erosion in Waikiki was made by the Board of Harbor Commissioners, Territory of Hawaii in 1948. The completed study in 1951 recommended a number of improvements to the shore at Waikiki Beach. The Waikiki Beach Erosion Control Project was initiated in response. This project initiated what would turn out to be a 50-year series of uncoordinated attempts to restore Waikiki Beach.

PHYSICAL SETTING

Waikiki Beach is located on the southeast coast of Oahu, in the Hawaiian Islands (Figure 2). Wave conditions along this shoreline are subject to seasonal variations of northeast tradewind waves, long period swell generated in the southern hemisphere, and kona (southwesterly) storm waves. Tradewind waves may be present throughout the summer, with wave heights of 1–3 m and periods of 6–10 s. Waikiki, however, is sheltered from the direct approach of tradewind waves, such that refraction around Diamond Head crater can result in their approach from the south at a reduced level of energy. The summer season is dominated by swell waves generated by strong winds over long fetches in the southern hemisphere. These events usually have deep-water wave heights of <1 m with periods of 14–22 s, and breaking wave heights from 1 to 2 m. Kona waves are produced by winds generated by local fronts or tropical storms characteristic of the winter season. Since they are of local origin, they can be particularly energetic, generating wave heights of 3–5 m at periods ranging from 6–10 s (NODA and ASSOCIATES, 1991; U.S. ARMY CORPS OF ENGINEERS, 1992). Kona fronts have been reported to cause extensive damage to south and west facing shores in Hawaii (MOBERLY, 1968; ARMSTRONG, 1983; ROONEY and FLETCHER, 2000). Waikiki is also openly exposed to hurricane-generated waves from the south and southwest. Since the 1950s, there are five hurricanes on record affecting the island of Oahu. Historically, however, Waikiki has not been susceptible to beach erosion during these events. Wave refraction plays an important role in shaping the nearshore wave environment. Due to refraction, both wind-generated waves and swell waves approach nearly perpendicular to bathymetric contours in the Waikiki nearshore (GERRITSEN, 1978; NODA and ASSOCIATES, 1991).

The Waikiki shoreline is 3.2 km in length, but supports only 2.6 km (81%) of beach ranging from approximately 6 to 48 m in width. Physical structures established during past engineering projects (*i.e.* groins, breakwaters, storm drain culverts) create morphologically distinct littoral cells. Seven cells will be referred to from south to north as: (1) Kaimana, (2) Queens, (3) Kapiolani, (4) Kuhio, (5) Royal Hawaiian, (6) Halekulani, and (7) Ft. DeRussy. A list of engineering events by littoral cell is recorded in Table 1. Sand characteristics are variable along the shoreline owing to uncorrelated engineering histories. Thus, sand is composed of fine grains with a median diameter of 0.2 mm to very coarse grains with a median diameter of 2.0 mm. Foreshore slopes range from 1:6 to 1:12.

The Waikiki nearshore is characterized by a fringing fossil reef that extends offshore about one mile (GERRITSEN, 1978). The reef is intersected by several paleostream channels and has been altered by dredging activities at a few sites. Reef carbonate sand production and some minor volcanic sand production are considered the only natural sources of sand for the beach. Production of most Hawaiian beach sand peaked during the Kapapa Stand of the sea (+2 m above current sea level) 1,500 to 4,000 years before present (HARNEY *et al.*, 1999). Today, carbonate sand production is a relatively insignificant contribution to littoral sediment budgets (HARNEY *et al.*, 1999.

METHODOLOGY

Short-Term Shoreline Change

Beach Profiles

To document shoreline behavior, a series of twenty-two cross-shore beach profiles were established along the Waikiki shoreline. An initial survey was completed in October 2000, with subsequent surveys generally commencing every other month for nearly two years. Profiles were surveyed randomly with respect to tide level and wave state. Survey data were collected using a Geodimeter laser total station that tracks a prism on a telescoping rod, measuring points at 3 to 5 m intervals or at every major break in slope and geomorphic feature. Surveys typically extend from the landward boundary of the beach, which is typically the base of coastal armoring structures, to beyond the first occurrence of hard substrate at the reef to sand interface. This depth varies along the length of the shoreline and may approximate depth of closure. However, none of the profiles reach depth of closure as predicted by HALLERMEIER (1981), since beach response is limited by the presence of fringing reef. Sand volume calculations are based on the observation that sand extends continuously to the depth of the fringing reef along the entire length of the profile.

Profile Temporal Trends

Volumetric and morphologic changes in beach profiles are compared to a time series of daily wave heights for the study period. Wave heights were provided by the University of Hawaii National Oceanographic and Atmospheric Administration (NOAA) Data Center, Honolulu, Hawaii. Wave heights are based on daily visual observations of breaking wave height from the closest available location to Waikiki, Ala Moana, located only 3 km to the northwest. Since these observations are subjective by nature, there is a margin of error in each observation, estimated at ± 10% for waves under 10 ft and ± 20% for those over 10 ft. However, they are found by DAIL *et al.* (2000) to be significantly correlated with wave buoy heights at Waimea Bay, Oahu.

Historical Shoreline Change

Photogrammetry

A high-resolution aerial photogrammetric analysis was conducted for Waikiki Beach to assess historical shoreline change. The procedure is outlined in Figure 3. Historical

Figure 2. Map of the study area at Waikiki Beach, Oahu, Hawaii. Along the shoreline, physical structures create seven littoral cells. Beach profile locations are designated by yellow lines, labeled 1–22 from southeast to northwest. Profiles were surveyed approximately every other month for 20 months (October 2000–May 2002).

shoreline positions were acquired from aerial photographs and one NOAA National Ocean Survey (NOS) topographic sheet (T-sheet). Only large scale, vertical, survey quality photos were chosen. The resulting photos date from 10/02/1951, 11/11/1970, 03/25/1975, 08/07/1985, 01/17/1992, 02/17/1999, and 01/06/2001 at scales from 1:6,000 to 1:15,400. A 1925 T-sheet at the 1:5,000 scale for the south shore of Oahu was obtained from NOS. According to the T-sheet, the Waikiki shoreline maintained approximately 0.7 km of beach in 1925, compared to approximately 2.6 km of beach today.

A survey of the Waikiki area was completed in April and May 2001 for acquisition of ground control points (GCPs) utilized in photo rectification. Twelve GCPs were collected using a differential global positioning system (DGPS) at a resolution of $\pm$ 2 cm in horizontal and vertical dimensions. Scanned images were orthorectified and mosaicked with a pixel resolution of 0.5 m following the methodology of COYNE *et al.* (1999).

The landward and seaward boundaries of all historical beaches were digitized. The landward boundary of the beach

Table 1. *Engineering events and anthropogenic activities at Waikiki Beach.*

Littoral Cell	Year(s)	Brief Description
Kaimana	1927	Construction of the War Memorial Natatorium (US Army Corps of Engineers, 1992).
	periodic	Beach grading by the City and County of Honolulu. Latest grading in February 2002.
Queens	1956	Construction of the Queens groin. Construction of a uniform beach from Queens groin to the Natatorium (US Army Corps of Engineers, 1963).
Kapiolani	1951	Beach construction with 38,000 m^3 of sand fill (US Army Corps of Engineers, 1963).
	1975–1985	Landward shift of the vegetation line.
	1985–1992	Seaward shift of the vegetation line.
	2001	Seaward shift of the vegetation line for City and County sidewalk improvements and landscaping.
Kuhio	1939	Construction of submerged offshore breakwater (−1.0 ft @ mllw). Creation of 210 m beach, forming today's north basin (Gerritson, 1978).
	1951	Kapahulu storm drain installed. Construction of beach for south basin from 38,000 m^3 of sand fill (US Army Corps of Engineers, 1963).
	1952	Installation of t-head groin centered in the southern basin. This was a short-lived feature (Noda and Associates, 1991).
	1953	Southern breakwater (+3 ft @ mllw) installed. Construction of two groins: one centrally located between basins and a terminal groin in the north basin. Removal of 9,174 m^3 of coral by dredging. 3,440 m^3 of sand fill added (Department of Public Works Application, 1951).
	1959	14,335 m^3 sand fill added (US Army Corps of Engineers, 1992).
	1970–1975	Seaward shift of the promenade.
	1972	Improvements to the central groin and the northern terminal groin. 9,174 m^3 sand fill added. Reconfiguration of the sandy beach (Gerritson, 1978).
	1975	Segments of the northern breakwater extended to +3 ft. Additional improvement of the northern terminal groin. 7,263 m^3 sand fill added (Gerritson, 1978).
	1991	Beach area enlarged by 3,981 ft^2 with sand fill (Noda and Associates, 1991).
	2000	1,066 m^3 sand fill added to south basin in demonstration project (Noda and Associates, 1999).
	2001	Seaward shift of the promenade and construction of seawalls on former beach.
Royal Hawaiian	1927	Construction of the Royal Hawaiian groin.
	1951–1970	Seaward shift of the vegetation line.
	1975–1985	Landward shift of the vegetation line with elimination of the Waikiki Beach center.
Halekulani	1920s/1930s	Experimentation with groins (Department of Public Works, 1931).
Ft. DeRussy	1917	Concrete storm drain installed (US Army Corps of Engineers, 1992).
	1969	Storm drain lengthened (US Army Corps of Engineers, 1992).
	1969–1971	Beach expansion/construction with screened, crushed coral. Construction of rubble mound groin next to storm drain (US Army Corps of Engineers, 1992).
	1975	Additional 0.6 m layer of sand added (US Army Corps of Engineers, 1992).
	1981	Removal of coral fragments from beach. 382 m^3 sand fill added (US Army Corps of Engineers, 1992).

is delineated by the seaward edge of coastal armoring structures. The beach toe identifies the seaward boundary of the beach and defines the shoreline change reference feature (SCRF) after COYNE *et al.* (1999). The digitized high water line (HWL) from the T-sheet was shifted seaward by a distance equal to the median difference between the HWL and the beach toe from one year of beach profile data. This produced a beach toe vector for 1925. All historical shorelines were overlain on the 2001 mosaic to produce a complete time series of landward and seaward beach boundary positions. Statistically robust long-term shoreline change rates were calculated by analyzing the time series of toe positions at 137 shore normal transects with a spacing of 20 m (66 ft) along the shoreline. Rates were calculated using a reweighted least squares (RLS) regression after ROONEY and FLETCHER (2000). Uncertainties for RLS derived shoreline change rates reflect an 80% confidence interval for the slope.

Historical Volume Change

To facilitate the development of a sediment budget, linear shoreline change was converted to volumetric units. Two components were considered in calculating beach volume change between consecutive photo years. The first term evaluates volume change of the beach face relating to movement of the beach toe. A model relating beach width change to beach volume change in the profiles was developed and applied to historical toe position differences to estimate historical volume fluctuations of the beach face. Modified from BODGE (1998), the model compares changes in volume (ΔV_1)

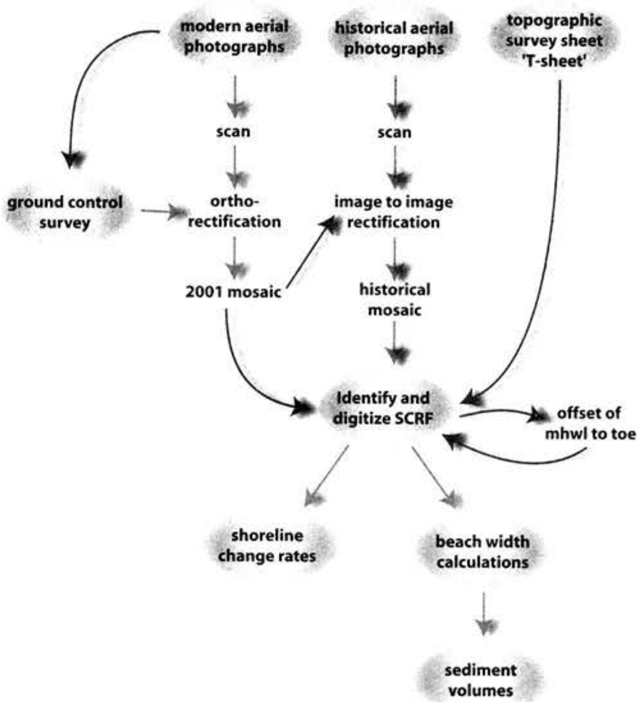

Figure 3. Photogrammetry procedures.

between consecutive profile surveys to a corresponding change in beach width (ΔX_1). The slope of a linear regression line fit to the data and forced through the origin yields the dV/dX relationship, or G_p value, expressed as:

$$G_p = \frac{\Delta V_1}{\Delta X_1} = \frac{\text{volume change per unit shorelength}}{\text{change in beachwidth}}$$

The G_p value is applied to historical beach width fluctuations at each transect. A single G_p was computed for each littoral cell (Figure 4). A second term accounting for historical volume change relates to movement of the landward boundary of the beach. The product of the horizontal movement of the edge of beach (ΔEOB) with the depth of the fringing reef defines this volumetric change under a 1 m wide strip of profile.

Net volume change for each 20 m transect is then expressed by (Figure 5):

$$\Delta Vol_{total} = [(G \times \Delta X_2) + (\Delta EOB \times \Delta Z)] \times 20, \quad \text{where}$$

ΔV_{total} (m^3) = total volume change for 20 m wide shore normal transect, G_p = slope of least median of squares regression relating ΔV and ΔX_1, ΔX_2 (m) = horizontal change in shoreline position, ΔEOB (m) = horizontal movement of vegetation line, ΔZ (m) = elevation difference between the depth of the fringing reef and the edge of beach. Volumetric changes were calculated between successive photo years (*i.e.* 1951 to 1970, 1970 to 1975, 1975 to 1985, etc.) for each littoral cell.

RESULTS

Short-term Shoreline Change

Beach profile characteristics are presented in Table 2. Subaerial beach widths vary significantly along the shoreline and within littoral cells. Larger beach widths are typically observed at the northwest ends of the littoral cells. The seaward extent of profiles is determined by the depth and proximity of the fringing reef. In general, profiles extend farther offshore and reach slightly greater depths along the central portion of the shoreline where the fringing reef is least distinct. Vertical and horizontal changes in the profiles occur from the berm crest to the beach toe, beyond which beach response is limited by the presence of fringing reef. Profile volumes (per alongshore distance) range from 21 m^3/m at profile 6 to 207 m^3/m at profile 15. We estimate a total mean volume of 167,000 m^3 for Waikiki Beach, with an estimated uncertainty of 15 to 40%, owing to non-linear beach widths and uncertainty of bottom topography. Sand volume change is calculated between consecutive surveys. A net volume loss of approximately 5,200 m^3 is found for Waikiki Beach over the study period, with the Royal Hawaiian Beach accounting for 93% of the loss.

Profile volume changes relative to the mean are plotted to reveal spatial and temporal beach change trends (Figure 6). At Kaimana Beach, most volume change occurs at profile 2. A net volume increase of 10 m^3/m at profile 1 is influenced by a February 2002 beach-grading project performed by the City and County of Honolulu. At Queens Beach, volume fluctuations are largest at profile 5, adjacent to a 110 m concrete and rubble mound groin. Profile changes at Kapiolani Beach are nearly imperceptible. Volume changes for profiles 9 and 10 at Kuhio Beach are impacted by human intervention. Note rapid volume fluctuations in May 2001 and May 2002, owing to an engineered sand transfer from profile 10 to profile 9. Net losses of 2 to 5 m^3/m are observed at the centrally located profiles 10 and 11. Volume changes for profiles 11 and 12, in the Kuhio Beach north basin, are synchronized and show minor variations over the study period. Volume fluctuations are greatest in the Royal Hawaiian littoral cell, being dominated by losses at profiles 15 and 16 at the north end of the beach adjacent to a concrete groin. A net volume loss of 25 m^3/m and 26 m^3/m is found at profiles 15 and 16, respectively. Volume change at these two sites is frequently opposing. At Halekulani Beach, profiles 17 and 19 exhibit similar volume change trends. These trends are commonly opposing volume changes occurring at profiles 18 and 20. Net losses on the order of 5 to 6 m^3/m are observed at profiles 17 and 18. Ft. DeRussy Beach shows relatively small volume changes over the study period, with most variation occurring at profile 21. Volume gains at profile 22 equal in magnitude to volume losses at profile 21.

The seasonal wave regime affecting Waikiki Beach is well defined by the distribution of wave heights over the study period. A comparison of daily wave heights to the sand volume change at each profile site reveals a general relationship between profile volume and seasonal wave behavior. Increased wave heights from south swells between May and October often correspond to a period of volume increase,

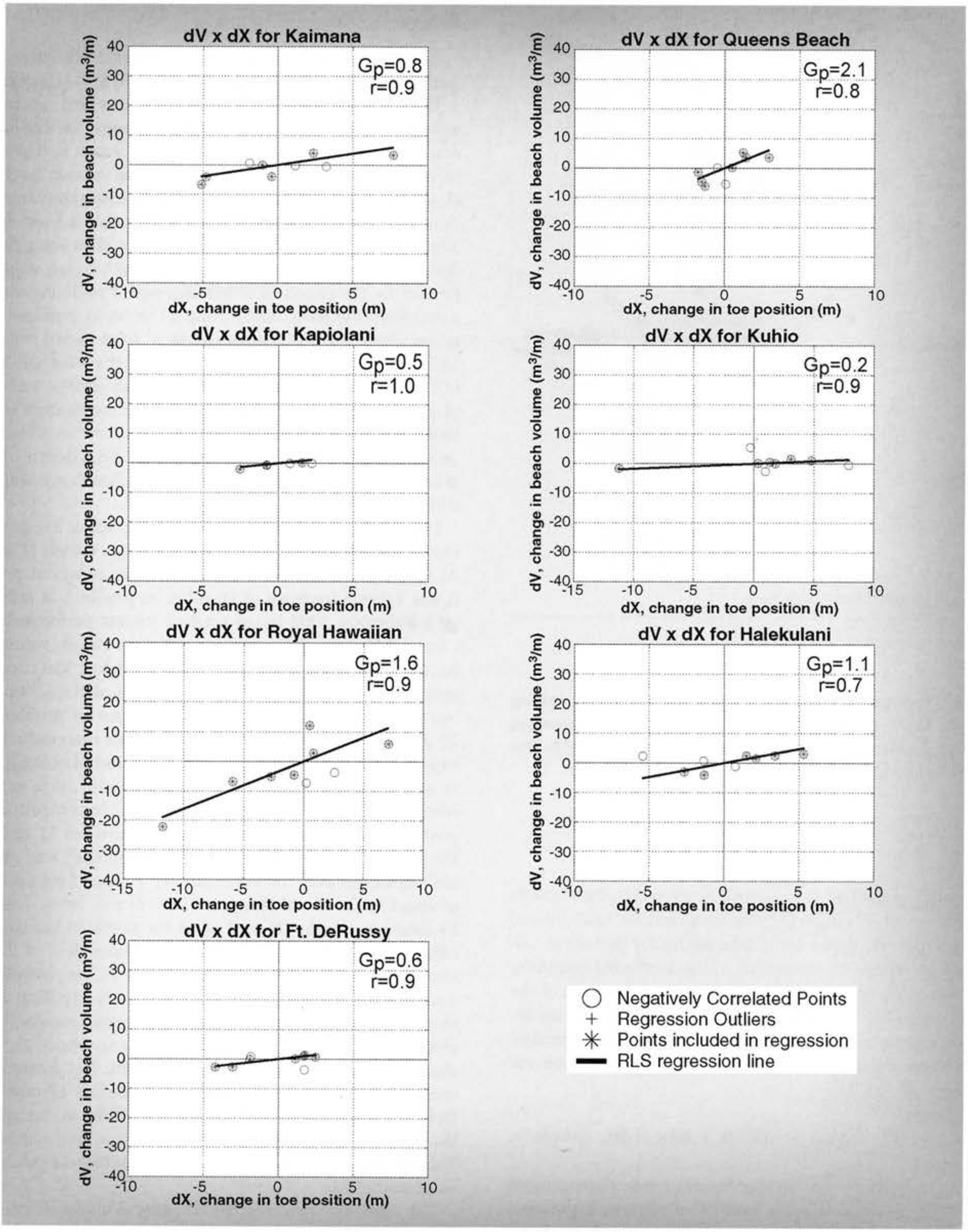

Figure 4. Relationship between change in volume and change in beach width (dV/dX) for each littoral cell.

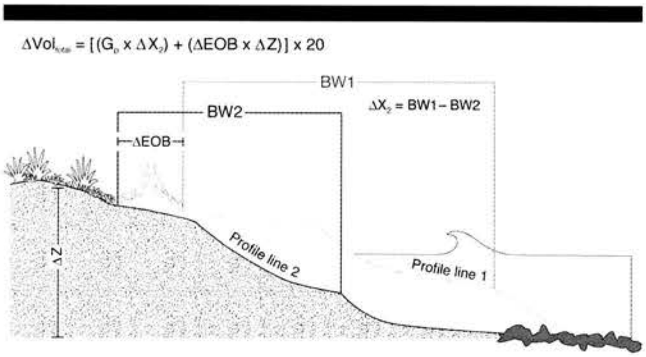

Figure 5. Historical volume change model. Volume change based on fluctuations of the beach toe are added to volume changes related to movement of the landward edge of the beach.

while short-period wind waves predominating between November and April regularly correspond to sand volume losses.

Historical Shoreline Change

Photogrammetry Results

Mean shoreline change rates are calculated for each littoral cell (Figure 7). Due to extensive historical shoreline reconstruction, only the most recent trend in shoreline position is reported for each cell. Two littoral cells, Kaimana and Halekulani, are characterized by long-term accretion. One littoral cell has shown long-term stability. Minor to moderate erosion characterizes the remaining four littoral cells. Erosion rates range from 0.1 ± 0.0 m/yr to 0.6 ± 0.1 m/yr with a mean erosion rate of 0.3 ± 0.1 m/yr.

Mean beach width for all littoral cells for each year of photographic coverage are given in Table 3. Overall mean beach width has increased by 7 m, or 32%, over the fifty-year study period, reflecting human intervention in Waikiki. However, erosional cells show significant decreases in beach width over recent periods.

Historical Volume Change

Profile volume changes are compared to corresponding changes in beach width. This relationship is used to account for historical fluctuations in sediment volume resulting from changes in historical beach width. Figure 8 illustrates spatial and temporal volume change trends for the fifty-year study period. Volume fluctuations prior to 1975 relate to extensive beach construction and beach nourishment (cool colors) with a period of erosion (hot colors) frequently following. Volume gains are documented across the entire shoreline between 1975 and 1985. Widespread chronic erosion characterizes the years after 1985.

Table 4 gives net volume change for the Waikiki shoreline for each historical time interval as well as the volume change rate for each time period. A net volume increase of 3,616 ± 461 m^3 is found for the Waikiki shoreline over the fifty-year photographic history. Fluctuations of the beach toe account for 54% of the net volume change, while anthropogenic activities affecting the landward boundary of the beach account for the remaining 46%. Only two time intervals show a net volume increase for the shoreline. An increase of 9,789 ± 130 m^3 is observed for Waikiki Beach between 1951 and 1970 (515 ± 7 m^3/yr). Additionally, a significant increase of 13,694 ± 130 m^3 is recorded between 1985 and 1992 (1,370 ± 19 m^3/yr). All other time periods document volume losses for Waikiki Beach. The greatest volume change rate for Waikiki, −1,492 ± 43 m^3/yr, is recorded over the short 3 year time period between 1999 and 2001. Figure 9 shows volume change by littoral cell. The largest volume increase for a single littoral cell, 8,847 ± 23 m^3, is recorded at Queens Beach

Table 2. *Beach profile characteristics.*

Littoral Cell	Profile	Approx. subaerial beach width (m)	Approx. depth of closure (m)	Maximum volume (m^3/m)	Minimum volume (m^3/m)	Net volume change (m^3/m)
Kaimana	1	25	1.1	61	45	+10
	2	44	1.8	175	164	−8
	3	46	1.5	162	152	−4
Queens	4	14	1.6	58	54	+2
	5	21	1.4	67	55	+1
Kapiolani	6	13	0.9	24	21	+3
	7	34	0.8	84	79	−1
	8	29	1.2	90	86	+2
Kuhio	9	17	1.5	60	52	+8
	10	28	1.3	91	81	−5
	11	24	1.2	67	71	−2
	12	32	1.6	112	109	+1
Royal Hawaiian	13	57	1.6	188	171	+10
	14	17	1.4	46	38	−1
	15	25	2.0	207	154	−25
	16	27	1.5	106	71	−26
Halekulani	17	21	1.3	63	56	−5
	18	10	1.4	47	33	−6
	19	20	0.8	39	29	+6
	20	27	0.8	69	63	−2
Ft. DeRussy	21	19	0.6	35	28	−2
	22	28	1.0	56	52	+2

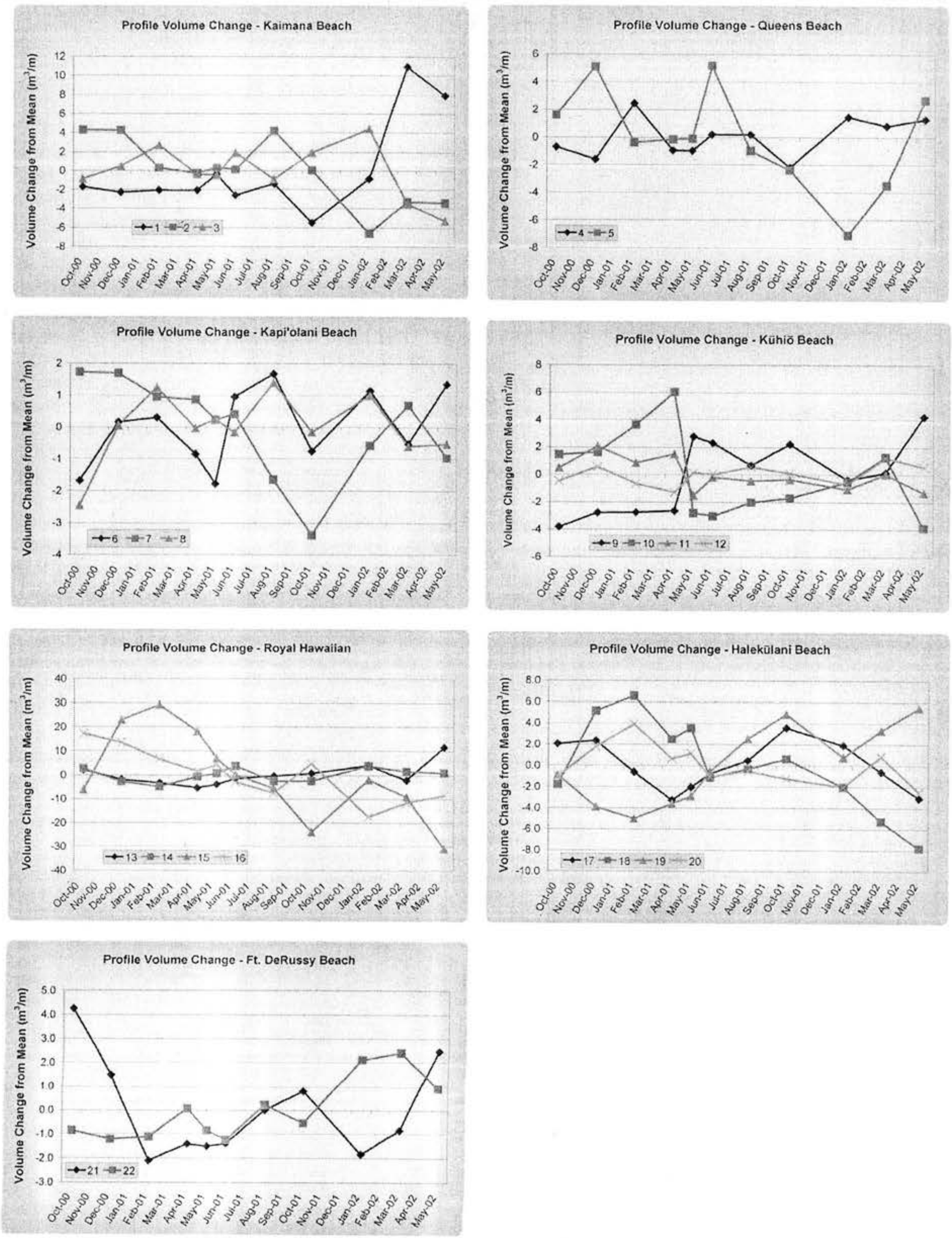

Figure 6. Beach profile volume changes, relative to the mean, for 22 profiles in 7 littoral cells.

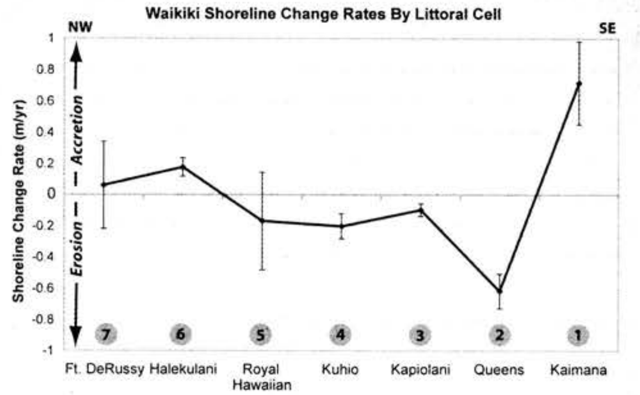

Figure 7. Average shoreline change rates by littoral cell, determined by a reweighted least squares regression.

between 1951 and 1970. The largest volume loss for a single littoral cell, $-4{,}704 \pm 13$ m^3, is recorded at Kapiolani Beach between 1985 and 1992.

DISCUSSION

Littoral Cell 1: Kaimana Beach

Short-term Behavior

Due to a beach-grading project in February 2002, a discussion of volume change is simplified by observing trends over time periods that distinguish natural behavior from artificial behavior. Prior to the February 2002 beach grading (October 2000 to January 2002), a net loss of 250 m^3 was recorded for Kaimana Beach. Profile 2, showing a net volume decrease of 11 m^3/m, solely accounted for the losses, while profile 1 recorded a net volume increase of 1 m^3/m and profile 3 showed an increase of 5.3 m^3/m. These results show that fluctuations in the littoral budget may be controlled by profile 2. Since profile 2 is located at the mouth of a shore-perpendicular paleostream channel, this would seem to implicate the channel's role in littoral transport. This suggests an avenue for cross-shore transport, possibly serving as the mechanism whereby Kaimana Beach has experienced historical accretion. Accretion at profile 3, in addition to a wide beach configuration at the north end of the beach, is indicative of net north longshore transport with sand impoundment against the south wall of the Natatorium (Figure 10A).

Volume changes for the entire study period (October 2000 to May 2002) record a net sand loss of 131 m^3. A net volume increase at profile 1 is indicative of the February 2002 beach grading, since beach sand was transferred from the north end of the beach to the south end. Net losses for Kaimana Beach over the study period are concurrent with volume losses documented from 1999–2001 in the historical portion of the study.

Sand losses tend to be greatest during winter months, an indication that the winter wave regime may be most responsible for beach erosion. This process is exemplified by especially large volume fluctuations in January 2002 following approximately 1 week of kona winds and waves. GERRITSEN (1978) showed similar results with beach profiles, generally noting the stability of Kaimana Beach, but also pointing out volume losses during winter months. Recovery is observed during the summer season.

Table 3. *Mean beach width by littoral cell for each year of photographic coverage*.*

Littoral Cell	Mean Beach Width by Year (m)						
	1951	1970	1975	1985	1992	1999	2001
Kaimana	—	22	32	33	39	39	38
Queens	2	17	16	11	9	6	6
Kapiolani	39	26	26	44	35	37	34
Kuhio	47	17	34	32	36	32	27
Royal Hawaiian	23	28	35	38	38	37	33
Halekulani	8	14	14	14	18	16	16
Ft. DeRussy	13	54	45	46	48	46	48
Entire Shoreline	22	26	29	31	32	30	29

* Beach width is defined here from the landward edge of the beach to the beach toe.

Historical Behavior

Kaimana Beach is one of only two littoral cells in Waikiki characterized by accretion of sand over the past 30 years. The once narrow beach has widened 16 m since 1970 at a rate of 0.7 ± 0.3 m/yr. The 1970 shoreline provides the baseline for comparison, since photos dating 1951 failed to capture the southern terminal end of the Waikiki shoreline. However, NODA and ASSOCIATES (1991) estimated an average beach width of 5 m in 1951, indicating a possible expansion of more than 30 m since that time. A second data gap occurs in 1975, where partial lack of aerial photo coverage prevents calculation of the average beach width and skews volume change data (toward a lower magnitude) for that time period as well. Still, a sand volume increase of 770 ± 15 m^3 occurred between 1970 and 1985. Inspection of aerial photos reveals that most of the accretion occurred between the years of 1975 and 1985. Hurricane Iwa (November 23–24, 1982) provides a possible explanation. The hurricane was responsible for damage to south and west facing shorelines throughout the islands, but no wave damage was reported in Waikiki. Indeed the wide and shallow reef plays a large role as a barrier against beach erosion from the energy of large storm waves. Therefore, resulting nearshore waves may have triggered onshore delivery of sand to the Kaimana cell from deeper offshore regions or from sand topping the reef surface. Beach progradation is also observed between 1975 and 1985 in other littoral cells, pointing to a consistency of this trend along the shoreline. NODA and ASSOCIATES (1991) noted the same trend, stating that some beach areas were wider in December 1982 than at many other times recorded by their aerial photo record.

Seaward progression of the beach toe continued until 1992, producing an additional 5 m and 242 ± 15 m^3 of beach, accumulating primarily at the north end of the beach. However, recent landward migration of the toe (1992 to 2001) may signal a change in Kaimana's accretionary behavior.

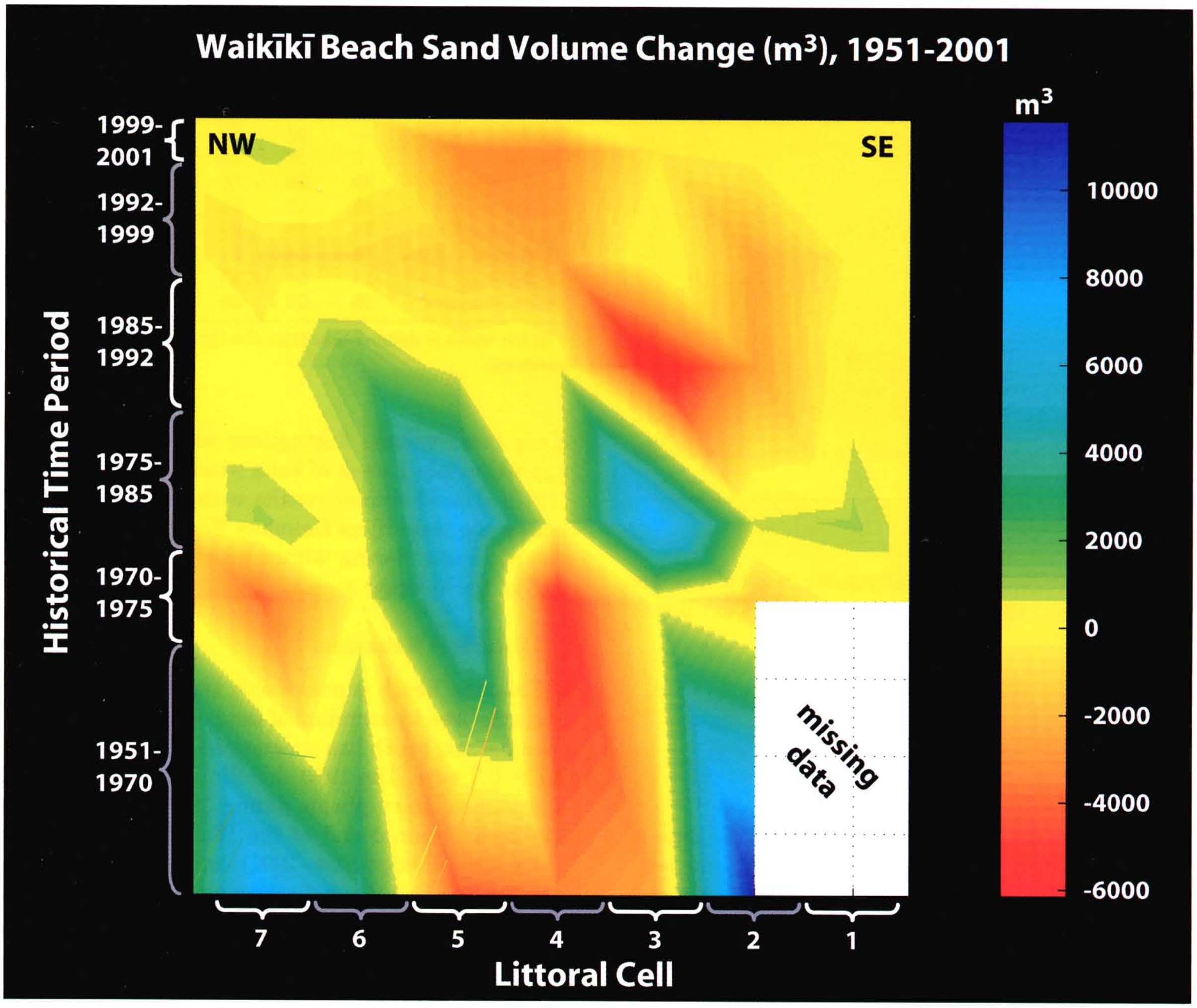

Figure 8. Waikiki Beach volume change between successive historical photo years. Volume fluctuations prior to 1975 relate to extensive beach construction and beach nourishment, frequently followed by a period of erosion. Volume gains are documented across the entire shoreline between 1975 and 1985. Widespread chronic erosion characterizes the years after 1985.

Littoral Cell 2: Queens Beach

Short-term Behavior

A net volume increase of 212 m³ is recorded for Queens Beach over the study period, contrasting expectations posed by historical erosion trends. This may be related to a reduced presence of Kona fronts over the study period. Despite showing a lesser net volume change, profile 5 proves to be more dynamic than its neighbor, implying that most beach change occurs in close proximity to the groin. This may be related to

Table 4a. *Net volume change by littoral cell for each historical time interval.*

	Volume Change By Time Interval (m³)					
Littoral Cell	1951–1970	1970–1975	1975–1985	1985–1992	1992–1999	1999–2001
Kaimana	—	16 ± 15	754 ± 15	242 ± 15	−125 ± 15	−17 ± 15
Queens	8847 ± 23	−1356 ± 23	529 ± 23	−1968 ± 23	−1901 ± 23	−42 ± 23
Kapiolani	−1982 ± 13	43 ± 13	6019 ± 13	−4704 ± 13	408 ± 13	−274 ± 13
Kuhio	−2668 ± 5	−4344 ± 5	−113 ± 5	248 ± 5	−1926 ± 5	−2405 ± 5
Royal Hawaiian	−3139 ± 46	4489 ± 46	5467 ± 46	30 ± 46	−1106 ± 46	−2511 ± 46
Halekulani	2826 ± 33	−114 ± 33	302 ± 33	1406 ± 33	−814 ± 33	74 ± 33
Ft. DeRussy	5905 ± 20	−3105 ± 20	737 ± 20	−43 ± 20	−766 ± 20	699 ± 20
Entire Shoreline	9789 ± 130	−4371 ± 130	13694 ± 130	−4789 ± 130	−6231 ± 130	−4476 ± 130

Table 4b. *Net volume change by littoral cell for each historical time period, normalized by years.*

Littoral Cell	Volume Change Rate By Time Interval (m^3/yr)					
	1951–1970	1970–1975	1975–1985	1985–1992	1992–1999	1999–2001
Kaimana	—	3 ± 3	75 ± 2	35 ± 2	−18 ± 2	−6 ± 5
Queens	466 ± 1	−271 ± 5	53 ± 2	−281 ± 3	−272 ± 3	−14 ± 8
Kapiolani	−104 ± 1	9 ± 3	602 ± 1	−672 ± 2	58 ± 2	−91 ± 4
Kuhio	−140 ± 0	−869 ± 1	−11 ± 1	35 ± 1	−275 ± 1	−802 ± 2
Royal Hawaiian	−165 ± 2	898 ± 9	547 ± 5	4 ± 7	−158 ± 7	−837 ± 15
Halekulani	149 ± 2	−23 ± 7	30 ± 3	201 ± 5	−116 ± 5	25 ± 11
Ft. DeRussy	311 ± 1	−621 ± 4	74 ± 2	−6 ± 3	−109 ± 3	233 ± 7
Entire Shoreline	515 ± 7	−874 ± 26	1369 ± 13	−684 ± 19	−890 ± 19	−1492 ± 43

high surf rip currents forming adjacent to the groin (Figure 10B).

At profile 5, a net loss of 4.5 m^3/m for winter months contrasts a net gain of 5.6 m^3/m for summer months, suggesting that winter environmental conditions control erosion at Queens Beach. It is notable that a substantial erosional event ensued during winter 2002 after persistent kona conditions. A volume deficit of about 7 m^3/m at profile 5 after this period (January 2002) equates to a 1.5 m decrease in beach width. Recovery at profile 5 began immediately, but significant progress toward recovery was achieved after a large summer swell event with wave heights up to 2 m. The beach nearly returned to its pre-erosion condition, showing that summer swells tend to restore sand to the beach.

Historical Behavior

Queens Beach is an erosion hotspot on the Waikiki shoreline, retreating at an average rate of 0.6 ± 0.1 m/yr. A sand volume increase of 8,847 ± 23 m^3 between 1951 and 1970 is indicative of the 1956 beach construction project. However, the beach has narrowed approximately 11 m since 1970. Our analysis is limited to photo coverage, but a more severe loss would be reflected if beach width directly following the 1956 beach construction could be assessed. In fact, ancillary photos of Queens Beach in 1962 depict a narrow, undernourished beach along the southern 240 m of shoreline. By 1969, all of the sand along that section had disappeared.

Sand loss since 1970 has been chronic, contributing to continual beach narrowing. A net volume loss of 4,738 ± 52 m^3 since 1970 reveals that over half of the sand volume placed on Queens Beach in 1956 has disappeared. These long-term losses may result when longshore currents deflected by the Queens groin during high surf activities transport suspended beach sediments offshore. Additionally, the position of Queens Beach, downdrift of the Natatorium and the naturally nourished Kaimana Beach, is detrimental to sand stability. There are no significant avenues or sources of sand for natural beach replenishment. If erosion continues at the measured rate, Queens Beach may nearly disappear within 10 years.

Littoral Cell 3: Kapiolani Beach

Short-term Behavior

Profile changes at Kapiolani Beach are nearly imperceptible, implicating a relatively stable setting. Artificial changes to the position of the vegetation line, however, have lead to significant historical decreases in beach width and sand volume. Gerritsen (1978) noted similar results from profile data, observing neither nourishment nor loss of beach sands and concluding stability at Kapiolani Beach. A 513 m^3 sand volume gain is observed over the study period, with a slight loss of 1 m^3/m observed only at the centrally located profile 7 (Figure 10C).

Historical Behavior

Kapiolani has exhibited overall stability since its construction. The position of the beach toe today is slightly landward of the 1951 toe position, contributing to a narrowing of approximately 5 m. The erosion rate is only 0.1 ± 0.0 m/yr.

An average beach narrowing of 13 m from 1951 to 1970 corresponds to a volume loss of 1,982 ± 13 m^3. This can probably be credited to an initial loss of sediment following beach construction. The U.S. Army Corps of Engineers (1992) verify that erosion continued until a position approximating equilibrium was attained.

Since that time, beach toe position has been fairly static, excepting the period from 1975 to 1985. A 6 m seaward migration of the toe position is partially responsible for a wide beach in 1985. Hurricane Iwa (November 23–24, 1982) again surfaces as a possible explanation for triggering natural beach replenishment with onshore sand transport. Additionally, artificial landward movement of the vegetation line along a 160 m section of shoreline by an average of 17 m accounts for 83% of the 6,019 ± 13 m^3 volume increase between 1975 and 1985. However, subsequent changes to the vegetation line in the seaward direction account entirely for beach narrowing and a 4,700 m^3 sand volume loss between 1985 and 1992.

An August 2001 City and County of Honolulu landscaping project furthered seaward encroachment of the vegetation line. The most recent aerial photos were flown prior to the project; thus, the 2001 shoreline does not reflect vegetation line changes. However, beach profiles show that the addition of new sidewalks and grassy berms is responsible for a seaward shift of the vegetation line of 4 m at profile 6 and 30 m at profile 7. This contributes to a 23% and 63% reduction in beach width, respectively. Sand loss along this 210 m of shoreline results in a volume decrease of up to 9,100 m^3 for Kapiolani Beach.

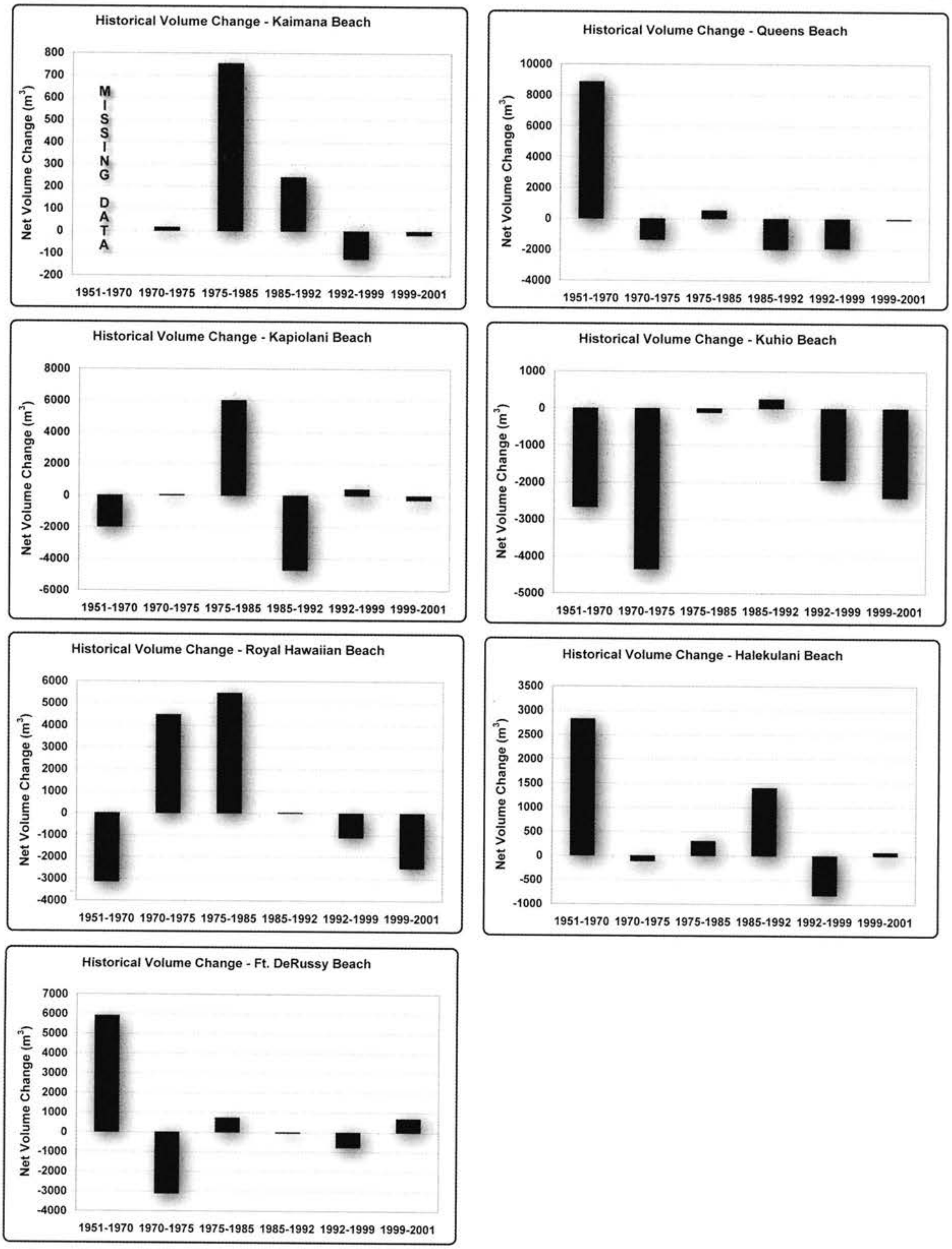

Figure 9. Volume change for historical time intervals by littoral cell.

Littoral Cell 4: Kuhio Beach

Short-term Behavior

A 223 m^3 net volume gain is observed for the basins over the 20-month study period. Losses are recorded only at the two centrally located profiles, probably due to their positions near small gaps in the offshore breakwaters. Sand losses occur at these sites occur when wave overtopping of the breakwaters creates seaward-directed return flow, scours bottom sediments, and transports sand outside the basins (Figure 10D). The same forces may be responsible for a gradual shallowing effect as sand accumulates in offshore regions of the basins.

Northwest transport in the south basin is evident by beach configuration. Coupled with basin shallowing, the effects have prompted City officials to shift sand in that basin to the south and landward after periods of gradual impoundment against the central groin. Results of those efforts are revealed in volume change data for April 2001 and again in April 2002, where losses at profile 10 equate to gains at profile 9.

Profiles 11 and 12, in the north basin, behave in unison showing minor variation with time. The varying elevation of the offshore breakwater maintaining the north basin results in diffraction of incoming waves, contributing to a non-linear beach shape and making transport patterns variable and difficult to decipher. Volume loss at profile 11 may partially result from transport to the south and may be responsible for sand accumulation in the southwest corner of the basin.

Despite short-term gains, Kuhio Beach remains in a degraded state, failing to achieve its potential recreational contributions. The condition of the beach was worsened when recent improvements to the promenade (1999–2001) managed to encroach on the sandy beach by an additional 8 m at a few sites. The lack of a sufficient elevated berm makes the beach area susceptible to large wave events and regular inundation at high tide. Under high wave conditions, there is no dry sand beach.

Historical Behavior

Despite numerous reconstruction and sand replenishment efforts, the Kuhio shoreline has demonstrated chronic erosion at an average rate of 0.2 ± 0.1 m/yr. Evidence of the first major beach construction is documented by comparing our T-sheet shoreline with the 1951 shoreline. The 1925 T-sheet shows sandy beach along a 105 m segment of shoreline located in today's north basin. The toe position records the 1939 beach construction with an approximately 39 m seaward shift of the toe between 1925 and 1951.

The beach retained its widest configuration, an average width of 47 m, directly following construction of the south basin in 1951. Prevailing erosion gave rise to Kuhio's narrowest configuration in 1970 at a loss of approximately 30 m of sandy beach and spawned further attempts to engineer the beach.

Restoration efforts are responsible for the 17 m increase in beach width from 1970 to 1975, regardless of seaward repositioning of the edge of the beach by an average 7 m with a new sea-walled promenade. Despite significant beach progradation, a volume loss of $4{,}344 \pm 5$ m^3 is observed between 1970 and 1975. There are two reasons for a discrepancy between beach width change and beach volume change. Profile data at Kuhio Beach reveal that changes in the position of the toe on the modern beach result in small profile volume changes. Note the minimal slope (0.2) of the regression line forming the dV/dX relationship at Kuhio Beach. This effect is directly related to the sand trapping effects of the Kuhio basins. Under normal wave conditions, beach sand migrating from the subaerial beach over time can become trapped within the basins and create a shallowing effect. As a result, volume may remain nearly constant while the beach progrades. On the other hand, basin configuration prior to 1975 was not identical to basin configuration today. We therefore assume beach behavior may have been significantly different. We conclude that using the modern dV/dX relationship to derive historical volumes may not be appropriate. Despite beach widening, the overall volumetric result is minimized by the slope of the dV/dX regression line. In addition, the volume loss is compounded by a seaward shift of the promenade between 1970 and 1975.

After 1975, problems associated with methodology are less pronounced, presumably because most construction had been finalized by that time and the beach began to behave in a manner similar to the modern setting. The addition of the central groin seems to have played a large role in stabilizing the beach into the future. Minor to moderate erosion prompted a 1991 nourishment. Sand fill is evidenced by a 4 m increase in average beach width and a minor volume increase between 1985 and 1992.

Beach loss has characterized the past decade with an average 9 m narrowing of the beach. Progressive landward migration of the beach toe, along with additional seaward advancement of the promenade seawall, contributes to the observed losses.

Littoral Cell 5: Royal Hawaiian Beach

Short-term Behavior

The Royal Hawaiian Beach exhibits the most dynamic behavior in Waikiki. Most beach changes occur along the western half of the beach at profiles 15 and 16. A sand volume loss of 5,800 m^3 is documented for the Royal Hawaiian Beach over the study period. While profile 13 has managed accretion, losses are magnified with proximity to the groin in the north. Net losses at profiles 15 and 16 relate to the reduced presence of reef and the high potential for rip currents offshore of the Royal Hawaiian groin (Figure 10E). Several researchers have documented the existence of strong offshore currents adjacent to the Royal Hawaiian groin (CHAVE and TAIT, 1973; GERRITSEN, 1978). GERRITSEN used dye to record the offshore current with velocities over 0.9 m/s. The study concluded that the Royal Hawaiian rip current likely represented the largest source of sediment loss for Waikiki Beach. Current documentation of sand loss at profiles 15 and 16 implies that an offshore rip current may still be responsible for permanent offshore sand loss from the Royal Hawaiian littoral cell. The effect of the rip current, coupled with longshore transport to the west and termination of historical sand sup-

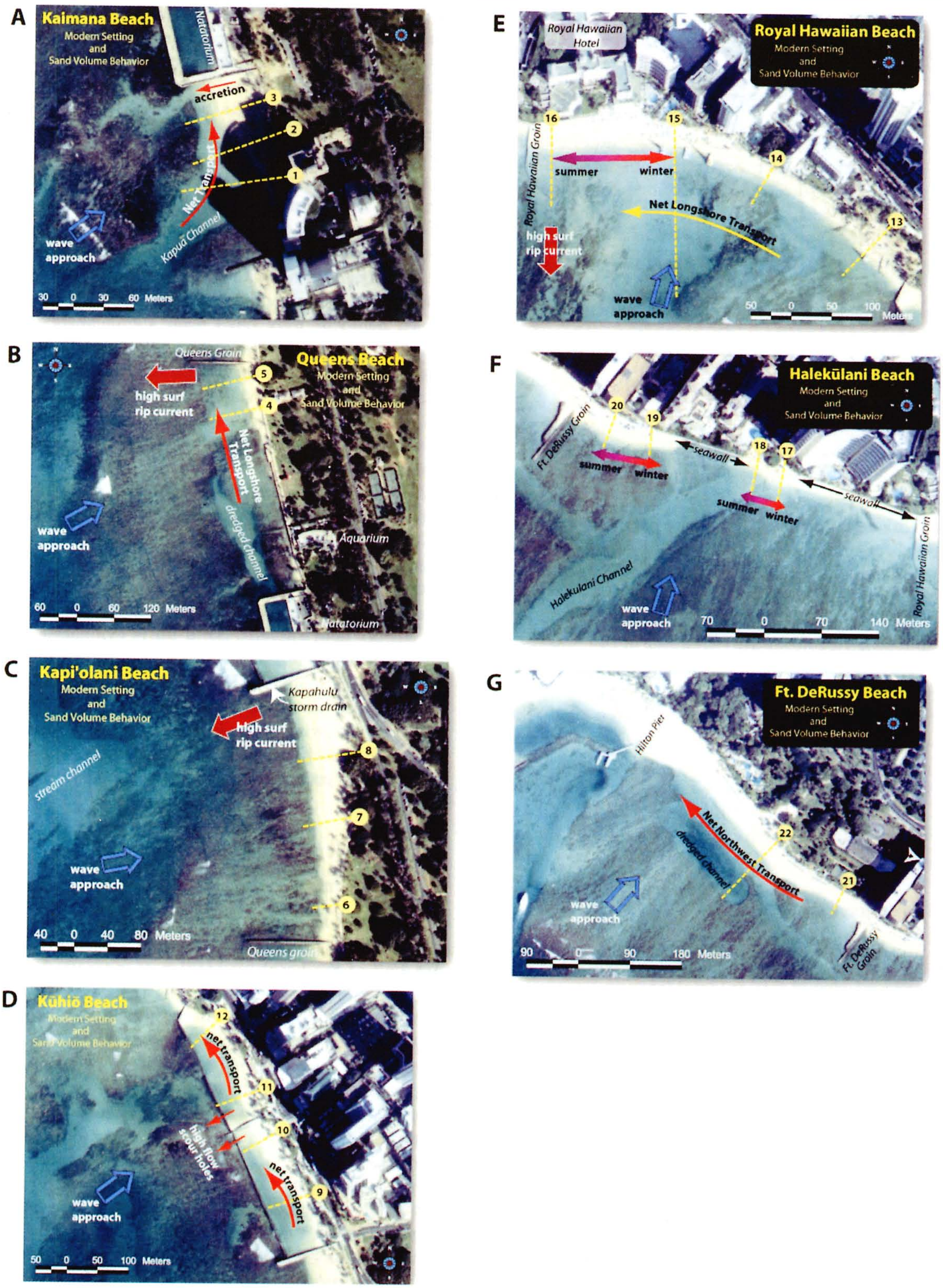

Figure 10A–G. Modern environmental setting and sand volume behavior by littoral cell, observed from beach profiles. (A) Kaimana Beach: Kapua Channel is an avenue for cross-shore transport. Net longshore transport is to the north, with accretion adjacent to the Natatorium at profile 3. (B) Queens Beach: Net longshore transport is to the north. Interruption of longshore currents by the Queens groin during high wave events can create an offshore rip, responsible for sand loss from the littoral cell. (C) Kapiolani Beach: Profile data indicate a stable setting. Interruption of longshore currents by the plies, can also account for observed beach narrowing over the past 16 years.

A wide beach configuration at the west end of the littoral cell implies net northwest longshore transport. However, short-lived shifts in the direction of longshore transport can occur due to variations in the seasonal wave regime. This often occurs during winter months as short period, high-energy kona waves direct transport to the east. This pattern is observed in the profile volume change data for January 2001 and January 2002, where volume losses at profile 16 correspond to volume gains at neighboring profile 15. Generally, this results in beach narrowing at profile 16 during winter months, with at least partial summertime recovery. The opposite is true at profile 15, where narrowing occurs during the summer season and recovery begins in winter. At an extreme level during summer 2002, beach narrowing undermined a lifeguard tower near profile 15 and officials were forced to relocate the structure landward.

Historical Behavior

Aerial photos dated to 1927 depict a long, sandy beach fronting the Royal Hawaiian and Moana Surfrider Hotels. The remainder of the shoreline was without beach at the time. A groin west of the Royal Hawaiian hotel is most likely responsible for the beach's survival and perhaps its origin. Today's beach is still heavily used and comprises an important thoroughfare between the east and west ends of Waikiki Beach.

The early years between 1925 and 1970 show a trend of accretion with an average 27 m seaward migration of the toe. The accretion is at least partially a product of terminal sand trapping by the Royal Hawaiian Groin. Historical reports have documented the success of this particular groin, while denouncing others (U.S. Army Corps of Engineers, 1992). However, distinct downdrift starvation is caused to Halekulani Beach to the west, in front of the Sheraton Waikiki Hotel.

Between 1951 and 1970, the beach experienced widening by an average 5 m. However, gains in beach width are surpassed by a corresponding volume loss attributed to an artificial seaward shift of the landward edge of the beach along 380 m of shoreline by an average of 12 m.

Kuhio Beach sand appears to have migrated to the Royal Hawaiian Beach following the 1972 Kuhio restoration, rendering the Royal Hawaiian Beach 9 m wider over the short 5-year period from 1970 to 1975. This resulted in a 4,489 $\pm$ 46 m^3 sand volume increase. However, northwest transport of Kuhio sands probably halted when structural changes were implemented at Kuhio in 1975.

A 39 m landward shift of the edge of beach along 90 m of shoreline is responsible for the 5,467 $\pm$ 46 m^3 volume increase between 1975 and 1985. However, the average beach toe position between those years remained constant. Since 1975, the beach has demonstrated erosion with a general landward shift of the toe at a rate of 0.2 $\pm$ 0.3 m/yr. Given that the erosion rate is based on the most recent trend in shoreline position, the short time scale is partially responsible for the high uncertainty. In addition, profile data have shown the dynamic nature of this beach, lending explanation to high residuals caused by short-term fluctuations of the toe from year to year. Despite the high uncertainty, consistent landward migration of the toe implies that the rate is probably well representative of the trend and should not be ignored or discounted. Recent erosional trends are exemplified by steadily decreasing beach widths and volumes. A narrowing of approximately 5 m is recorded since 1985.

Littoral Cell 6: Halekulani Beach

Short-term Behavior

A sand volume loss of 218 m^3 is recorded for the study period. Profiles 17 and 18 have experienced net losses, possibly relating to their positions at the mouth of the Halekulani channel (Figure 10F). Offshore flow under high wave conditions will seek the path of least hydraulic resistance through the channel, potentially carrying sediment offshore as well (Noda and Associates, 1991). The process is exemplified by recorded losses for May 2002 following a late April high surf event with wave heights reaching over 2 m.

Longshore transport in this region can be variable. The wave setting typically creates a condition of western transport, probably credited with the observed net gain at profile 19. Alternatively, winter wave conditions can periodically induce sand transport to the east. This is possibly the reason for lack of sand impoundment at the Ft. DeRussy groin to the west.

Historical Behavior

Halekulani Beach has experienced long-term accretion at a rate of 0.2 $\pm$ 0.1 m/yr. Beach width has fluctuated through the years, but has ultimately rendered the beach approximately 6 m wider today relative to 1951. The 1925 T-sheet designates sandy beach filling approximately the same space as the modern beach. A 16 m seaward shift of the toe is documented along those sections between 1925 and 2001. The seawall to the west of the Halekulani channel, separating the two regions of beach, has never supported sand.

The beach segments widened by approximately 6 m between 1951 and 1970, corresponding to a volume increase of 2,826 $\pm$ 33 m^3. That volume was distributed mostly over the eastern region of the littoral cell, including the area in front of today's Sheraton seawall (west of the Royal Hawaiian

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Kapahulu storm drain during high wave events can create an offshore rip current. (D) Kuhio Beach: High flow scour zones are created at gaps in the offshore breakwaters during high wave events. These are responsible for sand loss from the basins. (E) Royal Hawaiian Beach: Longshore exchange of sediment between profiles 15 and 16 varies with season. A strong rip current adjacent to the Royal Hawaiian groin is responsible for loss of sand from the littoral cell. Net longshore transport is to the north. (F) Halekulani Beach: Longshore exchange of sand between profiles varies according to the seasonal wave regime. (G) Ft. DeRussy: Net longshore transport is to the north.

groin) where there is currently no sand. It is difficult to determine from vertical aerial photos whether the newly accumulated sand attained enough elevation to augment a dry, sandy beach. However, beach profile data collected just west of the Royal Hawaiian groin from 1971 to 1973 record beach widths ranging from 15 m to 23 m (GERRITSEN, 1978). In addition, possible evidence of a historical beach has surfaced from personal communication with long-time residents and beachgoers. The source of the sand is somewhat of a mystery, but nourishment by sands from the Ft. DeRussy littoral cell during its construction (1969–1971) may be a feasible explanation.

By 1975, a good portion of the sand fronting the Sheraton seawall had disappeared and the sandy beach at the mouth of the Halekulani Channel had narrowed. But, losses in the eastern region of the littoral cell were nearly equaled by gains along the beach area west of the channel. Average beach width remained constant until 1992. Seaward migration of the beach toe is responsible for a beach progradation of 4 m and a volume increase of 1,406 ± 33 m^3 from 1985 to 1992. The opposite case accounts for a beach narrowing of about 2 m between 1992 and 1999, corresponding to a volume loss of 814 ± 33 m^3. The beach has maintained its configuration over the monitoring period from 1999 to 2002.

Ft. DeRussy Beach

Short-term Behavior

Profile changes at Ft. DeRussy Beach are nearly imperceptible. A 35 m^3 sand volume gain is observed over the study period, with net losses at profile 21 nearly equaling net gains at profile 22. This result documents the northwest longshore transport mechanism that is responsible for the observed historical trends (Figure 10G).

Volume changes relative to the mean tend to be largest at profile 21, an indication that the south end of the beach is responsive to variations in seasonal wave conditions. Profile 21 shows volume deficits during winter months with recovery during the summer. Profile 22 to the west often displays the opposing behavior during winter months, showing volume gains due to northwest-directed longshore transport from profile 21.

Historical Behavior

Average beach width increased by 41 m between 1951 and 1970 credited to beach construction in 1969 and 1970. Volume change between those years fails to show the magnitude of sand importation due to a simultaneous seaward extension of the landward edge of beach by an average of 20 m. The expansion in effect reduces the volume gain by 33%.

Erosion of the beach was rapid in the first years after construction, possibly relating to initial loss of fine-grained sediments. Average beach width narrowed by 9 m between 1970 and 1975, corresponding to a volume loss of 3,105 ± 20 m^3. Since post-construction re-equilibration, longshore transport to the northwest has been the dominant force acting on the beach. Sand from the southeast has drifted to the northwest where it is impounded against the Hilton Pier. The net result is approaching zero shoreline change, with an eroding southern section (−0.3 m/yr) equally contrasting an accreting northern section (+0.3 m/yr). There is a nodal point in the center of the beach where no shoreline change is recorded. Except for a slight widening and volume increase credited to sand importation between 1975 and 1985, the beach has remained impervious to net change.

Overall Waikiki Beach

Sand volume changes in Waikiki are best perceived through a simple sand volume budget. Sand volume additions resulting from beach construction and beach nourishment projects after 1951 total at least 77,000 m^3 (Note: Some nourishment sand volumes were left unrecorded. Thus, this number should conceivably be larger, but is unlikely to be smaller). Documenting a net sand volume gain of only 3,600 m^3 since 1951, we recognize that 74,100 m^3 of sand are unaccountable. Permanent offshore sand loss is concluded. An offshore rip-delivery process at the Royal Hawaiian Groin is probably responsible for Waikiki Beach loss prior to 1975. The same process is still responsible for sand loss from the Royal Hawaiian cell today.

CONCLUSIONS

Methodological

We found the methods here to be an effective way to analyze beach changes on a heavily engineered shoreline. The RLS method of linear regression was found to be satisfactory for determining shoreline change trends. Estimating volumetric change using a two-term model was useful to integrate changes resulting from beach toe movements and fluctuations of the landward edge of the beach. The second term is especially significant in Waikiki due to the frequency and magnitude of anthropogenic changes to the landward edge of the beach. Such changes account for 46% of the net volume change in Waikiki.

Given the engineered nature of the shoreline, occasional discrepancies arise between historical observations of beach width and the corresponding volume change. This suggests that volume change calculations must be carefully analyzed in areas where severe alteration of the shoreline has taken place.

Area Specific

Surveyed beach profiles reveal a general seasonal variability relating to the wave forcing, with erosion in winter and recovery or accretion in the summer. A net volume loss of approximately 5,200 m^3 is found for the 20-month study period. We find that 93% of the loss is accounted for by the Royal Hawaiian littoral cell, due to the reduced presence of fringing reef and the dominance of an offshore rip current in the west part of the cell evidenced by a sand shoal offshore.

Due to variable beach construction and nourishment histories, the most recent trend in shoreline position is used to compute long-term shoreline change rates. Two of seven littoral cells have shown accretion and one littoral cell has been stable, while the remaining four are characterized by chronic erosion. Observations of beach widths and volumes over the 50-year study period reflect the high level of human intervention in Waikiki, with a 32% increase in beach width and a net volume increase of 3,616 ± 461 m^3. However, erosional littoral cells show significant decreases in beach width over more recent time intervals. In addition, a sediment budget for Waikiki accounting for natural and artificial sand inputs and subsequent sand losses documents a large sand volume deficit. We conclude that permanent offshore sand loss accounts for this deficit.

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