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Hawaii Regional Sediment Management: Application of SBAS for ArcGIS© 10 to Develop Regional Sediment Budgets for the Island of Maui, HI

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PURPOSE. This Coastal and Hydraulics Engineering Technical Note (CHETN) summarizes the methods and tools used to develop a regional sediment budget for two regions (Kahului Region and Kihei Region) on the Island of Maui, HI, as part of the Hawaii Regional Sediment Management (RSM) initiatives funded by the US Army Corps of Engineers (USACE) RSM Program. This CHETN identifies programmatic lessons learned during this application, and recommends future applications of RSM tools and methods for similar projects.

BACKGROUND. RSM refers to the beneficial use of littoral, estuarine, and riverine sediment resources in an environmentally effective, operationally efficient, and economically feasible manner. RSM changes the focus of engineering activities from the local or project-specific scale to a broader scale that is defined by the natural sediment processes. A prime motivator for the implementation of RSM principles and practices is the potential to reduce construction, maintenance, and operation costs for Federally-authorized navigation, to reduce storm damage, and to undertake and complete environmental restoration projects. Implementing RSM principles also has the potential to positively impact projects' ability to meet their authorized purposes.

The overall RSM strategy of the US Army Engineer District, Honolulu, HI (POH) is to investigate RSM opportunities along all shoreline regions in Hawaii. Initial RSM regions on Maui include the Kahului Region on the north shore, and the Kihei Region on the west shore of the island (Figure 1). Federal navigation projects in these two regions are the Kahului Deep Draft Harbor Project, the Kahului Light Draft Harbor Project, and the authorized modifications for Maalaea Small Boat Harbor. There is also an ecosystem restoration project at Kanaha Pond Wildlife Sanctuary, and shore protection projects adjacent to the Kahului Wastewater Plant and at the southern limit of Kihei Beach at Kalama Park. The preliminary Maui RSM strategy (Moffatt and Nichol, and EA/HHF JV 2011) provides detailed background on these Federal projects, defines the objectives of the investigations, describes the geo-morphological setting, and quantifies coastal processes within the regions.

Kahului Region. Figure 2 shows the seven littoral cells that define the Kahului Region shoreline: (1) Paukukalo, (2) Kahului Harbor, (3) Kanaha Beach, (4) Spreckelsville, (5) Baldwin Park, (6) Paia East, and (7) Hookipa. Generally, the littoral cells are delineated by headlands extending seaward of the nominal shoreline orientation. Kanaha Beach, which is the longest cell in the region, contains relatively long stretches of sandy shoreline. On the other hand, Paukukalo and Kahului Harbor are the shortest of the littoral cells. These two cells provide minimal exchange of sediment to adjacent cells. Kahului Harbor is bounded by the harbor breakwaters, and the Paukukalo shoreline is naturally hardened with basalt outcrops, boulders, and cobbles.

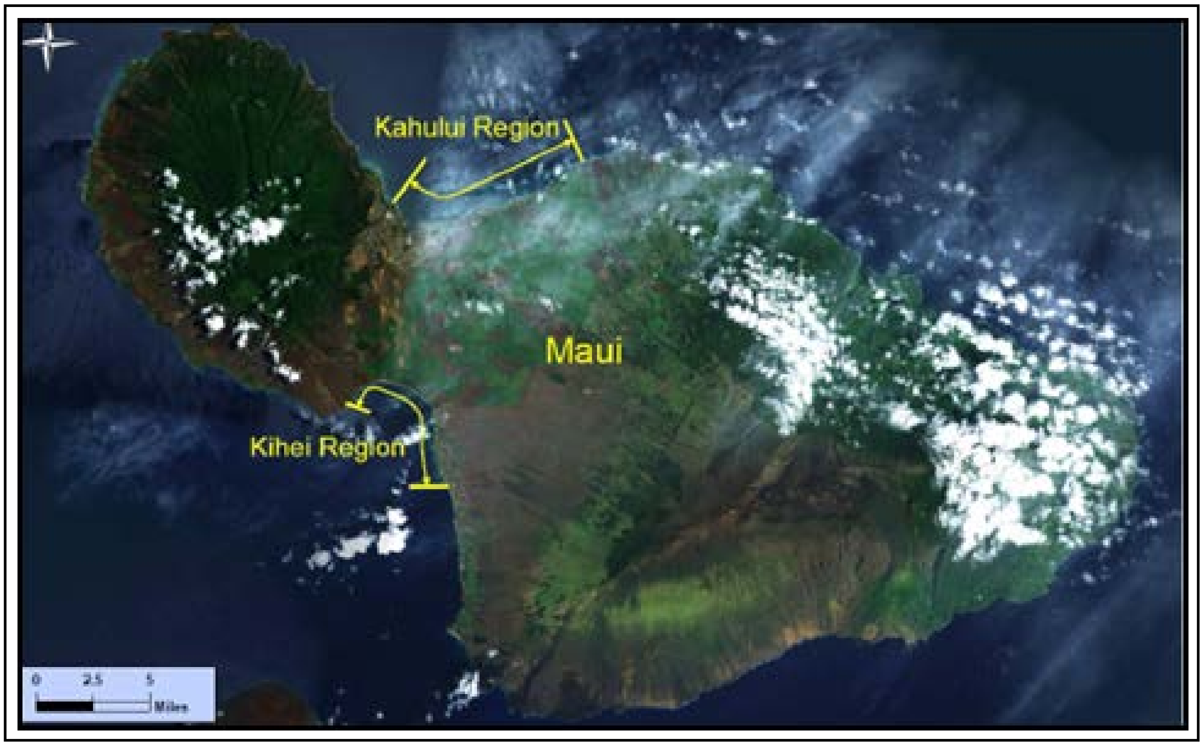

Figure 1. Initial RSM efforts on the Island of Maui included the Kahului and Kihei Regions.

Figure 2. Littoral cells in the Kahului Region of Maui.

Spreckelsville (located at the center of the region) has a history of shoreline development and chronic erosion. Portions of the shoreline have been nourished with upland as well as offshore sand. Baldwin Park consists of a series of public beach parks while the Paia shoreline is highly developed. The Hookipa littoral cell on the eastern limit of the region gives way to a more natural shoreline famous for its world class wind- and kite-surfing beaches.

Kihei Region. Figure 3 shows the seven littoral cells that define the Kihei Region shoreline: (1) West Maalaea, (2) Maalaea Harbor, (3) Maalaea Bay Beach, (4) Kealia Pond, (5) North Kihei, (6) Kawililipoa Beach, and (7) Kalama. The Kihei Region is approximately 7.5 miles long and lies within the hook-shaped Maalaea Bay. The region is defined as the coastline from just southwest of the Maalaea Harbor on its western boundary and extending to the Kalama Beach Park on its eastern boundary. The region includes Maalaea Harbor, formed by rubble mound shore-perpendicular breakwaters on its south and north sides, with several well-known surf breaks just offshore of the harbor. To the southwest of the harbor, the east-facing shoreline includes one small pocket beach interspersed among hard shoreline and basaltic headlands. Immediately to the northeast of the harbor is a south facing shoreline lined with beach-front residences fronted by seawalls and/or rock revetments. Mined sand from inland dunes has been placed in front of some residences and condos for the purposes of beach nourishment. Further west is the low-lying Maalaea Bay Beach and Kealia Pond area. Along the west-facing shoreline of the Kihei Region are narrow sand beaches backed by vegetated dunes.

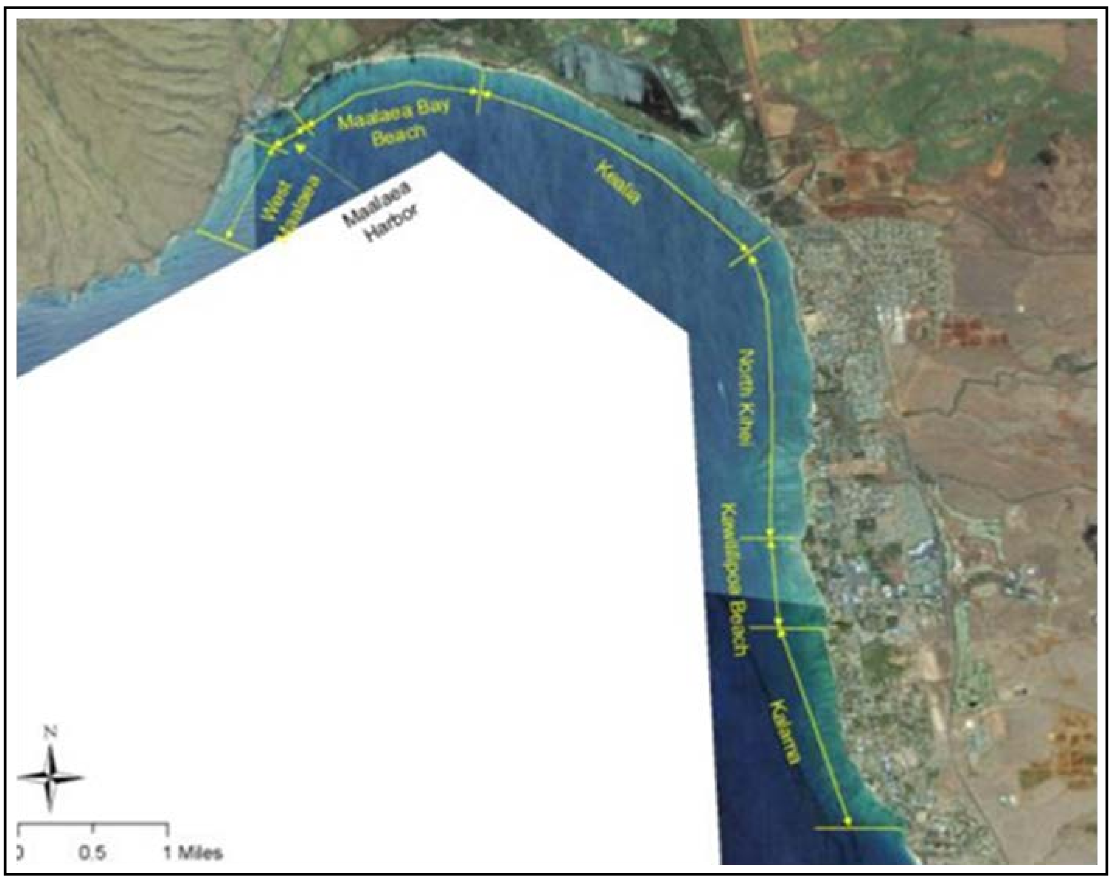

Figure 3. Littoral cells in the Kihei Region of Maui.

The fringing reef along the west-facing coastline extends to the northern limit of the North Kihei cell through the Kalama cell. Beach-front homes in the Kawililipoa Beach and Kalama cells are protected with vertical seawalls, stone, or geobag revetments. A rock revetment fronts the beach park at Kalama Beach.

APPROACH AND CHALLENGES. The initial phase of RSM investigations in the Kahului and Kihei Regions included the quantification of volume changes inferred through a shoreline change analysis. Shoreline erosion maps, including shoreline position change rates (as derived from historical aerial photographs) along much of the study regions, have been developed by the University of Hawaii Coastal Geology Group (UH CGG) (Fletcher et al. 2012) for the US Geological Survey (USGS) as part of the USGS Coastal Hazard Mapping program. The historical volumes of sediment on the beaches were estimated based on these rates and using a conversion factor for volume of 0.40 cu yd per sq ft of beach area gained or lost. This factor is based on the results of beach profile analysis recently conducted along the south coast of Oahu (Diamond Head to Pearl Harbor RSM strategy), and is also described in previous studies of the Kihei Region (USACE 1966). Ideally, detailed beach profile surveys and/or nearshore bathymetric surveys would be used to verify and further refine these calculations; however, these data are not currently available for either of the study regions.

Figures 4 and 5 show historical beach volume changes for each of the littoral cells in the Kahului and Kihei Regions, respectively, from the early 1900s up to 2003. These graphs also show historical events that had the potential for impacting the beaches within the regions. An average volume change rate over the entire time period of shoreline records was also calculated for each littoral cell. The rates are based on a linear fit of the beach volume and seasonal fluctuation/error data using a weighted least squares approach. For both regions, the beach sediment change rates are complicated by trend (accretion/erosion) reversals, historic shoreline structures, and seasonal effects. Tables 1 and 2 list the volume change rates for each littoral cell over the entire time period of shoreline record and over recent history for the Kahului and Kihei Regions, respectively.

The second phase in the RSM investigations was development of the nearshore wave climate in the regions through the use of numerical wave transformation modeling. Analysis of wave parameters from selected output stations within the US Army Engineer Research and Development Center (ERDC) Wave Information Study (WIS) (Hubertz 1992) Pacific hindcast available for the years 1980 – 2004 indicated the most frequent combinations of wave height, period, and direction occurring offshore of each study region. These wave conditions were transformed to nearshore observation points within each region through the use of the STeady WAVE (STWAVE) numerical model (Smith et al. 2001). Nearshore STWAVE grids were generated for the Kahului and Kihei Regions using the island-wide bathymetry data developed for the Surge and Wave Island Modeling Studies (SWIMS) being conducted by USACE, the University of Hawaii, and Notre Dame University, in combination with high-resolution LIght Detection And Ranging (LIDAR) data in the nearshore from USACE Joint Airborne LIDAR Bathymetry Technical Center of Expertise (Figures 6 and 7).

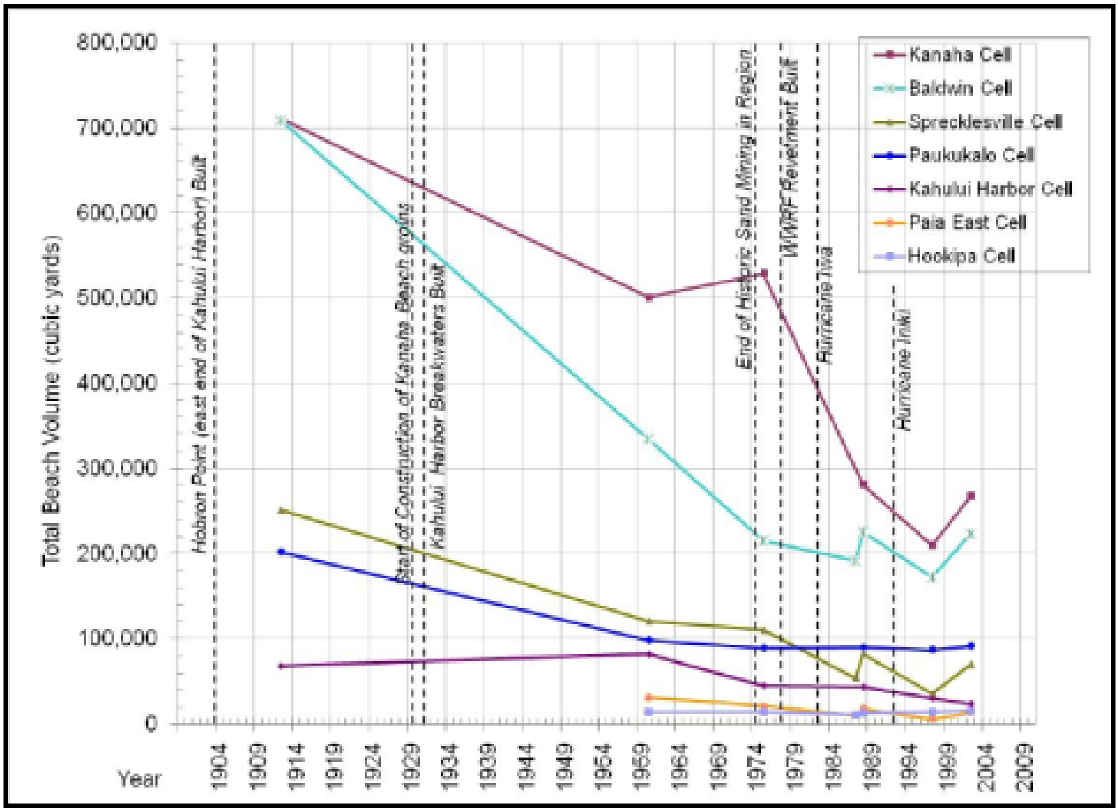

Figure 4. Historical beach volumes of Kahului Region of Maui by littoral cell.

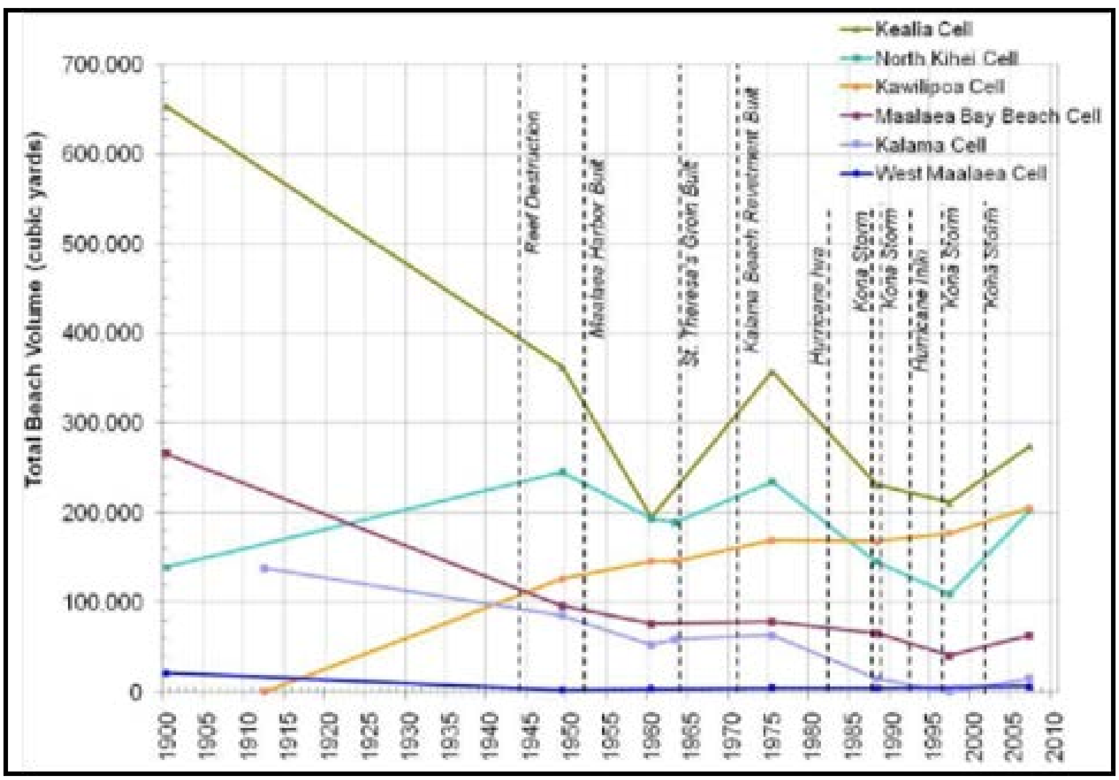

Figure 5. Historical beach volumes of Kihei Region of Maui by littoral cell.

Table 1. Kahului Region Long-Term and Short-Term Volume Change Rates.

Littoral Cell	Accretion(+)/Erosion(-) Rate Over Entire Time Period of Record (cu yd/yr)	Accretion(+)/Erosion(-) Rate Over Recent Period (cu yd/yr)
Paukukalo	–1,200	0
Kahukui Harbor	–1,100	–800
Kanaha Beach – Total	–6,500	–10,550
Preckelsville	–2,300	–2,400
Baldwin Park	–4800	–400
Paia East	-500	–500
Hookipa	0	0

Table 2. Kihei Region Long-Term and Short-Term Volume Change Rates.

Littoral Cell	Accretion(+)/Erosion(-) Rate Over Entire Time Period of Record (cu yd/yr)	Accretion(+)/Erosion(-) Rate Over Recent Period (cu yd/yr)
West Maalaea	–100	+50
Maalaea Harbor	0	0
Maalaea Bay Beach	–1,300	–800
Kealia	–2,300	–2,800
North Kihea	–800	+8,800
Kawililipoa Beach	+1,400	+1,200
Kalama	-1,400	-1,600

Observation points were placed at the 10-m (33-ft) contour and along the nearshore at approximately 1- to 3-m (3- to 10-ft) depth (also visible in Figures 6 and 7 as triangles). A database (“lookup table”) of wave parameters that correlates the most frequent offshore wave conditions at the offshore WIS station to the resulting nearshore wave conditions at the selected observation points was developed for several hundred wave transformations for each region. Finally, a program was developed to automate the “lookup table” process, so that the hourly time series of wave data from three years (1984, 1992, and 1994, representing low, average, and high wave energy) of WIS data could be converted to nearshore wave parameters at each observation point along each region’s shoreline.

The next step in the process was to use the 3-year time series of wave parameters at each of these nearshore observation points in combination with the sediment change volumes for each littoral cell to estimate the net and gross sediment transport rates and transport direction between each cell along the shoreline. The general guidelines of the wave energy flux method developed by Jarrett (1991) and outlined in Engineer Manual EM 1110-2-1100 *Coastal Engineering Manual*, Part III Coastal Sediment Processes (Chapter 3 Longshore Sediment Transport, Section III-2-3 Predicting Potential Longshore Sediment Transport); and Part V Coastal Project Planning and Design (Chapter 6 Sediment Management at Inlets, Section V-6-3 Inlet and Adjacent Beach Sediment Budgets) (USACE 2003) were followed to develop the longshore transport rates and directions.

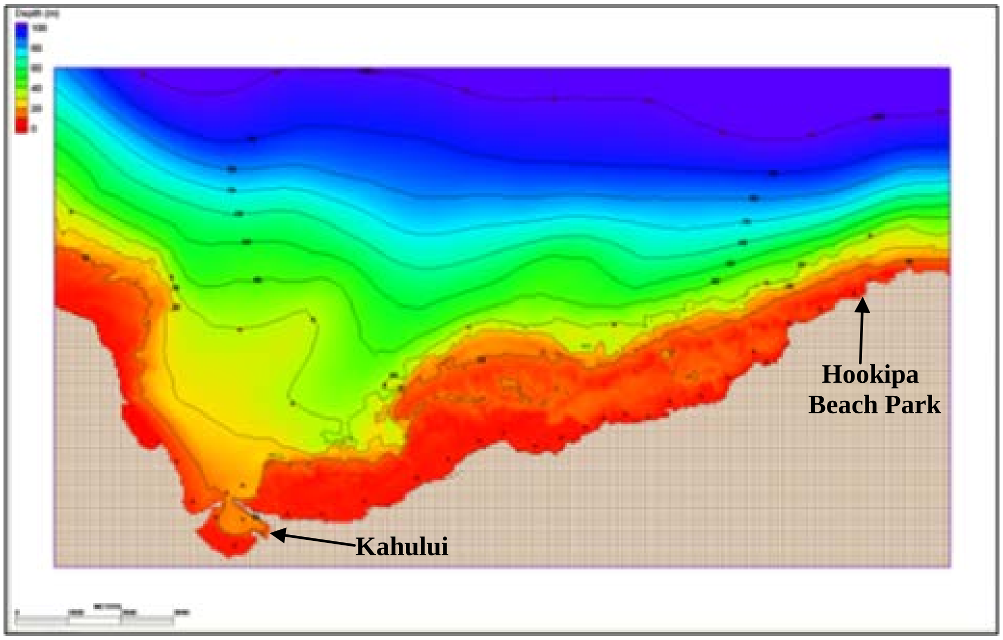

Figure 6. STWAVE grid for the Kahului Region (10-m contours and nearshore observation points).

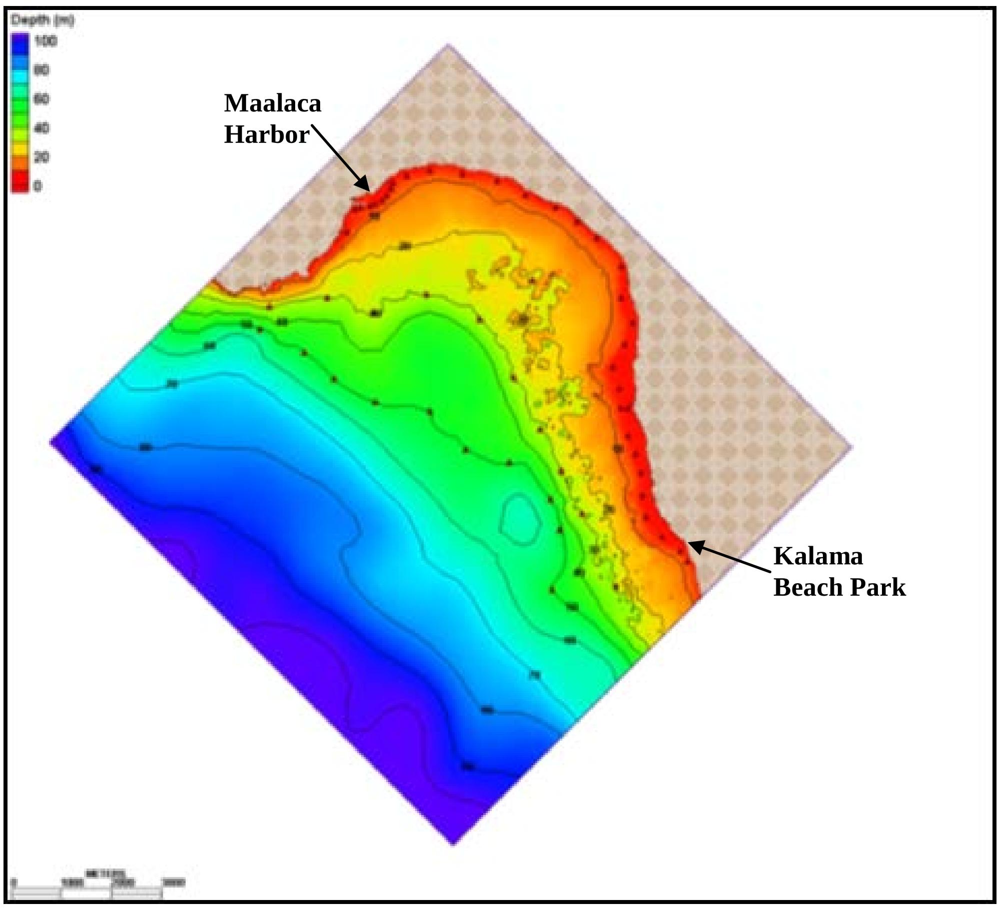

Figure 7. STWAVE grid for the Kihei Region (10-m contours and nearshore observation points).

This method involves calculating the longshore component of wave energy flux (P_l) using breaking wave height, depth at breaking and breaking wave angle, as shown in Equations III-2-7a and V-6-46, derivations of the commonly known "CERC formula". The annual summation of this hourly calculation of longshore wave energy flux (potential sediment transport) at each nearshore observation point was averaged over the three selected years to arrive at an annual potential sediment transport rate in cu yd per year in the positive, negative, and gross transport directions.

The gross transport value was then used to solve for the value of the empirical proportionality coefficient K in Equation III-2-7b or β in Equation V-6-46 (β will be referenced from this point forward), using the previously determined annual volume change rates (as well as placement and removal volumes) for each littoral cell. Since the Hawaii RSM regions do not have inlets per se, and are considered "closed" littoral regions, the method of selecting the proportionality coefficient used by Jarrett (1991) at inlets or at the ends of the region was not feasible. Alternatively, the proportionality coefficient for each region was determined by examining solved values of β at all nearshore observation stations, and then using a mean value as well as engineering judgment to determine a final β value. This coefficient was then applied to all values of potential sediment transport (both positive and negative values) to determine final longshore transport rates at the limits of each littoral cell. Because cross-shore transport is believed to be a significant process in the Hawaiian Islands (due to large periodic Kona storms and hurricanes, as well as the complexity of onshore sediment transport over reefs and, in some areas, wind driven transport), cells were balanced using cross-shore components of transport as well.

SEDIMENT BUDGETS USING SBAS. The final step in the sediment budget process was the use of the Sediment Budget Analysis System (SBAS) software for ArcGIS© 10 toolbar (Rosati and Kraus 2001, Dopsovic et al. 2002) in combination with the sediment budget equation (Equation 1) to complete final cell balancing calculations and to create a visual representation of the calculated transport rates and directions. Figures 8 and 9 show the results of this step. The next section gives details regarding this application and recommendations for future use of SBAS for ArcGIS© 10.

$$\Sigma Q_{source} - \Sigma Q_{sink} - \Delta V + P - R = \mathbf{Residual} \qquad (1)$$

where:

Q_{source} = sediment transport rate into the cell
Q_{sink} = sediment transport rate out of the cell
ΔV = volumetric change rate within the cell
P = artificially-placed sediment rate into the cell
R = artificially-removed sediment rate from the cell.

Residual in Equation 1 indicates the balancing of the cell (negative is eroding, positive is accreting, zero is balanced).

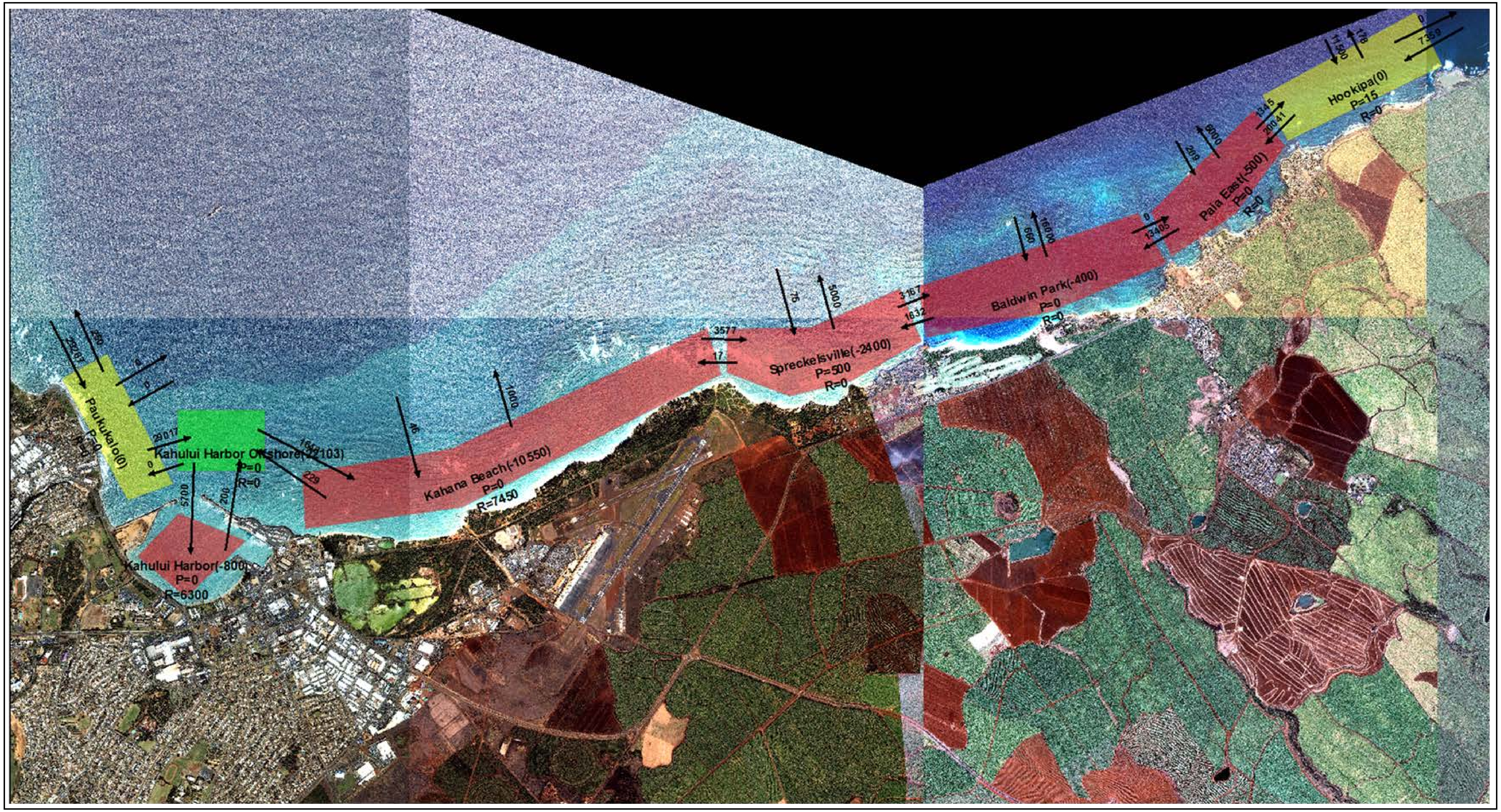

Figure 8. Sediment budget for Kahului Region, developed using Sediment Budget Analysis System (SBAS) for ArcGIS©10.

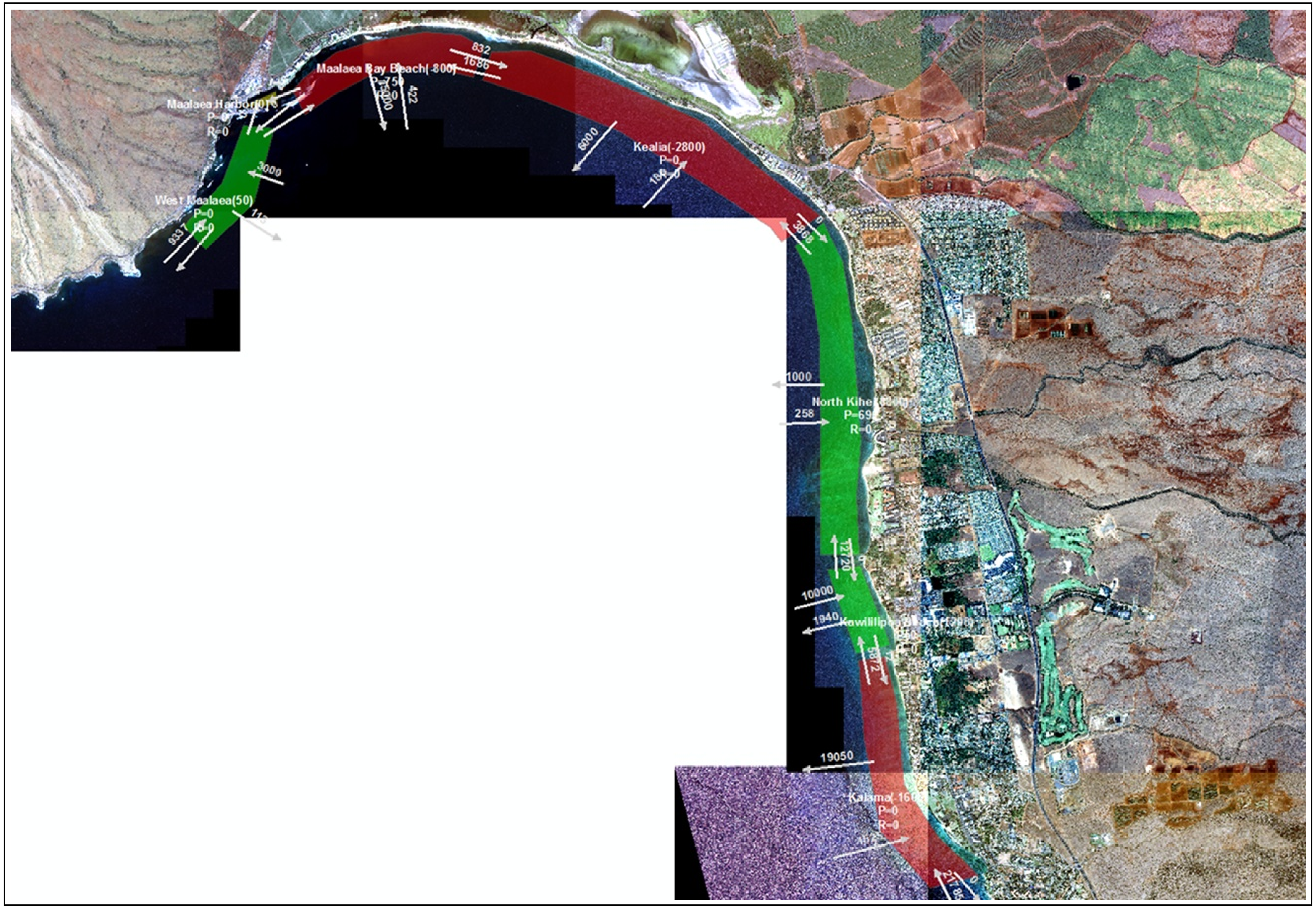

Figure 9. Sediment budget for Kihei Region, developed using Sediment Budget Analysis System (SBAS) for ArcGIS©10.

Each of the terms used in Equation 1 has the units of volume per unit time (e.g., cu yd per year). The terms P and R represent regular maintenance activities such as dredging, bypassing, or nourishment. The regions addressed in this study have experienced one or more of these activities, although not on a regular basis. This present study which produced the present-day sediment budgets did not take into account such occasional placement or removal of sediment.

UNCERTAINTIES. In an effort to document and share information that may apply to other RSM regions, some of the challenges and uncertainties in developing a balanced sediment budget along these shorelines are listed below.

- These regions have comparatively small sediment quantities (thousands of cubic yards per year as compared to tens of thousands or more elsewhere) due to the primarily calcareous sources of sediment supply. These small quantities made it difficult to measure volume changes and sediment transport, and resulted in an empirical sediment transport coefficient (<1.0) that is too small to be realistic.
- Hawaii has a seasonal wave climate in which wave energy can vary widely in magnitude and direction during different times of the year. This often results in bi-directional sediment transport and annual gross transport direction that can change depending on the strength of the storms and climatic tradewind conditions for that particular year.
- The coastline morphology includes many bays and other changes to shoreline orientation over relatively short distances (~10s of miles). This can result in dramatic shifts in longshore transport rates and directions within a region.
- There are often many intermediate littoral barriers such as headlands and complex submerged nearshore features such as coral reefs that can create sub-cells within each littoral cell, limiting the applicability of accepted longshore sediment transport equations.
- Cross-shore sediment transport during large Kona storms and/or hurricanes may be a significant factor in sediment transport patterns along these shorelines, particularly in areas with wide, fringing reefs. However, there are little data or empirical methods available to quantify how significant this component may be.

PRACTICAL APPLICATION OF SBAS FOR DEVELOPMENT OF REGIONAL SEDIMENT BUDGETS. The ability to create a visualization of the calculated RSM sediment budgets for the Maui regions using the SBAS toolbar within ArcGIS©10 aided in refining the preliminary sediment budgets, and provided an invaluable communication tool for discussions with sponsors and stakeholders of the RSM program. The use of SBAS to generate sources, sinks, and flux rates was critical in the process of balancing littoral cells for this application. Using SBAS within Arc View allows the user to overlay littoral cells and sediment pathways onto an aerial photo of the region, thus assisting with the practical understanding of how sediment movement occurs in the nearshore as well as exchanges between cells in the overall region. Though not used in this application, the ability to integrate other data (such as shoreline change data or bathymetry) directly into ArcGIS©10 could also prove highly valuable in development of the sediment budget by refining volume and flux numbers based on this additional spatial data.

The flexibility of being able to create irregular polygons (and other shapes rather than just rectangles) to represent littoral cells enables the use of the tool along shorelines with complex and variable geomorphologic features. Additionally, the program's creation of a shapefile for both littoral cells (indicated by drawn polygons) and fluxes (indicated by drawn arrows) with all necessary attributes already included was a helpful and time saving feature, especially for those who may not use ArcGIS©10 on a regular basis.

There are some aspects of the SBAS tool that could use improvement or refinement in future iterations of the software. The default display of volume in the littoral cells is the Residual volume (imbalanced volume remaining after preliminary sources and sinks have been entered) from Equation 1. Although the ability to view this value may be useful in the process of the balancing of the sediment budget, the end goal is to arrive at fully balanced littoral cells where the residual volume is zero. A default label to display estimated historical volume change within the cell (ΔV) would be more helpful in the final visualization, thus providing an indication of which cells are chronically erosive, accretive, or stable. In future versions, it would also be useful if the program had a default display of labels for placement (P) and removal (R) volumes, below the volume change (ΔV) label. This would more easily allow someone looking at the sediment budget to see how the sources, sinks, and fluxes balance in each cell.

The default display uses a color palette of yellow, purple, and green fill for littoral cells to represent Residual volume. These colors are not immediately associated with an eroding or accreting shoreline. Although this can be changed relatively easily within ArcGIS©10, it would seem appropriate to make the default color scale something more clearly associated with eroding, stable, and accreting cells, such as red, yellow, and green, respectively. In this application, there were some issues with changes in format (cell labels and fill colors) reverting back to the default settings after refreshing or saving. This required a "work around" to create new layers with the desired symbology that were used as a "mask" over the SBAS shapefiles that were created to achieve the preferred final display.

Finally, in this application of the SBAS toolbar within ArcGIS©10, the user had difficulty with using the Edit Cell/Flux Values button on the toolbar. In some cases, changes made in the cell properties datasheet to volume or flux values did not automatically update the shapefile's attribute table, so the changes to labels and/or symbology did not appear on the ArcGIS©10 display of the cells/fluxes. This required the user to manually change the attribute table to see the changes. There were also some instances where the cell properties datasheet did not appear when the Edit Cell/Flux Values button was clicked, also requiring manual updates to the shapefile attribute table. If these small changes and "bug fixes" are implemented in future versions of SBAS for ArcGIS©10, it would definitely be a highly useful and efficient tool to create visualizations of a regional sediment budget with applications for both technical and communications aspects of the RSM program.

CONCLUSIONS. This CHETN has provided a brief overview of the development of regional sediment budgets in support of RSM activities on the Island of Maui, HI. Challenges experienced in the island environment that may also apply to other RSM study areas have been noted. Additionally, the application of the SBAS for ArcGIS©10 tool was documented, including advantages and suggestions for improvement. As additional data and/or analysis methods become available, efforts to improve sediment budget estimates and uncertainties discussed herein should be implemented.

ADDITIONAL INFORMATION. This Coastal and Hydraulics Engineering Technical Note (CHETN) was prepared as part of the Hawaii Regional Sediment Management (RSM) initiatives funded by the USACE RSM Program. This CHETN was written by Jessica H. Podoski, USACE Honolulu District (POH), Honolulu, HI. Additional information pertaining to the RSM Program can be found at the RSM website: http://rsm.usace.army.mil

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ACRONYMS AND ABBREVIATIONS.

Term	Definition
CERC	Coastal Engineering Research Center
CHETN	Coastal and Hydraulics Engineering Technical Note
CHL	Coastal and Hydraulics Laboratory
EM	Engineer Manual
ERDC	Engineer Research and Development Center
LIDAR	LIght Detection And Ranging
POC	Point of Contact
POH	US Army Engineer District, Honolulu, HI
RSM	Regional Sediment Management
SBAS	Sediment Budget Analysis System
SR	Special Report
STWAVE	STeady WAVE (numerical model)
SWIMS	Surge and Wave Island Modeling Studies
UH CGG	University of Hawaii Coastal Geology Group
US	United States
USACE	US Army Corps of Engineers
USGS	US Geological Survey
WIS	Wave Information Study