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NUMERICAL MODELING AND ANALYSIS OF COASTAL SEDIMENT BUDGET AT WEST MAUI, HAWAII

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Abstract

Waves, water levels, flow, and sedimentation numerical models in the Coastal Modeling System (CMS) were applied to estimate the regional sediment budget at West Maui, Hawaii. The dynamics of the coastal area are complex with a wave climate affected by longshore currents, wind, and island sheltering. The littoral transport is affected by wave breaking along shore, oceanographic currents among islands, wind-driven currents, tidal currents, and occasional eddy formation nearshore West Maui coast. Numerical modeling results show the net longshore transport and sediment output from river streams are overall small in the region.

Key words: Coastal Model System, West Maui, coastal processes, particle tracking, river stream, sediment budget

1. Introduction

The West Maui region, located on the Island of Maui, incorporates a thin coastal margin backed by steep mountainous terrain that has been vastly altered by agricultural and urban development (Figure 1). Inland sediment makes its way from the five watersheds (Honolua, Honokahua, Kahana, Honokowai, and Wahikuli) in the West Maui to the coastal waters via streams and drainages (Figure 2). The federally authorized West Maui Watershed Study is included within the larger West Maui “Ridge to Reef” (R2R) Initiative, which engages various federal, state, and county agencies in the implementation of strategy to reduce the threats of land-based pollution to coral reefs in West Maui. Collaboration and coordination of U.S. Army Corps of Engineers (USACE), Honolulu District, Hawaii Reginal Sediment Management (HRSM) investigations in the West Maui region, and the work being conducted through the West Maui R2R Initiative, are being utilized to enhance the utility of the products being developed. The investigation includes the fate of inland sediment inputs within the nearshore littoral environment of West Maui, Hawaii.

As a joint investigation with R2R and HRSM, the U.S. Army Engineer Research Development Center (ERDC) has participated in the study to conduct numerical modeling to simulate coastal processes, river streams, and littoral transport for the West Maui coast. This requires modeling Maui and other four neighboring islands: Oahu, Molokai, Lanai, and Kahoolawe (Figure 3).

In 2011, the U.S. Coral Reef Task Force added a priority watershed partnership designation to the Wahikuli and Honokowai watersheds, the two southernmost in the West Maui region. The coral reef at the base of the Honokowai watershed is designated as one of two priority coral reefs in the United States by the National Oceanographic and Atmospheric Administration (NOAA). NOAA has sponsored the development of a Wahikuli-Honokowai Watershed Management Plan (Sustainable Resources Group International, Inc. 2012) for these watersheds as part of the West Maui R2R Initiative, and proposed projects intended to decrease land-based pollution to the reef. The University of Hawaii, Water Resources Research Center, had assisted the plan and developed runoff hydrographs and sedographs for 2-, 10-, 25-, 50-, and 100-year recurrence storms (Babcock et al. 2014). In the present study, the Honokowai Stream is used as a representative example of upland sediment input to the nearshore region for the West Maui sediment budget estimate. Summaries include the stream and upland sediment inputs, and the results from nearshore wave-hydrodynamic-sediment transport modeling.

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2. Stream and Upland Sediment Inputs

The Honokowai Stream drains approximately 70 percent (%) of the total area of the Honokowai Watershed. During and following periods of moderate to high rains, it flows and carries fine and coarse sediments as well as plant matter and animal waste to the coast outlet (Sustainable Resources Group International, Inc., 2012). The stream has an annual peak discharge range of 120 to 4520 cubic feet per second (cfs), according to U.S. Geological Survey (USGS) data obtained from 1961 to 2009, with an average of 753 cfs (http://waterdata.usgs.gov). While the Honokowai stream was once considered perennial, it is more of ephemeral (Babcock et al. 2014) today. The Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model (Downer and Ogden 2006) was applied to develop runoff hydrographs in the Honokowai Stream for 2-, 10-, 25-, 50-, and 100-year recurrence storms (Figure 4). The routing of runoff through the basin and the retention of sediment in the basin were modeled using the Environmental Protection Agency's Storm Water Management Model (SWMM) (Babcock et al. 2014).

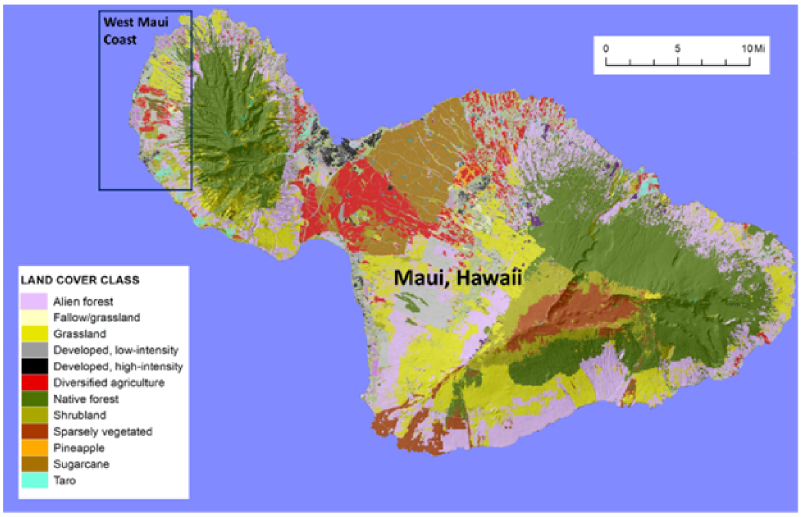

Figure 1. Location map of Maui and land cover class.

Figure 2. Five watersheds located in the West Maui region.

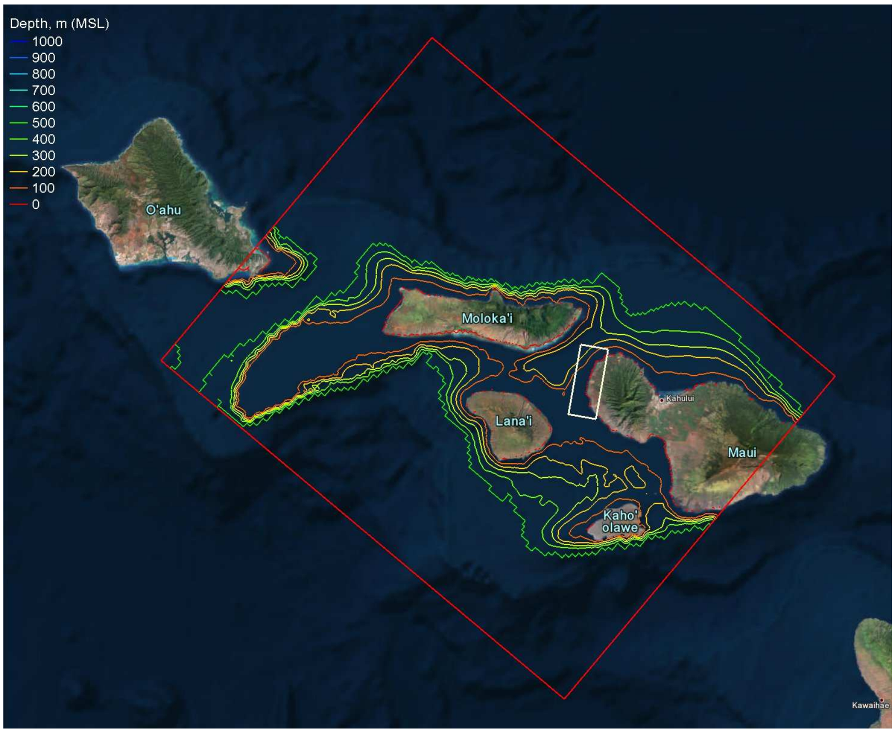

Figure 3. Coastal modeling includes islands of Maui, Oahu, Molokai, Lanai, and Kahoolawe.

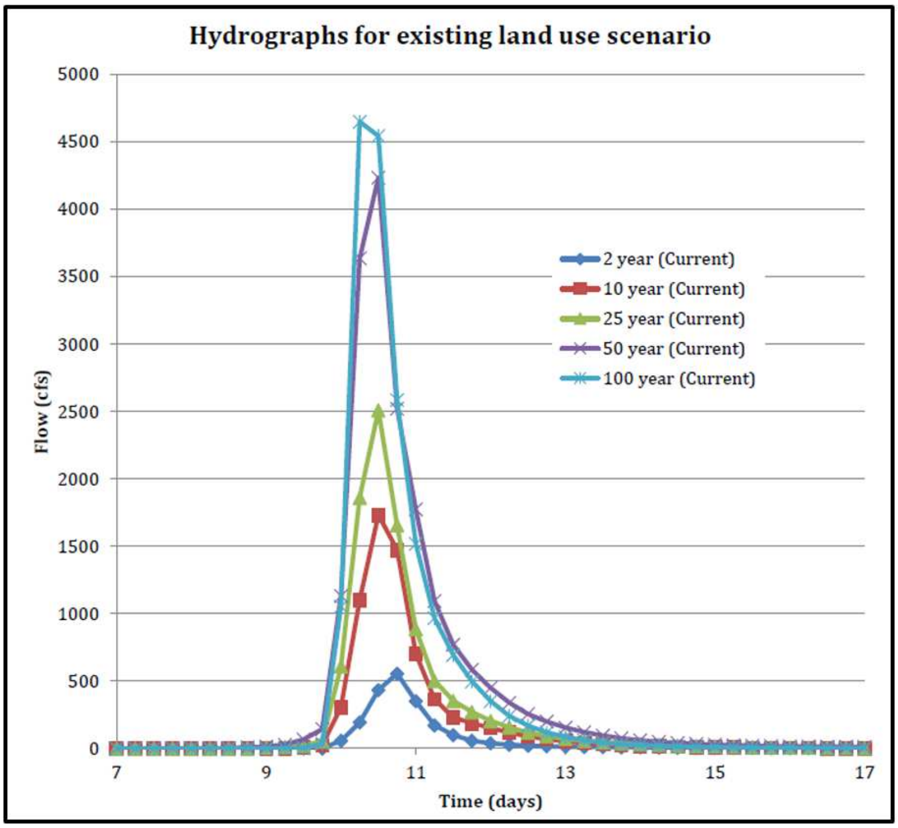

Figure 4. Honokowai Watershed hydrographs for existing land use (Babcock et al. 2014).

Sediments at upland locations in West Maui show varying composition of gravel, sand, medium silt, fine silt, and clay. The majority of gravel and sand is transported as bedload and, therefore, is likely to be retained in the sedimentation basin (Babcock et al. 2014), leaving relatively more silt and clay to be transported to the stream mouth and coast waters as suspended load.

3. Numerical Models

Coastal Modeling System (CMS) numerical models (Demirbilek and Rosati, 2011) were implemented in the West Maui region. The CMS is a suite of numerical hydrodynamic, wave, and sediment transport models consisting of CMS-Flow, CMS-Wave, and CMS-PTM. Physical processes calculated by CMS-Flow are circulation, sediment transport, and morphology change (Buttolph et al. 2006). CMS-Wave is a two-dimensional wave spectral transformation model that contains approximations for wave diffraction, reflection, wave transmission, wave run-up, and wave-current interaction (Lin et al. 2008). CMS-PTM is a Particle Tracking Model (MacDonald et al. 2006) capable of computing the fate and pathways of sediment and other waterborne particles in the CMS-generated flow field.

CMS-Flow and CMS-Wave can be run separately or coupled on a non-uniform Cartesian grid. In the coupling mode, the variables passed from CMS-Wave to CMS-Flow are the significant wave height, peak wave period, wave direction, wave breaking dissipation, and radiation stress gradients. CMS-Wave uses the update bathymetry, water levels, and currents from CMS-Flow. The coupling can be operated through the Surface-water Modeling System (SMS, Zundel, 2006) by providing the total simulation period of CMS-Flow with the constant interval of running CMS-Wave. Coupling CMS-Flow and CMS-Wave can simulate many important short-term and long-term processes like the shoreline change, channel infilling, breaching to shore and damage to coastal structure, and storm-induced flooding and erosion. Both models have the nested grid capability as an alternative for circulation, sediment calculation, and wave transformation in the local higher resolution area.

4. Methodology

A nested grid system consisting of two grids were used in the CMS simulations: (1) a parent grid with coarser resolution covering the regional area, and (2) a child grid representing the key features in the West Maui coastal area such as reefs, irregular shorelines, headlands, coves and bays (Figure 1). Prevailing wind wave (under trade wind) and predominant wave transformation (including north, northwest and south swell) were simulated by coupling of CMS-Wave and CMS-Flow to capture the interactions of winds, waves and currents with island sheltering effects. The parent grid is used to simulate wave and flow fields, while the child grid is used to calculate waves, currents, sedimentation, and morphology change. This nested grid system was necessary to properly estimate wave, current, and sediment transport fields along the west coast of Maui. The child grid was also used for the river stream and CMS-PTM simulations.

The parent grid simulation was driven by directional spectra and water levels specified along the open water boundaries and with surface wind forcing over the model domain. The parent grid model results, including water levels, currents and wave spectra, were used as input to the child grid. Model results were used to quantify sediment volumetric change in the West Maui coastal region.

Figure 3 shows the parent grid model domain (red box) and child grid domain (white box). The CMS grid bathymetry was created using the Hawaiian Islands dataset maintained by the University of Hawaii, Ocean and Resources Engineering Department (http://www.ore.hawaii.edu). The parent grid domain was 82.6 mi x 102.5 mi (130 km by 165 km), covering parts of eastern coast of Oahu and four neighboring islands (Maui, Molokai, Lanai, and Kahoolawe). The grid had variable cell size ranged from 5,000 ft x 5,000 ft (1500 m x 1500 m) away from Maui to 820 ft x 1,640 ft (250 m x 500 m) near Maui. The child grid domain was approximately 10 km by 20 km, covering a smaller area of the west coast of Maui. It had variable cell size from 820 ft x 820 ft (250 m x 250 m) offshore to 65 ft x 65 ft (20 m x 20 m) nearshore. The CMS models were calibrated for the period of July to September, 2003, with wave and current measurements at four Acoustic Doppler Current Profiler/velocimeter (ADCP) instruments installed by the U.S. Geological Survey (USGS) along the West Maui coast (Vitousek et al. 2007). Figure 5 shows the location map of five ADCPs on the inner shelf in water depths along the 33-ft (10-m) isobath.

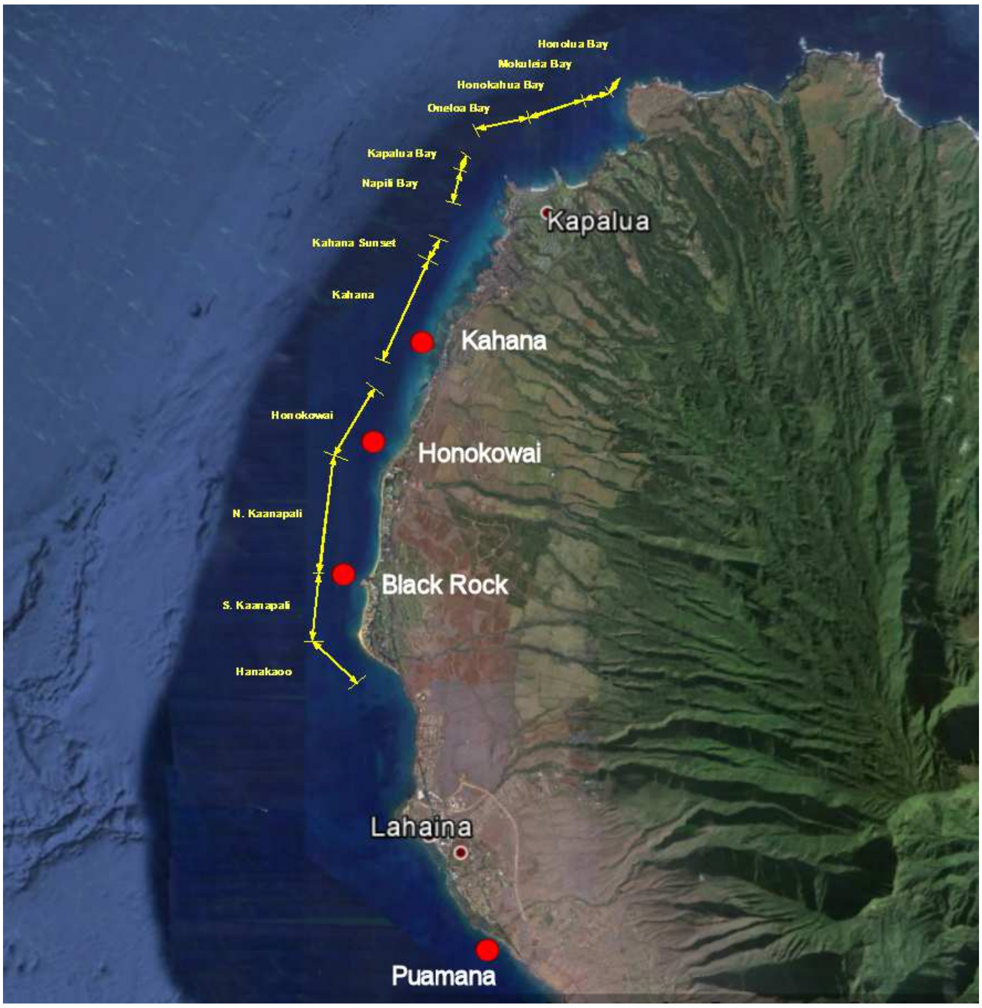

Figure 5. Location map of twelve littoral cell ranges (yellow segment) and four ADCPs (red circle).

5. Model Forcing and Calibration

The northeast trade winds occurring throughout the year affect west Maui region strongly from April to November. These winds intensify in the channels between the islands of Maui, Molokai and Lanai due to a funneling effect. Tide effect is relative small because the local tidal range is less than 1 m. Water level data were available from two nearby NOAA tide gauges from Sta 1615680 at Kahului Harbor, and Sta 1617433 at Kawaihae Harbor (Figure 3). For ocean wind and wave forcing, the U.S. Army Engineer ERDC Wave Information Study (WIS) hindcasting data were used (http://wis.usace.army.mil/hindcasts.html). Figure 6 shows the WIS stations available around Hawaii Islands.

The CMS model calibration was conducted for July-October 2003. The CMS-Wave parent grid simulation was forced with incident waves and winds from WIS along the northern and southern model boundaries. Data from WIS Stations 82517 (north of Maui) and 82546 (south of Maui) were used for the northern and southern model boundaries, respectively. The CMS-Flow parent simulation was coupled to CMS-Wave using measured water levels from two NOAA tide gauges at Kahului Harbor and Kawaihae Harbor. Figures 7 and 8, respectively, show wind, wave and water level inputs to the parent grid for July-September 2003. Model results from parent grid were used to drive the child grid. Variable bottom friction was used in parent and child grids to account for the coastal reef effects. The CMS models were calibrated with data from four USGS ADCPs (Figure 5) at Kahana (APT), Honokowai (HKW), Black Rock (BRK), and Puamana (PUM).

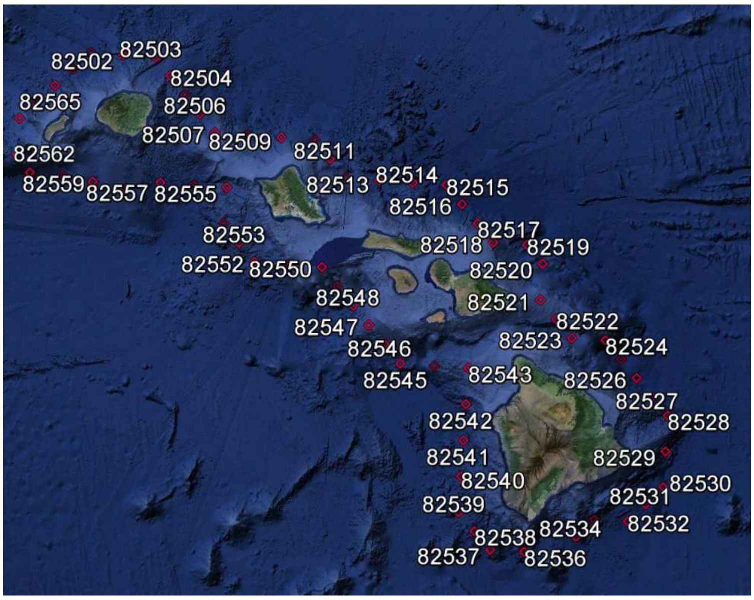

Figure 6. WIS stations available around Hawaii Islands.

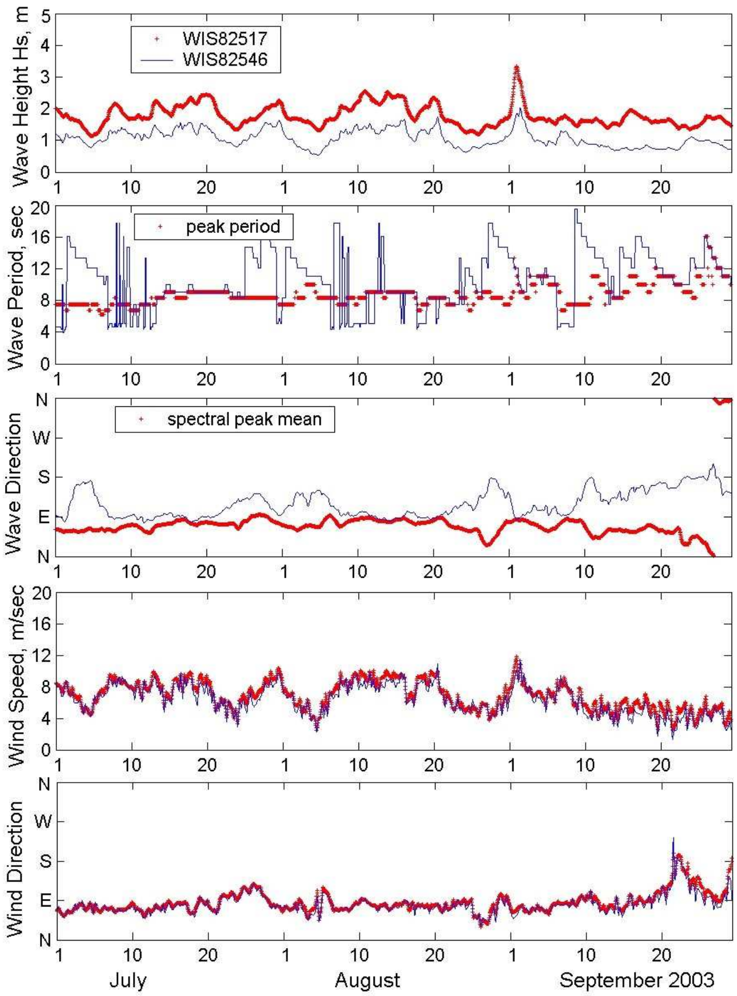

Figure 7. Wind and wave data at WIS Stations 82517 and 82546, July-September, 2003.

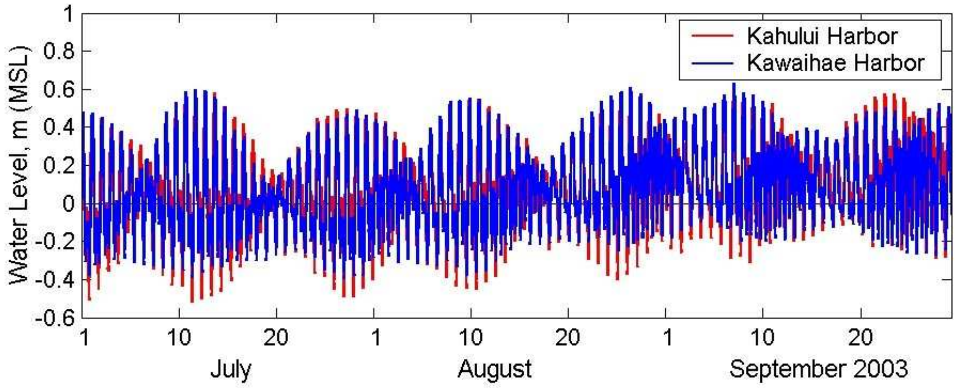

Figure 8. Water level data at Kahului Harbor and Kawaihae Harbor, July-September, 2003.

Figure 9 shows the wind and wave roses at WIS Stations 82517 and 82546 for 2003. The WIS hindcasting wave heights from Station 82517 (north of Maui) are generally greater than wave heights at Station 82546 (south of Maui) as Station 82517 is exposed more to larger waves come from NE (Gulf of Alaska), NW (Japan Sea), and E directions (easterly waves generated by the trade winds). On the south side of Maui, the coast is sheltered to waves from E, NE, N, and NW. The wave periods from Station 82546 are overall greater than waves at Station 82517 as the majority of waves south of Maui is the swell comes from the distant southern Hemisphere. The southerly and easterly wave directions at Station 82546 (south of Maui) are the result of southern swell mixed with local wind waves generated by the trade winds.

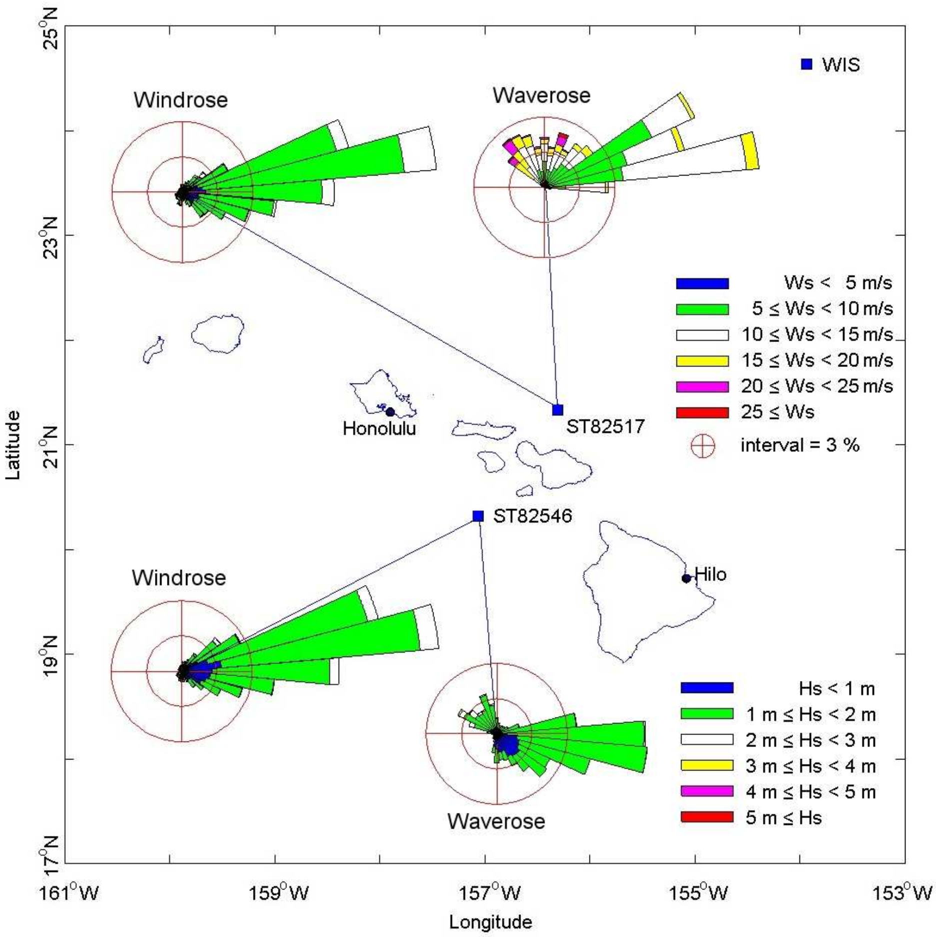

Figure 9. Wind and wave roses at WIS Stations 82517 and 82548 for 2003.

Figure 10, for example, shows the model calculated water levels and USGS data at APT (Kahana) and PUM (Puamana) for July 2003. Figure 11 shows model current results and data at HKW (Honokowai) for July 2003. Figure 12 shows the comparison of model wave height and period data at BRK (Black Rock) and PUM for July 2003.

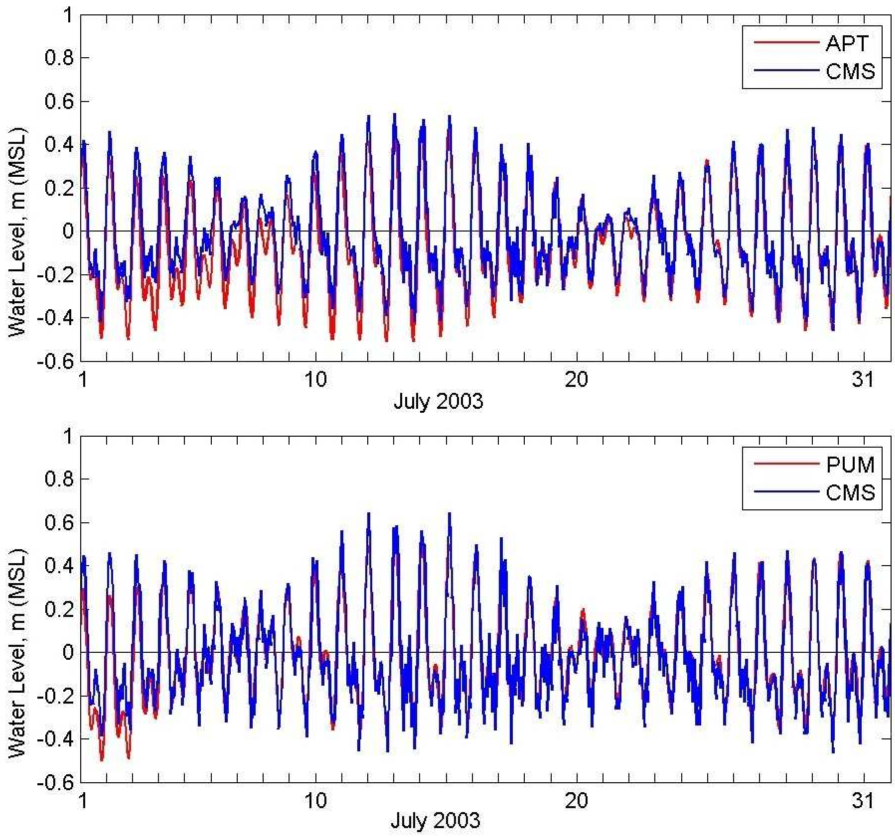

Figure 10. Calculated water levels vs data at Kahana (APT) and Puamana (PUM) for July 2003.

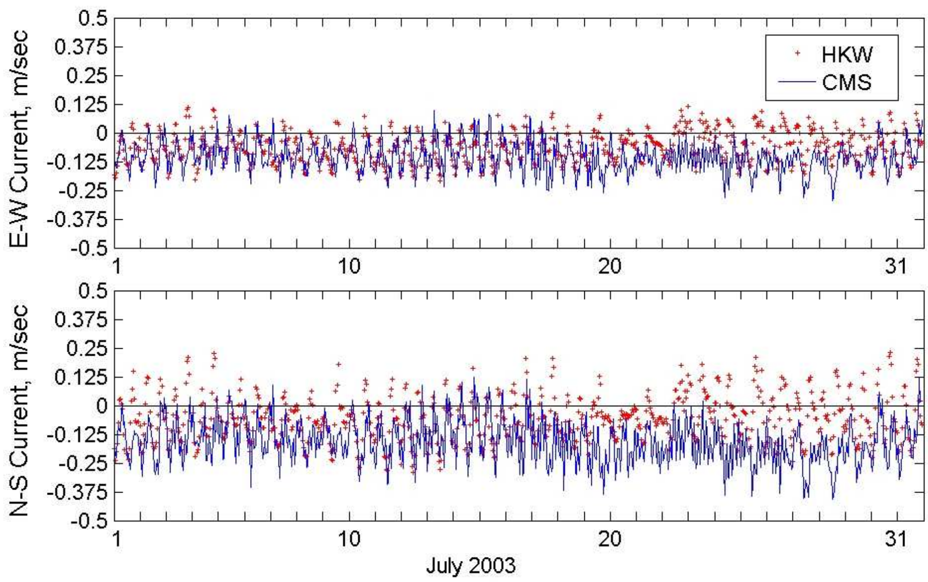

Figure 11. Calculated and measured current components at Honokowai (HKW) for July 2003.

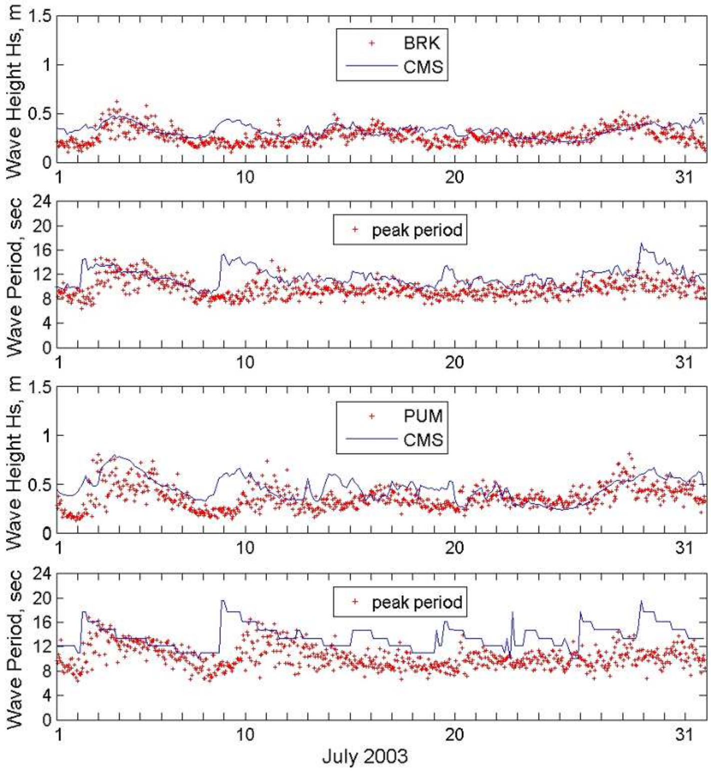

Figure 12. Model wave heights vs data at Black Rock (BRK) and Puamana (PUM) for July 2003.

6. Model Simulation and Sediment Budget Analysis

The CMS simulation was conducted for one-year period of 2003 representing a typical annual wave climate condition. Hindcasting winds and wave spectra from WIS Stations 82517 (north of Maui) and 82546 (south of Maui) were used as input wind and wave forcing along the north and south open boundaries, respectively, of the parent grid. Water surface elevation data from two nearby NOAA coastal stations 1615680 (Kahului Harbor, Maui) and 1617433 (Kawaihae Harbor, Hawaii) were used as input water levels along the north and south offshore boundaries, respectively, in the parent grid. The parent grid run simulated water levels, waves and flow fields. The wave and flow models were coupled in 3-hr intervals. Model results from the parent grid were used to drive the child grid. The child grid run calculated water levels, waves, currents, sediment transport, and morphology change. It included the Honokowai Stream (Figure 13) as a representative example of upland sediment input to the nearshore region of the West Maui. The flow input to Honokowai Stream was specified to a constant 555 cfs based on the 2-year recurrence interval (see Figure 4). At the flow input boundary of Honokowai Stream, the average current velocity was 0.06 m/sec. At the outlet of Honokowai Stream to the coast, the current magnitude was ranging from 0.5 to 1.3 m/sec between high to low tide water levels. Wave asymmetry and undertow options were triggered in the child grid simulation and a median grain size of 0.23 mm was used in the sediment transport calculation. The model estimate of sediment transport rate for 2003 was approximately 1,200 cubic-yard/year (CY/YR). This estimate was likely more than the actual rate as a constant flow rate of 555 cfs for Honokowai Stream was applied in the model simulation.

Model sediment transport results were compared with sediment volumetric change in the West Maui coastal region. Figure 14 shows the example of CMS calculated one-month morphology change in January 2003 along the West Maui coast. Based on shoreline change data between 1932 and 2014, compiled by the USACE, USGS and University of Hawaii School of Ocean and Earth Science and Technology (Fletcher et al. 2012; http://pubs.usgs.gov/of/2011/1051), the sediment volume change rates were estimated for twelve littoral cells (see Figures 5 and 14) in the region. Table 1 presents the comparison of model sediment volume changes (simulation of 2003) versus annual average volume change rate data in twelve littoral cells.

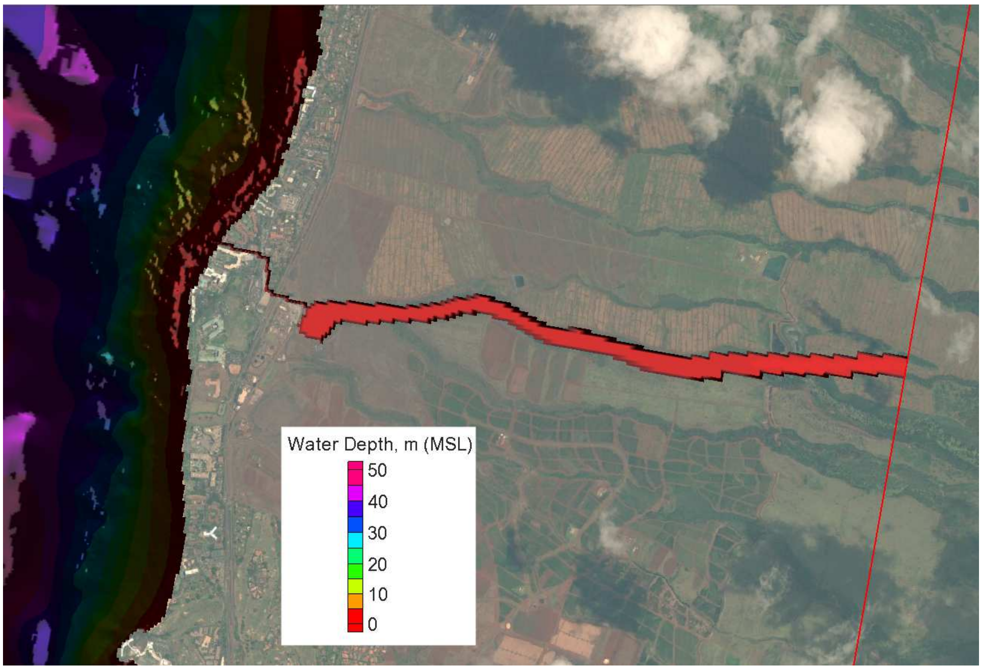

Figure 13. Honokowai Stream included in the child grid.

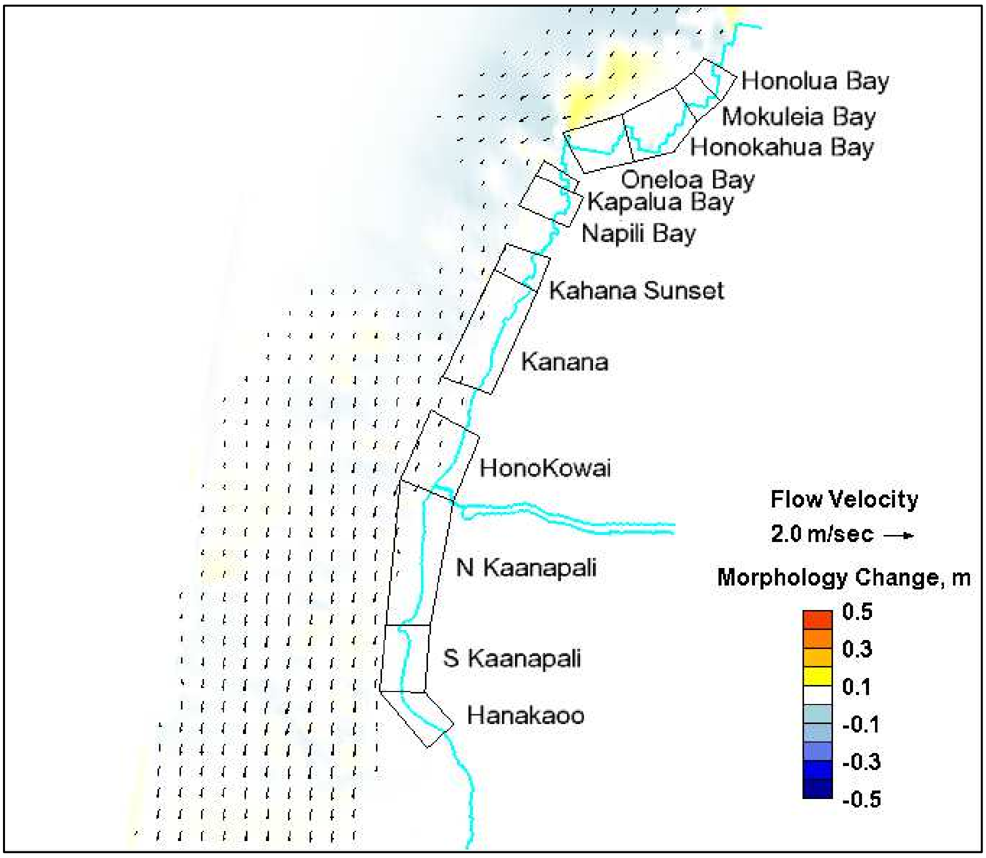

Figure 14. One-month morphology change and current field at 0000 GMT, 1 February, 2003.

Table 1. Annual volume change rates (CY/YR) in West Maui region, 1932-2014.

Littoral Cell	Data 1932-1997*	Data 1997-2014	Data 1932-2014*	CMS 2003**
Honolua Bay	-18	224	26	7
Mokuleia Bay	-181	559	-46	-109
Honokahua Bay	-138	1,676	193	-120
Oneloa Bay	16	1,138	221	1,013
Kapalua Bay	-20	356	49	120
Napili Bay	-154	809	22	-18
Kahana Sunset	-278	247	-182	-83
Kahana	-1,248	1,446	-756	-785
Honokowai	-1,367	2,429	-673	591
N. Kaanapali	-886	4,101	25	641
S. Kaanapali	854	3,308	1,303	-88
Hanakaoo	241	-2,148	-195	43
Sum (All Cells)	-3,180	14,145	13	1,210

* excluded extraordinary maximum accretion/erosion volumes
** CMS simulation included Honokowai Stream input (2-year recurrence flow)

PTM simulations were conducted with the 2-year recurrence stream flow for suspended sediment during 18-30 November 2003. The circulation pattern in the region during this time was dominated by southward directed offshore flow while alongshore current is predominately northward forming a counter-clockwise eddy in North Kaanapali littoral cell south of the stream. Figure 15(a) shows a snapshot of the PTM simulation at 2100 GMT, 26 November 2003. Red dots are representative sediment particles; yellow sticks are "tails" showing sediment particle movement in the previous 30 minutes. Suspended sediments moving with the nearshore eddy remained for approximately 3 to 4 days, and gradually migrated to the south and eventually heading towards offshore. Figure 15(b) shows the snapshot of sediment particle tracks from the same time period but with sediment input at the stream mouth reduced by 60%. In the scenario of reducing the flow discharge and sediment transport in Honokowai Stream, the suspended sediment would still follow the same general nearshore circulation patterns as in the existing condition but result in a lesser density of particles in the water column.

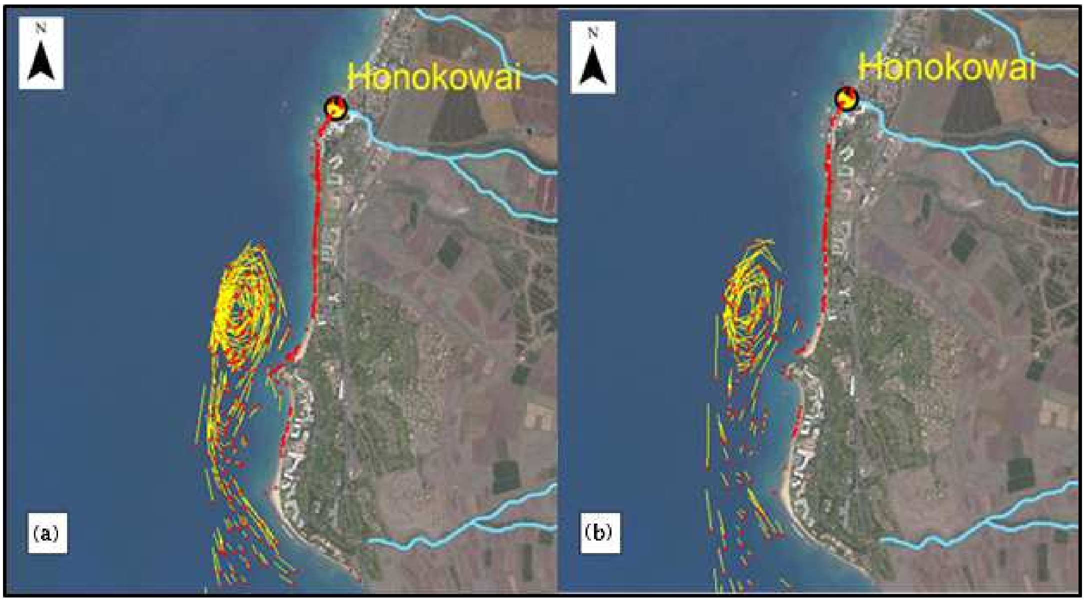

Figure 15. Snapshots of particle tracks at 2100 GMT, 26 November 2003 for (a) the 2-year recurrence stream flow, and (b) a reduction of sediment input by 60% in Honokowai Stream.

7. Conclusions

The present study applies the Coastal Modeling System (CMS) including wave and circulation models paired with the particle tracking simulation to develop regional sediment budget and investigate suspended sediment movement along the West Maui coast. The sediment supply, mainly from several river streams, is limited in the region. The CMS modeling and historical shoreline change data show relatively low rates of annual volume change as the majority of sediment transport was rather stabilized within twelve littoral cells. By excluding the extraordinary storms, the net sediment volume change along the West Maui coast is relatively small on the annual basis. As a demonstration, the CMS simulates the 2-year recurrence stream flow for Honokowai Stream. Model results show some moderate increase of sediment accretion in two southcentral littoral cells of Honokowai and North Kaanapali. The actual increase of this local sediment accretion is likely much lesser as all river streams in the West Maui are more of ephemeral in general.

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