Sediment Management Measures in West Maui Watersheds

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Abstract

Vitally important coral reefs in West Maui have declined by as much as 50% in the recent past, and have been targeted by Federal, State, and private entities for watershed planning efforts. The intent of the West Maui Watershed Study was to contribute to the restoration, enhancement and resiliency of West Maui coral reefs and nearshore waters through the reduction of land-based pollution threats. Sediment has been identified as one of the two major land-based pollutants in West Maui. This sediment is coming from a variety of sources, the largest contributor being the in-stream erosion of historic agricultural fill terraces within stream gulches. There are several dams and basins functioning as debris and flood risk reduction structures in West Maui that capture some sediment (to varying degrees of efficiency) as flood runoff travels to the coastal waters. Despite this, sediment plumes are often seen in West Maui after small and large storm events. Flow frequency relationships and corresponding sediment loads were roughly estimated for each watershed in the study area, supported by new field investigations and monitoring data. Several alternatives were developed to reduce the amount and frequency of riverine sediment being discharged into the ocean. The initial array of alternatives considered includes modification of the existing detention basins, use of a flocculant, flow diversion, manual excavation of highly erodible material from the stream banks, construction of loʻi terraces, and construction of small detention basins. Ultimately, modification of the existing detention basins and construction of smaller detention basins throughout the study area had the greatest potential for efficient sediment capture.

Introduction

Problem Statement

In West Maui, nearly one-fourth of all living corals were lost during the survey period of 1994 – 2006 (State of Hawaiʻi, Division of Aquatic Resources 2008). The causes of coral reef decline are complex and vary among location. However, there are strong indicators that anthropogenic stressors (e.g., shoreline development, overfishing, land-based pollution) contribute to the decline of coral cover. While there are also natural threats (e.g., weather-related damage), coral reefs that are subjected to numerous and sustained stresses lose the ability to recover entirely.

Coral reef decline threatens the economy, ecosystem and community in West Maui. Coral reefs are widely recognized as critical to Hawaiʻi's economy, recreational and commercial fisheries, ecological biodiversity and for being the first line of defense against coastal hazards.

Study Area: The study area includes an area of approximately 24,000 acres on the leeward side of the West Maui Mountains, from Kāʻanapali northward to Honolua and from the summit of Puʻu Kukui to the outer reef. There are approximately eleven adjacent watersheds in the study area (Figure 1).

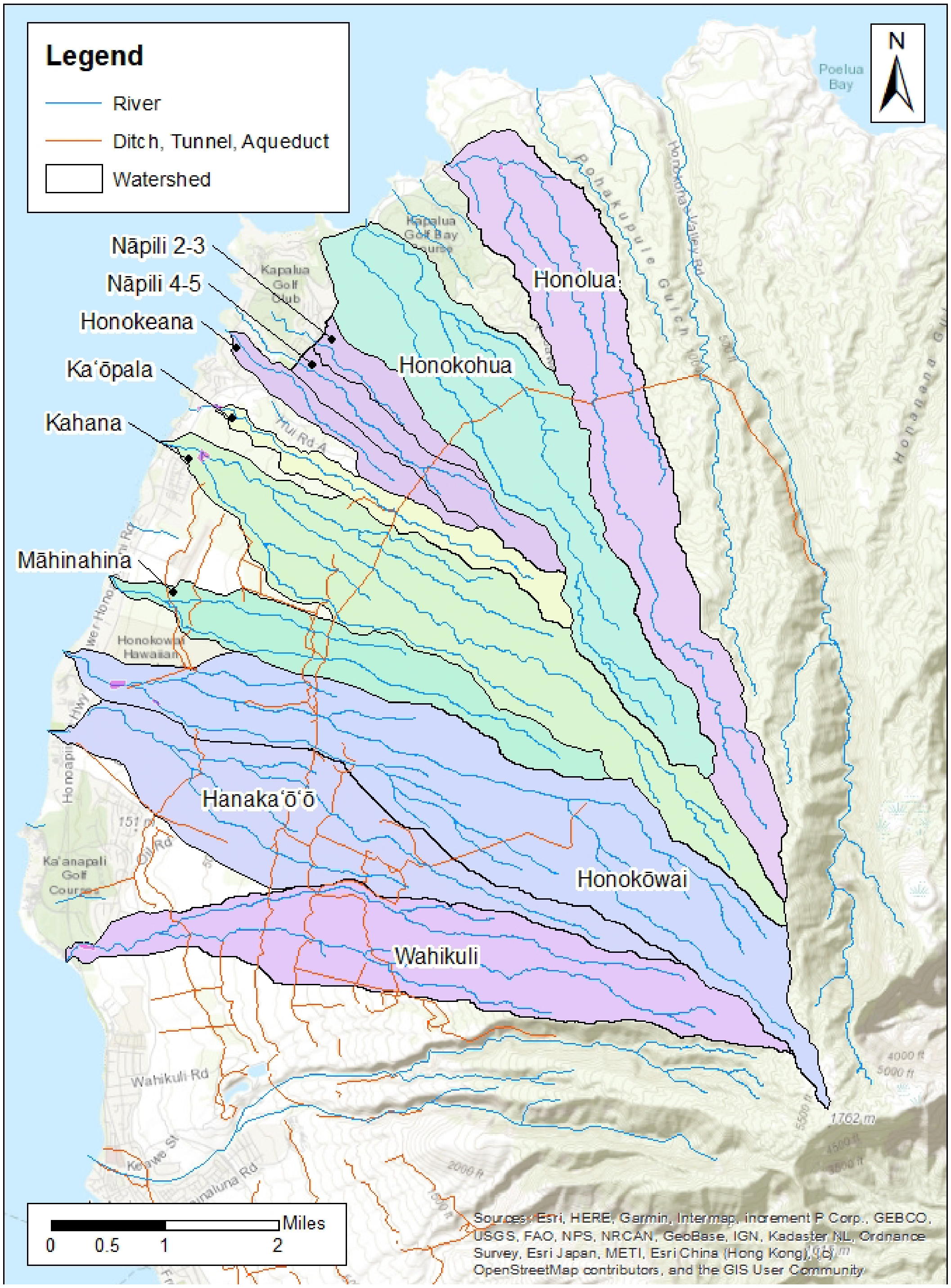

Figure 1. Watershed Map, West Maui, Hawaii

Key Pollutant Source: Terrestrial sediment is a key land-based pollutant affecting West Maui coral reefs. Furthermore, erosion of fine-grained, fill terraces that line the stream banks along much of the lower channel are believed to be the primary source of terrestrial sediment. These historic fill terraces were deposited by past agricultural practices as fine sediment was pushed into the valley as sidecast (Figure 2; Stock & Cerovski-Darriau 2021).

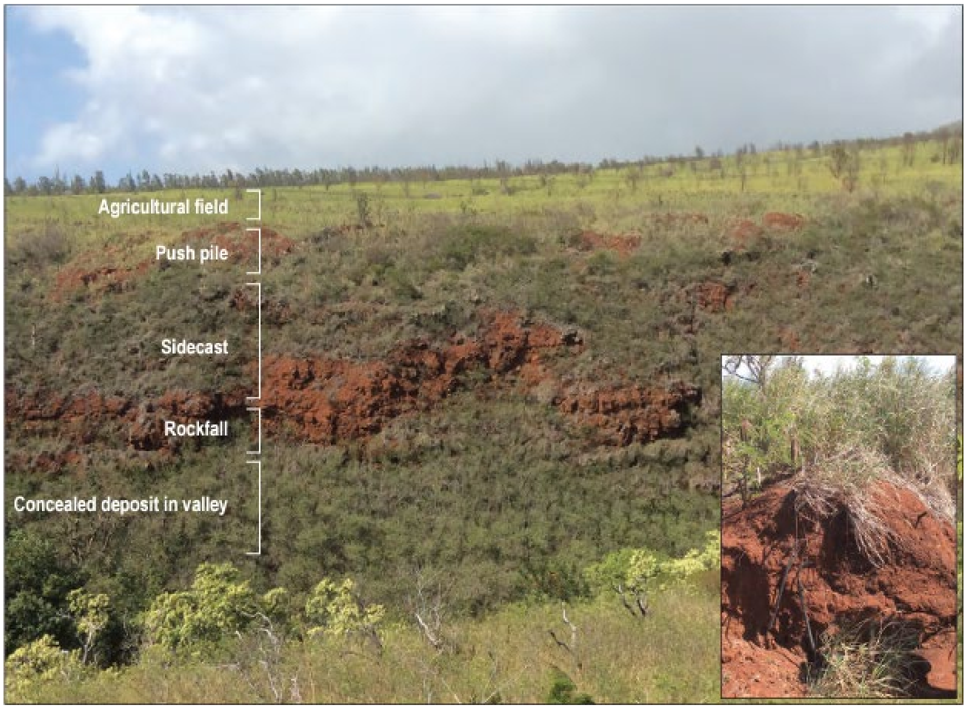

Figure 2. Watershed Map, West Maui, Hawaii

Field investigations indicate an anthropogenic layer of mixed sediment atop naturally occurring alluvial sediment in the West Maui stream valleys. Mixed cobble, gravel and large boulders that are not conducive to large-scale agriculture are found along the perimeter of the fields and adjacent to stream valleys. Red-orange silty sediment traces from the agricultural fields down the sides slopes of the adjacent valley. All evidence of side cast material from atop the agricultural plateau to the bordering stream valleys. Investigations into the composition of the stream valley bed and banks indicate a layer of sandy silt over coarser grained deposit, some deposits featuring irrigation remnants and historical artifacts. This layer extends up the side slopes of the valleys up to the agricultural fields. These fine-grained deposits form historic fill terraces that line the stream banks along much of the lower channel.

Study Objective: The intent of the West Maui Watershed Study was to contribute to the restoration, enhancement and resiliency of West Maui coral reefs and nearshore waters through the reduction of land-based pollution threats from the summit of Puʻu Kukui in the West Maui mountains to the outer reef. The objective of the study was to develop a list of recommendations for strategic implementation over the next 50 years that 1) reduces current and future pollutant sources and 2) reduces the *conveyance* of those pollutants, with special attention given to reducing terrestrial sediment contributions by West Maui watersheds. Terrestrial sediment in the marine environment was previously identified as a primary stressor to local coral reef ecosystems.

Data Collection

Climate Stations

Rainfall in West Maui occurs primarily via tradewind-driven orographic rain, typical of Hawaiʻi's subtropical location, carrying moist air from the sea in a westerly direction and upwards over Hawaiʻi's east facing mountain ranges. Orographic rain or the "Rain Shadow Effect" drives the climate gradient characterized by a wet windward side and a dry leeward side. There are notable differences in hydrology between the wet, northern watershed of Honolua and the dry, western watershed of Wahikuli.

Climate data (e.g. rainfall) was available at one U.S. Geological Survey (USGS) and four National Oceanic and Atmospheric Administration (NOAA) rain gages within or near the study area. There are also four other rainfall stations located within the study area that are monitored by West Maui Ridge to Reef Initiative (West Maui R2R). These gages provide instantaneous data in either 5 or 15-minute intervals.

Stream Gages: There are three USGS crest-stage gages within the study area, but only one provided a sufficient record to support calibration of the hydrologic model (16630200 in Honokōwai). Additionally, there was one instantaneous streamflow gage in an adjacent watershed (16620000 in Honokōhau) that provided continuous streamflow data in 5-minute intervals, with a period of record of 30 years (1990 to 2020), and peak flow data for a period of record of 101 years (1914 – 2019, intermittently).

New stream monitoring stations were installed at three sites in 2017, in partnership with West Maui R2R and the State of Hawaiʻi, Department of Land and Natural Resources, Commission on Water Resource Management (CWRM). These stream monitoring stations were sited in Honokōwai and Honolua. Cross sections of the three sites were surveyed when the new monitoring stations were installed in September 2017 and again in November 2018. These gages record stage only. Rating curves were developed by CWRM and USACE using different methods to compute the relation between stage and streamflow (discharge).

Coastal Camera Analysis: In 2017, USGS installed cameras along the West Maui shoreline to capture daily photos at the river outlets of Wahikuli, Honokōwai, Kahana, and Kaʻōpala Stream. This data was reviewed by the West Maui Watershed and Coastal Management Coordinator who provided a summary of how often plumes occurred during the period of record. There are significant data gaps in the period of record, but the information is still useful for identifying what types of events trigger plumes and how often they typically occur. This analysis showed that ephemeral streams, which are typically dry, tend to have plumes more frequently as almost any flow in the stream will pick up fine sediments that were not able to reach the ocean during a previous event.

Field Survey of Historic Fill Terraces: The extent of bank erosion was estimated by surveying the extent of historic fill terraces in four valleys: Honokōwai Stream, Kaʻōpala Gulch, lower Honolua Stream, and Pāpua Gulch (a tributary of Honolua Stream). These surveys showed that fill terraces occupy approximately forty percent (40%) of streambank length (Stock & Cerovski-Darriau 2021).

Erosion Pin Test: Annual bank erosion rates at four representative sites in the study area were estimated by periodic cross section surveys and erosion pins. At each site, twenty or more long nails were installed at even increments across the channel and pushed or lightly hammered until the rim of the pin was just below the surface. Periodic surveys of each cross section over one year of observation provided approximate lowering rates in the channels at each site (Figure 3). Lowering rates in the higher annual rainfall channels of Honolua and its tributary Pāpua are much higher than those found at Māhinahina, an ephemeral channel on the "dry side" (Table 1). The median lowering rate for all three sites on the "wet side" was estimated to be 14 mm/yr (Stock & Cerovski-Darriau 2021).

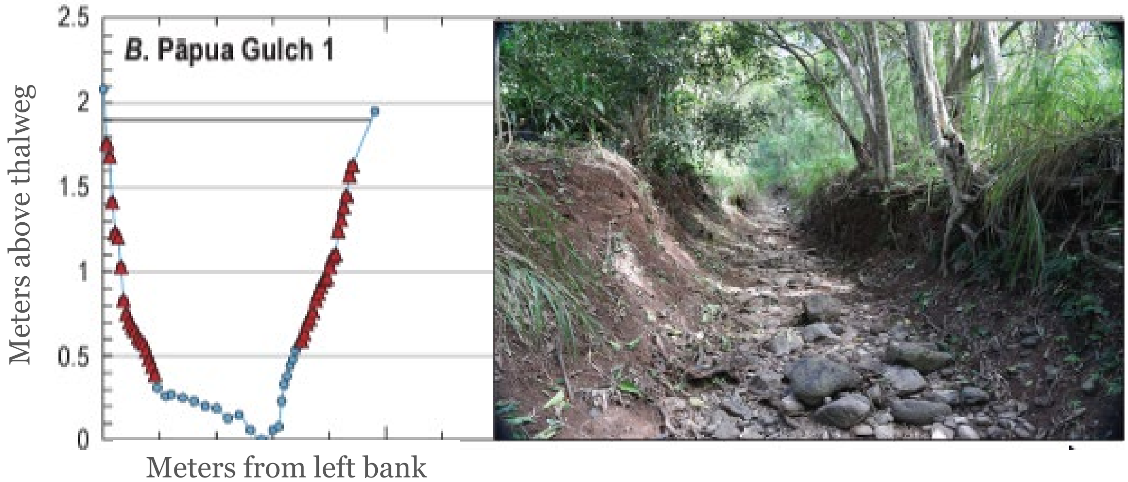

Figure 3. Cross section of the stream channel at an erosion pin test site shown by the blue line connecting blue dots; red triangles denote erosion pins installed to measure bank erosion.

Table 1. Annual lowering rates at erosion pin sites

Site	No. observations	Mean (mm/yr)	Standard deviation (mm/yr)
Honolua	40	9.3	8.0
Pāpua 1	45	15.1	8.7
Pāpua 2	21	29.0	17.2
Māhinahina	19	4.7	2.2

Cohesive Strength Meter "Jet" Test: In 2017, USGS performed cohesive strength meter (CSM) testing to estimate the cohesive strength of fill terrace sediment (the ability for the sediment to resist shear stress). This test was performed at six locations: the four erosion pin sites, and two additional sites at Honokōwai and Māhinahina. Cohesion values for initiation of bank erosion (90% transmission) at all West Maui fine-grained fill terraces range from 0.2 – 1.2 kPA, with no obvious geographic distribution. The average value of 0.61 kPa is an estimate for the regional value of bank cohesion at which erosion begins. The average value of 2.68 kPa is an estimate for the regional value of bank cohesion at which substantial erosion occurs (25% transmission).

Reconnaissance Sediment Budget: USGS constructed a watershed sediment budget by summing all of the areas for each geomorphic process in a watershed and multiplying each total by a measured or hypothetical lowering rate and a soil bulk density to produce a sediment load in units of metric tons per year (Figure 4). This was done for three time scales: 1) annual storms that involve only bank erosion, 2) decadal storms that erode agricultural fields, and 3) annual storms prior to human impacts (prehistoric). The final sediment budget estimated by USGS indicates that bank erosion of fill terraces from a few watersheds likely dominates the current annual fine sediment load to the nearshore, with Kahana Stream producing the largest annual input of 285 metric tons (Stock & Cerovski-Darriau 2021).

Estimating Event-Based Flow and Sediment Loads

Flow Frequency Analysis

The discharge-frequency relationships at key points in the study area were determined by developing rainfall-runoff models for twelve watersheds using the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS, version 4.8, 2021) software. The twelve watersheds selected include all eleven watersheds in the study area (Wahikuli, Hanakaʻōʻō, Honokōwai, Māhinahina, Kahana, Kaʻōpala, Nāpili, Honokahua, and Honolua) and one watershed adjacent to the study area that provides essential streamflow data (Honokōhau).

It was not possible to calibrate this model effectively to specific historical storm events due to the limited number of sites and storm events in the available record. However, a Bulletin 17C stream gage analysis on two sites in the Honokōhau and Honokōwai watersheds provided a strong level of confidence based on long periods of record and the rainfall-runoff model was calibrated to match these results. The calibrated peak flow estimates computed by the rainfall-runoff model were adopted as the final peak flow estimates to be carried forward for use in this study (Table 2; Figure 5).

Table 2. Peak flow estimates at each basin outlet

Basin ID	Watershed	Peak flow (ft^3/s)[1]							
		1/2	**1/5**	**1/10**	**1/25**	**1/50**	**1/100**	**1/200**	**1/500**
1	Wahikuli	1,270	2,330	3,220	4,750	6,080	7,460	9,010	11,400
2	Hanakaʻōʻō	667	1,370	1,980	3,030	4,020	5,080	6,290	8,170
3	Honokōwai	646	1,190	2,280	3,460	4,490	5,640	7,020	7,230
4	Māhinahina	453	933	1,360	2,060	2,680	3,340	4,090	5,180
5	Kahana	252	1,100	1,690	1,720	2,340	3,090	4,030	8,630
6	Kaʻōpala	182	396	584	887	1,180	1,500	1,860	2,410
7	Honokeana	241	434	597	839	1,050	1,260	1,500	1,840
7B	Nāpili 4-5	128	190	258	442	574	725	898	1,190
7C	Nāpili 2-3	117	168	222	365	457	564	679	857
8	Honokahua	341	751	1,130	1,830	2,450	3,235	4,210	5,980
10	Honolua	227	467	717	1,160	1,560	2,050	2,670	3,820
[1]: rounded to three significant figures									

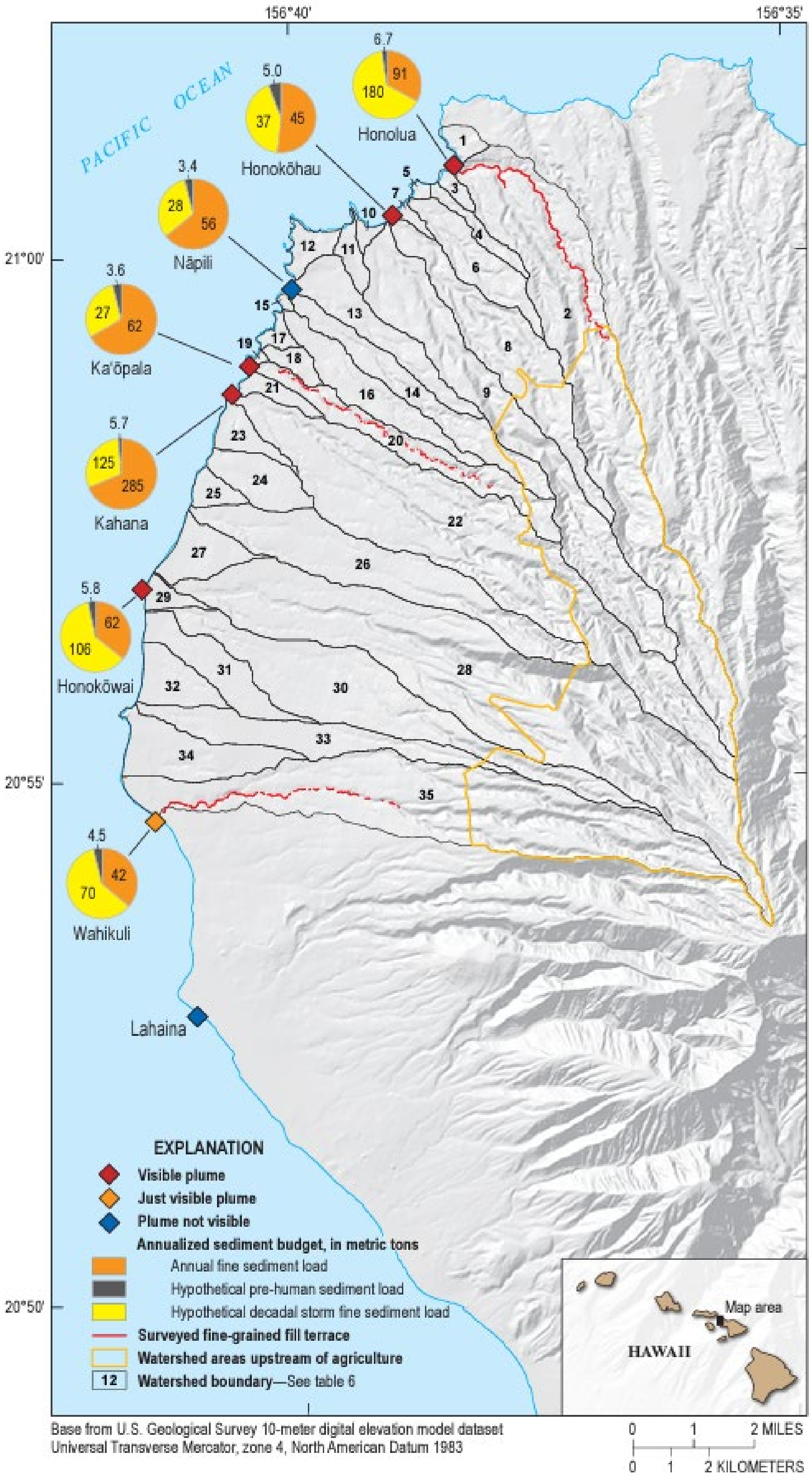

Figure 4. Annualized sediment budget for various watersheds in West Maui

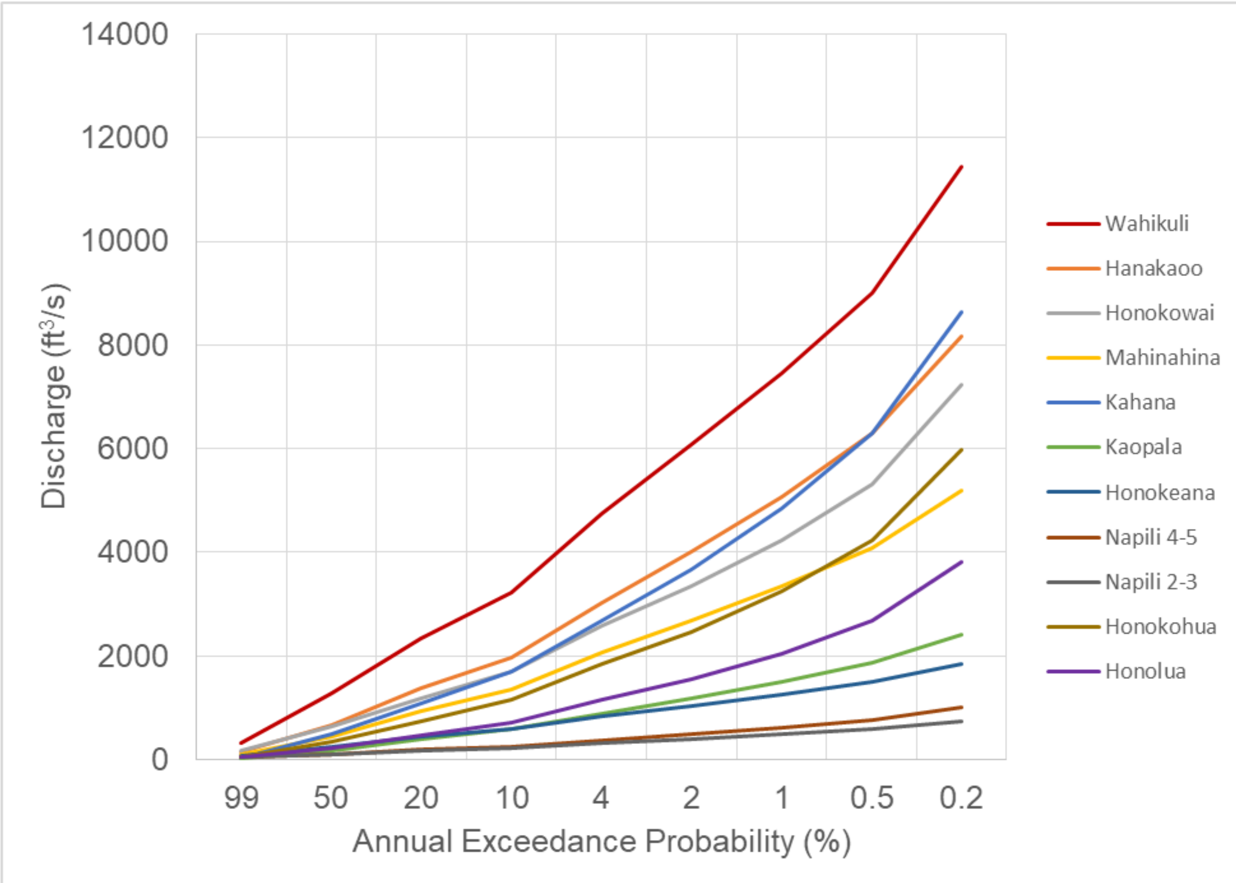

Figure 5. Flow Duration Curves for West Maui Basins (at the outlets)

Continuous Flow Simulations: To evaluate terrestrial sediment dynamics in the nearshore environment, flow and sediment load time series data representative of a specific event (i.e. the 50% AEP flood) were needed as input for a hydrodynamic-sediment transport model. The methodology for determining event-based flow and sediment loads relies on the sediment transport functions in the rainfall-runoff model to distribute the total annual sediment load across a one-year continuous flow simulation. This method accounts for the total annual sediment load, does not require the modeler to make an assumption regarding the total sediment load for a particular event when there is no calibration data to support it, and provides an opportunity to calibrate the frequency of plume-triggering events simulated with those observed by coastal cameras. Additionally, the reservoirs included in the model could evaluate trap efficiency and compute the new sediment output relatively quickly.

To simulate typical sediment loads expected throughout the year, historical rainfall data from 1 November 2014 to 1 November 2015 was used as input into the rainfall-runoff model, paired with annual sediment loads for each watershed previously estimated by USGS. The period 1 November 2014 to 1 November 2015 was selected because it was determined to be a good representation of typical rainfall (no significant storms or drought periods).

By distributing the annual sediment load over a one-year period, it was possible to estimate typical sediment loads for the various low flow events occurring throughout the year (Figure 6).

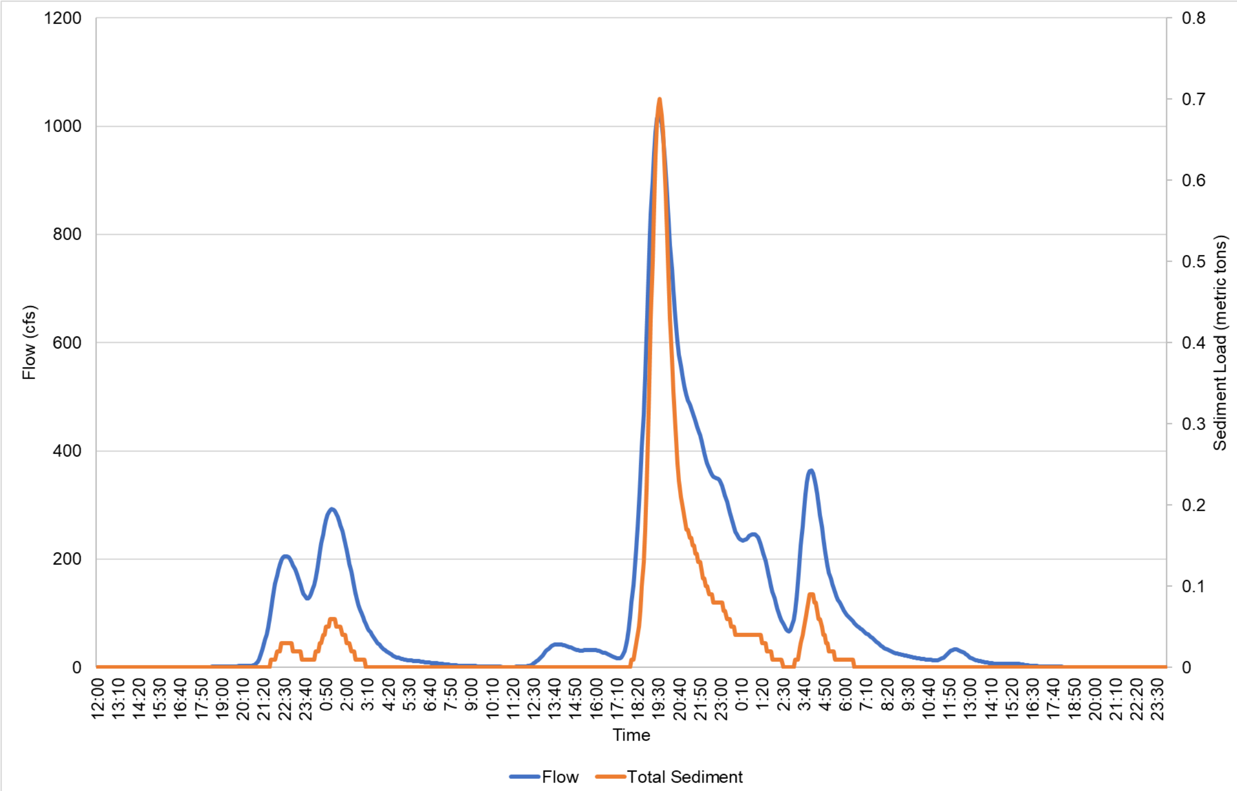

Figure 6. Hydrograph and Sedigraph for Flow and Sediment Load entering Honokōwai Basin, 22-24 December 2014

Trap Efficiency of Existing Detention Basins: Additionally, the trap efficiencies of the existing detention basins were also computed by applying Chen's Sediment Trap in the rainfall-runoff model. The existing basins were very effective at capturing sand and gravel, but not very effective at capturing clay and silt.

Table 3. Trap Efficiency of Existing Detention Basins, Annual Storm

	Honokōwai Basin	Māhinahina Basin	Kahana Basin	Ka'ōpala Basin	Nāpili 4-5 Basin
Clay	1%	3%	35%	11%	12%
Silt	34%	13%	65%	100%	96%
Sand	100%	100%	100%	100%	100%
Gravel	100%	100%	100%	100%	100%
Total Sediment	49%	51%	68%	86%	84%

Magnitude-Frequency Analysis of Suspended Sediment Loads: The continuous flow simulation provided estimated sediment loads for various low flow events experienced in 2014 and 2015. Additionally, USGS provided an estimate for the decadal storm load (Figure 5). This was paired with the estimated peak flow for the 10% AEP "decadal" event (Table 2). Together, a sediment-frequency curve was developed to provide approximate loads for events up to and including the 10% AEP flood event (Table 4, Figure 7).

Table 4. Magnitude-Frequency Estimates of Suspended Sediment Load Entering Honokōwai Detention Basin

AEP	Peak Flow, cfs[1]	Sediment Load, tons[1]
0.5	845	8.99
0.2	1,580	518
0.1	2,280	1,060

[1]: rounded to three significant figures

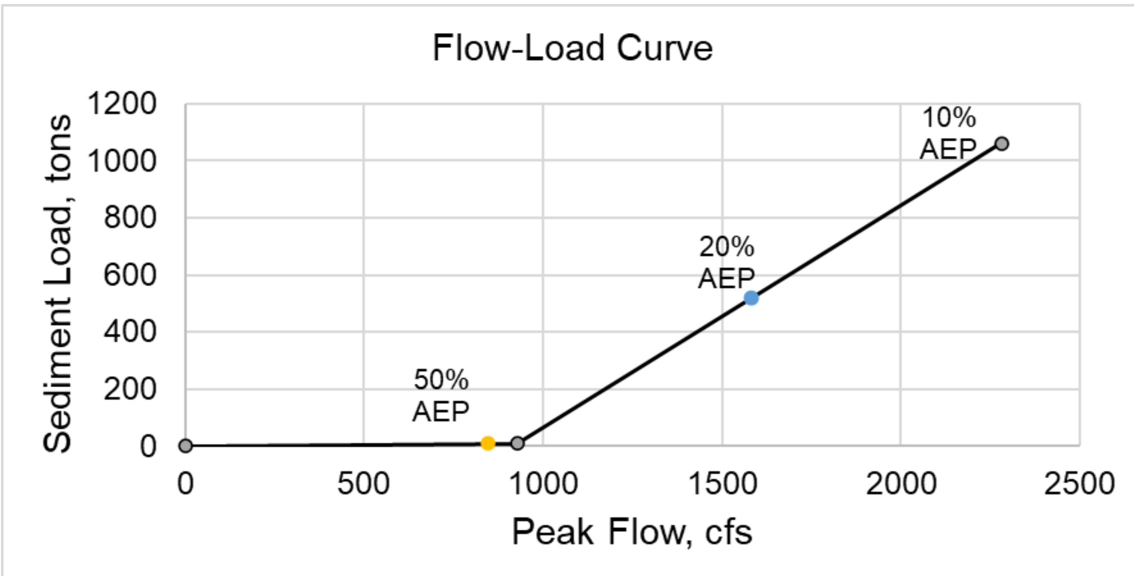

Figure 7. Peak Flow vs Sediment Mass Load Entering Honokōwai Detention Basin

Development of Alternatives

Design Flow

Corals can survive occasional short-term siltation events. However, chronic silt plumes or a single large event will kill coral. When sediments settle upon corals, they inhibit photosynthetic production. Many corals will attempt to clean themselves of this sediment by a combination of mucus secretion and ciliary action. However, with repeated influxes of sediment, the corals essentially become exhausted from continuously trying to rid themselves of sediment. This directly impacts coral recruitment, growth, mortality, and the ecosystem. Reducing very fine sediments (clay and silt) to the maximum extent practical during the 50% annual exceedance probability (AEP) flood event was the target objective.

Sited Management Measures: Several management measures were initially proposed for reducing the amount of terrestrial sediment being discharged by West Maui streams. The team's approach began by focusing on either 1) reducing flow using an upstream feature, 2) implementing a feature mid-stream, or 3) capturing sediment with a downstream feature. After an initial assessment of each measure using various screening criteria (e.g. technical feasibility, environmental impacts, cost of construction), the management measures considered to be feasible were explored in greater detail, before being sited and included in a conceptual plan. The management measures carried forward were 1) loʻi terraces, 2) micro basins, and 3) modification of existing detention basins.

Loʻi Terraces: There is strong community support to restore taro patches (loʻi terraces) at former sites in Honokōwai and Honolua, with an opportunity to also use it to capture sediment from daily low flow conditions. Traditionally in flooded taro, a loose wall of rocks slows down waters in the main channel and creates enough headwater that some flow is diverted into a rock-lined canal. From this canal, water flows into each loʻi at its upper corner and out into the next patch from its lower corner, eventually returning to the main channel. The water level in each loʻi is controlled at openings in the bank to keep the base of the plant submerged and maintain continuous flow.

In 2012, a 7-month long field study by Koshiba et al. demonstrated cultivated taro fields in Palau to trap an average of 90% of the sediment entering into the field (2014). The high sediment trapping efficiency was determined to be the result of water flow management (slowing down flow with vegetation) and water depth management (water entering the fields were maintained at relatively shallow depths – 10 to 50 cm by field observation – as they spread out across the entire width of the field), which allowed fine sediment to fall out of suspension more easily. Effects to the main channel regarding reduced sediment loads were not quantified by this study.

However, the median average water use for a loʻi complex is 150,000 gallons per acre per day. Converting this to flow units, water use is only 0.232 cubic feet per second (ft^3/s). Although this measure was believed to be effective in reducing fine sediments in waters entering the loʻi complex, it had a negligible effect overall on reducing fine sediments from the main channel due to the limited volume of water being diverted into the loʻi complex.

This measure was sited in the Honolua and Honokōwai watersheds, but ultimately, not recommended due to its limited effectiveness on removing fine sediments from the overall system.

Micro Basins: This measure proposes the construction of medium-sized detention basins, either in-line with the stream or offset. The focus on this measure is finding optimal pond characteristics to maximize trap efficiency with considerations to cost and the land area available. The trap efficiency of each basin to retain sediment during a specific type of flood event (e.g., the 50% AEP flood) were estimated using Camp's 1946 settling velocity equations. The settling velocity of clay, silt, and fine sand in stormwater were estimated using Stoke's Law. For particles larger than fine sand, such as coarse gravel, the equation by Ferguson and Church was used. Based on average diameter limits for various soil types, typical settling velocities are provided in Table 5.

Table 5. Typical Settling Velocities Based on Soil Type

Name of soil separate	Diameter limits (mm)	Equation	Settling velocity, Vs (m/s)	Settling velocity, Vs (ft/s)
Clay	< 0.002	Stoke's Law	8.99E-07	2.95E-06
Silt	0.002 – 0.05	Stoke's Law	6.07E-04	0.002
Very fine sand	0.05 – 0.10	Stoke's Law	5.05E-03	0.017
Fine sand	0.10 – 0.25	Stoke's Law	2.75E-02	0.090
Medium sand	0.25 – 0.50	Ferguson and Church	0.203	0.666
Coarse sand	0.50 – 1.00	Ferguson and Church	0.812	2.66
Very coarse sand	1.00 – 2.00	Ferguson and Church	3.25	10.7

In estimating the minimum treatment surface requirements for various soil types and various outflow rates, maximizing the use of available land and restricting the outflow were not enough to create an effective detention or micro basin. Other methods would need to be incorporated to encourage settlement of the clay and silt, such as use of a coagulant to promote flocculation or retaining the water for an extended period. Using the settling velocities presented in Table 5, the estimated time it would take for various sediment types to settle 1-, 5-, and 10-feet are presented in Table 6. This applies universally to all watersheds in the study area. From this table, it seems that most of the silt can be captured by holding onto the water for a couple of hours (depending on the water depth). However, this would only capture a small portion of the clay particles. Typically, it is not recommended to leave water standing for more than 72 hours to effectively suppress mosquito production.

Table 6. Approximate Settlement Times for Various Depths

Name of soil separate	Diameter limits (mm)	1 ft Depth	5 ft Depth	10 ft Depth
Clay	< 0.002	4 days	20 days	39 days
Silt	0.002 – 0.05	8 min	42 min	83 min
Very fine sand	0.05 – 0.10	1 min	5 min	10 min
Fine sand	0.10 – 0.25	11 sec	1 min	2 min
Medium sand	0.25 – 0.50	1.5 sec	7.5 sec	15 sec
Coarse sand	0.50 – 1.00	0.38 sec	1.9 sec	3.8 sec
Very coarse sand	1.00 – 2.00	0.1 sec	0.5 sec	0.9 sec

This measure was recommended for the Honolua, Kaʻōpala, and Wahikuli watersheds.

Modification of Existing Detention Basins: There are three existing basins worth evaluating under this study for potential modification: Kaʻōpala Gulch Basin, Kahana Basin, and Honokōwai Basin. The primary deficiency with these basins is their inability to control the pool elevation and sediment retention time.

The open outlet pipe at Kaʻōpala allows sediment-laden waters at the bottom of the reservoir pool to be released downstream immediately (Figure 8). The proposed modification at this site consists of a series of sluice gate panels that are manually opened by the dam operator to allow flow to enter the original, underground outlet pipe from the top-down. The existing basin is relatively effective at trapping silt, sand and gravel. Settlement of clay is moderately improved by modifying the dam to retain more water and lowering the reservoir from the top-down.

However, the higher pool elevation that is created by the modification results in earlier activation of the principal spillway. This results in more silt escaping the basin and a lower trap efficiency overall (Table 7).

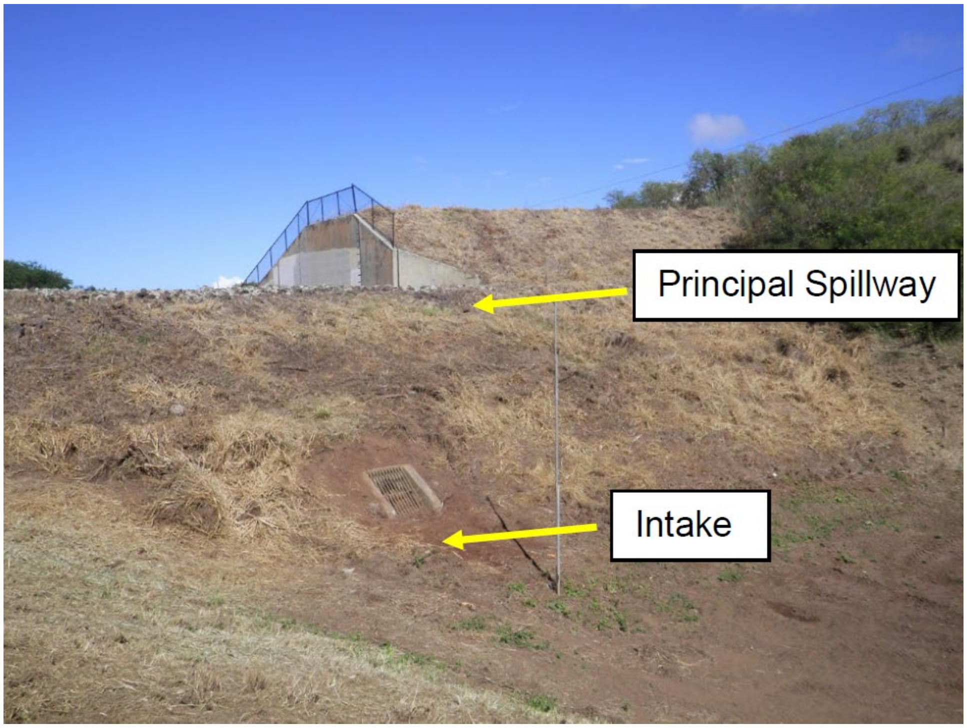

Figure 8. Existing Principal Spillway and Intake, Kaʻōpala Dam

Table 7. Evaluating the Sediment Load and Trap Efficiency of Kaʻōpala Dam, 50% AEP Event

	Inflow (ft^3/s)	Existing		Modified	
		Outflow (ft^3/s)	Trap Efficiency	Outflow (ft^3/s)	Trap Efficiency
Peak Streamflow (ft^3/s)	182	80.8	--	135	--
Sediment – Total (tons)	64.9	7.79	88%	11.0	83%
Sediment – Clay (tons)	10.1	7.68	24%	5.45	46%
Sediment – Silt (tons)	21.9	0	100%	4.82	78%
Sediment – Sand (tons)	24.5	0	100%	0.00	100%
Sediment – Gravel (tons)	0.17	0	100%	0.00	100%

Similarly to the Ka‘ōpala Gulch Basin, the open ports on the Honokōwai riser structure also allow sediment-laden water to be released immediately (Figure 9). The proposed modification at this site was to allow for controlled release of flow from the top-down via stoplog panels. These panels could be installed over the existing, open ports. The modification would include eight panels, 4 ft wide by 3 ft high. An elevated work platform would also be necessary to provide operation and maintenance personnel access to the control structure during flooded conditions. As the Honokōwai Dam is a regulated dam, any modification would require further evaluation to verify there is no increased flood risk downstream.

Construction of the stoplog panels would slightly increase the surface area of the reservoir, but mostly importantly reduce the rate of flow leaving the reservoir. Increased retention time allows for increased settlement and a greater trap efficiency (Table 8).

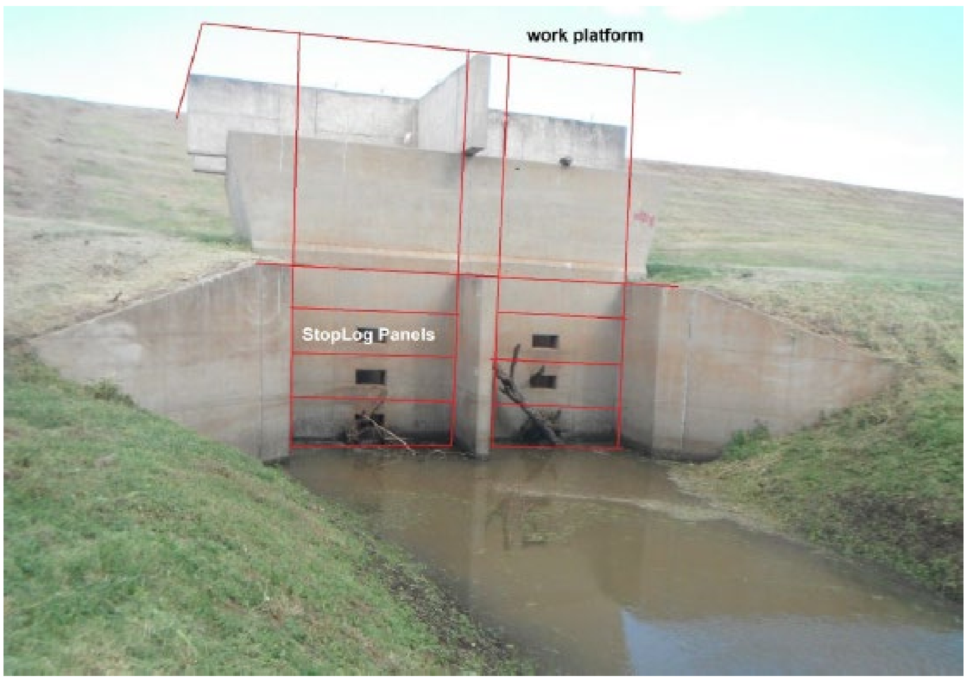

Figure 9. Proposed StopLog Panels and Work Platform at the Honokōwai Dam riser structure

Table 8. Sediment Loads and Trap Efficiency for the Honokōwai Basin Modification, 50% AEP Event

Condition	Sediment (tons)				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Inflow	12.3	2.42	5.69	3.68	0.33
Existing Outflow	6.09	2.49	3.58	0	0
Modified Outflow	5.66	2.37	3.19	0	0
Condition	**Trap Efficiency (%)**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Existing Outflow	51	1	36	100	100
Modified Outflow	54	2	44	100	100

The proposed action recommended for the Kahana Basin (Figure 10) is regular excavation of the deposited sediments in the basin. Excavating the basin improves the trap efficiency of silt from 47% to 79% but was not very effective for clay particles.

Figure 10. Riser structure and saturated conditions, Kahana Dam

Conclusion

The sediment measures developed under this study were formulated specifically to address the legacy agricultural deposits. Ultimately, the recommended measures included one micro basin in the Honolua Watershed, three micro basins in Wahikuli, annual excavation of the Kahana Basin, and modification of the Honokōwai Basin riser structure. Targeting land-based pollution will increase the resistance and resiliency of West Maui coral reef health thereby improving the local West Maui economy.

References

Koshiba, S., Besebes, M., Soaladaob, K., Ngiraingas, M., Isechal, A., Victor, S., and Golbuu, Y. 2014. “2000 years of sustainable use of watersheds and coral reefs in Pacific Islands: A review for Palau.” Estuarine, Coastal and Shelf Science 144 (2014) 19-26.

State of Hawaiʻi, Division of Aquatic Resources. 2008. “Status of Maui’s Coral Reefs.”

Stock, J. and Cerovski-Darriau, C. 2021. “Sediment Budget for Watersheds of West Maui, Hawaii.” U.S. Geological Survey, Reston, Virginia. Scientific Investigations Report 2020-5133.