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The influence of seasonal patterns on a beach nourishment project in a complex reef environment

Shellie Habel *, Charles H. Fletcher, Matthew Barbee, Tiffany R. Anderson

School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, United States

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ABSTRACT

Royal Hawaiian Beach, located in Waikiki, Hawaii received sand nourishment of 17,551 m^3 during the spring of 2012. Carbonate sand, dredged from a reef-top sand field 0.6 km offshore, was placed along 520 m of shoreline. Post-nourishment monitoring of the beach and offshore quantifies performance and provides transferable information for future nourishment projects in the study area and in regions with similar fringing reef environments and wave climates. Elevation data were collected along cross-shore profiles prior to sand placement and quarterly thereafter for a period of 2.7 years. The time-sequence of profile data was used to construct digital elevation models (DEMs); a method designed for this study to achieve heightened spatial accuracy relative to two-dimensional profile comparisons that often ignore measurement inconsistency. Various analyses were performed using survey DEMs, including empirical orthogonal function (EOF) analysis and surface comparison. Monitoring data were analyzed in concert with seasonal incident wave conditions to further understand processes that drive beach movement. Overall, the beach lost volume at a rate of 760 ± 450 m^3/yr over the entire monitoring period, consistent with the design rate of 1070 m^3/yr. Seasonal cycles caused beach volume to fluctuate between 2000 m^3 to 4000 m^3, i.e., 15% to 30% of total nourishment additions.

In agreement with preceding studies, we confirm predominant westward transport that we describe as counterclockwise rotation. Cross-shore sand transport through an offshore channel is also evident, as we observe the channel acting as both a sediment source and sink depending on seasonal wave conditions: a source during seasonal and storm-related swell events, and a sink otherwise.

1. Introduction

Hawaii's beaches are popular destinations, used by residents and visitors to the islands as the principal source of recreation. Unfortunately, 70% of Hawaii's beaches are chronically eroding due to both natural and anthropogenic causes (Fletcher et al., 2012; Romine et al., 2013). The Waikiki region, in particular, is host to Hawaii's premier resort hub where beaches are crucial to the state's tourism economy (Miller and Fletcher, 2003). Yet the degraded state of beaches has caused surveyed visitors to indicate their reluctance to return (Lent, 2002; USACE, 2002). In response to the impact of beach degradation on the visitor industry, engineering efforts have been ongoing for more than a century in Waikiki with the goal of retaining sediment and improving access (Wiegel, 2008).

Beach nourishment is the preferred method of maintaining chronically eroding coastlines in Waikiki; this approach reestablishes the sediment budget and effectively maintains usable beach widths while protecting beachside property (Crane, 1972). Since the 1950's, more than 229,000 m^3 of sand have been imported and placed on beaches between Honolulu Harbor and Diamond Head (Wiegel, 2008). Following placement, much of the nourished sand is thought to have been transported seaward by nearshore dynamics (Environmental Assessment, 2010). Offshore sand deposits now provide a proximal and sustainable source of sediment for beach re-nourishment. The State is currently developing a long-term and cost-effective strategy for maintaining Waikiki's beaches that employs the quasi-periodic recycling of offshore sand deposits to eroded beaches. To date, three nourishment projects have been conducted in Waikiki since the year 2000 that utilize this offshore sediment source (Environmental Assessment, 2010). The third project was carried out in early 2012 and monitored for a period of 2.7 years following sand placement; this monitoring effort is the topic of the present study.

As sea level rise continues, erosional trends are expected to accelerate on Hawaiian beaches (Anderson et al., 2015). Efficient planning of future beach maintenance efforts will be crucial in mitigating prospective impacts. However, the development of a streamlined maintenance program requires a strong understanding of post-nourishment beach behavior. Monitoring studies improve our understanding of sediment transport within the unique reef-fronted, carbonate beach environments of Hawaii,

* Corresponding author:
E-mail address: skey@hawaii.edu (S. Habel).

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and routinely provide observations employed in model calibrations. This allows continuing improvement in the design of subsequent nourishment projects (Dean, 2002). There are currently few published examples of carbonate beach fills where sediment transport is complicated by a fringing reef platform (Benedet et al., 2007; Muñoz-Perez et al., 2001). The results of this study, then, are valuable additions to the global literature pertaining to nourishment efforts within tropical regions. The primary objectives of the present study are (1) to evaluate the behavior and stability of the nourished beach, (2) to provide observations that can be used to establish an efficient schedule for future beach maintenance, (3) to link quantitative measures of beach change with wave forcing in the reef environment, and (4) to improve understanding of sediment behavior in reef environments.

2. Location description and nourishment project

2.1. Project background and objectives

In the spring of 2012, a beach nourishment project was completed along the Royal Hawaiian Beach segment of Waikiki on the island of Oahu, Hawaii. This was the largest nourishment effort to take place in 40 years within the Hawaiian Islands (Sullivan and Smith, 2014). The nourishment was completed at a cost of $2.9 million, funded by a joint public-private partnership including contributions from the State of Hawaii, the Hawaii Tourism Authority, and Kyo-ya Resorts. The Department of Land and Natural Resources (DLNR), the trustee of Hawaii beaches and coastal lands, oversaw the project. The objectives of the nourishment were to restore the esthetics and recreational usage of the beach in response to long-term chronic erosion, and to promote lateral access along the shore (Environmental Assessment, 2010).

As part of the nourishment project, the following components were proposed (Environmental Assessment, 2010):

- Recovery and dewatering of 18,350 m^3 (24,000 yd^3) of sand from sources located approximately 0.6 km offshore of the nourishment site.
- Emplacement of sand along a 520 m (1700 ft) segment of coastline with the goal of increasing the beach width by an average of 11.2 m (37 ft), restoring the beach width to the extent of the 1985 shoreline and not beyond.
- Increase of beach area above the high tide line by 6040 m^2 (7900 yd^2).
- Removal of two dilapidated sand bag groin structures located near the easternmost end of the project area. Groin removal was advised owing to their poor condition, blockage of access along the beach, and lack of significant effect on littoral processes for sand retention and transport.

The original beach design featured a 1V:7.5H slope, a crest elevation of +2 m, and a toe elevation of −1 m. The beach slope and crest elevation were predicted to reach an equilibrium profile similar to the pre-nourished beach (Environmental Assessment, 2010). Beach width was expected to reduce by half approximately 10 years following initial replenishment. Hinging on the success of this first phase of nourishment, a second phase was planned that included sand placement of an additional 9000 m^3. These two project phases were designed to maintain beach width for 20 years following the initial replenishment.

The sand used for nourishment was recovered from offshore sand deposits using a submersible Toyo DB75B slurry pump. The pump was suspended from an 80-ton capacity crawler crane that was stationed on a barge from which sand was pumped through an 8-inch pipeline to an onshore dewatering basin (Fig. 1). Mined sand was composed of carbonate and reported as having the same grain size distribution, texture, and similar color as the existing beach sand. The sand source had a median diameter of 0.34 mm with no coarse material, minimal fines and was composed of calcareous skeletal fragments of corals, coralline algae, mollusks, echinoids and foraminifera.

The original project design proposed the use of a pneumatic conveyance system to transport sand from the dewatering basin to placement locations. However, inadequate transport speeds of the conveyance system necessitated an alternative approach to distribute sand along the project length. Grading and sediment transport was ultimately accomplished using an 18 metric ton DK6 Dozer, and several CAT 725 dump trucks weighing over 45 metric ton when fully loaded.

Various forms of evidence suggest that the truck haul method of sediment conveyance caused compaction of nourished sands. Project engineers reported a 10% compaction factor based on sediment compaction tests designed to replicate the sand placement method (Sullivan, unpublished results). The DLNR attributed a 0.3–1 m hardened berm that formed along the seaward edge of the haul route as the product

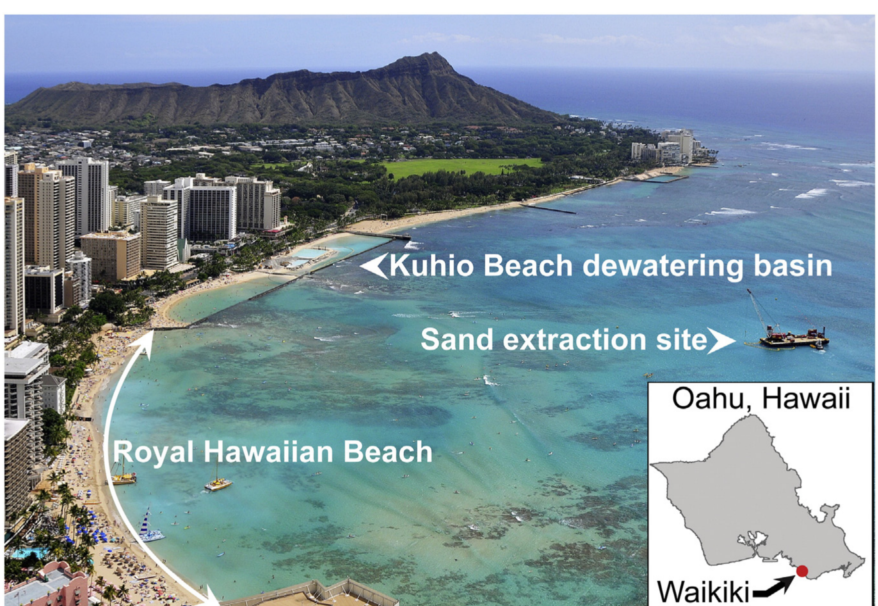

Fig. 1. Aerial image of Royal Hawaiian Beach and Kuhio Beach, which are respective locations of the 2012 nourishment project and dewatering basin. Image shows beach condition immediately prior to sand placement. West is towards the bottom of the figure.

of truck hauling (DLNR, 2013). Chemical compaction may have also resulted from the method of sand placement as extreme loading has been shown to cause chemical compaction in the form of carbonate dissolution (Croizé et al., 2010). Visual observation of a fine sediment plume throughout the course of nourishment support the probability of carbonate dissolution, as it was verified that no fines were present in the mined sand field prior to dredging and transport.

2.2. Project location

The Royal Hawaiian Beach extends 520 m in a crescent shape between two structures that compartmentalize the littoral system. Structures include the Royal Hawaiian groin at the western end of the beach, and the Kuhio Beach Ewa groin at the eastern end (Fig. 2). The Royal Hawaiian groin extends 50 m perpendicular to shore, transitioning then to a nearly 60 m arcuate section that continues in the southeastern direction; the Kuhio Beach Ewa groin extends approximately 60 m perpendicular to shore. At present, the groins prevent significant longshore transport into or out of this littoral cell; thus, sediment additions/subtractions occur mainly through cross-shore transport.

Towards the central and western end of the study area, currents move through a shallow submarine channel that acts as a conduit through which cross-shore sediment transport occurs; currents have been observed in this channel with velocities of over 0.9 m/s (Gerritsen, 1978). The Royal Hawaiian littoral cell has been shown to account for 93% of the sediment loss in Waikiki, partially resulting from sediment transport by strong currents through this offshore channel (Miller and Fletcher, 2003).

Other than the channel region, the project shoreline is fronted by a wide and shallow carbonate reef platform extending more than 1000 m offshore. The shallow bathymetry engenders dynamic wave and current conditions as waves propagate towards shore. The resulting wave-induced longshore current flows predominantly to the northwest at velocities generally below 0.15 m/s (Gerritsen, 1978), reversing occasionally due to seasonal changes in swell direction (Gerritsen, 1978; Miller and Fletcher, 2003).

Waikiki is directly exposed to south swell generated by storm activity in the Southern Ocean, and Kona swell, produced by local fronts that develop to the southwest. North swell, known to produce Hawaii's world-class surfing conditions, is blocked by the island and has little effect on Waikiki beaches. South swell occurs with a frequency of 53% over the summer months (Apr–Oct), generating average significant wave heights and relatively longer periods of 0.8 m and 13.1 s respectively (Homer, 1964). Kona swell generally occurs over the winter season with a frequency of 10%, producing average significant wave heights of 1 m with larger waves ranging from 3 to 5 m, and relatively shorter periods ranging from 8 to 10 s (Homer, 1964). Waikiki has been shown to experience general erosion under shorter period winter waves, recovering in the summer under longer period southern swell (Miller and Fletcher, 2003; Norcross et al., 2003).

Tropical cyclone-generated waves can affect the Waikiki area when storms track to the south of the island chain. Two such storms, formed during the 2014 central North Pacific hurricane season, generated large waves and strong winds; Hurricane Iselle, downgraded to a tropical storm, passed to the south in early August, and Hurricane Ana, a category 1 storm, passed to the south in late October (NOAA, 2014).

3. Monitoring methodology and analysis

3.1. Beach surveying

A monitoring program was initiated with the following three objectives: establishing a baseline for pre- and post-nourishment beach comparison, evaluating beach behavior and stability following the nourishment project, and observing long-term seasonal influence on changes in beach morphology. Monitoring included the collection of a time series of measurements documenting change in beach width, volume, and morphology. The methodology for surveying employed standard techniques developed by the United States Geological Survey (USGS) for the Hawaii Beach Profile Monitoring project (Gibbs et al., 2001).

Surveying was conducted approximately one month prior to the start of the project to establish a baseline for post-nourishment analysis.

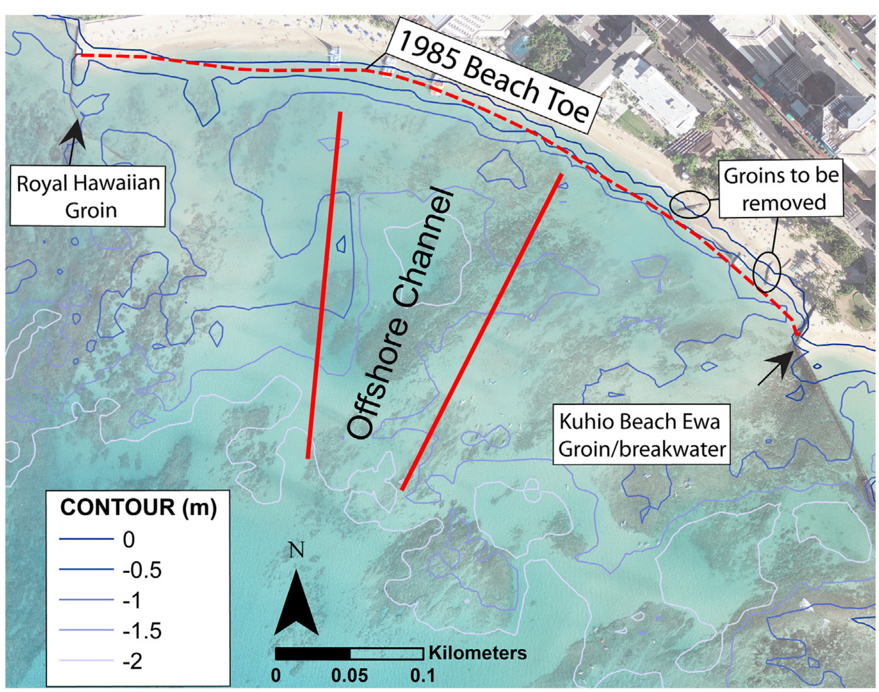

Fig. 2. Location of the submarine channel offshore of the nourished beach area, terminal structures, removed dilapidated groins, and the 1985 beach toe used by project engineers as a seaward boundary for nourishment design. Bathymetry contours provide an approximate location of the offshore channel; however, contours likely shift as a result of sand movement.

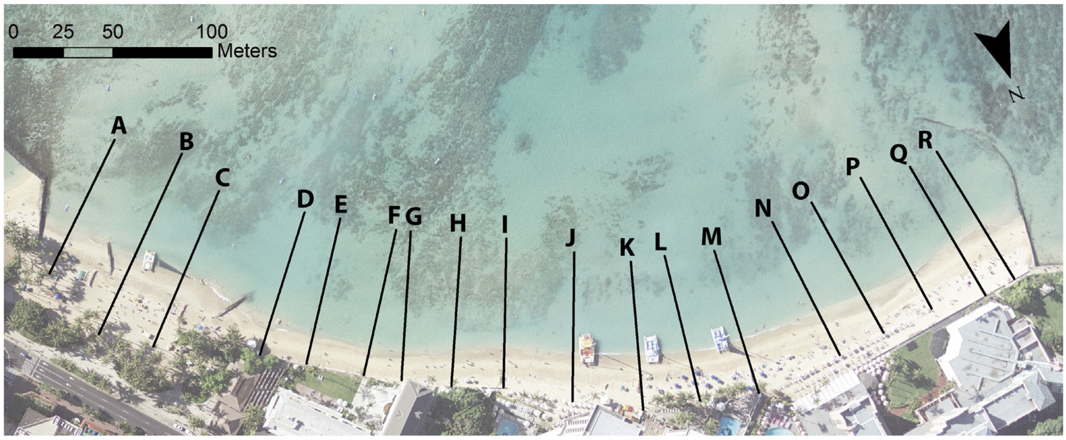

Fig. 3. Cross-shore profiles denoted by letter from A to R. Length of lines not intended to depict survey extent.

The nourishment project began in January of 2012, followed by one mid-nourishment survey and eleven quarterly post-nourishment surveys. The initial post-nourishment survey, accomplished 10 days following the completion of sand placement, was used in determining total nourished volume.

As shown in Fig. 3, eighteen shore-normal profiles were established at roughly 30 m intervals along the 520 m project. Profiles extended from hard structures located at landward boundaries to offshore distances of more than 150 m. Offshore measurements were taken along transects to points beyond the fringing reef, or to depths of 2–3 m where fringing reef was absent.

Using a Leica TC407 Total Station, profiles were surveyed by tracking a swimmer moving a rod-mounted prism across the beach, into nearshore waters, and over the fringing reef. The swimmer followed respective transect lines collecting measurements every 3–5 m and at pertinent geomorphic features. Surveying was accomplished randomly with respect to wave state and tidal cycle. A reference frame was defined for this study by migrating measurements into WGS84z4 coordinate space using six control points surveyed by contractors prior to nourishment.

3.2. Shoreline analysis

Profile measurements were used to construct a time series of Digital Elevation Models (DEMs). The DEMs were constructed using the triangulated irregular network (TIN) method of interpolation. Prior to DEM construction, data were processed using the following methodology, demonstrated in Fig. 4: each profile data set was aligned using surveyed control points; data coverage was enhanced by including positions of exposed hard substrate measured over the entire monitoring period, as well as sand elevations measured at the contact between engineered structures and the beach surface; following interpolation, each TIN was corrected for profile shape by forcing elevation congruence between similar morphologic features on adjacent profile lines. The time series of DEMs were used as part of all methods of analysis including volume,

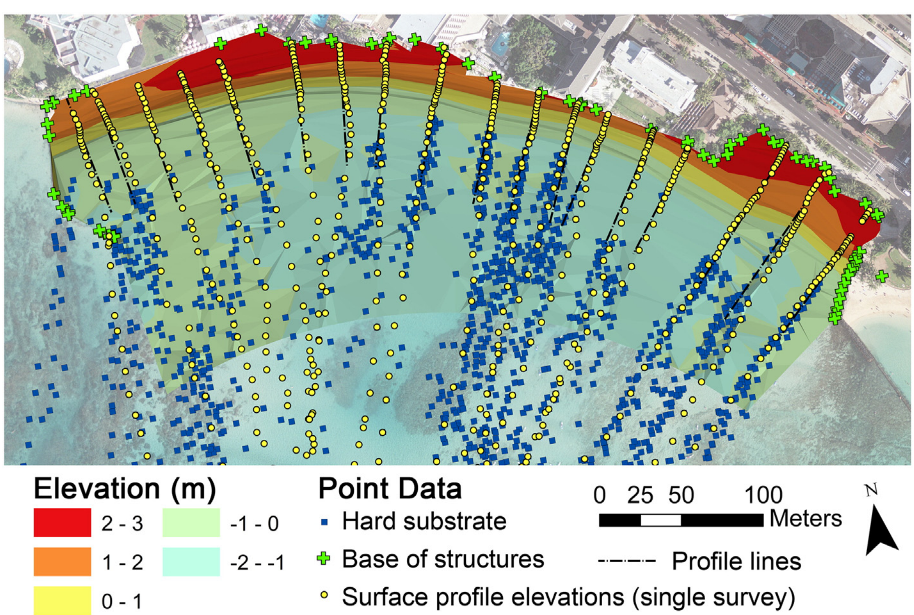

Fig. 4. Demonstration of DEM construction methodology. Predefined profile bearings are shown as black dashed lines. Elevation data are superimposed on the corresponding interpolated TIN that ranges in color to illustrate general elevation change (blue to red). Elevation data include: surface elevations measured during a single representative survey (yellow points); sand elevation measurements taken at the base of engineered structures (green crosses); cumulative measurements of exposed hard substrate collected over the entire monitoring period (blue squares). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

area, and width calculations, surface comparisons, and empirical orthogonal function (EOF) analysis.

3.3. Volume calculations

The depth of closure is commonly used to provide an essential basis for calculating beach width and volume (Dean, 2002; Hallermeier, 1978). However, depth of closure is complicated within the study area by the presence of fringing reef, sand patches, and an offshore channel. Due to the lack of an obvious equilibrium seaward boundary, volumes were calculated for the beach area extending a nominal 20 m seaward of the initial post-nourishment beach toe; herein, we refer to this as "beach volume". Volumes were additionally calculated for an area that includes the beach volume but which extends an additional ~150 m seaward of the beach toe to capture changes in offshore volume; herein, we refer to this as "system volume". Volume was calculated for each DEM using the ArcGIS tool "Surface Volume" that sums the volumes of triangles that make up a TIN surface down to a reference elevation (−4 m). Since all volume calculations involve taking the difference between volumes with identical spatial footprints, the reference elevation is arbitrary.

3.4. Uncertainty

Two main sources of elevation error are identified; these are survey measurement error and surface interpolation error. Instrument error is considered negligible as the measurement device has millimeter accuracy. Survey measurement error was found to be 5.8 cm based on the standard deviation of the discrepancy between measured and established control point elevations.

Surface interpolation error was estimated by conducting a separate survey in which both profile measurements and random elevation measurements were recorded. The profile measurements were used to interpolate a surface from which elevation values at random point locations were extracted. Interpolation error was found to be 10.5 cm based on the standard deviation of disparities between interpolated and measured elevations. The quadrature sum of survey measurement and surface interpolation error was multiplied by the beach area, and separately by the system area, to estimate the uncertainty in volume calculations.

Calculations of beach width and area were accomplished using the Mean Higher High Water (MHHW) datum contour as a seaward boundary for each survey. This boundary was used to maintain consistency when comparing width and area measurements with the nourishment goals stated by project engineers. The main source of uncertainty was identified as the lateral discrepancy in projected MHHW contours resulting from vertical measurement and interpolation error. The lateral uncertainty was estimated by projecting elevation contours that assume vertical error above and below the MHHW datum.

3.5. Empirical orthogonal function (EOF) analysis

Empirical orthogonal function (EOF) analysis was used to quantify spatial-temporal modes of variability in beach profile data (e.g. Aubrey, 1979; Dick and Dalrymple, 1984; Losada et al., 1991; Norcross et al., 2003; and Winant et al., 1975). This multivariate analysis has been designed to reveal dominant modes of variability within data sets and is routinely used to study beach profile evolution along coastlines. To maintain consistent points for evaluation, surface elevations were extracted from interpolated surfaces at 10 m intervals along predefined profile lines. The time average was removed so the analysis would describe variations from the mean beach profile. We focus on the first four modes, which describe abrupt additions of sediment across the beach resulting from the nourishment project, as well as seasonal variations in sediment transport; together they represent nearly 80% of the total data variance.

3.6. Shoreline response to wave forcing

To reveal seasonal influence on beach stability, a comparison was made between the performance of nourished additions and the regional wave conditions following Eversole and Fletcher (2003). Time series of regional hourly significant wave height (H_{mo}), mean direction and mean period (T_m) were acquired from the Simulating Waves Nearshore (SWAN) Regional Wave Model for the island of Oahu. This model was designed to capture shallow water effects and nearshore coastal dynamics with a 7-day output at approximately 500 m resolution. Data were acquired for the most proximate grid cell, representing 21.27 N and 202.17 E and were provided by PacIOOS (www.pacioos.org), which is a part of the U.S. Integrated Ocean Observing System (IOOS®), funded in part by National Oceanic and Atmospheric Administration (NOAA). Wave energy was quantified by calculating incident wave energy flux by means of integrating potential and kinetic energies along the full length of the wave. This calculation yields total energy density and is related directly to wave height, while the rate at which wave energy travels depends on wave period. Incident wave energy flux assuming shallow-water wave speeds is given by $P = (\rho g^2 H_{mo}^2 T_m)/16\pi$ where T_m is period, H_{mo} is significant wave height, g is gravitational acceleration, and ρ is the density of water (Komar, 1998).

4. Results of monitoring and analyses

4.1. Immediate additions

Sand placement progressed along the beach from east to west over a 20-day period that began during the week of 3/12/12. Incremental measurements of placed sand volume were conducted daily by contractors, yielding a total estimated volume of 17,551 m^3 sand placed in the littoral cell (Sullivan, unpublished).

As part of this study, a mid-nourishment survey was accomplished on 4/5/12 and used to evaluate additions in beach width for the completed eastern extent of the study area. An average beach width increase of 9 ± 1 m was confirmed based on this survey. Sand placement was completed on 4/25/12, and on 5/4/12 the initial post-nourishment survey was carried out with the purpose of evaluating total nourished volumes. An average width increase of 7 ± 1 m was confirmed based on this survey in addition to an area increase of 3800 ± 500 m^2, a beach volume increase of 12,700 ± 3700 m^3, and a system volume increase of 13,700 ± 6300 m^3.

4.2. Endurance of nourished sand and seasonality

Fig. 5 illustrates the performance of nourished additions over 2.7 years following project completion. The percentages of total remaining (or augmented, owing to increases above 100%) additions in width, area, beach volume and system volume are plotted with respect to time; no corrections have been made regarding background erosion rates. Remaining and augmented placements have been plotted alongside incident wave energy flux and wave direction to illustrate relationships relating to volume change.

The time series illustrating nourishment performance reveals a cycle of erosion and accretion in phase with seasonal wave conditions, which varied by up to a factor of 4 between summer (May–Oct) and winter months (Nov–Apr). Incident wave energy during the winter months generally ranged between 2000 and 8000 kgm/s^3. Incident wave energy increased above 10,000 kgm/s^3 during the summer months and peaked to more than 20,000 kgm/s^3 during the particularly active 2014 hurricane season. Variations in nourishment additions roughly shadowed the seasonal swell cycle, characterized by a post-winter minimum and a mid to late summer maximum.

The pattern of volume, area, and width change exhibited more dynamic behavior during the first year, during a period of post-

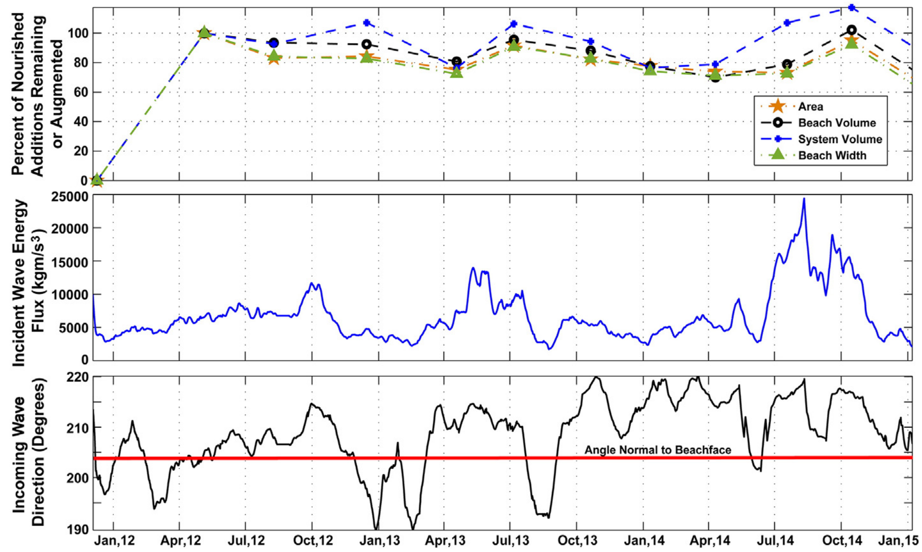

Fig. 5. Performance of beach fill compared to a monthly moving average of wave energy flux and direction. Symbols in top graph indicate survey dates.

nourishment equilibration. However, increases in wave energy appear to have moderated the rate of erosion during this time, and over the following two years resulted in substantial increases in area, width and volume. The peak in wave energy during the summer of 2014 correlates with increased beach and system volumes that essentially neared or surpassed the original nourishment volume.

Generally, the most significant seasonal fluctuations occurred in the system region; however, the positive correlation of wave energy to beach volume, area and width is discernible.

Overall, the beach region lost volume at a rate of 760 ± 450 m^3/yr over the entire monitoring period, which is consistent with the design rate of 1070 m^3/yr (Environmental Assessment, 2010). Seasonal cycles caused beach volume to fluctuate between 2000 m^3 to 4000 m^3; corresponding to 15% to 30% of total nourished additions. By the end of monitoring, during the more erosive point in the season, 75 ± 22% of the nourished beach volume remained. Volumetric measurements including the system region illustrated a particularly stable sediment environment, exhibiting a not significant accretional 100 ± 700 m^3 rate of annual change. Seasonal and hurricane-related fluctuations in the system region were roughly 5000 m^3, which boosted volumes near or above that of the original nourished volume during the summer seasons, likely indicating exchange with offshore deposits. By the end of monitoring, 90 ± 35% of the original nourished volume remained within the system region. Note that substantial reported uncertainties in volume result from applying a small vertical error across sizable areas.

The overall average rate of width loss was 0.50 ± 0.25 m/yr over the entire study period, which is consistent with the historical erosion rate of 0.5–0.7 m/yr from 1985 to 2009 (Environmental Assessment, 2010). By the end of monitoring, 65 ± 13% of the average nourished beach width remained.

4.3. Non-uniform beach change

Presented in Fig. 6 is the performance in beach width of each measured profile in the study beach. The annualized erosion/accretion rates for individual beach profiles were evaluated using simple linear regression analysis; seasonal influence altered the exponential signal of shoreline equilibration generally observed following nourishment projects (Dean, 2002).

The eastern portion of the beach (transects A–H) experienced the highest rates of erosion, ranging from 1.6–2.9 m/yr. Much of the western extent of the study area experienced accretion; these transects (K–O) front the offshore channel that is known to act as a conduit for sand transport (Gerritsen, 1978).

4.4. Elevation change

Figs. 7 and 8 confirm sediment placement and subsequent shoreline evolution over the course of monitoring. Changes relative to pre-nourishment conditions are illustrated in map view as a time sequence of contour maps (Fig. 7), and in cross-section (Fig. 8) along two profiles

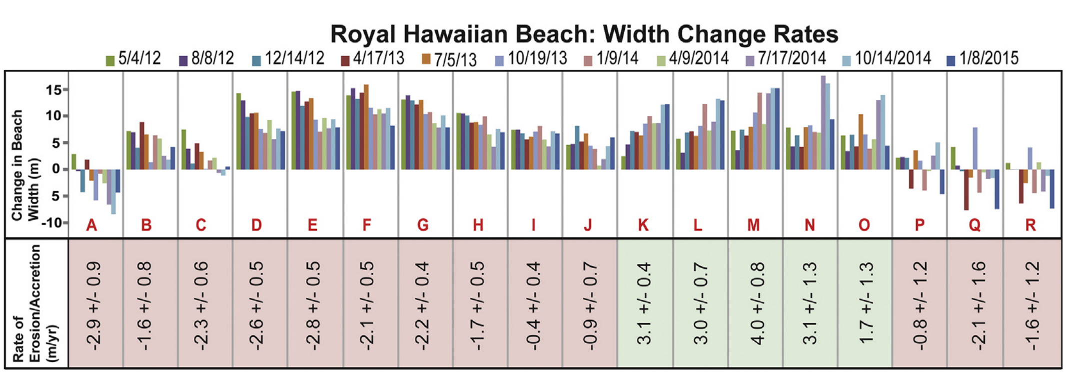

Fig. 6. Successive width measurements for individual beach profiles relative to pre-nourishment conditions (top); rates of shoreline change evaluated at individual beach profiles (bottom); negative values indicate erosion and positive values indicate accretion.

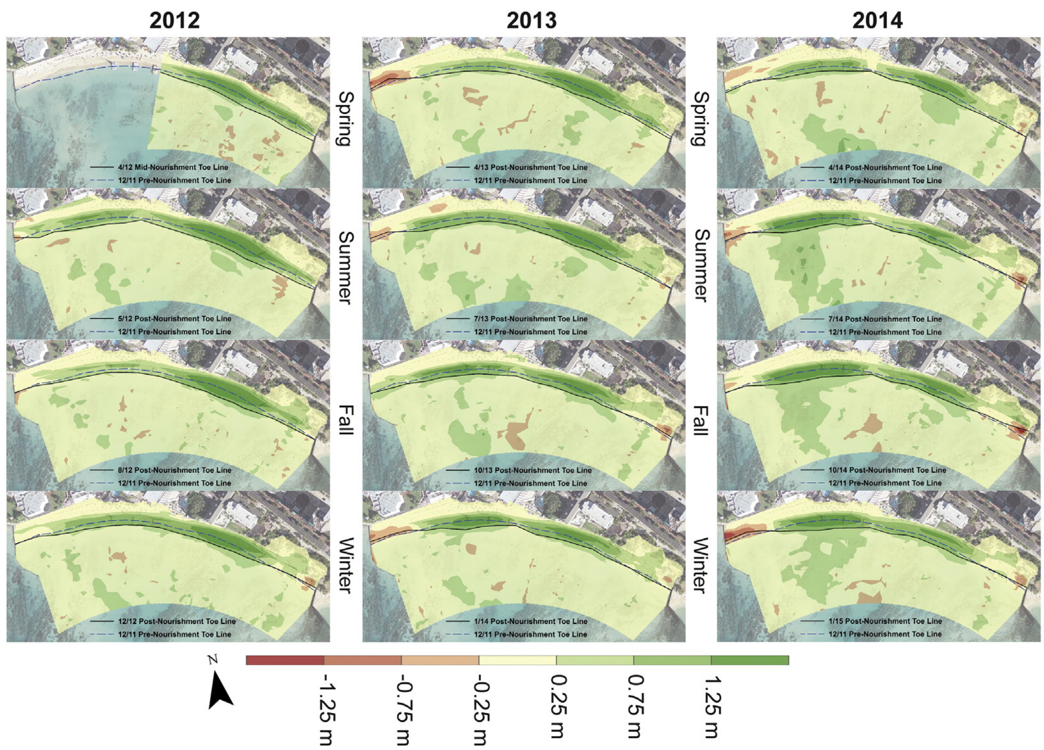

Fig. 7. Contour maps illustrating post-nourishment elevation change relative to pre-nourishment conditions. Respective survey and pre-nourishment beach toe locations are superimposed on contour maps.

that represent the highest rates of erosion (profile E) and accretion (profile M) respectively. The two profiles are presented here to show the long-term counterclockwise rotational signal between the eastern end of the beach and the region fronting and within the offshore channel.

The sequence of contour maps confirms elevation increases, immediately following nourishment, of more than 1 m, especially across the eastern extent of the study area. Over the course of monitoring, nourished additions diminished along the eastern extent of the beach and increased along the west, indicating net westward transport. Sediment exchange occurred between the eastern and western ends of the beach, evidenced by erosional hotspots in the west during winter and spring, and in the east during summer and fall. The offshore channel experienced elevation fluctuations, especially throughout the summer of 2014 when significant elevation gains ensued.

Cross-shore profiles confirm the occurrence of a significant seaward shift of the beach toe directly following nourishment. Along profile E, the beach toe shifted progressively landward over the course of monitoring. Seasonal shifts were nearly indistinct along this profile, with only slight increases in landward movement over the summer months and into early winter. Along profile M, the beach toe shifted progressively seaward over the course of monitoring. Seasonal shifts in the profile were more distinct at this location, building seaward over the summer months and eroding landward over the winter months. During the summer of 2014, coinciding with elevated storm activity, significant seaward shifts of the beach toe ensued in concert with sediment buildup in the offshore channel.

4.5. Empirical orthogonal function (EOF) results

The EOF analysis clearly identifies the nourishment project as the dominant source of data variance over the monitoring period (Fig. 9). The dominant mode demonstrates abrupt net increase in elevation across the subaerial beach resulting from sand placement, especially on the eastern extent of the beach. The initial nourishment is followed

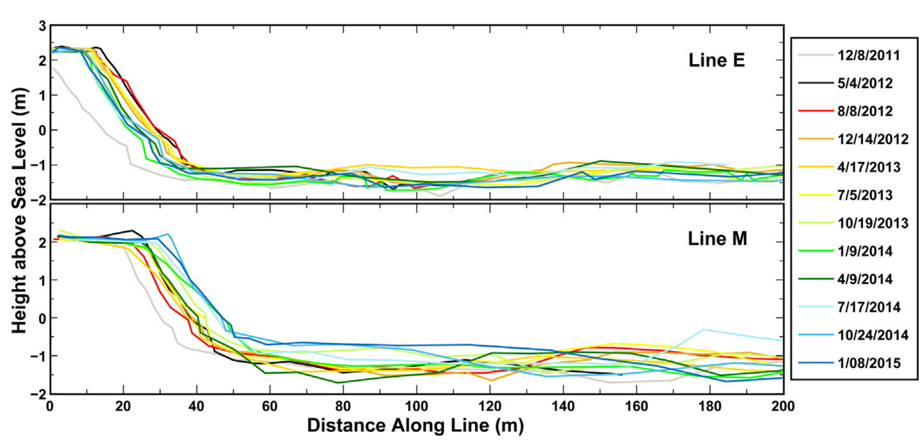

Fig. 8. Cross-shore profiles at representative transects: (Upper) most erosive transect (profile E) and (Lower) most accretive transect (profile M). The pre-nourishment profiles (12/8/11) and post-nourishment profiles (5/4/12) are included as grey and black lines respectively.

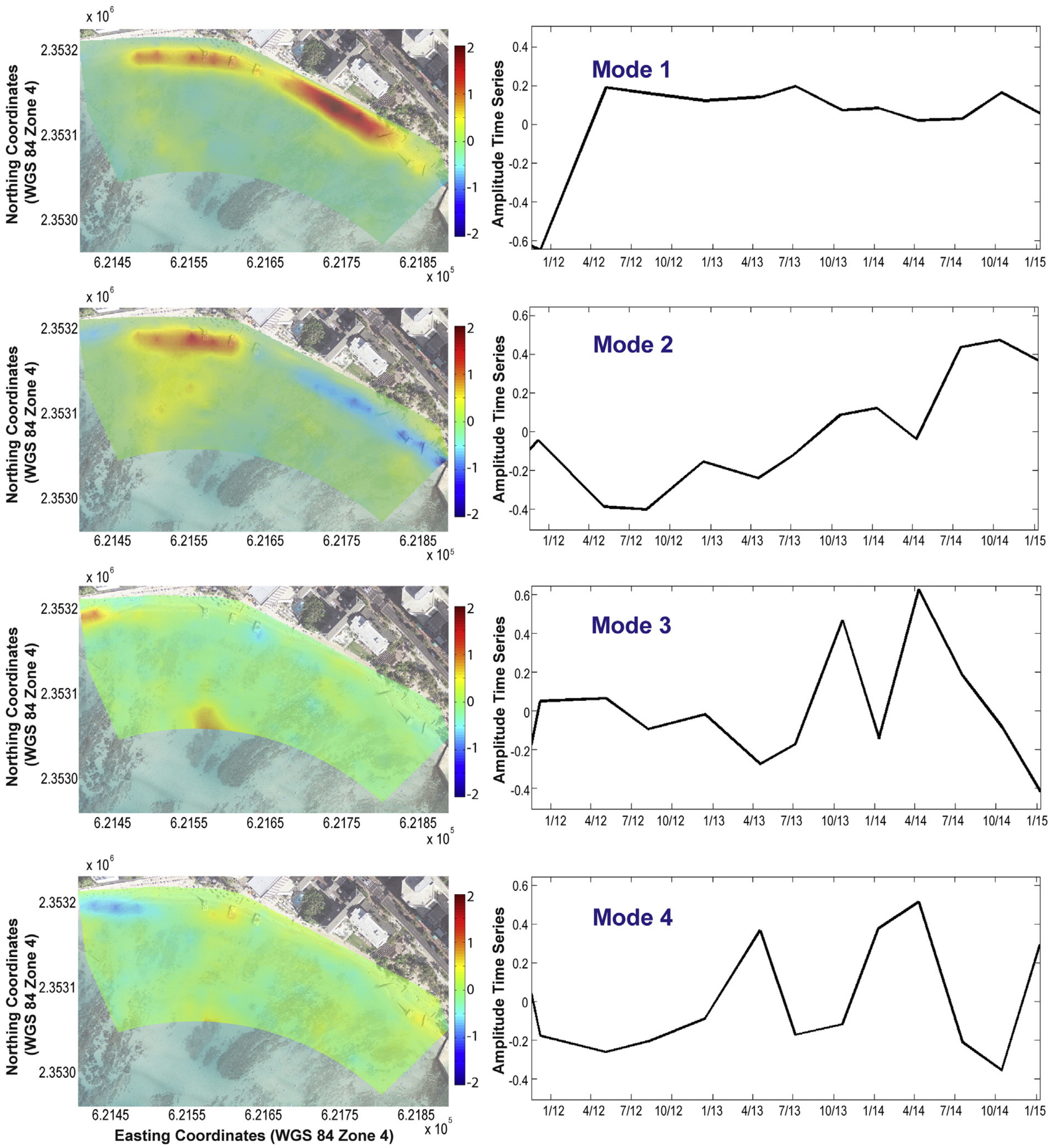

Fig. 9. Spatial and temporal plots of the first four principal components of surface variability over the study period. Regional plots (left) are map views with values that can be coupled with the temporal plots (right) to arrive at the magnitude of variance throughout the study period. The first four modes represent nearly 80% of the total variance; the first mode (representing the nourishment) explains over 35%, while the second mode (representing longshore and cross-shore channel transport) explains over 25%. Modes 3 and 4 (representing small scale exchanges of sand) explain a total of 17%.

by slow decline, interrupted by moderate gains that coincide with increases in wave energy. The spatial component also indicates a modest elevation increase in portions of the offshore channel, as well as west of the channel during the nourishment; it is likely that this increase is a product of beach erosion as it correlates to a period when the offshore channel would otherwise experience sediment loss.

A rotational signal between the eastern end of the beach and the offshore channel is described by the second mode. Rotation is likely produced by a combination of longshore and cross-shore sediment transport processes. Regions within and fronting the offshore channel experienced overall inflation over the monitoring period in addition to inflation and deflation in sync with summer and winter seasons respectively; the remainder of the beach demonstrated the opposite behavior. Cross-shore sediment transport through the offshore channel also appears to have reversed in direction seasonally; however, seasonal transport directionality cannot be discerned solely by means of the present EOF analysis. Inflation clearly occurred in the offshore portion of the channel during the summer months; yet, sediment buildup could have resulted from seaward transport of nourished sediment to the offshore channel, or by landward transport of sediment from sources outside of the monitored region.

The third and fourth modes explain smaller scale sediment exchanges. The third mode describes sediment exchange from the western end of the beach and offshore channel region to the center of the beach. The cause of this signal is unclear; hence, we assume that sensitive sediment transport systems exist in the study area that cannot be solely characterized by wave parameters from the PacIOOS SWAN model. Conversely, the fourth mode explains a clear seasonal signal of sediment exchange from the western end of the beach to the central and eastern beach extents. Patterns of inflation and deflation along the western end of the beach during the summer and winter months respectively correspond to the known seasonal reversal of longshore transport direction.

5. Discussion

5.1. Performance

The nourishment performed well when considering physical performance measures of long-term width and volume stability, and seasonal recovery. The majority (90 ± 35%) of the baseline post-nourishment volume remained within the system region by the end of monitoring and the background rate of volume and width loss in the beach region was found to be consistent with that anticipated by project engineers. The project did not include measures to correct historical erosion rates; hence moderate erosion was expected to persist. Unexpected losses in overall width and volume were not observed; however, unexpected volume gains occurred following increases in incident wave energy flux above 10,000 kgm/s^3.

5.2. Offshore transport of sediment during nourishment

Initial monitoring surveys conducted approximately two weeks following project completion revealed a sand volume addition in the beach region of 12,700 ± 3700 m^3, a lesser volume than the contractor estimate of 17,551 m^3. Some of the volume difference likely resulted from rapid beach profile adjustment following initial placement and sediment compaction caused by the method of sand placement. Rapid beach profile adjustment is supported by the 2 m loss in beach width that occurred over the 31 day period between the mid-nourishment survey and the subsequent post-nourishment survey. In addition, the initial post-nourishment survey revealed a volume increase in the system region of 13,700 ± 6300 m^3. Although the data do not reveal a significant difference between volumes of the beach and system regions, they may indicate that a modest and highly uncertain volume of sand was transported offshore during the 20 days of sand placement and shortly after the nourishment. This finding is supported by contour maps and the EOF analysis indicating increases in elevation within the offshore channel and to the west of the channel. If true, these initial offshore gains occurred during a season when the channel would otherwise experience sediment loss, and during a period of unexceptional wave energy.

5.3. Seasonal erosional hotspots

Localized erosional hotspots were observed adjacent to terminal groin structures. Peak rates of erosion were measured at the far eastern end of the beach, adjacent to the Kuhio Beach Ewa Groin, resulting in the temporary exposure of an antecedent hard structure usually buried beneath the beach face. Erosional hotspots likely formed in response to seasonal reversals in rotation that shifted sediment towards or away from terminal structures. The lack of sand inputs from adjacent sources ("flanking") is the likely mechanism for erosion. Due to the removal of dilapidated groins that might otherwise act as a barrier to sediment transport, erosion issues were naturally resolved by reversals in rotation that allowed seasonal recovery of the beach face and burial of antecedent hard structures.

5.4. Beach rotation

A long-term counterclockwise rotational signal of sediment transport was prominent throughout the monitoring period, punctuated by seasonal reversals in transport direction. The presence of a rotational signal is common in environments similar to that of the study area that host a bidirectional wave climate, terminal sediment barriers, and non-uniform wave exposure (Dolphin et al., 2011; Harley et al., 2011). The observed rotational signal strengthened during the summer months in concert with seasonal increases in incident wave energy flux above 10,000 kgm/s^3 and an overall southwesterly wave approach. This pattern is indicated by the second mode of EOF analysis that shows long-term inflation of the western and offshore channel regions in concert with deflation of the eastern region. Profile accretion rates also support this finding, revealing long-term accretion of up to 4 m/yr in the region fronting the offshore channel, and long-term erosion across the remaining profiles. Temporary seasonal reversals in rotation are indicated by the temporal plot of the second mode of EOF analysis. The plot shows an opposite pattern of inflation/deflation in sync with decreases in incident wave energy flux below 10,000 kgm/s^3 and a more southerly wave approach. The seasonal exchange of sediment supports the presence of rotation that is controlled by seasonal wave energy.

The beach and offshore regions experienced seasonal volume increase and decrease during the summer and winter months respectively. Summertime volumes cyclically approached or surpassed total nourishment volumes, followed by wintertime volume decreases of approximately 10 to 20% of the total nourished volume. Volume increases generally coincided with summer conditions of counterclockwise rotation and upticks in incident wave energy flux above 10,000 kgm/s^3. Inversely, volume decreases appeared to coincide with winter conditions of clockwise rotation and incident wave energy below 10,000 kgm/s^3. These patterns of cyclical volume change suggest the presence of a proximal location that acts as a sediment source and sink during respective summer and winter months. Because longshore transport is obstructed by terminal structures, it is likely that sediment exchange is facilitated almost solely by cross-shore transport to and from a region located offshore of the study area.

The relationship between the pattern of erosion/accretion and cross-shore sediment transport remains unresolved. Confirmation of a proximal sediment source/sink would require elevation data from regions further offshore of the present study area. As we cannot confirm the source and seasonality of cross-shore transport, we can only speculate that observed increases in volume were caused by the onset of increased incident wave energy flux during the summer months. The increase in wave energy may have transported sediment onshore through the offshore channel, in addition to partially obstructing the prevailing flow of counterclockwise transport.

6. Summary and conclusions

Quarterly monitoring data collected over 2.7 years following the 2012 Royal Hawaiian Beach nourishment have provided insight into its performance and subsequent endurance. The project location hosts a unique reef-fronted, carbonate beach environment. Such environments are underrepresented in the global literature; thus, this study provides additional understanding of beach and sediment behavior for future nourishment projects. Overall, seasonal patterns of recession and advance were found to coincide with seasonal wave conditions and variations in rotational transport direction. During the summer months, the beach generally experienced overall advance as sediment was transported west and as wave energy increased; over the winter months, the beach experienced overall recession as wave energy decreased and as sediment transport slowed and become more variable. These observations of predominant counterclockwise transport and channelized cross-shore transport are consistent with previous studies. Much of the volume and width accretion occurred adjacent to the offshore channel, which may have resulted from the convergence of predominant westward transport towards the channel and incident wave energy traveling landward through the channel. Flanking along terminal structures became temporarily problematic; however, the eroded areas recovered seasonally. Physical and chemical compaction likely occurred as a result of the sand placement method; loaded dump trucks repeatedly traversed fragile carbonate sand to reach placement locations. Such methods of placement may need to be avoided or compensated for in future nourishment designs.

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