West Maui Watershed Study

West Maui, Hawai‘i



FINAL WATERSHED MANAGEMENT PLAN May 2023

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Prepared for:
State of Hawai‘i, Department of Land and Natural Resources, Division of Aquatic Resources

DISCLAIMER

The information presented in this document is to provide a strategic framework of potential options to address problems within the West Maui watershed. Options identified will follow normal authorization and budgetary processes of the appropriate agencies. Any costs presented in this document are rough order magnitude estimates used for screening purposes only.

Cover Photo: USGS, 2009

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EXECUTIVE SUMMARY

Study Authority

The Honolulu District, U.S. Army Corps of Engineers (USACE) is partnered with the State of Hawai‘i Department of Land and Natural Resources (DLNR), Division of Aquatic Resources (DAR) to jointly pursue watershed planning efforts for the West Maui watershed, Island of Maui, Hawai‘i, in accordance with Section 729 of the Water Resources Development Act (WRDA) of 1986, Public Law 99-662, as amended (33 U.S.C. 2267a; hereinafter “Section 729”). Section 729 authorizes the development of watershed plans that are multi-purpose and multi-objective in scope and developed in cooperation with Federal, State and local government entities.

Non-Federal Sponsor

The non-federal Sponsor for the West Maui Watershed Management Plan is the State of Hawai‘i, as represented by DLNR-DAR. DLNR-DAR manages the State’s aquatic resources and ecosystems through programs in ecosystem management, place-based management, and fisheries management with a mission to work with the people of Hawai‘i to manage, conserve and restore the State’s unique aquatic resources and ecosystems for present and future generations. DLNR-DAR and USACE entered into a cost-share agreement on August 9, 2012 to assess the water resources needs of the West Maui watershed pursuant to Section 729.

Study Area

The West Maui watershed study area covers approximately 24,000 acres (9,712 hectares), includes five watersheds (Wahikuli, Honokōwai, Kahana, Honokahua, and Honolua), and the coral reef habitat north of Lahaina on the northwestern coast of the Island of Maui in the State of Hawai‘i (Figure ES-1). West Maui was designated a Priority Watershed by the U.S. Coral Reef Task Force in 2011 which encourages federal and jurisdictional agencies to work together to target restoration, pollution control, and monitoring to improve coral reef condition (USCRTF, 2019).

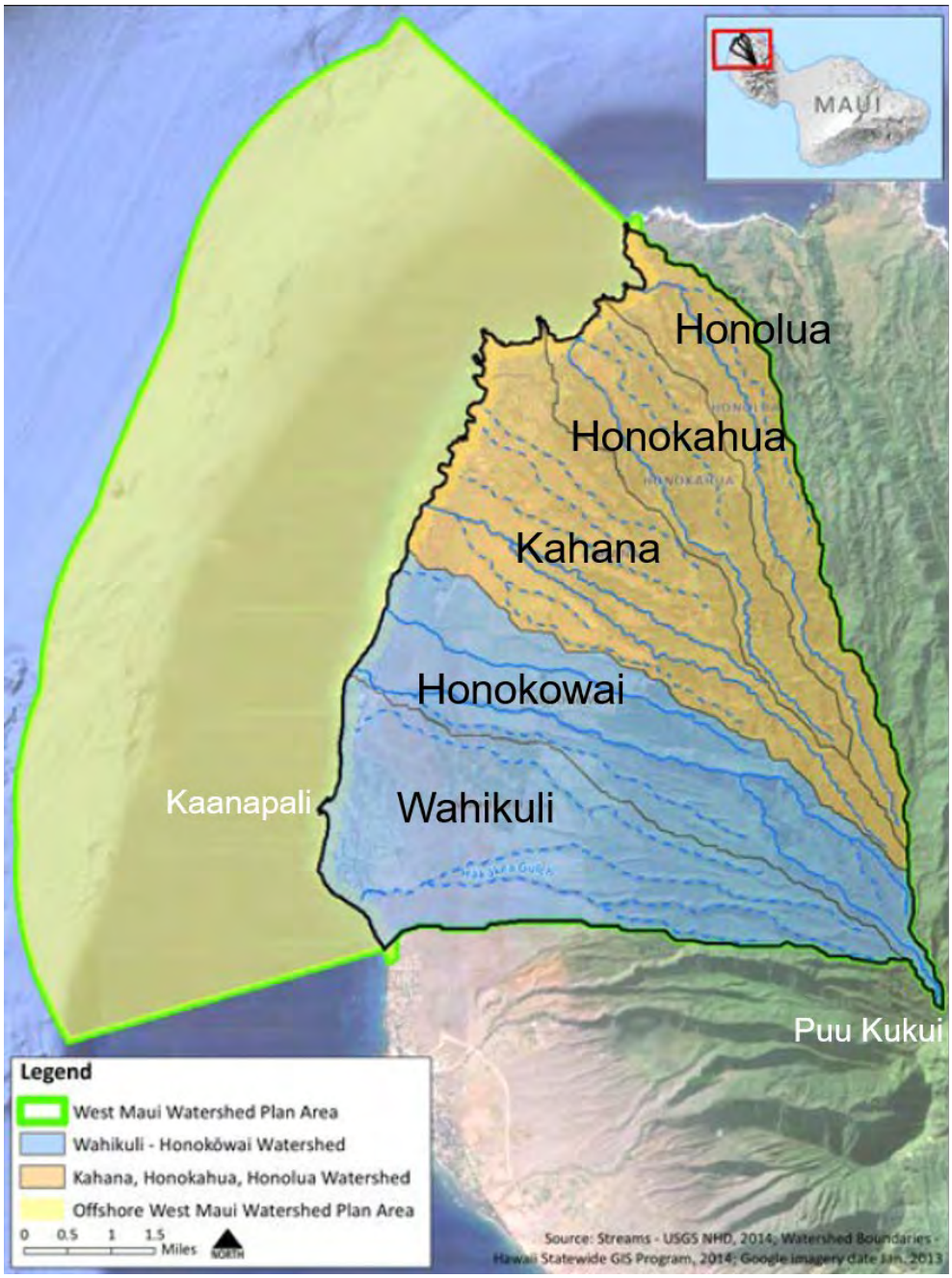


Figure ES- 1 West Maui Watershed Study Area

West Maui Coral Reefs

West Maui coral reefs provide several benefits to the local community, from attracting tourists that substantially support the local economy to sustaining recreational and commercial fisheries and protecting coastal property and infrastructure in addition to ecological and biodiversity benefits. Like coral reefs across the world influenced by the pressures of climate change, land-based pollution and overfishing, West Maui reefs were not able to escape this tragedy—nearly 30% of coral reef cover in West Maui was lost in the last 30 years (USGS, Storlazzi, 2019).

Interagency Coordination and Collaboration

In 2012, initiated by local agency and community partners, the West Maui Ridge to Reef(R2R) Initiative was formalized in support of the goals of the Initiative, including establishment of the West Maui Watershed and Coastal Management Coordinator. USACE worked with R2R partners to develop this objective which influenced the Shared Vision for this study.

The overarching recommendation from the R2R partners was to draft a comprehensive five-watershed management plan that compiles background data, identifies info gaps to date and proposes and prioritizes strategic implementation measures across the entire study area over the next 50 years and including adaptive management of measures in response to projected natural and anthropogenic changes throughout West Maui (e.g. population growth, resource demand, climate change, etc.).

The USGS has partnered with USACE on this study to provide marine transport dynamics analysis of the management measures to better understand the physical linkage between land-based sedimentation and coral reef degradation. The USGS has completed numerous water budget, groundwater, and stream discharge studies within the existing study area and brings regionally specific scientific expertise to this study.

Public Involvement

USACE sought public input on the development of the West Maui Watershed Management Plan, co-hosting a public information meeting with the West Maui R2R and soliciting feedback on the study scope and the initial suite of sediment management measures on August 30, 2018. Overall, a watershed-scale management plan tailored to

meet the needs of the West Maui community is desire. Incorporation of Native Hawaiian cultural practices and eco-sensitive alternatives is preferred. Any proposal for new construction involving hardening, channelizing, increasing impervious surface, diverting water or other deliberate manipulation of natural, physical features is strongly advocated against. These sentiments were considered in developing the scope of the Watershed Management Plan. The community recommendations investigated included Loʻi Kalo (taro plantings) and micro basins improvements in lieu of hardened structures and large detention basins.

The Draft Watershed Management Plan was circulated internally and released externally for concurrent review. Technical, policy and legal comments received from USACE reviewers were evaluated by the PDT and appropriate revisions incorporated into this final document. USACE posted the draft plan to both USACE and West Maui R2R websites from June 17 to July 17, 2021 to solicit public comment. Comments from the FAST and County of Maui Department of Public Works were received and responses incorporated into this final document. No other public comment on the draft plan was received.

Cultural Considerations

The watershed concept or traditional *ahupuaʻa* was historically integral to Native Hawaiian culture, lifestyle and identity. It remains integral to this day and should inform natural resource management and planning into the future.

The *ahupuaʻa* extends from mountain to ocean or *mauka* to *makai*. Hawaiʻi's streams and rivers form a lifeline joining the land and sea by an inseparable bond. The complex interconnectivity of *mauka* to *makai* as a single system, an *ahupuaʻa*, must form the context under which future watershed planning efforts are developed, to be successful. Since the arrival of humans to the Hawaiian Islands, Hawaiʻi's incredibly unique ecosystems have and continue to succumb to the external anthropogenic forces of deforestation, urbanization and other activities that introduce manmade threats to the natural environment (DLNR-DAR, 2020).

Shared Vision

Plan formulation for this watershed management plan adhered to the SMART (Specific, Measurable, Attainable, Risk Informed, and Timely) Watershed Planning Process, as described in USACE Planning Bulletin (PB) 2019-01. USACE worked with the members and agencies of the West Maui R2R to formulate the shared vision,

> *"[to] Develop a watershed management plan that addresses impacts from ridge to reef to improve West Maui coral reefs that provides coastal storm damage and shoreline protection and supports the West Maui economy".*

Problems, Opportunities, Objectives, Constraints and Considerations

From the shared vision, USACE, DLNR-DAR and the West Maui R2R identified the study problems, opportunities, objectives and constraints to begin formulating measures that would meet the study objective.

Problem Statement. Coral reef decline threatens the economy, ecosystem and community in West Maui.

Opportunities. The Project Delivery Team (PDT) compiled those measures that address this problem and also provide the following secondary benefits: protecting and restoring native ecosystems, incorporating cultural practices/restoration, promoting environmentally sensitive commercial agriculture, controlling invasive species, increasing and incorporating outdoor recreation and other low-impact activities and development such as greenspaces and community gardens, involving and educating the West Maui community and landowners, reducing coastal storm risk and also opportunities that give rise to ecotourism.

Objective. The objective of the study is to develop a list of recommendations for strategic implementation over the next 50 years that 1) reduces current and future pollutant sources, 2) reduces current and future conveyance of pollutants that threaten West Maui coral reefs, 3) Reduce land-based pollution to the marine environment to increase resistance and resiliency of West Maui coral reefs for the next 50 years. Completing this study aligns with the U.S. CRTF Priority Watershed designation furthering national initiative underscored in Presidential Executive Order 13089 to preserve and protect the biodiversity, health, heritage, and social and economic value of U.S. coral reef ecosystems and the marine environment.

Constraints and Considerations. The measures and recommendations were formulated given the following constraints and considerations: limited baseline data availability (e.g. Light Detection and Ranging [LIDAR], rainfall, stream flow data, etc.) throughout West Maui, recommendations on private lands require support from landowner(s), minimize adverse effects to cultural resources/historic properties, minimize loss of floodplain, avoid proliferation of invasive species, waterways are regulated and affects streamflow/available water, impacts to tourism and the projected growth and housing demand in West Maui. As expressed by the West Maui community, construction that increases impermeable surfaces or otherwise artificially modifies natural waterways is not preferred.

Plan Formulation

Recommendations from prior management plans that have not yet been implemented, remain relevant and continue to be advocated by the West Maui R2R were carried forward as recommendations of this study (Section 9). A subset of structural measures designed to address land-based sedimentation of coral reefs were further developed to conceptual design (Section 7), evaluated against the Water Resources Council's National Evaluation Criteria: completeness, effectiveness, efficiency and acceptability (Section 8) and assigned implementation priority (Section 9) based on the results of the USGS marine transport dynamics analysis (Appendix E).

Recommended Conceptual Alternatives/Strategies

The following management measure are recommended for implementation throughout the West Maui Watershed by this study:

- Engineering Analysis and Stabilization Designs at Wahikuli Gulch
- Burn Area Emergency Response Plan
- Urban Pollution Control: Bioretention Cell e.g. Rain Garden
- County Storm Water Management Plan
- Enforcement of Temporary Construction Storm water Best Management Practices (BMPs)
- Post Construction Storm water Ordinance: Drainage Master Plan Requirement

- Requirement for BMP Management Plans and Reporting by Large Scale Nutrient and Pesticide Users
- Water Quality Monitoring Program
- Agricultural Conservation Plan Requirement for Ag Lands
- Establish Storm Water Fees
- Low Impact Development (LID) Requirement for development, redevelopment and improvement projects > 1 acre (State, County and private sector) to incorporate LID measures into design and construction
- Golf Courses and Landscaping BMP Management Plans
- Pool and Vehicle Wash Water Discharge Policy
- Storm Water Management Asset Mapping
- Regional Drainage Analysis
- Stop sediment from entering streams and gulches via
    - Push pile assessment and stabilization
    - Stream crossings stabilization
    - Access road improvements
- Stop existing in-stream sediment deposits from transporting sediments downstream to the ocean via
    - Identification of sediment terraces in streams and gulches
    - Researching, piloting and implementation of stream/gulch bank management measures
    - Restoration of traditional loʻi kalo
- Increase groundwater recharge and slow surface flows via
    - Conservation boundary fencing
    - Active ungulate & invasive weed management
    - Landscape restoration
- Monitor and assess roadside erosion at Honoapiʻilani Highway and Lower Road
- Urban Storm Water Management Retrofits
- Continue to fund existing outreach initiatives and outreach coordinators
- Community Water Quality Monitoring Program

- Multiple Sediment Capture and Groundwater Recharge Basins at Wahikuli and Hāhākea Gulches*
- Sediment Capture and Groundwater Recharge Basins Complex Combined with Recreational Open Space at Wahikuli Gulch and Hāhākea Gulch
- Gulch buffers adjacent to Wahikuli Gulch and Hāhākea Gulch
- Gulch Buffer Stacked Practices via optimal combinations of the following:
    - Ripping, Terraforming, Micro-basins, Key lining/ripping on contour, Vetiver eyebrows in kickouts, Contour planting vetiver, Native plant establishment, Hydro-mulching and Check dams
- Ocean-Friendly Landscaper Outreach Program
- Wildland Fire Management Measures e.g. Fire breaks
- Improve existing sedimentation measures*
- Micro Basins*

Management measures denoted above with an asterisk (*) were further developed to comprise the following subset of alternatives. These ten (10) conceptual alternatives were sited in the watershed and furthered to conceptual design in order to develop parametric cost estimates for initial construction and subsequent maintenance, determine sediment trap efficiency and analyze marine transport dynamics through a partnership with the USGS which provided insight into the physical connection between land-based sediment sources and final disposition of transported sediments in the nearshore environment, including West Maui coral reefs.

Sited Structural Alternatives:

- Honolua Loʻi
- Pāpua Gulch Micro Basins
- Kaʻōpala Basin Outlet Modification
- Kaʻōpala Rock Weirs
- Annual Excavation of Kahana Basin
- Honokōwai Loʻi
- Honokōwai Basin Riser Structure Modification
- Upper, Middle and Lower Wahikuli Micro Basins

This comprehensive five-watershed management plan serves to guide future decision-making for DLNR-DAR and the growing West Maui community for the next 50 years. Recommendations for preservation and protection of cultural resources and for climate change resilience are also described.

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LIST OF ACRONYMS & ABBREVIATIONS

AEP	Annual Exceedance Probability
BMP	Best Management Practices
CWRM	Commission On Water Resource Management
DAR	Division Of Aquatic Resources
DLNR	Department Of Land And Natural Resources
DOA	U.S. Department Of Agriculture
DOC	U.S. Department Of Commerce
DOH	State Of Hawai'I, Department Of Health
DOI	U.S. Department Of The Interior
ERDC	U.S. Army Engineer Research and Development Center
FAST	Funding And Agency Support Team
LID	Low Impact Development
LiDAR	Light Detection And Ranging
LMSL	Local Mean Sea Level
MKWP	Mauna Kahālāwai Mountain Watershed Partnership
NFWF	National Fish And Wildlife Foundation
NNN	Nitrate-Nitrite-Nitrogen
NOAA	National Oceanic And Atmospheric Administration
NRCS	National Resources Conservation Service
OFR	Open-File Report
PDT	Project Delivery Team
R2R	Ridge To Reef
ROM	Rough Order Of Magnitude
SIR	Scientific Investigations Report
SMART	Specific, Measurable, Attainable, Risk Informed, And Timely
State	State Of Hawai'i
UH	University Of Hawai'i
USACE	U.S. Army Corps Of Engineers
USCRTF	U.S. Coral Reef Task Force
USFWS	U.S. Fish And Wildlife Service
USGS	U.S. Geological Survey
WRDA	Water Resources Development Act
WWRF	Wastewater Reclamation Facility

1 Introduction

1.1 Purpose

The intent of the West Maui Watershed Study is 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 purpose of this final watershed management plan and its prioritized list of conceptual recommendations is to assist the West Maui community and its leaders in strategic planning and future decision-making.

1.2 Authority

The authority for the West Maui Watershed Study is provided by Section 729 of the Water Resources Development Act (WRDA) of 1986, Public Law 99-662, as amended (33 U.S.C. 2267a; hereinafter "Section 729"). Section 729 authorizes the development of watershed plans that are multi-purpose and multi-objective in scope and developed in cooperation with federal, state, and local government entities.

This Watershed Management Plan was prepared in accordance with internal U.S. Army Corps of Engineers (USACE) guidance and policy at Planning Bulletin 2019-01, Engineering Regulation (ER) 1105-2-100, ER 1100-2-8162, Engineer Technical Letter 1100-2-1 and 1100-2-3, Engineering and Construction Bulletin 2018-14

1.2.1 Non-Federal Sponsor

The non-federal sponsor for the West Maui Watershed Study is the State of Hawaiʻi, as represented by its Department of Land and Natural Resources (DLNR), Division of Aquatic Resources (DAR). DAR manages the State's aquatic resources and ecosystems through programs in ecosystem management, place-based management, and fisheries management. It is the mission of DAR to work with the people of Hawaiʻi to manage, conserve and restore the state's unique aquatic resources and ecosystems for present and future generations. The State of Hawaiʻi, as represented by DAR, and the USACE signed a cost-share agreement on August 9, 2012 to assess the water resource needs of the West Maui watershed pursuant to Section 729.

1.2.2 Watershed Planning

Watershed planning goes beyond project planning for specific USACE projects towards more comprehensive and strategic evaluations and analyses that include diverse political, geographic, physical, institutional, technical, and stakeholder considerations. Watershed planning addresses identified water resources needs from any source, regardless of agency responsibilities, and provides a shared vision of a desired end state that may include recommendations for potential involvement by USACE, other federal agencies, or non-federal interests. Watershed studies may identify potential USACE projects consistent with priority missions; however, this is not the primary consideration of watershed planning. In conducting watershed planning, USACE uses its planning capability in a broader sense to meet the changing water resources needs of the nation. Ultimately, watershed studies should inform multiple audiences and decision makers at all levels of government and provide a strategic roadmap to inform future investment decisions by multiple agencies. In addition, under Planning Bulletin 2019-01:

> "*Watershed planning addresses identified water resources needs from any source, regardless of agency responsibilities, and provides a shared vision of a desired end state that may include recommendations for potential involvement by USAGE, other federal agencies, or non-federal interests. Watershed studies may identify potential USAGE projects consistent with priority missions; however, this is not the primary consideration of watershed planning. In conducting watershed planning, USAGE uses its planning capability in a broader sense to meet the changing water resources needs of the nation. Ultimately, watershed studies should inform multiple audiences and decision makers at all levels of government, and provide a strategic roadmap to inform future investment decisions by multiple agencies.*"

1.3 Scope

Through previous planning efforts that investigated numerous sources of pollutants (summarized in Section 4), terrestrial sediment in the marine environment was identified as the primary stressor to local coral reef ecosystems causing coral reef health to decline. This study will focus on addressing the terrestrial sediment contributions by

West Maui watersheds to the ocean, and their impact on West Maui coral reefs. Secondary problems, needs, and opportunities in the watershed are also identified.

1.3.1 Study Area

The study area includes an area of approximately 24,000 acres on the leeward side of the West Maui Mountains, from Kā‘anapali northward to Honolua and from the summit of Pu‘u Kukui to the outer reef (Figure 1-1). There are approximately eleven adjacent watersheds in the study area, identified in Table 1-1 and Figure 1-2. These watersheds are grouped by the State of Hawai‘i into five surface water hydrologic units: Wahikuli (6009[1]), Honokōwai (6010), Kahana (6011), Honokahua (6012), and Honolua (6013).

Table 1-1: Hydrologic Unity and Watershed Identification

Surface Water Hydrologic Unit Code	Hydrologic Unit	Watershed	Drainage Area (mi^2)
6009	Wahikuli	Wahikuli	3.89
		Hanaka‘ō‘ō	3.37
6010	Honokōwai	Honokōwai	5.80
		Māhinahina	1.80
6011	Kahana	Kahana	4.35
		Ka‘ōpala	0.812
		Honokeana	0.554
		Nāpili 4-5	0.814
		Nāpili 2-3	0.433
6012	Honokahua	Honokahua	4.13
6013	Honolua	Honolua	4.28

[1] Each surface water hydrologic unit has a unique 4-digit code assigned by the State’s Commission on Water Resource Management.

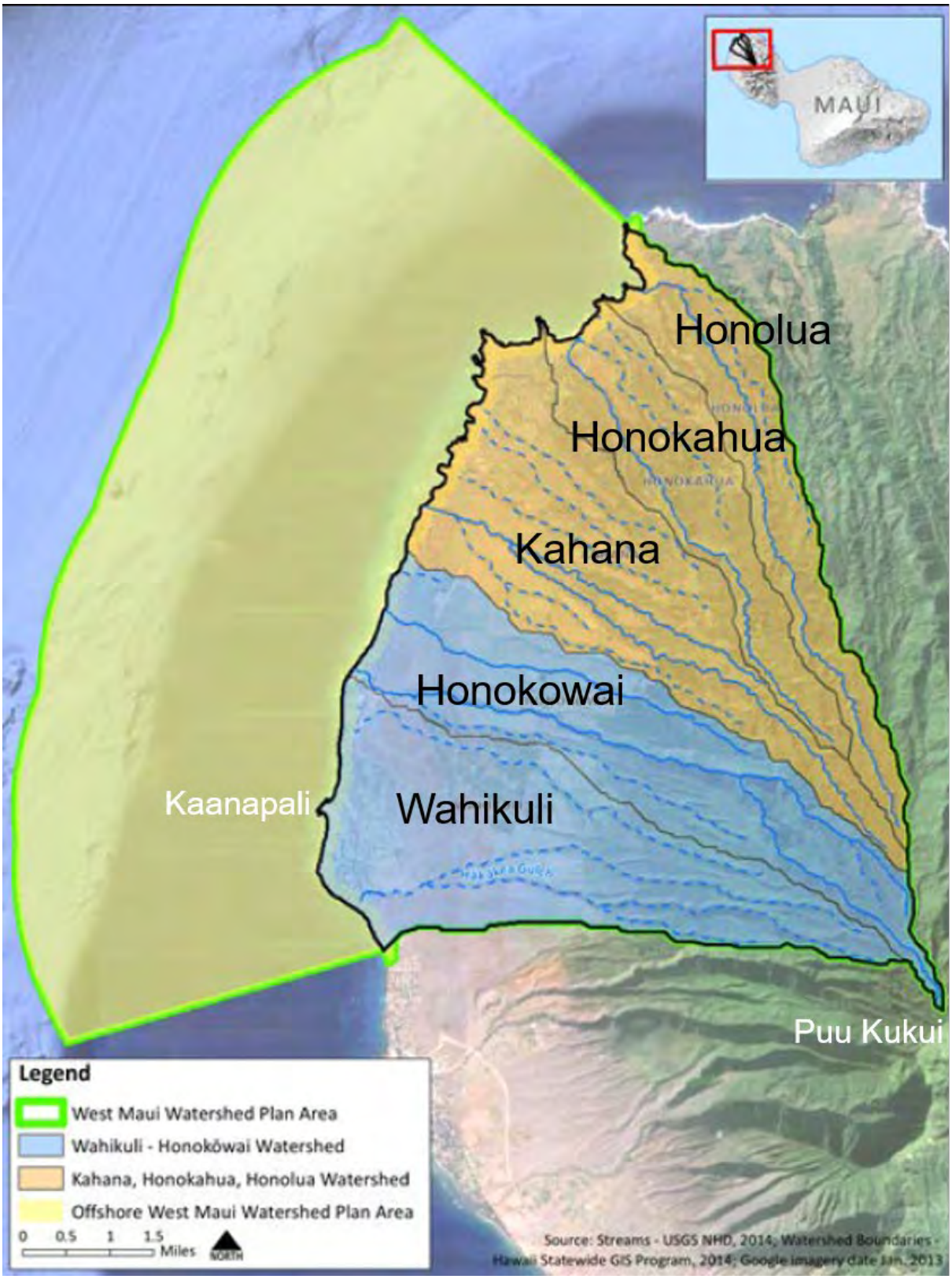


Figure 1-1: Study Area

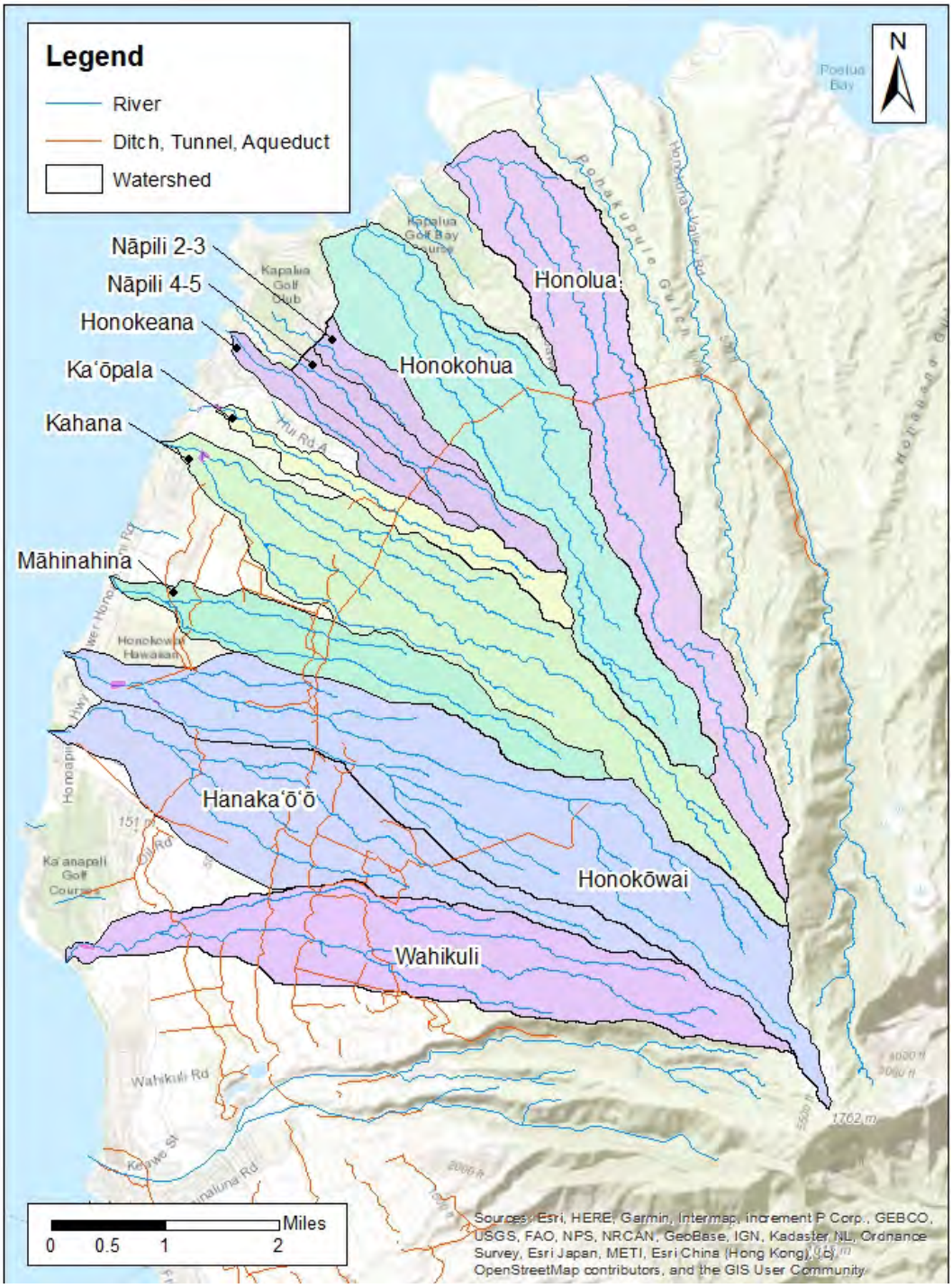


Figure 1-2: Watershed Map, West Maui, Hawai'i

2 Watershed Planning

USACE follows a six-step, iterative planning process in its water resource development studies to formulate solutions that solve, in whole or in part, the problems identified under the study (Figure 2-1).

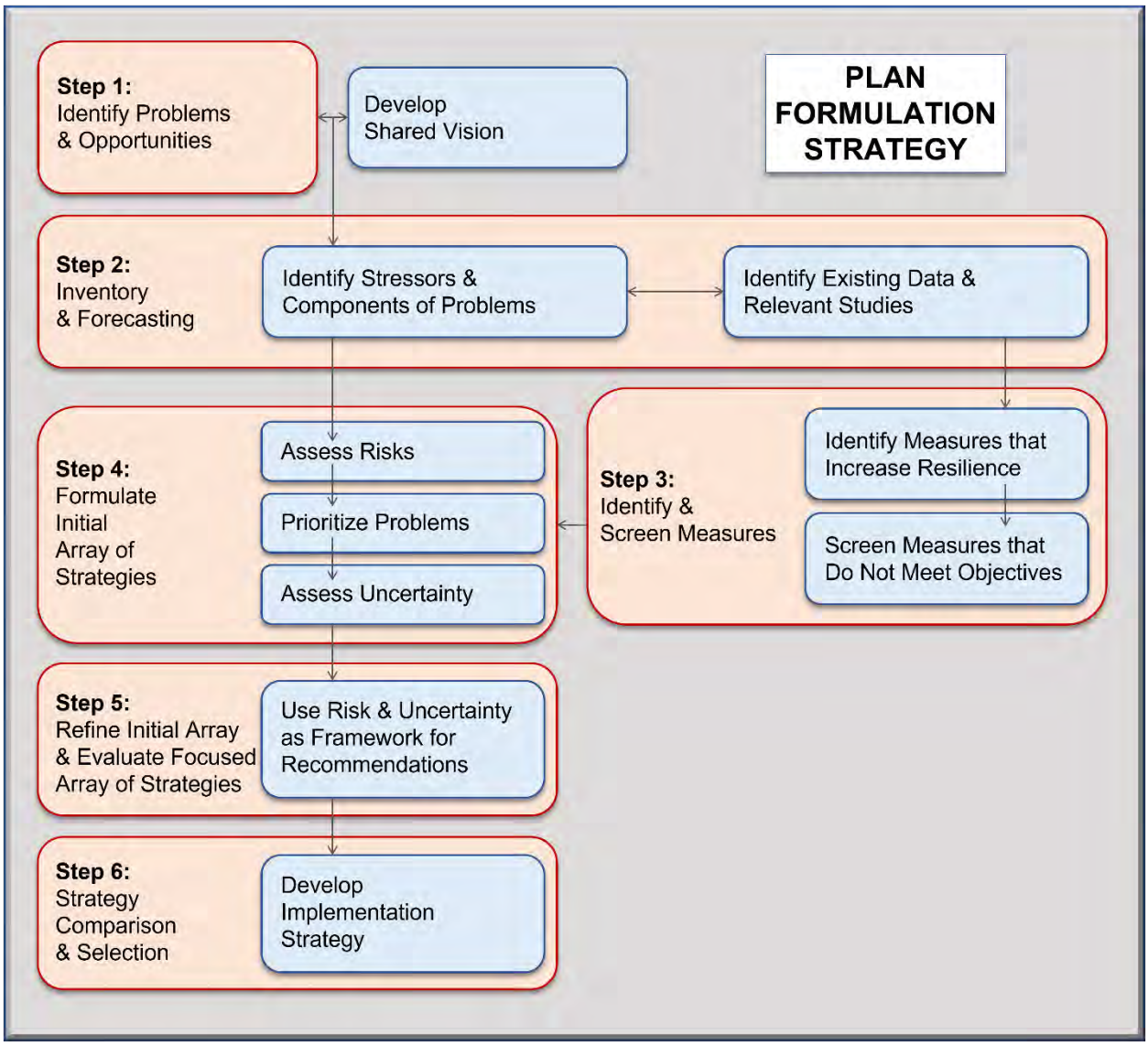


Figure 2-1: Plan Formulation Strategy Flow Chart

Step 1: Identify Problems and Opportunities

The first step in the USACE watershed planning process is to identify problems and opportunities in the study area with input from study partners, stakeholders, resource agencies and the public. Problems are existing, negative conditions. The problem that motivates this study is "*coral reef decline threatens the economy, ecosystem and community in West Maui*," as described in Section 2.2. Opportunities are listed in Section 2.3. Objectives are described in Section 2.4. Constraints are listed in Section 2.5. Coordination and collaboration with study partners, stakeholders, resource agencies, and the public is presented in Section 3.

Step 2: Inventory and Forecasting Conditions

Step 2 is the information gathering step. Gathering information about historic and existing conditions produces an inventory. Gathering information about potential future conditions requires forecasts. A summary of the historic, existing, and future conditions of natural, economic, and social resources is described in Section 5. A literature review of previous investigations and studies is summarized in Section 4. Additional information regarding data collection is included in Appendix B.

Step 3: Formulating Alternative Strategies

This step of the planning process produces solutions that achieve one or more planning objectives. Solutions are alternative plans built from management measures. Comprehensive management measures to improve coral reef health are presented in Section 6. Targeted solutions to address terrestrial sediment contributions to the nearshore environment by riverine systems is presented in Section 8.

Step 4: Evaluating Alternative Strategies

The essential purpose of the evaluation step is to determine whether a plan that has been formulated is worthy of further consideration. Each plan is held up to a situation-specific set of criteria and determined whether it deserves further consideration or not. The alternatives developed under this study are evaluated in Section 8.

Step 5: Comparing Alternative Strategies

The previous evaluation step looked at the effects of each plan individually. Step 5 looks at the important effects across all plans. It is only by comparison that a plan is no longer good enough, or that a good plan becomes the best plan. The purpose of plan

comparison is to identify the most important effects, and to compare the plans against one another across those effects. Alternative plans developed for this study are compared in Section 8.3.

Step 6: Selecting a Strategy

The final iteration of Step 6 completes the planning process. Decision makers must purposefully choose the single best alternative future path from among all those that have been considered. Recommendations are made in Section 9.

2.1 Ahupua‘a Planning

In consideration of the Native Hawaiian culture, the study team ensured incorporation of the traditional *ahupua‘a* (watershed) concept into the study. *Ahupua‘a* was historically integral to Native Hawaiian culture, lifestyle and identity. It remains integral to this day and should inform natural resource management and planning into the future.

The *ahupua‘a* extends from mountain to ocean or *mauka* to *makai*. Hawai‘i’s streams and rivers form a lifeline joining the land and sea by an inseparable bond. The complex interconnectivity of *mauka* to *makai* as a single system, an *ahupua‘a*, must form the context under which future watershed planning efforts are developed, to be successful. Since the arrival of humans to the Hawaiian Islands, Hawai‘i’s incredibly unique ecosystems have and continue to succumb to the external anthropogenic forces of deforestation, urbanization and other activities that introduce manmade threats to the natural environment (DLNR-DAR, 2020).

The Hawaiian cultural “renaissance” that began in the 1970s and continues today is the impetus for increasing interest in cultural, biocultural and ecological restoration throughout the islands.

> *“The task is ongoing, and the idea arises now that in the next phase of the Hawaiian Renaissance, a goal should be to demonstrate that Hawaiians were, and can again be, masterful ecologists, naturalists, landscape engineers, and resource managers. Surviving an era of conscious suppression, during which both Hawaiian ecosystems and Hawaiian culture were gravely damaged, we enter a phase of rebuilding, recovery,*

and reestablishment of the relationships that originally resulted in a millennium of sustainable co-existence of people and nature" (Gon, 2019).

Globally, Hawaiian practices and values centered in sustainability are being praised and even considered to give insight to how large populations can survive harmoniously in their environment. These practices are firmly rooted in the traditional Native Hawaiian concept of *mālama ʻāina*, literally, care for the land, which establishes a stewardship and wields a relationship between humans and the land where humans are the caretakers of the land, which sustains human life. This innate and inherent responsibility creates the foundation for ancient Hawaiian land management. As stated in Senator Kenneth Brown's speech on the Senate Floor of the Hawaiʻi State Capitol,

"All of man's acts in Hawai`i must be dominated by the spirit of "Mālama". The Pūkuʻi-Elbert Hawaiian Dictionary defines "Mālama" thus: "To take care of, care for, preserve; to keep or observe, as a taboo; to conduct, as a service; to serve, honor, as God; care, preservation, support; fidelity, loyalty; custodian, caretaker." Because he knows so many ways to destroy his natural environment, Man must now become its custodian and caretaker for his own sake. He must exercise mālama, because if he starts selling parts of his natural environment abroad for creature comforts, he will lose it all, and be unable to survive here. If he uses up his landscapes, mountains, valley and vistas, or if he degrades his air and waters, he will destroy the beauty and hence the spirit of Hawai`i, and in so doing, his own spirit. Mālama is thus an imperative. It is applicable to our entire lives in Hawai`i." (Brown, 1973).

West Maui experienced many changes in land use and land management over time (Figure 2-2). From historic Native Hawaiian habitation to moderate expansion and colonization by religious missionaries, to the extensive and intrusive plantation era, to the

overthrow and statehood resulting in rapid and expansive development across the State (COM, 2021).



Figure 2-2 West Maui land use over time

Each of these epochs contributes to the cultural and historic backdrop of the study area. As such, the implementation of any of these projects must consider potential impacts to both cultural and historic resources. Any Federal action (e.g. expenditure of Federal funds, issuance of a Federal permit, and issuance of a Federal grant) would require compliance with Section 106 of the National Historic Preservation Act of 1966, as amended.

2.2 Problem Statement

The problem that motivates this study is "*coral reef decline threatens the economy, ecosystem and community in West Maui*." In West Maui, nearly one-fourth of all living corals were lost during the survey period of 1994 – 2006 (DAR & HCRI, 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, aquatic ecosystems, and community in West Maui.

Coral reefs are widely recognized as critical to Hawai'i's economy, recreational and commercial fisheries, ecological biodiversity and for being the first line of defense against coastal hazards. A 2002 analysis estimated the annual net benefits derived from Hawai'i coral reefs is $360 million a year for Hawai'i's economy. The overall asset value of the State's 410,000 acres of coral reefs is estimated at nearly $10 billion[2] (Cesar, et.al., 2002).

Degradation is not just about a loss of coral cover. Habitat quality and topographical complexity are also in decline. The biodiversity that supports ecosystem services, biological resources, and social benefits are diminished. The recreational and commercial value of reefs declines. Fish stocks migrate away or die. Related ocean resources decline.

With the decline of coral reef resources also come social impacts on local communities such as changes to lifestyle, inability to rely on sustenance from ocean resources, and impacts to the Native Hawaiian culture which considers coral reefs a building block of their culture (USGS, Field, et. al., 2019). The West Maui coral reefs are a vitally important resource that are at risk of being lost without intervention.

2.2.1 Federal Interest

Under Executive Order 13089, Coral Reef Protection, all federal agencies are called to use their programs and authorities to protect and enhance coral reef ecosystems. In 2011, the U.S. Coral Reef Task Force (USCRTF) designated Wahikuli and Honokōwai as priority watersheds[3], later extending to include Kahana Honokahua, and Honolua. Under the authority of the Water Resources Development Act of 1986 (WRDA 1986), Section 729 , USACE can partner with local sponsors to investigate the problems, needs, and opportunities in the watershed to contribute to the enhancement,

[2] This is a conservative estimate based on actual economic value and does not consider the intrinsic value of these reefs beyond their utility.

[3] USCRTF uses the term "watersheds," but is actually referring to the five hydrologic units (Wahikuli, Honokōwai, Kahana, Honokahua, and Honolua), as delineated by the State of Hawaii and inclusive of eleven watersheds.

restoration, and resiliency of West Maui coral reefs and nearshore waters through the reduction of land-based pollution threats.

2.3 Opportunities

In proposing management measures and developing strategic recommendations, the study team looked for solutions that incorporated the following opportunities for secondary benefit(s):

- Protect and restore native ecosystems
- Incorporate cultural practices/restoration
- Environmentally sensitive commercial agriculture
- Invasive species control
- Increase/Incorporate outdoor recreation and low-impact activities (greenspaces, community garden, low impact development, etc.)
- Involve and educate West Maui community and landowners
- Reduce coastal storm risk
- Create and promote ecotourism
- Close data gaps

2.4 Objectives

Objectives are statements that describe the desired results of the planning process by solving the problems and taking advantage of the opportunities you identified. The watershed planning objectives for this study have been identified in collaboration with the West Maui Ridge to Reef Initiative (Section 3.2):

- Address pollutant source(s). Develop list of recommendations that reduce current and future (+50 years) land-based sources of pollution throughout West Maui watershed
- Address pollutant conveyance(s). Develop list of recommendations that reduce current and future (+50 years) conveyance of pollutants to West Maui coral reefs
- Reduce land-based pollution to the marine environment to increase resistance and resiliency of West Maui coral reefs for the next 50 years.

2.5 Constraints and Considerations

Unlike planning objectives that represent desired positive changes, planning constraints represent restrictions on the planning process and planning considerations are given additional thought through plan formulation. Conceptual plans should be formulated to meet the study objectives and to avoid violating constraints. Constraints and considerations identified and considered by the study team in developing recommendations for improving coral reef health are as follows:

- Constraints:
    - Limited data availability (e.g. Light Detection and Ranging [LiDAR], rainfall, stream flow data, etc.);
    - Recommendations on private lands require support from landowner;
    - In-stream flow standards are regulated by the State government, affecting watershed hydrology;
- Considerations:
    - Minimize adverse effects to cultural resources/historic properties;
    - Minimize loss of floodplain;
    - Avoid proliferation of invasive species;
    - Most of the land in the lower watershed is held in private ownership, and therefore any recommended strategies need to take into account the willingness and ability of the landowners to implement the recommended actions;
    - There are many different private and public landowners in the lower watershed making coordination a challenge;
    - Impact to tourism; and,
    - Projected growth, housing demand.

Due to an extensive history concerning water diversion and water rights issues, the West Maui community views any recommendation that significantly diverts, channelizes, hardens or otherwise manipulates natural streamflow, as regressive, and demands consideration of environmentally sensitive alternatives that work with the natural elements, rather than against.

3 Coordination and Collaboration

This section identifies some of the federal, state, and local resource agencies engaged during the development of this study. A comprehensive list is provided as Appendix A. Federal agency partnerships and expansive stakeholder involvement are necessary to collect a broad view of problems, needs and opportunities, including items that may not be seen in more conventional project planning, and reaffirm the purpose of the watershed study. Additionally, interagency collaboration can result in an overall cost-savings to the public as agencies work together more effectively towards watershed planning efforts.

3.1 Non-Federal Sponsor

As the non-federal sponsor of the West Maui Watershed Study, DAR was an active member on the USACE project delivery team (PDT). They participated in every phase of this study to ensure that the final recommendations made by this study are useful and address specific concerns in the watershed, as expressed by the community. Additionally, DAR partially funded the West Maui Watershed and Coastal Management Coordinator position as work-in-kind contribution under the cost-share agreement with USACE. DAR also collaborated with various agencies and community organizations to further ancillary efforts throughout West Maui that align with the objectives of this study.

3.2 Community Outreach

The study team sought public input on the development of the West Maui Watershed Management Plan, co-hosting a public information meeting with the West Maui Ridge to Reef (R2R) and soliciting feedback on the study scope and the initial suite of sediment management measures on August 30, 2018. Overall, a watershed-scale management plan tailored to meet the needs of the West Maui community is desired. Incorporation of Native Hawaiian cultural practices and eco-sensitive alternatives is preferred. Any proposal for new construction involving hardening, channelizing, increasing impervious surface, diverting water or other deliberate manipulation of natural, physical features is strongly advocated against. These sentiments were considered in developing the scope of the Watershed Management Plan. To the extent practicable and technically feasible, the team investigated nature-based measures that also met the

public's request to investigate cultural practices as well. The recommendations included Loʻi Kalo (taro plantings) and micro basin improvements in lieu of hardened structures and large detention basins. The Draft Watershed Management Plan was released for concurrent internal legal, policy and technical review and externally for public comment on the USACE and West Maui R2R websites from June 17 to July 17, 2021. The West Maui R2R FAST, DLNR and County of Maui commented on the draft plan, to which the PDT considered and incorporated appropriate revisions into this final document. No other public comment on the draft plan was received.

3.3 Agency Issues and Support

A comprehensive list of key stakeholders and partners relevant to this study is provided as Appendix A. Table 3-1 identifies the primary issues relevant to a limited selection of these stakeholders, or issues that are clearly within the statutory authority of a partner agency, as shaded cells. Agencies that have provided support for addressing the issue, such as technical expertise, direct funding, or participation on one or more of the working groups associated with this project, are indicated by a dollar symbol ($). This matrix highlights the large number of agency partners and shows the truly collaborative nature of the planning process.

Table 3-1: West Maui Watershed Study Agency Issues/Support

Issues	Agencies																	
	Funding and Agency Support Team (FAST)										Other Partners							
	USACE	USEPA	DOI-USFWS	DOC-NOAA	DOA-NRCS	USGS	DLNR / DAR	DLNR / CWRM	DLNR / DOFAW	HDOH	DHHL	MKWP	County of Maui	UH	NFWF	ML&P	NGO Community	WMSWCD
Land-Based sources of Pollutants (e.g. sediments and polluted runoff)	$	$	$	$	$	$	$	$	$	$	$	$	$	$	$	$	$	$
Fallow agricultural fields																		
Water supply						$		$					$					
Wildfire management				$			$		$			$	$			$		
Ecosystem restoration of upper watershed/ conservation area			$						$			$	$		$	$		
Ecosystem restoration of riparian habitat/gulches			$		$			$										
Ecosystem restoration of coral reefs		$		$	$	$	$						$	$		$	$	
Drought preparedness					$			$										
Climate change impacts	$	$	$	$		$												
Fishing pressure				$		$	$										$	

4 Previous Investigations and Studies

A list of previous work completed by the USACE and others is provided below, including a summary of key findings directly relevant to this study:

4.1 Wahikuli-Honokōwai Watershed Management Plan

In 2012, National Oceanic and Atmospheric Administration (NOAA) funded the development of a watershed management plan for the two southern hydrologic units of Wahikuli and Honokōwai. The *Wahikuli-Honokōwai Watershed Management Plan* was prepared by Sustainable Resources Group Intn'l, Inc. and comprised of two volumes.

Volume I: Watershed Characterization, summarized the current and proposed future environmental conditions of Wahikuli and Honokōwai, with an emphasis on identifying pollutant sources and types. This document identified terrestrial sediment as the key pollutant source from the Agricultural District and the effluent discharged by the Lahaina Wastewater Reclamation Facility (WWRF) into the nearshore environment as the key pollutant from the Urban District. *Volume II: Strategies and Implementation*, discussed strategies for management of non-point source[4] pollutants that adversely impact water quality and the coral reef ecosystem, as identified in Volume I.

Volume II recommended measures to reduce sediment erosion and transport from abandoned agricultural roads and fallow fields to the ocean, such as erosion controls, fertilizer management plans, and post fire rehabilitation plans in the Agricultural District. Management measures recommended in the Urban District revolve around reducing WWRF effluent discharges via injection wells by installing infrastructure necessary to increase number of end-users to beneficially reuse wastewater effluent and also reducing runoff carrying chemical pollutants to the ocean via stormwater retention/infiltration and storm sewer system retrofits.

4.2 West Maui Watershed Plan: Kahana, Honokahua and Honolua

USACE and DLNR-DAR co-funded development of a similarly constructed watershed management plan in 2016 for the Kahana, Honokahua, and Honolua

[4] Land-based pollutants generated across large areas and from diffuse sources are commonly referred to as non-point source pollutants

hydrologic units. This plan was prepared by Group 70 International, Inc. and also separated into two volumes.

Volume I: Watershed Characterization concluded that the primary contributors of land-based pollution to the marine environment are 1) terrestrial sediment deposited in stream valleys as a result of past agricultural practices and 2) current land uses that contribute fertilizers and animal waste pollutants to the marine environment. *Volume II: Strategies and Implementation* proposed various policy and management measures to address the issues identified in Volume I. The data, analyses and conclusions drawn in the 2012 and 2016 plans were based on existing data at the time of publication.

The overarching recommendation concluded by both 2012 and 2016 plans was to further these initial plans by drafting a comprehensive five-watershed management plan that would compile background data, identify info gaps to date, and propose strategic implementation of various measures across the study area over the next 50 years.

4.3 Sediment Budget for Watersheds of West Maui, Hawai‘i

USGS used mapping, field experiments, monitoring, and data analysis to create a sediment budget that estimates the annual export of fine sediment (clays, silts, and sands) from the West Maui watersheds. Most of the fieldwork occurred between 2014 and 2016. An Open-File Report (OFR), *Reconnaissance Sediment Budget for Selected Watersheds of West Maui, OFR 2015-1190*, was published in 2015 to provide immediate information (preliminary findings) to stakeholders. Some of the key takeaways from this document include:

- Streambank erosion of historic terraces of sands, silts, and clays, are likely the primary source of sediment in the channel system, resulting in annual plume generation in the nearshore waters of West Maui, Hawai‘i.
- Treatments of former agricultural fields, roads, and reserve forests are not likely to measurably affect sediment pollution from smaller, more frequent storms.
- As a reconnaissance budget, erosion-rate estimates were based on work elsewhere in the Hawaiian Islands and have great uncertainties.

The Scientific Investigations Report (SIR), *Sediment Budget for Watersheds of West Maui, Hawaii, SIR 2020-5133*, was published in 2020 and includes the final documentation on this investigation. Additional takeaways from this document include:

- Coastal sediment plumes occur at least 3-5 times per year in source watersheds.
  - Although total rainfall has decreased since the 1970s, more of it now occurs during short, intense storms capable of causing runoff and erosion.
- Historic fill terraces (the primary source of sediment) are found only downstream of historic agricultural fields and are composed of silt and fine sand.
- Several field experiments were conducted, including a survey of historic fill terraces, the installation and periodic monitoring of erosion pins, and cohesive strength meter testing, which are described in Appendix B.
- Bank erosion of fill terraces from a few watersheds likely dominates the current annual fine sediment load to the nearshore, with Kahana producing the largest annual input of 285 metric tons, the equivalent of 29 dump-truck loads every year.
- The storms capable of generating widespread runoff from agricultural fields are decadal events.

4.4 The Major Coral Reefs of Maui Nui, Hawai‘i

An article in the September 2015 Journal of the International Society for Reef Studies, Coral Reefs, titled *The influence of grain size, grain color, and suspended-sediment concentration on light attenuation: Why fine-grained terrestrial sediment is bad for coral reef ecosystems* advocates for coral restoration efforts and engineering solutions to focus on preferentially retaining fine grained soils, rather than coarse silt and sand particles (Storlazzi, Norris, & Rosenberger, 2015). Finer-grained sediment particles settle more slowly and are more susceptible to resuspension. By remaining in the water column longer, they cause greater net impact by reducing light essential for photosynthesis over a greater duration.

4.5 Stream Restoration Technical Solutions

In 2017, the Coral Reef Alliance published a report identifying possible solutions for addressing terrestrial sediment contributions to the nearshore environment by the Wahikuli and Honokōwai watersheds. Their report, *Stream Restoration Technical*

Solutions, Wahikuli and Honokōwai Watersheds, West Maui, refines some of the recommendations made in the *Wahikuli-Honokōwai Watershed Management Plan* published by NOAA in 2012, and proposes new solutions for specific use in West Maui. They have also developed several resource documents related to rain gardens, traditional Hawaiian agriculture, and low impact design (LID). Their report outlines nine technical solutions to address two types of land-based sediment pollution:

Solutions for landscape erosion and sediment transport to streams:

1. Stream erosion mitigation using stream corridor riparian buffer setbacks from the top of the gulch
2. Vetiver and native plant sediment traps in road kickouts
3. Vetiver and native plant sediment traps to decommission old agriculture roads
4. Hillslope stabilization using vetiver and native plants

Solutions for in-stream legacy sediment 'fill terraces' found along stream banks:

5. Traditional Hawaiian taro cultivation within a loʻi kalo designed to capture and retain sediment
6. Excess stream water diversion during high flow events into suitable retention/infiltration structures that include the following solutions as appropriate to the site:
   a. Infiltration wells, trenches, or French drains
   b. Retention/infiltration basins (in-stream and off-stream)
   c. Multipurpose area with retention (of stormwater), recharge (of groundwater), and recreation (within a community park amenity).

4.6 Instream Flow Standard Assessment Reports

The State of Hawaiʻi, DLNR, Commission on Water Resource Management (CWRM) has the responsibility of establishing instream flow standards (IFS) on a stream-by-stream basis whenever necessary to protect the public interest in the waters of the State. Three draft assessment reports were completed on the Honokōwai, Honolua, and Honokōhau hydrologic units (PR-2019-01, PR-2019-02, and PR-2019-03, respectively).

These reports include information on surface water hydrology, instream uses, non-instream uses, and their interrelationships.

4.7 Atlas of the Reefs of West Maui

In July 2020, The Nature Conservancy, with funding provided by NOAA's Coral Reef Conservation Program, published the *Atlas of the Reefs of West Maui*. This report describes the region's coral reefs and their associated fishes. It details changes in the abundance and diversity of marine life in West Maui, based on surveys conducted between 1999 and 2019. The Atlas was designed to provide the community and government partners with a shared understanding of how, when and where the reefs have changed so that targeted and effective strategies for reducing local pressures, increasing reef resilience and restoring reef fisheries can be developed.

4.8 Other

- *Low-Flow Characteristics of Streams in the Lahaina District, West Maui, Hawaii.* Scientific Investigations Report 2014-5087, (U.S. Department of the Interior, U.S. Geological Survey [USGS], 2014).
- *Spatially Distributed Groundwater Recharge Estimated Using a Water-Budget Model. for the Island of Maui, Hawai'i, 1978-2007.* Scientific Investigations Report 2014-5168, (USGS, 2014).
- *West Maui Wahikuli & Honokōwai Priority Watershed Area, Reef Condition Report* (DAR, 2016).
- *Observations of coastal circulation, waves, and sediment transport along West Maui, Hawai'i (November 2017–March 2018), and modeling effects of potential watershed restoration on decreasing sediment loads to adjacent coral reefs.* Open-File Report 2022–1121. (USGS, Storlazzi, 2023).

5 Watershed Characterization

This section summarizes baseline watershed conditions, from R2R, across the study area. Detailed information characterizing the Wahikuli, Hanakaʻōʻō, Honokōwai, and Māhinahina watersheds is provided in the *Wahikuli-Honokōwai Watershed Management Plan, Volume I: Watershed Characterization*, published by NOAA in 2012 (Section 4.1). Detailed information characterizing the Kahana, Kaʻōpala, Honokeana, Nāpili 4-5, Nāpili 2-3, Honokahua, and Honolua watersheds is provided in the *West Maui Watershed Plan: Kahana, Honokahua, and Honolua Watersheds Characterization Report*, published in 2016 by USACE and the State of Hawaiʻi (Section 4.2).

5.1 Location

The entire study area is approximately 36 square miles (mi^2) and encompasses a collection of eleven adjacent watersheds (Figure 1-2) on the leeward side of the West Maui Mountains, north of the town of Lahaina, Maui. A watershed is an area of land that drains all the streams and rainfall to a common outlet. Whereas previously, the West Maui study area has been referred to as a "five-watershed priority area," the study area includes at least eleven watersheds with streams that discharge into the Pacific Ocean independently of each other. These eleven watersheds have been identified as Wahikuli, Hanakaʻōʻō, Honokōwai, Māhinahina, Kahana, Kaʻōpala, Honokeana, Nāpili 4-5, Nāpili 2-3, Honokahua, and Honolua.

The State of Hawaiʻi's classification system groups these individual watersheds into just five surface water hydrologic units: Wahikuli (6009[5]), Honokōwai (6010), Kahana (6011), Honokahua (6012), and Honolua (6013) consistent with the U.S. Coral Reef Task Force designation of Wahikuli, Honokōwai, Kahana, Honokahua, and Honolua as priority watershed areas in 2011.

5.2 Topography

The summit of Puʻu Kukui is the highest point in the study area at 5,785 feet above mean sea level (ft MSL). The steep river profile originating in the mountains results in

[5] Each surface water hydrologic unit has a unique 4-digit code assigned by the State's Commission on Water Resource Management.

each basin having an oblong shape as water travels west-northwest toward the Pacific Ocean with limited meandering. Watershed lengths range from 3.6 miles (mi) for Ka‘ōpala to 8.2 mi for Honokōwai. Honokōwai is the steepest basin, with an average basin slope of about 53 percent (%). Wahikuli, Kahana, Honokahua, and Honolua are also steep with an average basin slope between 40-50%. The smaller watersheds that originate at a lower elevation (e.g. Hanaka‘ō‘ō, Māhinahina, Ka‘ōpala, Honokeana, and Nāpili) have an average basin slope between 15-30%.

5.3 Geology and Soils

The West Maui Mountains were formed through at least three series of major volcanic eruptions during its shield building period: the Wailuku volcanic series, the Honolua volcanic series, and the Lahaina volcanic series. Following the cessation of West Maui volcanism 500,000 years ago, the rapid erosion and valley incision of West Maui has produced broad alluvial fans with unconsolidated dunes of lithified to semi-lithified calcareous sand on the western slopes.

5.4 Climate and Hydrology

Hawai‘i has a subtropical climate with temperatures that are mild and fairly uniform throughout the year. The mean annual temperature at Kahului[6], based on data collected over the last fifty years (1971 – 2021), is 76.1° Fahrenheit (F), with an average maximum of 78.6°F and average minimum of 74.0°F (Honolulu Weather Forecast Office, 2020).

The climate of the Hawaiian Islands is characterized by a two-season year; a 5-month summer or dry season and a 7-month winter or wet season; mild and uniform temperatures, strikingly marked geographic differences in rainfall, generally humid conditions, and prevailing dominance of trade wind flow from the northeast. During the 5-month summer from May through September, trade winds prevail 80-95 percent of the time. During the 7-month winter from October through April, the prevalence of the trade winds decreases to 50-80 percent. Although the northeasterly trade winds produce most of the annual rainfall over the Hawaiian Islands, it is during the absence of these winds that the flood producing rainfall occurs. In particular, southerly winds bring moist warm air

[6] *Kahului AP*, located in Kahului, is the closest National Weather Service station to the study area

that creates “Kona” storms which produce the damaging floods in Hawai‘i. These storms usually occur during the winter months. The climate of the West Maui watersheds is tropical with cooler and wetter areas at higher elevations in the belt of the northeasterly trade winds. The average monthly precipitation ranges from 3.35 inches in the wettest month (December) to 0.2 inches in the driest month (June) (U.S. Climate Data, 2017).

Volume 1 of the 2012 and 2016 Watershed Characterization Reports provides, in great detail, discussion of the following watershed characteristics: current and future population and land use characteristics including local land use designations, major landowners and managers, as well as physical and natural features of each watershed, including geology, topography, soils, land cover, climate—including precipitation, temperature and natural hazards, climate change, hydrology—both surface and groundwater, natural waterways and manmade diversions for agriculture, flora, fauna, water quality, and a discussion of the coral reef ecosystem. Updated inventory and forecast of relevant characteristics that contribute to the furthering of this study, in particular, pollutant sources and conveyance, and that address the problems and objectives identified in Section 1.5, are discussed below and are intended to supplement the data presented in Volume 1 of the 2012 and 2016 Watershed Characterization Reports.

5.4.1 Climate Change:

Of the physical changes in hydrology and sea level rise, the greatest concern for the West Maui areas is the potential impact of changing precipitation in the watershed. A primary root of the problems within the watershed is fragmented water systems with increasing demands on water for all uses. Drought conditions are likely to increase in frequency with climate change. While smaller storm events are expected to decrease in frequency, the large storm events are expected to increase in both frequency and intensity. Additionally, there is a significant amount of uncertainty around how species and ecosystems will respond to climate change shifts in Hawai‘i.

Regionally and within the study area, the following climate change indicators are relevant to this study:

1. Rising surface air temperatures: The surface air temperature in Hawai‘i is rapidly rising, averaging 0.3°F per decade (Fletcher, 2010). This could result in higher rates of evaporation and increases in rainfall.
2. Rising sea surface temperatures: Sea surface temperatures in the region are rising at a rate of 0.22°F per decade according to marine researchers at the University of Hawai‘i. Continued warming of Hawaiian surface waters potentially expose coral reefs and other marine ecosystems to negative impacts related to temperature increases. (Fletcher, 2010). Warmer waters mean less oxygen in the water, making it hard for corals and beneficial algae to survive (Hawai'i Climate Change Mitigation and Adaptation Commission, 2021).
3. Winds changing: trade winds are expected to change in the future, but there is still great uncertainty regarding the extent of these changes. Persistent northeasterly trade winds are important to Hawaii because they affect wave height, cloud formation, and precipitation over specific areas of the region.
4. More frequent El Niño-Southern Oscillation (ENSO) occurrences: It is unknown how the timing and intensity of ENSO will continue to change in the coming decades, but recent climate model results suggest a doubling in frequency of both El Niño and La Niña extremes in the 21st century as compared to the 20th century under scenarios with more warming (Keener, et al., 2018). As summarized by NOAA’s Pacific ENSO Applications Climate Center, an El Niño event would typically result in the following climate impacts in Hawai‘i:
    - More rain the beginning of the season, then rapidly less;
    - Weaker trade winds, with occasional westerly winds;
    - Near to slightly above normal sea level;
    - High run-up from distant swells;
    - Much warmer temperatures at and below the sea surface; and
    - Increased risk of tropical cyclones (storms form closer and move towards the islands).

5. Less frequent, but more intense rainfall: In addition to natural variations, mean rainfall in Hawaii has slowly declined overall as a result of long-term trends that might be caused by global warming. Despite this downward trend in mean annual rainfall, rainfall events in Hawai‘i are becoming more extreme. Heavy rainfall events and droughts are becoming more common. The number of consecutive wet days and the number of consecutive dry days are both increasing in Hawai‘i (Keener, et al., 2018).
    - Nonstationarity Analysis: To investigate whether a trend of changing peak annual flow is occurring, West Maui gage records were tested using the Nonstationarity Detection Tool in accordance with ETL 1110-2-3. Two USGS streamflow gages (16630200 and 16620000) were used in this analysis. These two analyses indicate that no statistically significant changes in the basin hydrology have occurred during the period of record.
6. More frequent and more intense tropical cyclones: The way climate change alters the frequency and intensity of tropical cyclones is complex. However, tropical cyclone frequency and intensity in the central Pacific are expected to increase. This is in part due to:
    - changes in tropical cyclone tracks
    - increased formation of tropical cyclones near Hawai‘i
    - weakening of the vertical wind shear that typically tears tropical cyclones apart as they approach the islands
    - Greater frequency of ENSO occurrences (Keener, et al., 2018).
7. Declining base flow in streams: Oki (2004) indicated that a long-term reduction in base flow (groundwater discharge to streams) in Hawaii during the 20th century is consistent with a reduction in rainfall.
8. Ocean acidification: Ocean acidification is the process by which ocean waters have become more acidic (have a lower pH) due to the absorption of human-produced carbon dioxide. Ocean acidification reduces the ability of corals to build and maintain reefs. Nutrient input can substantially exacerbate acidification of reef erosion. A study by Henson et al. (2016) found that the

climate change-driven trend in pH already exceeds the range in natural seasonal variability over most of the ocean. Analysis of the trend suggests that ocean acidification is likely to be anthropogenically driven.

9. Rising sea levels: USACE requires that planning studies and engineering designs consider alternatives that are formulated and evaluated for the entire range of possible future rates of sea level change (SLC). Designs must be evaluated over the project life cycle and include evaluations for three scenarios of *low*, *intermediate*, and *high* sea level change. An analysis of the potential sea level change was performed in the projected area in accordance with Engineer Regulation 1100-2-8162 and Engineer Pamphlet 1100-2-1 (USACE, 2019). The gage at Kahului Harbor (NOAA ID: 1615680) was used for the analysis. The result of the calculation indicates a relative sea level change of 5.15 feet was determined in the year 2100 at the *high* condition. For the *intermediate* condition, the change is 1.86 feet, and the *low* condition shows an increase of 0.82 feet. These values are relative to Local Mean Sea Level (LMSL). The resulting sea level rise curve is shown in Figure 5-1.

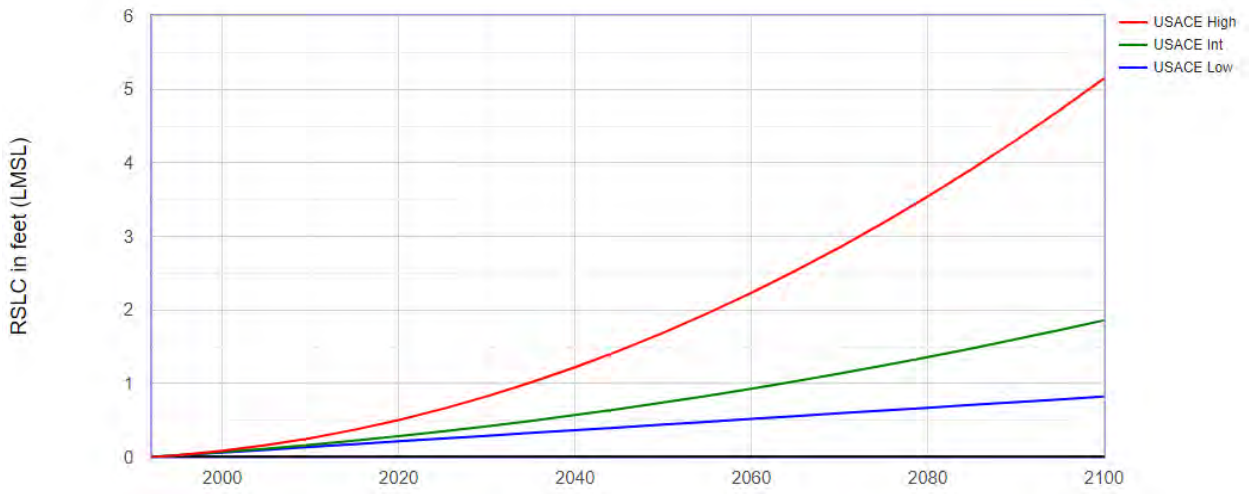


Figure 5-1: Estimated Relative Sea Level Change Projections – Gauge: 1615680, Kahului: Kahului Harbor, HI

Regionally and within the study area, the following climate change impacts are relevant to this project:

1. Less frequent riverine sediment contributions to the nearshore environment, but with larger yields: with rainfall occurring less frequently and base flow decreasing, there will likely be less occurrences of flow in West Maui streams and corresponding contributions of residual sediment to the nearshore environment in the future. However, with increasing intensity of rainfall also predicted, there is greater likelihood that when rainfall events do occur, they are more likely to result in larger peak flows and higher sediment loads in the river systems.
2. Greater sediment load contributions from floodplains: the occurrence of wildfires is likely to increase due to the combined effects from rising temperatures, a growing human population, and expanding invasive grass cover. This would also result in greater sediment loads entering the riverine systems.
3. Shoreline erosion: rising sea levels will continue to increase the risk of shoreline erosion. In some areas, resorts and large condominiums are already being visibly threatened by coastal erosion and in the forefront of the community's minds when thinking of potential sources of sediment to the marine environment.
4. Coral reef bleaching and loss. There are several climate indicators that affect the health of Maui's coral reefs:
    - rising sea surface temperatures
    - increasing frequency of ENSO occurrences
    - increasing frequency and intensity of tropical storms
    - ocean acidification, and
    - rising sea levels.

    Widespread coral reef bleaching and mortality have been occurring more frequently, and by mid-century these events are projected to occur annually, especially if current trends in emissions continue. Coral reefs have a greater

chance of surviving a larger climate event, such as bleaching, if local threats, such as terrestrial sediment, are reduced.

Additional information regarding climate change is available in Appendix B and C. Climate change discussions are in accordance with Engineering Regulation 1100-2-8162, Engineering Technical Letter 1100-2-1 and Engineering and Construction Bulletin 2018-14.

5.5 Socioeconomics

5.5.1 Land Ownership

The Conservation and Agricultural Districts are comprised of very large tracts of land owned by few private landowners. The Urban Districts are subdivided into much smaller parcels with many landowners. Kā‘anapali Land Management Corporation is the largest landowner in Wahikuli and Honokōwai watersheds, followed by the State of Hawai‘i. Maui Land & Pineapple, Inc. is the largest landowner of the remaining watersheds with approximately 80% of the landholdings comprised of over 9,600 acres. The largest of landowners have developed conservation and management plans with various agencies and organizations and regularly partner with local government and other organizations for conservation and restorative initiatives. As major landowners, support from these major stakeholders on watershed study recommendations involving private land is crucial to their success.

5.5.2 Population

The West Maui area encompasses 96 square miles, covering over 13% of the island of Maui. Although the West Maui region is somewhat isolated from the rest of the island, due to steep topography and limited highway access, the region had nearly 25,000 residents in 2017 (ESRI, 2017). The Kā‘anapali *moku* or district (comprised of Census Tracts 315.01 – 315.03, nearly identical to the study area) has 8,875 persons living in 3,587 households (ACS, 2019). Population demographics of the study area are 51% white, 19% Hispanic, 14% Asian, 5% Native Hawaiian or Pacific Islander, 0% black, and 10% two or more races (compared with all of Hawai‘i: 22% white, 10% Hispanic, 37% Asian, 9% Native Hawaiian or Pacific Islander, 2% black, and 19% two or more races) (ACS, 2019). People of color comprise 52% of the West Maui population, considerably

less than the 78% State average. 18% of West Maui's population is characterized as low-income, also less than the State average of 23% (USEPA, 2022).

Population growth rates between 2010 and 2017 were a combined 13.6% in West Maui—a faster rate in West Maui than the rest of Maui County and the state of Hawai'i (ESRI, 2017). Between 2004 to 2016, 59% of Maui County's population growth came from natural increase (local births minus deaths), 35% from international migration, and 6% from domestic migration (DBEDT, 2018).

West Maui is also a popular tourist destination and the second largest employment center in Maui, with an estimated average daytime population of 63,706 persons. This includes about 10,287 residents who remain in West Maui during the day, 19,868 workers both from West Maui and commuters to West Maui, and 33,551 visitors (ESRI, 2017) (DBEDT, 2018). West Maui also has the highest number of estimated visitor units on the island, at roughly 16,000 units (Hawai'i Tourism Authority, 2018), with over 4,000 visitor units in the study area specifically (ACS, 2019).

The study area, specifically, contains 5,143 employed individuals, over 5,000 of whom commute to work an average of 16 mins (roughly the travel time from Kapalua to Lahaina under light traffic conditions) (ACS, 2019). The major industries in the study area are entertainment & food service (42% of workers), professional services (12% of workers), retail (10%), insurance & real estate (9%), education & health care (8%), and construction (6%) (ACS 2019). 10.7% of households in the study area are below the federal poverty standards (compared to 10.5% nationally) while 70% of households have an income above the national median (ACS, 2019).

Table 5-1 West Maui Housing Inventory and Forecast

Housing Type	Total Units Needed by 2040	Units Available (2012)	Additional Units Needed by 2040
Resident	13,358	8,070	5,288
Non-Resident	3,359	1,724	1,635
Total	16,717	9,794	6,923
Source: DBEDT 2018; County of Maui Socio-Economic Forecast, 2014			

The increased number of people living, working, and spending time in West Maui is putting a strain on housing, roads, transit, infrastructure, and other public resources, in

addition to the natural environment. With the population of West Maui projected to grow to 33,750 by 2040 (an increase of 35%, or an annual growth rate of 1.31%), the demand for housing, water, and other infrastructure will continue to grow. It is estimated that West Maui will need a total of 13,358 housing units to accommodate this resident growth (County of Maui, Land Use Forecast, 2014), which means that an additional 5,288 new homes will need to be built, as well as an additional 1,635 visitor units (Table 5-1). This is about 247 housing units per year (including non-resident demand) to keep pace with growth. Between 2008 to 2017, development of new homes in West Maui did not keep pace with demand, so meeting this goal may be a challenge for local government.

Because of Hawai'i's high-priced housing market, lower-priced housing is especially scarce, despite the high demand. Low supply and limited housing options make it difficult for many individuals and families to find needed housing that they can afford. West Maui is one of the county's primary employment centers, but many jobs are low-paying service industry and tourism jobs that are vulnerable to downturns in the local and national economy. The shortage of affordable housing in West Maui makes it challenging for employers to find and retain qualified workers because many workers are not willing to make the long commute to West Maui.

Those who are willing to commute face increasing traffic congestion, which has a negative impact on the local economy. The long delays that are a daily occurrence on West Maui roadways restrict the free flow of freight, workers, and visitors, in addition to diminishing the quality of life of residents. The imbalance of jobs-to-housing in West Maui is a major contributing factor to this traffic congestion. West Maui had more than two jobs for every occupied housing unit. In 2017, more than 6,800 workers commuted into West Maui from elsewhere on the island (U.S. Census Bureau 2017). Blockage or damage to Honoapi'ilani Highway, the primary roadway connecting West Maui with the rest of the island, can leave the region cut off from critical services and resources, as well as cause major disruptions for businesses that rely on commuters to function. Because West Maui is likely to continue to grow faster than the rest of the county, this problem will only get worse in the future.

5.5.3 Planned Development

At the time the 2012 and 2016 Watershed Assessments were drafted, a total of approximately 2,500 acres of land were Planned/Committed[7] according to the County of Maui Planning Department's Long Range Division. Particularly large areas of planned development include Kāʻanapali expanding mauka within the Urban District and the approximately 800-acre Department of Hawaiian Homelands development in Honokōwai. The County of Maui is in the process of developing the West Maui Community Plan to update the 1996 West Maui Community Plan including updating maps, adding new elements required by Maui County Code Chapter 2.80B and ensuring consistency with the Countywide Policy Plan and Maui Island Plan. The updated West Maui Community Plan consists of a vision statement, goals, policies, and actions to guide growth and preservation in West Maui. Resource papers provide data to support the plan's policies and actions. The Plan was developed through an open and inclusive public process. The Plan is still in its Draft form, in its final of five phases, seeking Maui County Council review and final approval.

5.5.4 Land Use Districts and Habitat Areas

Volume 1 of the 2012 and 2016 Watershed Characterization Reports discusses at length an inventory and forecast of land use designations throughout West Maui watersheds, from the mauka Conservation District, through the middle Agricultural District and makai to the Urban District (Figure 5-2). Below is an updated discussion of land divisions based on manmade factors such as property ownership and local zoning designations and based on natural resource distribution in West Maui watersheds.

[7] According to the County of Maui, future developments identified as "Planned/Committed" are those projects that have appropriate conforming Community Plan and zoning entitlements, are approved agricultural subdivisions, or are approved affordable housing.

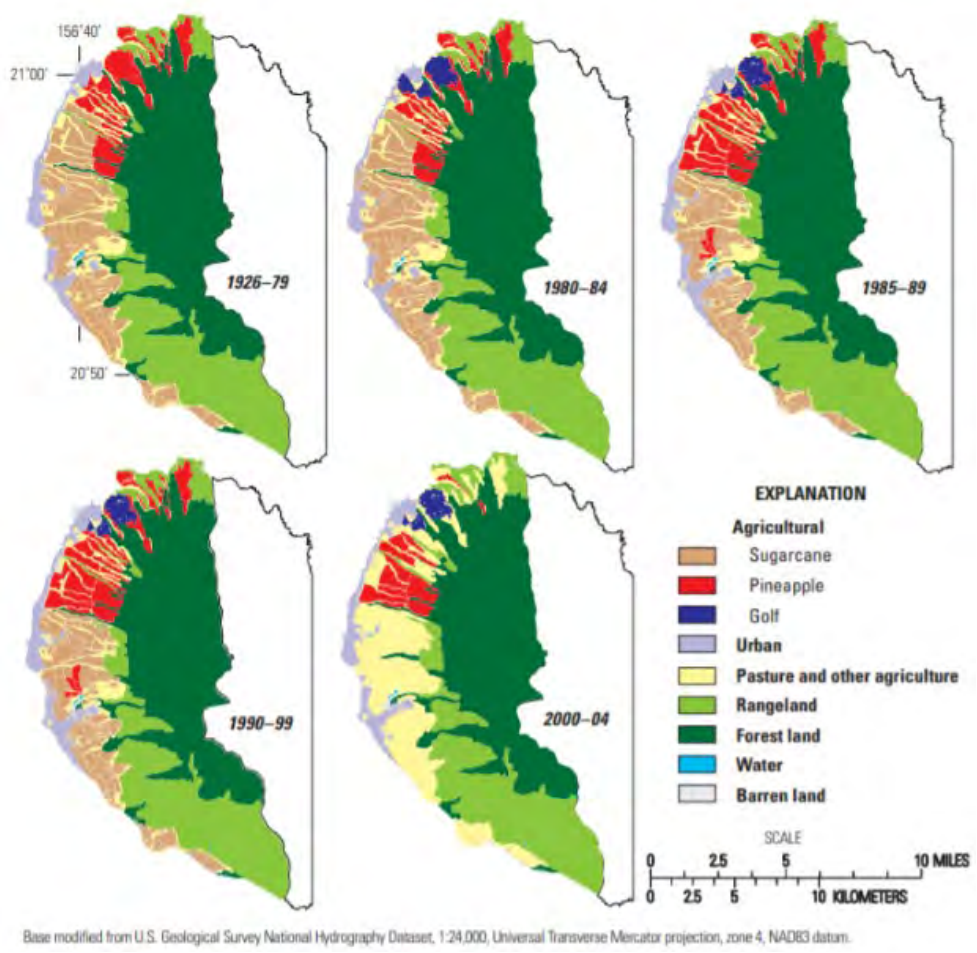


Figure 5-2: West Maui Land Use Over Time 1926 – 2004 (USGS, 2012)

West Maui watersheds include multiple resources and uses, and for discussion purposes is divided into the following land use districts and habitat areas: upper watershed, middle watershed, stream and wetland habitat, lower watershed and nearshore waters. Framing this under the USACE planning process, this report includes the inventory and forecast of the five watersheds. While the exact impact of climate change on West Maui is unpredictable and ever evolving, a brief discussion of current predictions is provided for each land use district and habitat area below.

The information presented is taken from various sources, including the Applying Risk Informed Decision-Making Framework for Climate Change to Integrated Water Resource Management Planning – West Maui Watershed Plan (USACE, April 2013) and

technical papers supporting the West Maui Community Plan presently undergoing final review by the Maui County Council.

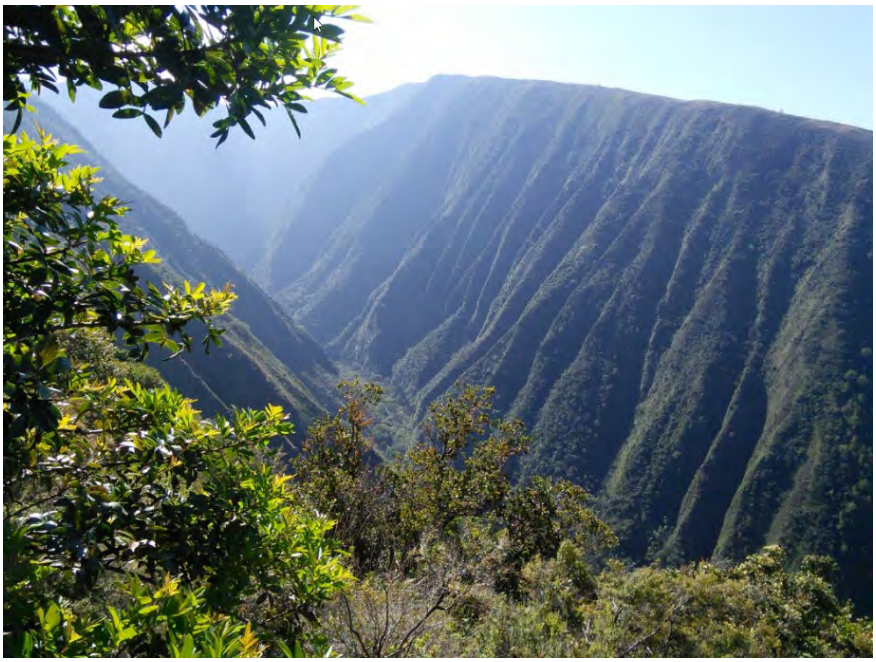
Upper Watershed

The upper watershed of West Maui (Photo 5-1) is managed by the Mauna Kahālāwai Mountain Watershed Partnership (MKWP), as a conservation area. The upper watershed is designated by the State of Hawai'i, a Conservation District, focused on preserving and restoring native forests. Through management efforts by the MKWP, pristine native forests and tropical montane bogs are protected. The MKWP successfully works to conserve these areas and to restore adjacent, buffering habitat. Invasive species, both aggressive plant species and introduced ungulate species, such as pigs, goats and increasingly deer, pose a primary threat to the native forests and bogs.

The upper watershed supports a variety of rare indigenous flora and fauna. Many of these species are listed as threatened or endangered under the Endangered Species Act. The habitats of upper watershed protected species have very specific ranges and are particularly sensitive to relatively small changes in temperature and precipitation. With the potential for significant increases in temperature, especially in higher elevations, and reduced mean annual precipitation, it is likely that the range that native species can inhabit will be reduced and the potential for increases in ranges of invasive species, especially plant species will increase. This is a concern for the overall stability of the ecosystem, as well as rare and endangered species which may become further stressed.

Impacts to the stability of the forested ecosystem are also a concern for water resources. As quality forest cover declines, the quality and quantity of water may also decline. The hydrology in Hawai'i forests that are dominated by invasive species, such as strawberry guava, significantly differs from that of native forests. Non-native dominant forests are typically associated with increased sedimentation and erosion as the invasive trees canopy, water uptake rates, and chemistry prevent the establishment of understory vegetation and soil retention. Climate change is likely to result in an increase spread in invasive species in the upper watershed and thereby an increase in sediment and erosion inputs into the lower watershed and nearshore. The increased dry periods may also render the forest more directly susceptible to fire, another source for sediment erosion. Once a fire moves through this area, the native forest is permanently degraded and can

no longer provide the same ecosystem services (Brosius, 2012). Additional climate change information is provided in Appendix B, Section 7.



Source: maunakahalawai.org

Photo 5-1**:** West Maui Upper Watershed, Conservation District

Middle Watershed

During the plantation era, from the mid-1800s to the mid 1900s, the middle watershed was historically dominated by agricultural uses, with sugarcane stopping approximately 20 years ago and pineapple production terminated in 2009 (COM, 2021). The middle watershed is currently dominated by invasive grass and tree species due to inactivity in most of the agriculture fields (the exception being coffee in Wahikuli watershed). Wildland fires are not part of the natural disturbance regime of Hawai‘i and the island of Maui. With the increase of human presence and invasive vegetation, wildland fires have increased, with several in the project area in the past decade. As increase in temperatures and decreases in mean annual rainfall are likely to occur with climate change (Appendix B, Section 7), the invasive grasses are likely to increase in the upper watershed, increasing the fuel source for wildland fires. The drier conditions are likely to trigger wildland fires at increased frequencies and enhance the ability of the fire to spread once started.

The middle watershed was once dominated by agricultural activities and required large amounts of water to support growth. Past agricultural practices altered the surface water supply, diverting surface flow from streams to irrigate lands. Plantation farming in the watersheds stopped due to the cost of growing commercial crops in Hawai‘i compared to other areas around the world. The area is now dominated by fallow fields, since naturally vegetated with grasses and scrub trees, limited diversified agriculture and one coffee farm. With the closure of the agricultural plantations, sediment and erosion management practices such as properly maintaining service roads, irrigation systems, smaller sediment basins and riparian buffers were also abandoned (Photo 5-2).

As climate change continues, it is likely that groundwater and surface water supplies may decrease due to a decrease in mean annual rainfall, a shift to more intense rainfall events even if annual rainfall means remain similar, and hydrologic shifts associated with increase in invasive species in the upper watershed (Appendix B, Section 7). If groundwater and surface water supplies decline, the cost of maintaining agricultural activities may continue to increase and the feasibility of continued agricultural practices declines further.

As seen presently, an increase in abandoned fields and/or shift to land uses with greater amounts of impervious surface will result in an increase in sediment, erosion and contaminants into the nearshore waters. The agricultural areas (when maintained) provide a greenbelt that helps protect the upper watershed from wildland fire, as well as maintains access for firefighting crews. An increase in abandoned fields could also result in an increase in wildland fires and associated erosion. In addition, monotypic fields provide a managed landscape which once insulated the native forest from the incursion of invasive species, such as weeds, which now dominate formerly farmed areas.



Source: Coral Reef Alliance

Photo 5-2: West Maui Agricultural District

Stream and Wetland Habitat

Similar to native forests, riparian habitats are threatened by invasive species. With the presence of non-native species and alterations to stream channels from land use activities, an estimated 40% of stream reaches along the agricultural district are currently storing unnaturally high levels of fine sediment originating from the fields above resulting in increased erosion and sediment transport to the nearshore areas. Instream flow has already been impacted by historic and existing irrigation systems. All of the streams in the lower four watersheds are dry and only flow on an intermittent basis due to stream diversions or the natural flow conditions.

Anticipated changes in climate for Hawai'i may include a decrease in mean annual precipitation that will likely reduce normal low flow conditions and increase opportunities for invasive species expansion. The large storm events are likely to become more frequent and with a greater intensity (Appendix B, Section 7). As the stream and riparian habitat changes, unstable banks and areas of exposed soils are likely to increase. With more large and intense storm events, erosion of these unstable areas is likely to increase.

The shifts in the upper and middle watersheds will also contribute more sediment to the system and to the nearshore reefs.

In addition, coral reef habitats have a constrained range of tolerance for freshwater inputs. Constant, diffuse, low flows of freshwater into the nearshore are typically tolerated by coral reefs. Where streams have been altered – low flow conditions are reduced, and high flow conditions increase. This change in water flow has resulted in damage to coral reefs as the freshwater input results from episodic events above the tolerance levels of coral reefs. Expected changes to hydrology from climate change are likely to cause similar conditions – reduced low flow and increased episodic high flows. The coral reef habitat may experience greater decline near stream mouths.

Historically, wetlands occurred throughout the watersheds, primarily in areas adjacent to the streams and in the lower flatlands of the watershed. Native Hawaiians converted many of the wetlands to taro ponds or fishponds (Photo 5-3). While altered, these ponds continued to provide wetland functions for floodwater retention and sediment catchment. All of the wetlands in the middle and lower watershed have been drained and converted to different land uses. There is an effort within the watersheds to reestablish wetlands, mainly taro ponds, for both their cultural and natural habitat functions. Changes in precipitation are likely to alter the surface hydrology and physical shift and reduce the ranges where wetlands may be able to establish. Shifts in precipitation and temperature patterns are likely to reduce groundwater availability. Associated increases in invasive species are likely to exacerbate these shifts.



Source: Bishop Museum

Photo 5-3: Historic loʻi in Honokōhau Valley

Lower Watershed

The lower watershed is dominated by coastal development (Photo 5-4); resorts and residential areas dominate the lower watershed and are continuing to expand into the middle watershed. Since European introduction, alterations, and fill to the coastal areas of Hawaiʻi resulted in significant loss of coastal wetlands and dune systems. The extensive resort and urban development along the shoreline have further altered this environment, increasing impervious surfaces (comprising approximately 10% of the study area) and decreasing natural processes that used to trap sediments behind the dunes prior to entering the ocean. The current practice is to instead use stormwater discharge outlets to allow the flow of water and related pollutants directly from the developed areas and roadways to the nearshore waters. Additionally, dune systems provided a buffer to natural and seasonal shoreline shifts and prevented erosion of terrigenous sediments into the ocean.

As sea level rises (Appendix B, Section 7), the pressure for shoreline hardening or other means to protect existing development will increase. If the shoreline is hardened, isolated processes, including littoral sediment transport, are altered. Typically, this results in reduced sediment availability and increased erosion to either side of the hardened

shoreline. Engineered solutions to adapt urban development to sea level rise could potentially increase impervious surfaces and storm-water discharge to nearshore areas. Many of the current utilities, including wastewater, occur in the coastal fringe.



Source: County of Maui, 2020

Photo 5-4: West Maui Urban District, Kahana Coastline

Presently, the coral reefs in the watersheds are stressed from the introduction of contaminants from wastewater and stormwater discharge, landscaping and agricultural activities that introduce pollutants into the groundwater and enter the nearshore at natural freshwater submerged discharge areas. As sea level rises and the saltwater influence in the groundwater moves landward, there is a potential for more of these sources to intercept submerged groundwater discharge routes. Other interim and long-term

solutions to sea level rise such as beach renourishments currently being pursued in three stretches of coast, and managed retreat will also have novel impacts not yet fully understood.

In recent years, sea level rise and high waves are already driving an increase in coastal erosion (Appendix B, Section 7). In areas where the sub surface is volcanic alluvium, land-based soil is accessed as waves run up higher and higher, creating highly turbid nearshore waters in areas where there are no stream inputs. Early data from Hui O Ka Wai Ola suggests that high turbidity is trending upwards for sites with eroding coastlines. As wave run up and sea level rise increase, this source of sediment stress to nearshore reefs will also increase.

Nearshore Habitat

The nearshore waters include sensitive coral reef ecosystems and are designated as part of the Hawaiian Humpback Whale National Marine Sanctuary. In addition to the Federally designated Marine Sanctuary, there are two State designated reef conservation areas including the Kahekili Herbivore Fisheries Management Area in the Honokōwai watershed and the Honolua/Mokulēʻia Marine Life Conservation District in the Honolua watershed (Photo 5-5). Much of the land area in the Honolua watershed is also zoned as conservation. Research has shown that healthy well-established coral reefs have a greater resiliency to withstand physical changes to the environment. Coral reefs in the study area are already impaired by a variety of threats, including land-based pollution.

Because of its cooler and deeper waters, Hawaiʻi is only recently beginning to experience coral bleaching associated with increased sea temperatures. The first widespread, mass bleaching event across Hawaiʻi occurred in 2014 and 2015. Predicted changes in sea temperatures are likely to increase coral bleaching (Appendix B, Section 7). Increasing ocean acidification associated with climate change will also impair the corals growth and health (Appendix B, Section 7). Added impacts from fishing pressure also exacerbate this decline. As the corals continue to decline from a variety of stressors including increased land-based pollution this decline will likely be exacerbated by climate change and their ability to recover may significantly decrease. Coral reefs are also

impacted by the re-suspension of fine sediments by certain wave patterns and energies (DLNR-DAR, 2017).

In summary, climate change is likely to increase sources of land-based pollution beyond existing conditions throughout the watershed if no action is taken to reduce these threats. Land-based pollution is one of the key threats impacting coral reefs in Hawai'i along with fishing pressure, increased sea surface temperatures, ocean acidification, overuse from recreational activities, spread of coral disease and aquatic invasive species. Both locally and globally and consistent with scientific literature, establishing a network of permanent no-take Marine Protected Areas and establishing a network of Herbivore Fishery Management Areas were the top ranked actions critical to post-bleaching coral recovery in Hawai'i. (DLNR-DAR, 2017).



Source: The Nature Conservancy

Photo 5-5 Honolua Coral Reef (The Nature Conservancy)

5.6 Water Quality

All State waters are required to meet Hawai'i Administrative Rules, Chapter 11-54, Water Quality Standards. However, funding and manpower limitations at the State of Hawai'i, Department of Health (DOH) prevent routine sampling and monitoring of all

waters across the State of Hawai'i, including across the entire shoreline of the West Maui study area to ensure this standard is met. Volume II of the 2016 Strategies and Implementation plan recommended comprehensive water quality monitoring to better understand the pollutant sources, conveyance pathways and efficacy of existing management measures throughout West Maui (G70, 2016).

Hui O Ka Wai Ola (Hui) is a West Maui community-based water quality monitoring initiative. Hui's network of volunteers works to routinely obtain ocean water samples at eleven sites throughout West Maui and input the data collected into a database. These sites are identified in Figure 5-3, with hot spots for turbidity (brown square) and nitrate-nitrite-nitrogen (green triangle) depicted.

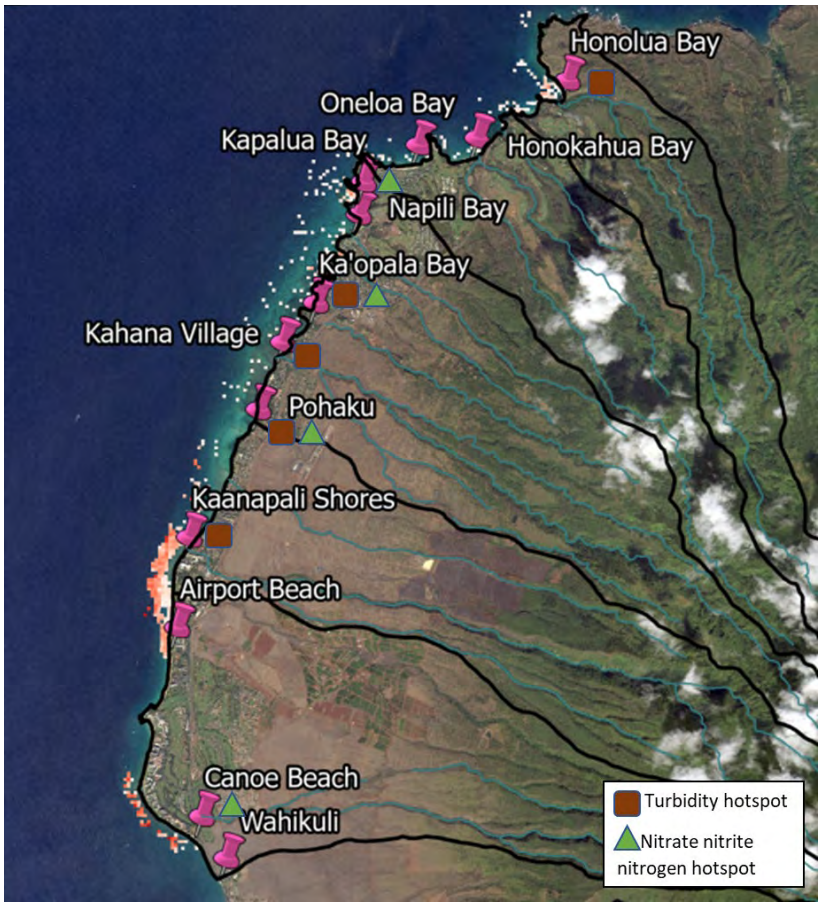


Figure 5-3 Locations of Hui O Ka Wai Ola coastal water quality sampling sites in the study area.

The water quality information presented here was collected and quality assured by Hui and is inclusive of data collected from 2016 through 2020 (although sampling in the

northern three watersheds did not start until 2017). The Hui collects the following coastal water quality data: salinity, pH, temperature, total nitrogen, nitrate-nitrite-nitrogen (NNN), ammonium, total phosphorus, phosphate, silicates, dissolved oxygen (DO) and turbidity at the following sites: Honolua, Oneloa, Kapalua Bay, Nāpili, Ka‘ōpala, Kahana Village, Pōhaku, Kā‘anapali Shores, Kahekili Two, Canoe Beach and Wahikuli. Some water samples are immediately tested at mobile labs, while others are processed for testing at the UH School of Ocean and Earth Science and Technology Laboratory.

High turbidity, a measure of water quality and presence of sediment, and elevated nutrients, in particular, NNN, are the most problematic of the water quality parameters tested in West Maui. Turbidity levels exceed the State standard of 0.2 NTU for all coastal testing sites in Maui. Throughout West Maui, geomeans exceed 4 to 44 times the State standard, with Kahana, Kapalua, Honolua and Pōhaku reporting the highest values. For nitrate-nitrites, 8 of 11 sites exceed the State standard of 3.5 ug/L. The highest site geomean in West Maui is Pōhaku Beach Park at 33 times the State standard, with Kapalua, Canoe Beach and Ka‘ōpala also showing elevated levels. This data supports the study objectives at Section 2.4 above, that mitigation measures are needed on the landscape to address land-based pollutant sources that impair coastal water quality. See Figure 5-4 and Table 5-2.

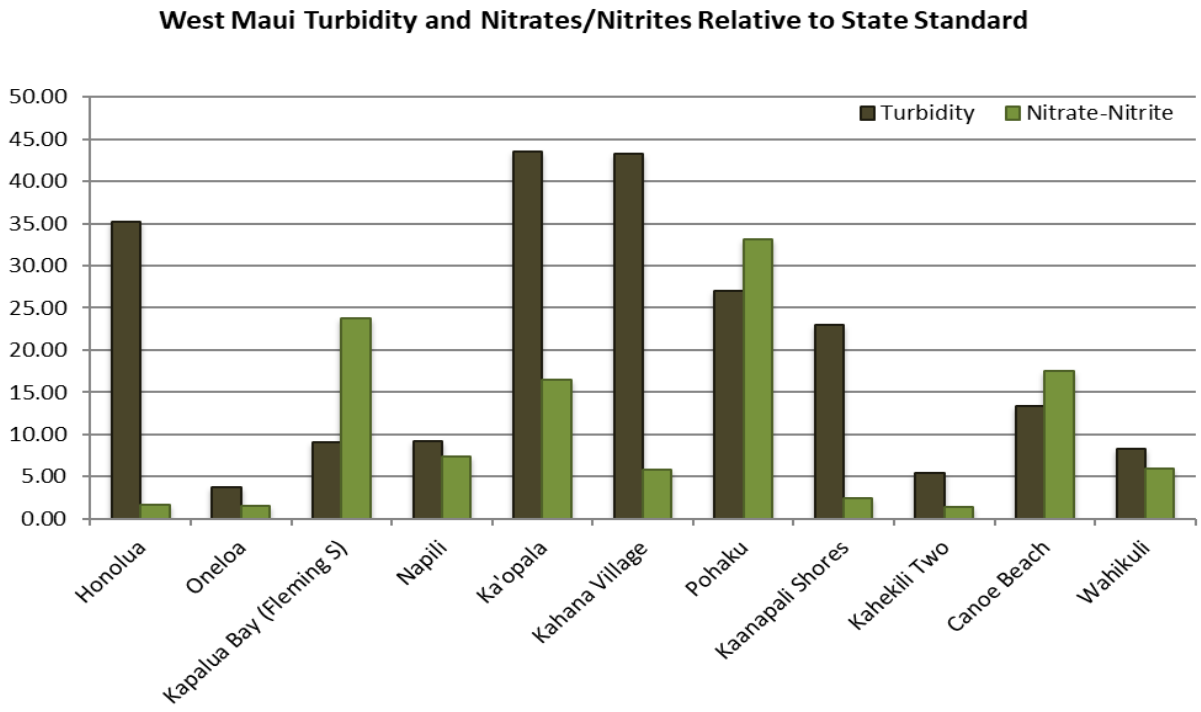


Figure 5-4 Geomeans for turbidity and nitrate nitrite nitrogen normalized relative to Hawai'i Department of Health standards

Figure 5-4 depicts turbidity and nutrient data collected in West Maui in comparison to the State standard. Values greater than one represent the number of times over the State standard. For example, samples taken at Honolua indicate turbidity is 35 times the state standard.

Table 5-2: Geomeans for all West Maui sites for Hui O Ka Wai Ola Data from 2016 (Wahikuli and Honokōwai watersheds) or 2017 (Kahana, Honokahua and Honolua watersheds) through 2020.

Site	Turbidity (NTU)	TN (ug/L)	TP (ug/L)	PO4 (ug/L)	NNN (ug/L)	NH4 (ug/L)	Silicate (ug/L)
Honolua	7.03	98.86	11.91	7.90	5.85	5.42	405.19
Oneloa	0.74	81.65	9.42	4.17	5.22	1.54	101.87
Kapalua Bay	1.81	174.06	17.76	14.30	83.24	3.71	861.02
Nāpili	1.84	118.28	12.80	8.57	25.80	3.94	415.84
Ka‘ōpala	8.71	131.02	13.30	10.35	57.50	2.83	537.27
Kahana Village	8.66	100.81	10.54	7.19	20.22	2.57	407.93
Pōhaku	5.41	204.32	17.02	13.51	116.13	3.97	900.78
Kā‘anapali Shores	4.59	92.16	11.10	6.47	8.45	3.32	284.86
Kahekili Two	1.07	95.38	7.69	4.31	4.65	1.94	138.60
Canoe Beach	2.66	143.00	13.42	8.50	61.38	3.81	584.10
Wahikuli	1.65	96.17	14.97	9.90	20.72	1.63	648.40

The two most problematic parameters use colors to indicate range of exceedance of state standards ranging from slightly in exceedance at yellow to progressively in exceedance through oranges and red.

5.6.1 Sediment Impacts on Coastal Turbidity

The largest source of sediment is in-stream accumulations in the bed and banks of streams in the Agricultural District that are conveyed by streams and gulches when it rains and that drives high turbidity in coastal waters (USGS, Stock, 2021) At higher rainfall intensities, the fallow agricultural landscape also becomes hydrologically connected, increasing the sediment loads coming from the streams (Appendix B, Section 7). The second main cause of turbidity is driven by coastal erosion as the sea level rises and wave run up events become more frequent.

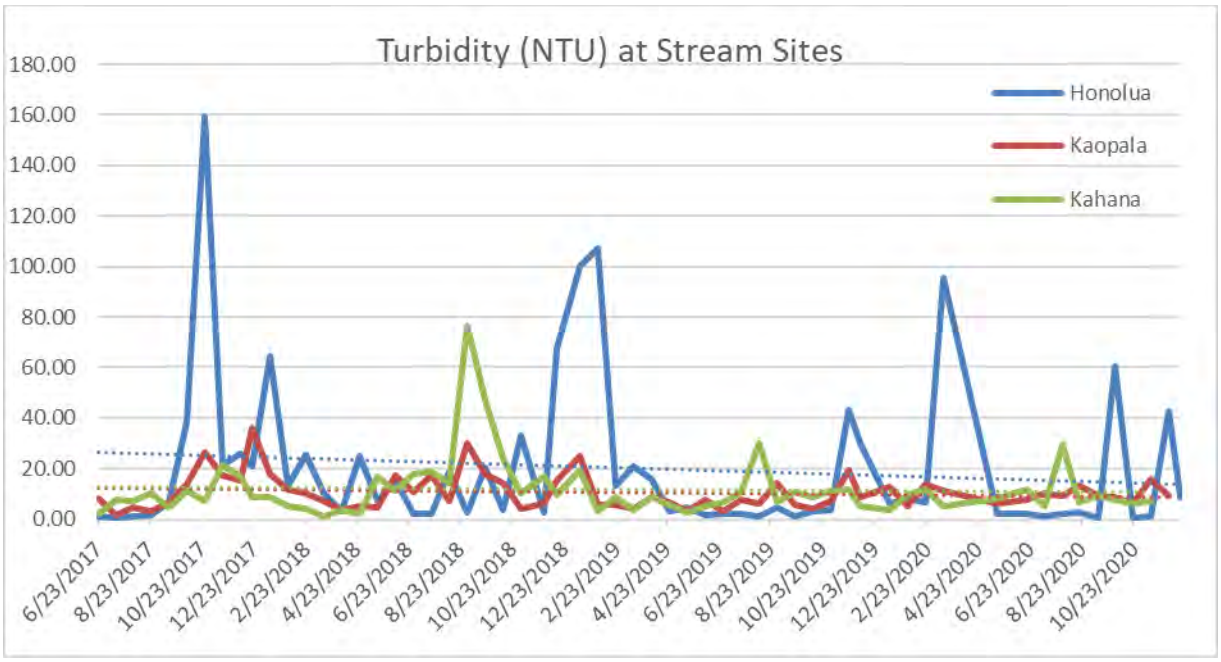


Figure 5-5 Turbidity trends over the past four years for northern three watersheds

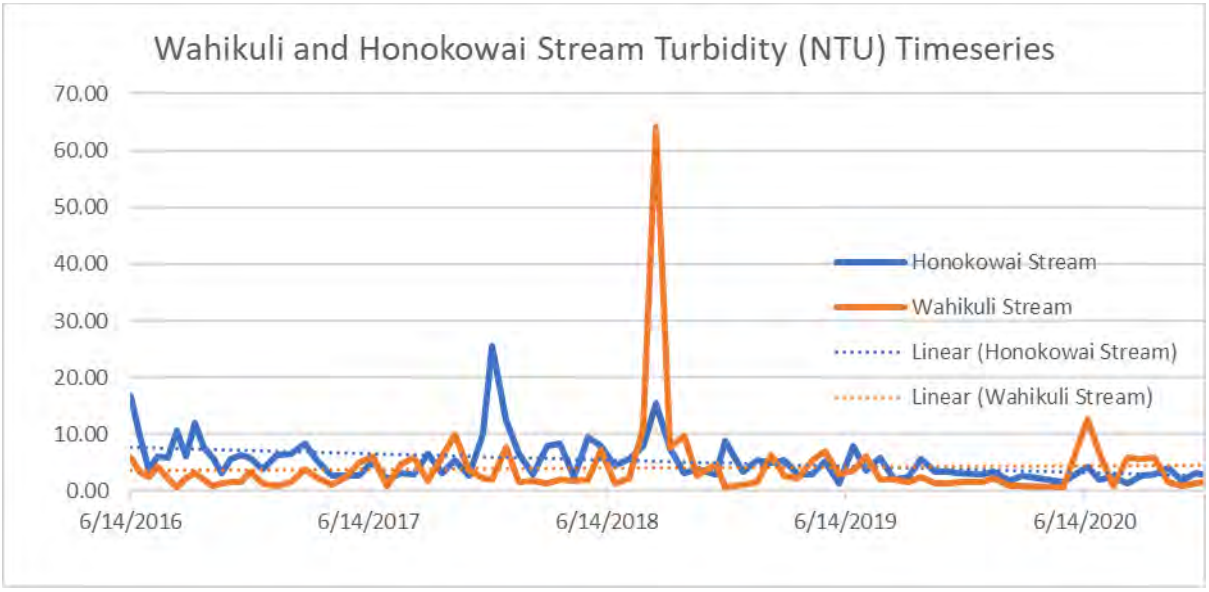


Figure 5-6 Turbidity trends over the past five years in southern two watersheds

Figure 5-6 and Figure 5-7 depict turbidity readings from 2017-2020 at Kahana, Honokahua and Honolua and from 2016-2020 at Wahikuli and Honokōwai, respectively. The data collected by Hui during this time period indicates a slight downward trend in turbidity in Honolua, Ka‘ōpala, Kahana and Honokōwai Streams and a slight upward trend

at Wahikuli Stream only. While informative, a longer time series is needed to confirm the reason for these trends. For example, the downward trend could indicate either declining number and/or size of land-based sediment sources or variability in storm size intensity, or some other plausible cause. Comparisons of coastal turbidity across sites illustrates that variability in rainfall, drainage size and elevation of headwaters in sub watersheds impact hydrologic connectivity, or in other words, brown water in one drainage during a rainstorm does not guarantee a turbidity spike at neighboring stream mouth sites.

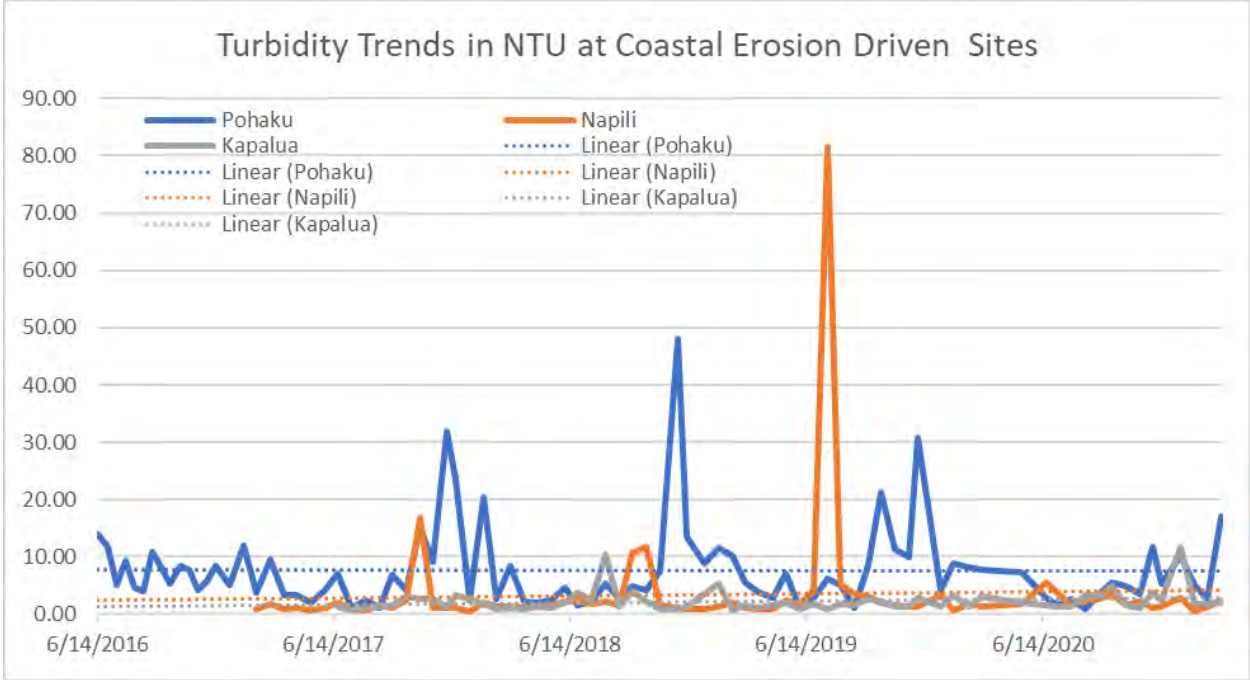


Figure 5-7 Turbidity trends for locations dominated by coastal erosion

Figure 5-8 depicts turbidity trends at the following locations selected due to presence of coastal erosion: Pōhaku, Kapalua and Nāpili over a four-year period. The spike at Nāpili in 2019 is a storm; the basin above overtopped and introduced sediment from the stream, so this value is not based on coastal erosion alone. Median turbidity readings at these select locations appear to be lower in comparison to stream sites. Turbidity readings depict a stable trend, with no upward or downward trend during the monitoring period. Stream conveyance of sediments in West Maui in response to certain rainfall events appears to contribute pulse-like, episodic, high turbidity, while coastal

erosion appears to contribute chronic, comparatively lower turbidity. Both delivery methods of turbidity negatively affect coral reef health, in similar, yet different ways.

To understand the totality of the problem of turbid coastal waters, it is important to not only look at individual high data points, but also frequency of high data points. For example, Honolua, Ka‘ōpala and Kahana streams yield high turbidity readings of ≥10 NTU more than 40% of sample days (Figure 5-9). Surveys of coral reefs in close proximity to these streams indicate these reefs are highly degraded.

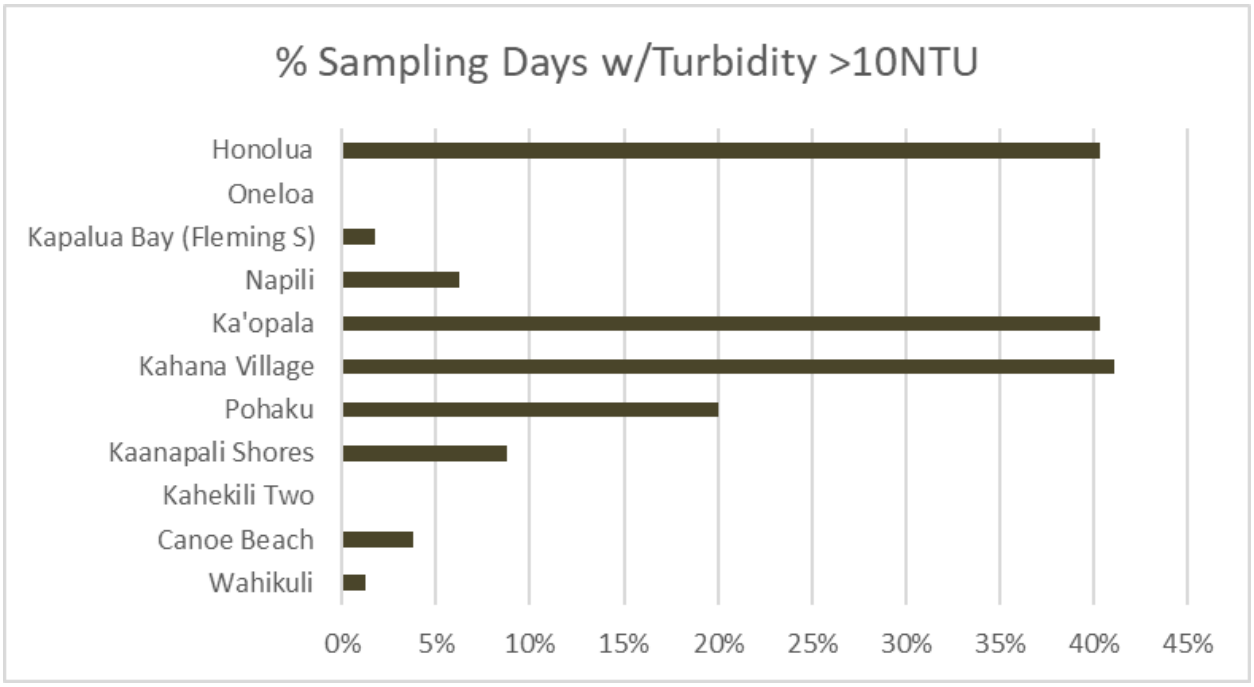


Figure 5-8 Percentage of days with high turbidity over 10NTU (very low water clarity) at West Maui coastal sampling locations

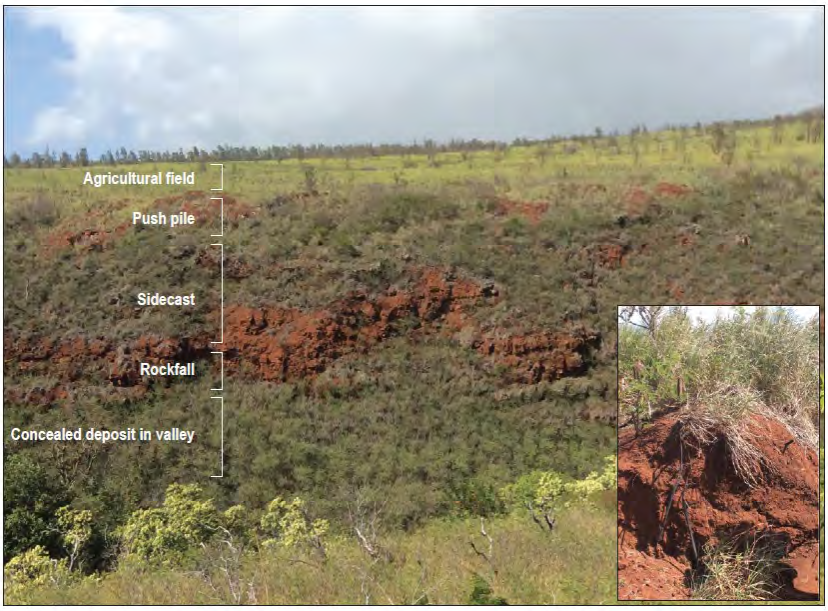
Another trend observed was values for sea surface temperature increasing slightly over the past approximately five years, suggesting climate change impacts measured elsewhere in Hawai‘i are also true for West Maui.

Given the number of sites in the West Maui R2R priority watersheds that exceed state standards for turbidity, it is important that land-based actions be pursued to improve water quality by reducing presence and conveyance of these land-based pollutant sources. Further research is needed to better understand nutrient dynamics.

5.7 Pollutants and Pollutant Sources

5.7.1 Sediment

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 slide 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 or legacy agricultural deposits that line the stream banks along much of the lower channel (Figure 5-10) (USGS, Stock, 2021).



Source: USGS, Stock, 2021

Figure 5-9 Historic deposits of fine sediment near Wahikuli Gulch (USGS, Stock, 2021)

Sediment in the Conservation District is characterized by coarse sediment and boulders, likely created by rockfalls and landslides and occupying up to a third of larger watersheds like Honolua, Honokahua, Kahana, Honokōwai, and Wahikuli. Side slope

deposits of fine-grained legacy agricultural soils occur only within the Agricultural District and below, occupying up to one-fourth of the area of larger watersheds, like at Ka‘ōpala. The mixed fine-grain composition atop alluvial deposits, the location only within the Agricultural District, the evidence of side casting and presence of agricultural artifacts supports the conclusion that the material deposited in the stream valleys are manmade and originated during and as a result of past agricultural practices (USGS, Stock, 2021).

USGS conducted pedestrian surveys starting from stream mouth up to the reach of the stream just above historic agricultural influence at four stream valleys to determine the extent of the fill terraces. Survey data was extrapolated to the remaining stream valleys to estimate fill terrace extent across West Maui watersheds. USGS found that fine-grained fill terraces account for approximately 40% of the total streambank length. These deposits vary in thickness, averaging approximately 85 cm thick, consisting of a silty loam, roughly 95 percent fine sediment (45% sand, 47% silt, and 8% clay) with a median grain size of 0.04 mm (Figure 5-11). Fill-terrace deposits are considerably siltier and finer than sediments found in agricultural fields (USGS, Stock, 2021). Sources include airfall from agricultural fields (red) and historic fill terraces (blue) in watersheds. Agricultural field airfall is characterized as a loamy sand and historic fill terrace

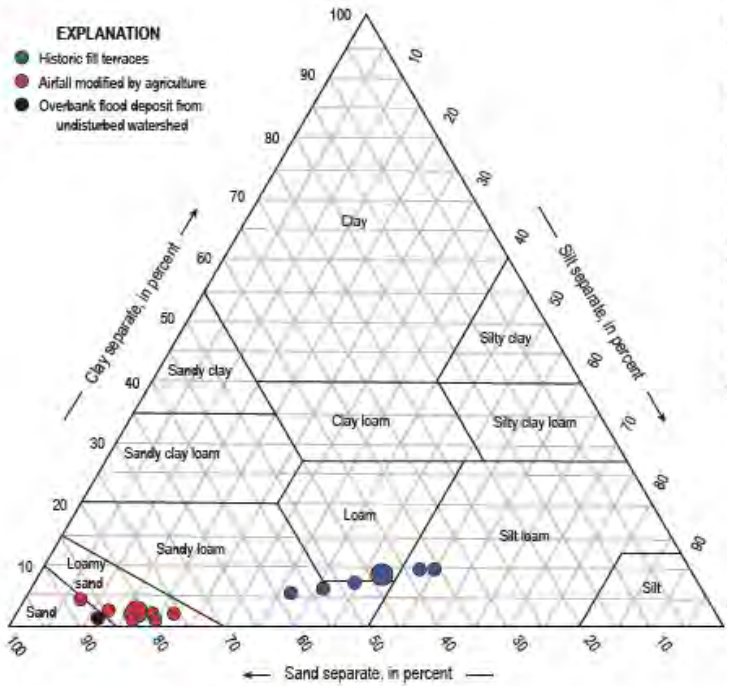


Figure 5-10 USDA soil classification diagram of potential sediment plume sources

A crude but defensible sediment budget indicates that this annual bank erosion sends a minimum of approximately 920 tons of fine sand, silt, and clay to West Maui's nearshore, the equivalent of about 93 dump-truck loads per year. Uncertainties in bank erosion rate imply that actual sediment loads could be 30–360 percent of estimated values. The sediment budget predicts that Kahana Stream produces almost a third of this total (USGS, Stock, 2021).

5.7.2 Precipitation

Rainfall in West Maui occurs primarily via tradewind-driven orographic rain, typical of Hawai'i's subtropical location, carrying moist air from the sea in a westerly direction and upwards over Hawai'i's east facing mountain ranges. Orographic rain or the "Rain Shadow Effect" drives the climate gradient characterize by a wet windward side and a dry leeward side. In West Maui, orographic rain starts on the east side of Maui, over the summit of Pu'u Kukui in the Conservation District and over into the Agricultural District before rain dissipates. Accordingly, the Conservation District and much of the Agricultural District in West Maui is forested and green, while the lower watershed Urban District is generally arid. While orographic rains are of moderate intensity and do not generally

trigger flash floods or landslides, instead their consistent occurrence (over 70% of rain events) and relatively long duration is the primary contributor of Hawai‘i’s water supply (USGS, Stock, et. al., 2020).

Other dominant rainfall events are attributed to episodic cyclones and thunderstorms that bring higher intensity rainfall on both windward and leeward sides of Hawaiian islands. These lower frequency, higher intensity rainfall events are caused by upper-level trough, *Kona* low, and cut-off low pressure systems, often exceeding 10 millimeters per hour (USGS, Stock, et. al., 2020).

Rainfall events exceeding 10–20 millimeter (mm) per hour over a minimum of two hours over watersheds that feature in-/near-stream sediment deposits generate terrestrial runoff, causing coastal plumes (Photo 5-6). Analysis of recent and historical rainfall indicates that West Maui communities can expect rainfalls of sufficient intensity and duration to generate coastal plumes to occur at least 3–5 times per year (USGS, Stock, et. al., 2020).



Photo Credit: Don McLeish

Photo 5-6: Sediment laden flow at Ka'ōpala Gulch outlet after storm event observed by USGS on 7/20/14

USGS examined historic rainfall records to determine rainfall trends over the past three decades. Historic records from West Maui stream gages in the Conservation District indicate the following: 1) annual rainfall totals have decreased, 2) cumulative hours (duration) of rainfall at intensities greater than 20 millimeters per hour (mm/hr) have decreased, 3) the frequency of storms with continuous intense rainfall has not changed. In summary, this means that although total rainfall has decreased since the 1970s, more rainfall now occurs during short, intense storms capable of causing runoff and erosion and generating coastal turbidity plumes (USGS, Stock, et. al., 2020).

5.7.3 In-Stream Erosion

During precipitation events of high enough intensity and for a long enough duration to generate in-stream erosion of fill-terrace deposits, high concentrations of silts and fine sands are shed into stream waters and transported downstream to the ocean These

episodic and recurring higher intensity rainfall events of 10-20 mm/hr and lasting a minimum of 2 hours generates coastal sediment plumes at least 3-5 times per year in West Maui. Far less frequently, even greater intensity rainfall events that exceed 50mm/hr and that could mobilize agricultural sediments, occur on a decadal cycle. An analysis of saturated soil hydroconductivity in the agricultural fields and dirt roads above the stream valleys indicates infiltration rates (50 mm/hr) far exceeding rainfall rates (10-20 mm/hr) necessary to generate offshore sediment plumes, meaning that rainfall at intensities that generate sediment plumes would readily infiltrate the ground within the agricultural fields and not cause surface runoff or conveyance of agricultural sediments into the ocean. USGS concludes that the frequent coastal plumes observed in West Maui are predominately a result of in-stream sediment transport, and not agricultural runoff.

On average, the rate at which fill terraces erode range from 4 to 24 mm annually, with higher rates in streams located in wetter watersheds like Honolua Stream and Pāpua Gulch than streams located in drier watersheds like Māhinahina Gulch. Generalized bank erosion rates of 14 mm/yr and 5 mm/y for perennial/intermittent and ephemeral streams, respectively, were used in conjunction with eroding bank length to estimate annual sediment loads to the ocean per stream. Annual loads are divided by watershed area to determine sediment yield measured in metric tons/km^2/yr.

The annual load from bank erosion ranges from zero for watersheds without identified channels to a high of 285 metric tons/year with most values within the range of 25–62 metric tons/year (Figure 5-12). When sediment enters West Maui's nearshore, imagery indicates that sediment is transported in three distinct along-shore cells, Northern Cell (Watersheds 1-12, starting at Līpoa Point and including Honolua Stream, Mokupe'a Gulch and Honokahua Stream), Middle Cell (13-33, starting at Nāpili 2-3 and including Honokeana, Ka'ōpala Gulch, Kahana and Honokōwai Streams) and Southern Cell (34-35, starting at Black Rock and ending at Wahikuli Gulch). Sediment loads from each activated stream channel combine within and per cell. For example, Kahana Stream, which has the highest value eroding bank length at 55 km and also the highest annual bank erosion load of 285 metric tons/year, combines with Ka'ōpala Gulch, which transports the second highest sediment yield in West Maui at 26 metric tons/km^2/yr to generate synergistically worse adverse effects within the Middle Cell (Figure 5-13). The

high annual load and high sediment yield within the same cell makes Kahana and Kaʻōpala prime targets for mitigation.

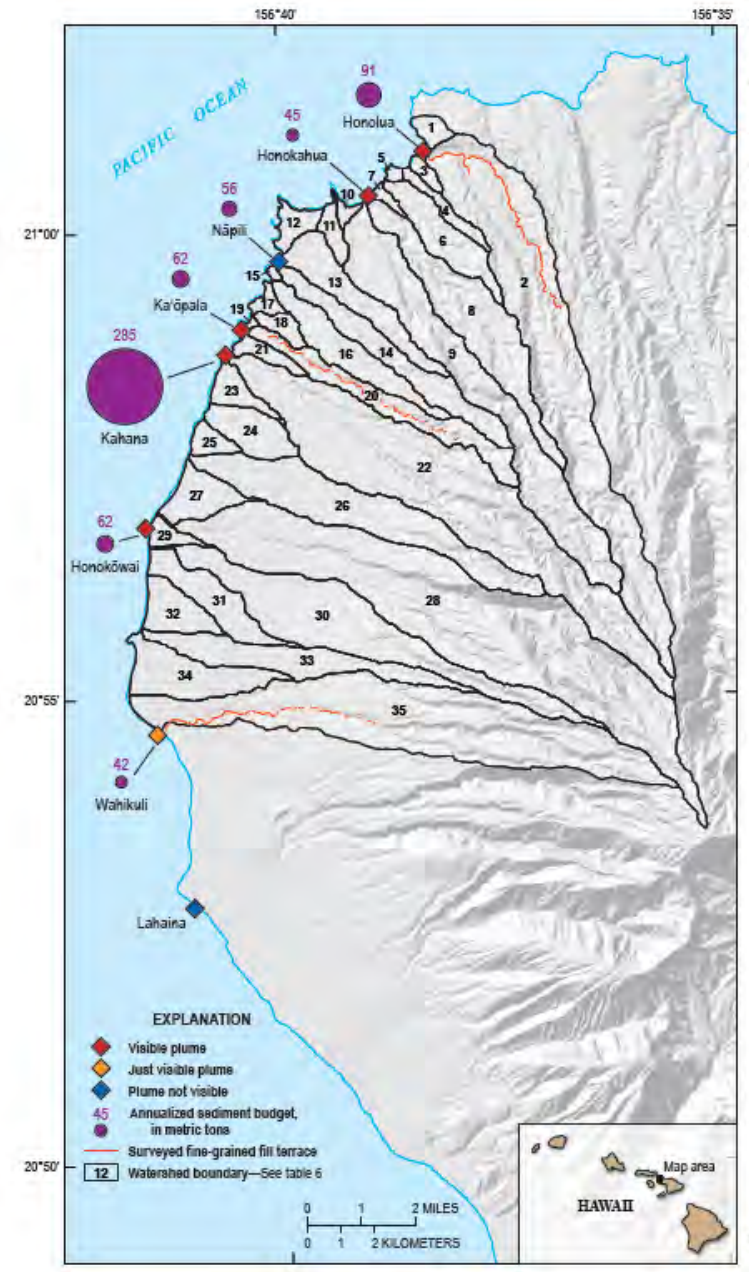


Figure 5-11 Map of West Maui Historic Field Terraces

Major watersheds and sub-watersheds are numbered. Surveyed historic field terraces (red line); all fill terraces occur within and downstream of agricultural areas. Purple circles proportionate to sediment budget in metric tons per year (USGS, Stock, 2021)

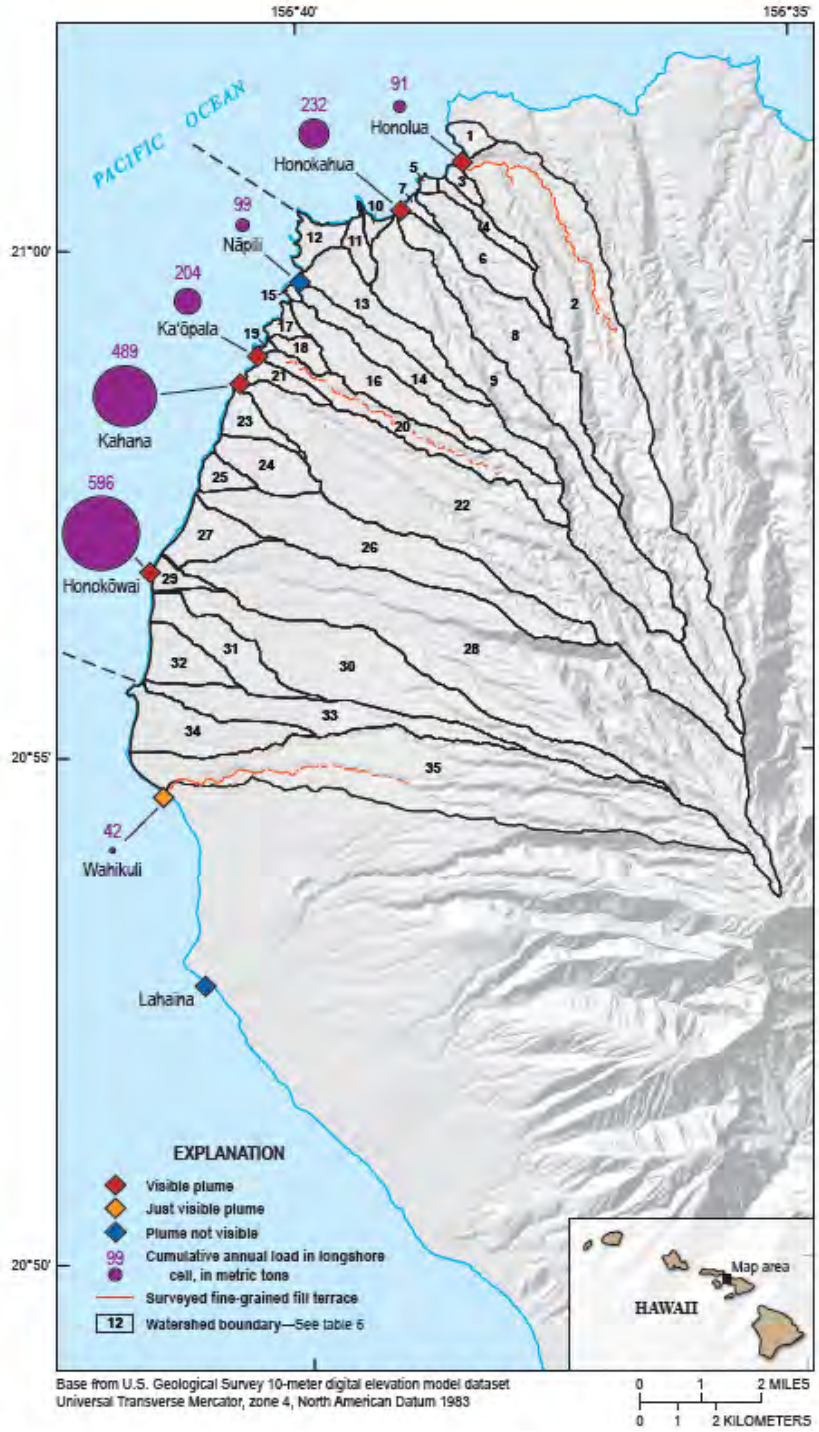


Figure 5-12 Map of West Maui Longshore Sediment Transport

Major watersheds and sub-watersheds are numbered. Longshore sediment transport cells (black dash). Purple circles show longshore accumulation of annual load in metric tons based on plume behavior (north to south, per cell) e.g. Honokōwai

contributes 62 metric tons/year, however, due to longshore plume behavior, ocean fronting Honokōwai is exposed to a cumulative 596 metric tons/year from all outlets within middle cell (Figure 5-13) (USGS, Stock, 2021).

5.7.4 Coastal Erosion

At the onset of the study and as the study evolved, coastal erosion as a source of pollution has not been a primary focus of the study, although it certainly is a source of terrestrial sediment. Annual Erosion Hazard Rates for the West Maui shoreline were previously estimated by the University of Hawai'i at Mānoa's Coastal Geology Group based on analyzing historical shoreline positions from 1912 to 1997, with light to moderate erosion expected (averages of -0.3 ft/yr to -1.0 ft/yr). The West Maui shoreline boasts several resorts and large condominiums, and the stability of these iconic structures are being visibly threatened by the loss of sandy beach. It is, for obvious reasons, at the forefront of the community's minds when thinking of potential sources of sediment to the marine environment (Photo 5-7); this, in comparison to the agricultural deposits at the back of the valley. However, its impacts to coral reefs are not clear and quantifying the extent of its impact is beyond the scope of this study. Generally, the primary concern (with consideration to coral reef health) would not be erosion of sand, but clay and silt banks.



Source: County of Maui, 2021

Photo 5-7: Costal erosion and water quality degradation fronting Kā'anapali Beach club

West Maui faces wave exposure from both the north and the south, on the west-facing coast, contributing to exceptionally high seasonal variations in beach width.

Overall, the West Maui region is considered "sand starved," with a limited sand supply prior to transition to terrigenous soil (as opposed to extensive sand dunes in Kihei and parts of Maui's north shore which act as a buffer for retreating shorelines) (COM, 2018). Data from Hui O Ka Wai Ola shows that over the past five years or so, coastal turbidity is trending slightly upwards at sample locations known to be impacted by coastal erosion. Continuing to test in the coming years is needed to better understand this trend.

The USGS Atlas of Natural Hazards in the Hawaiian Coastal Zone (Fletcher et al. 2002) study showed that areas in the West Maui region (Olowalu, Lahaina, Nāpili, and Honolua) and including the study area, has an overall hazard assessment level of moderate to high (5 out of 7), due in large part to the low coastal slope, which increases susceptibility to impacts from high waves, storms, high tides, coastal erosion, tsunami, and flooding. Dense development of the West Maui coastline and in low-lying areas increases vulnerability to these natural hazards. Climate change and sea level rise will increase the frequency and severity of impacts. An analysis of the potential sea level change was performed in the projected area in accordance with Engineer Regulation 1100-2-8162 and Engineer Pamphlet 1100-2-1 (USACE, 2019). The gage at Kahului Harbor (NOAA ID: 1615680) was used for the analysis. The result of the calculation indicates a relative sea level change of 5.15 feet was determined in the year 2100 at the *high* condition. For the *intermediate* condition, the change is 1.86 feet, and the *low* condition shows an increase of 0.82 feet. These values are relative to Local Mean Sea Level (LMSL). Further, sea level rise is projected to be higher than global averages around tropic regions, including Hawai'i. Flooding events during seasonal or extreme high tides will be experienced decades before the projected global sea levels are reached as is already occurring in West Maui. Long-term community and development planning should consider adaptive and innovative solutions that provide multiple benefits and that make the West Maui community resilient to the projected impacts of climate change and sea-level rise.

5.7.5 Groundwater

Groundwater seeps convey freshwater to the ocean and in effect, lowers pH of the water at and near the seep. Ocean acidification lowers pH on a global scale, as the ocean absorbs increasing amounts of CO_2 from the atmosphere. Lower pH (greater acidity)

slows calcification, the process by which corals and other marine species make their skeletons out of the mineral calcium carbonate. It also increases rates of coral bioerosion—the breakdown of coral by other organisms—and it can cause carbonate skeletons and sand to dissolve. A recent study by USGS shows evidence of local stressors such as freshwater and nutrient inputs compounding upon global climate change effects of ocean acidification and accelerating coral reef health decline (USGS, 2018). While well established that corals require clean, clear, low nutrient water to thrive, recent research more clearly illustrates the mechanisms and extent to which elevated sources of nitrogen can undermine coral health.

At Kahekili reef in the Wahikuli Watershed, treated wastewater effluent originating from the Lahaina Wastewater Reclamation Facility travels through submarine groundwater (confirmed through dye tracing) seeps onto nearshore reefs, transporting freshwater, lowering pH and creating a constant loading of nitrogen, on the order of 50x the normal nitrate concentration (USGS, 2018). Coral cores obtained from Kahekili reef indicate chronic exposure to polluted, low-pH groundwater resulted in bioerosion 8x higher than coral reefs without these influences (Prouty, et. al., USGS, 2017). Bioerosion is so active that the thin layer of coral that is alive is growing on a structure that can collapse, losing many benefits coral reef ecosystems provide such as providing habitat for fish and other marine biota and coastal protection. An additional Hawai‘i based study demonstrated that nutrient pollution could make reefs more vulnerable to global changes associated with ocean acidification and accelerate the predicted shift from net accretion to net erosion (Silbiger et.al., 2018).

While more recent water quality sampling by the seeps in Kahekili suggest that nitrate-nitrate-nitrogen concentrations in the injected wastewater have lowered due to improvements at the treatment plan, the documented significant degree of impact from elevated nutrients on coral reef structure supports continuing efforts to address nutrient pollution of coastal waters. Understanding the concerted impact of global and local stressors on local coral reef ecosystems supports measures that address local, land-based pollution inputs into the nearshore environment to improve coral reef health.

5.8 Marine Dynamics

In conjunction with this study, USGS collected physical oceanographic and sedimentologic data in the field to calibrate and validate hydrodynamic and sediment transport models used to analyze the coastal circulation, waves, and sediment transport along the West Maui watershed study area. USGS analyzed sediment transport in the nearshore environment under baseline (future without project) conditions and one hypothetical restoration scenario (representative of a combination of small and large management measures implemented across the study area (USGS, Storlazzi, 2023).

As observed in the field, wave energy and near-bed turbidity are positively correlated meaning sediment already deposited on the seabed is resuspended by wave action and subsequently transported by prevailing currents. The model simulations project that when large waves coincide with a flood event, post-storm sedimentation was generally reduced in the nearshore region but increased in the region offshore of the reefs.

The observed and modeled sediment dynamics indicate a contrast between coral reefs sheltered within embayments, like Honolua, or behind points, like Wahikuli, and coral reefs along the relatively open coastline from Kapalua to Honokōwai. For the sheltered site, once sediment enters the nearshore from a single stream mouth, it settles out and remains within the reef area for a prolonged period due to a lack of wave or currents. In contrast, the coral reefs along the “open” section of coastline are more exposed to waves and terrestrial sediment from multiple stream sources where fine-grained terrestrial sediment can rarely settle and remains in suspension even long after the storm has passed. Thus, the primary sediment impact to the reefs within sheltered areas is sedimentation while the primary sediment impact to reefs in along open coastline is persistent light attenuation from suspended sediment.

6 Comprehensive Management Recommendations

The Watershed Management Plan was prepared to guide current and future planning decisions and investments in the West Maui watershed and to comprehensively addresses problems within the watershed, while achieving the watershed objectives outlined in Section 1.5 of this report. Planning for the future of the watershed is crucial to decrease conveyance of land-based pollutants to the marine environment and improve coral reef health.

For this watershed management plan, a list of management measures to address the most pressing resource needs as identified in collaboration with the West Maui R2R Initiative, the West Maui community, and our study partner. An initial list of structural and non-structural management measures was derived by combining recommendations generated in Volume II of the 2012 and 2016 Strategies and Implementation Plans that investigated a wide range of problems and solutions (Section 6.1.1). Relevant measures that can still be implemented were carried forward.

USACE sought to identify natural, structural, or engineered measures to manage sediment sources and conveyance to the ocean, including measures to be implemented at the source of the sediment deposits, that capture the sediments once suspended, or that manage conveyance of the sediments prior to transport to the ocean. Based on the USGS Stock study that identified legacy agricultural sediment deposits as the greatest cache of pollutants that are readily being transported to the ocean, USACE explored alternative measures that would expound upon the recommendations from the 2012 and 2016 watershed assessments to improve existing sediment basins and stop existing in-stream sediment deposits from transporting sediments downstream to the ocean (Section 6.1.3). In addition, certain conceptual designs for sediment management measures were recommended by local organizations for incorporation in this study (Section 6.1.2).

In 2019, the U.S. Army Engineer Research and Development Center (ERDC), River and Engineering Committee collaborated with the study team and stakeholders to further evaluate the conditions to develop additional structural measures. In addition to the previous measures carried forward and the 2019 ERDC collaboration, USACE collaborated with USGS to further evaluate the structural measures through marine transport dynamics modeling. Recommended management measures that propose

structural, engineered solutions were transmitted to the USGS to model the marine transport dynamics, i.e. to which coral reefs are in-stream sediments transported and deposited.

6.1 Management Measures

A measure is a specific structural or non-structural action that could contribute to the plan objectives by reducing or eliminating the identified problems. Management measures may address one or more study objectives and are the "building blocks" for conceptual alternatives or recommendations (USACE, 2015). As part of the measure screening process, management measures are evaluated against the Water Resources Council's National Evaluation Criteria: completeness, effectiveness, efficiency, and acceptability.

1. Completeness – the extent to which a proposed alternative provides and accounts for all necessary investments or other actions to ensure the realization of the planned effects,
2. Effectiveness – the extent to which a proposed alternative alleviates the specified problems and achieves the specified opportunities,
3. Efficiency – the extent to which a proposed alternative is the most cost-effective means of alleviating the specified problems and realizing the specified opportunities, consistent with protecting the Nation's environment,
4. Acceptability – the workability and viability of the proposed alternative with respect to acceptance by state and local entities and the public and compatibility with existing laws, regulations, and public policies.

6.1.1 Measures Recommended by the 2012 and 2016 Volume II Strategies and Implementation Plans

The following list is a compilation of management measures recommended by past watershed assessments associated with this comprehensive study. Detailed descriptions of these measures are found in the sources identified. Note that these measures were relevant at the time they were recommended and may have either been implemented, are still needed, or have been rendered obsolete due to advances in data collection or increased knowledge and understanding of the watershed problems. A discussion of screening of these measures is provided in Table 6-1 at the end of this section.

2012 Volume II Strategies and Implementation Plan Recommended Measures:

- Road and Trail Inventory Assessment and Pollution Source Minimization Practices
- Fallow Agricultural Field Inventory Assessment and Pollution Source Minimization Practices
- Lāhaina Wastewater Reclamation Facility Alternate Disposal e.g. Increase production of R-1 water for reuse
- Engineering Analysis and Retrofit Design at Honokōwai Structure #8
- Engineering Analysis and Stabilization Designs at Wahikuli Gulch
- Fertilizer Management Plan
- Ocean-Friendly Landscaper Outreach Program
- Burn Area Emergency Response Plan
- Wildland Fire Management Measures e.g. Fire breaks
- Urban Pollution Control: Baffle Box
- Urban Pollution Control: Bioretention Cell e.g. Rain Garden

2016 Volume II Strategies and Implementation Plan Recommended Measures:

- Policy Measure: County Storm Water Management Plan
- Policy Measure: Enforcement of Temporary Construction Storm water Best Management Practices (BMPs)
- Post Construction Storm water Ordinance: Drainage Master Plan Requirement
- Policy Measure: Requirement for BMP Management Plans and Reporting by Large Scale Nutrient and Pesticide Users
- Policy Measure: Water Quality Monitoring Program
- Community Water Quality Monitoring Program
- Policy Measure: Agricultural Conservation Plan Requirement for Ag Lands
- Policy Measure: Establish Storm Water Fees
- Policy Measure: Low Impact Development Requirement for development, redevelopment and improvement projects > 1 acre (State, County and private sector) to incorporate LID measures into design and construction
- Policy Measure: Golf Courses and Landscaping BMP Management Plans

- Policy Measure: Pool and Vehicle Wash Water Discharge Policy
- Policy Measure: Storm Water Management Asset Mapping
- Policy Measure: Regional Drainage Analysis
- Stop sediment from entering streams and gulches via
  - Push pile assessment and stabilization
  - Stream crossings stabilization
  - Access road improvements
- Stop future sediment sources via
  - Construction best management practices (BMPs)
  - Grazing BMPs
- "Go Time" Wildfire Plan
- Stop existing in-stream sediment deposits from transporting sediments downstream to the ocean via
  - Identification of sediment terraces in streams and gulches
  - Researching, piloting and implementation of stream/gulch bank management measures
  - Restoration of traditional loʻi kalo
- Address current in-stream sediment movement via
  - Kahana desilting basin maintenance
  - Desilting basin monitoring and analysis
  - Desilting basin retrofits
  - Potential new desilting/sediment basins
- Measures to address in-stream sediment deposits and prevent transport downstream:
  - Micro basins in Kaʻōpala or Wahikuli
  - Lo'i terraces in Honolua or Honokōwai
- Basin modifications at Kaʻōpala, Kahana and Honokōwai
- Increase groundwater recharge and slow surface flows via
  - Conservation boundary fencing
  - Active ungulate & invasive weed management

- Landscape restoration

- Monitor and assess roadside erosion at Honoapi‘ilani Highway and Lower Road
- Cesspool Identification and Conversion
- Urban Storm Water Management Retrofits
- Continue to fund existing outreach initiatives and outreach coordinators

6.1.2 Measures Recommended by Community Organizations

Community Water Quality Monitoring Program. Additional measures have been proposed since publishing of the 2012 and 2016 West Maui Watershed Assessments. In particular, Hui O Ka Wai Ola is a West Maui community-based organization that has established a program consisting of a network of technical experts and community volunteers to conduct local water quality monitoring throughout West Maui (Photo 6-1). This measure currently implements a recommendation of the 2016 Watershed Assessment and is currently active in the community. Data collected by Hui O Ka Wai Ola has been incorporated into this study at Section 5.6, Water Quality.



Source: The Nature Conservancy, A. Yurkanin

Photo 6-1: Community Water Quality Sampling in West Maui by Hui O Ka Wai Ola

The following measures are proposed by the Maui Coral Reef Alliance whose work centers around restoring natural filtration processes within watersheds to prevent land-based water pollution from degrading reefs.

Multiple Sediment Capture and Groundwater Recharge Basins at Wahikuli and Hāhākea Gulches. Capturing and retaining sediment to prevent it from being conveyed downstream to the shoreline is a key strategy to protect coral reefs. This technical solution was identified in the Wahikuli- Honokōwai Watershed Management Plan. Unlike other west Maui watersheds, there are no existing sediment retention basins in Wahikuli watershed (PIFSC, 2017).

As part of its design considerations, USEPA recommends that sediment basins be designed to capture runoff from the 2-year, 24-hour rainfall event. The USEPA also cautions, "Do not put sediment traps or basins in or immediately adjacent to flowing streams or other waterways." (USEPA, 2007).

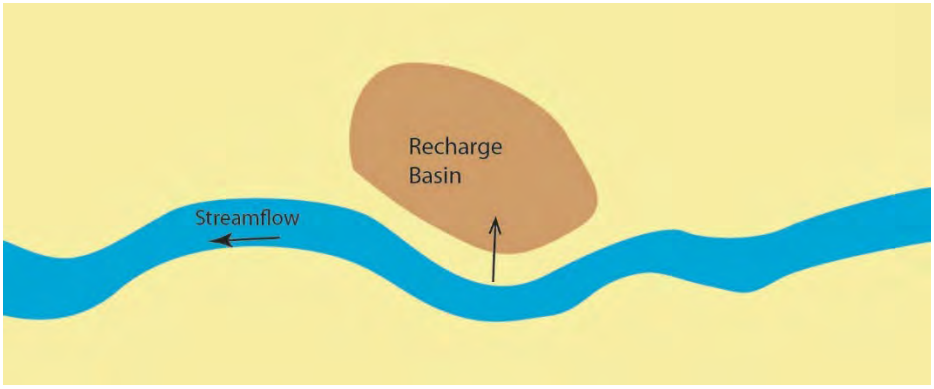


Figure 6-1 Multiple Sediment Capture and Groundwater Recharge Basins at Wahikuli and Hāhākea Gulches Concept Sketch

This measure could be implemented along Wahikuli Gulch and Hāhākea Gulch where the topography and channel conditions are naturally conducive to flow movement and storage. Ideally, existing boulders or logs would form natural weirs. Rather than one large sediment retention basin (as has been done in other west Maui watersheds), a series of smaller basins would be more feasible within the project timeline and regulatory environment (Figure 6-1).

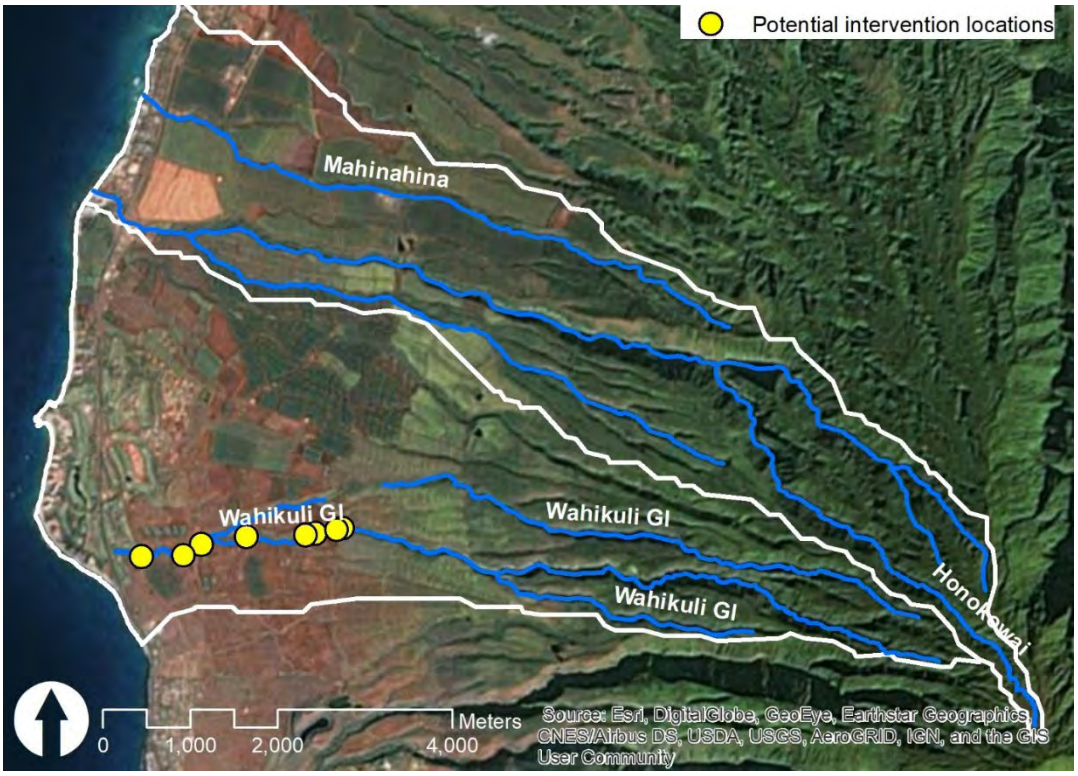


Figure 6-2: Potential Intervention Locations for Multiple Sediment Capture and Groundwater Recharge Basins at Wahikuli and Hāhākea Gulches

Sediment Capture and Groundwater Recharge Basins Complex Combined with Recreational Open Space at Wahikuli Gulch and Hāhākea Gulch. This technical solution would combine sediment capture and groundwater recharge with recreational elements (e.g. open space with trails/walk-run paths, native and regional vegetation for cultural and subsistence use, shade trees that are drought-tolerant, community garden, seating, play areas, etc.). The recharge and recreation area would be approximately 250 meters (820 feet) long and 50 meters (160 feet) wide and located on the south overbank, parallel to Wahikuli Gulch from the railroad trestle to Honoapi'ilani Highway (Figure 6-2:). The first overflow to the pond system would be located upstream end on the left bank (looking downstream) of Wahikuli Gulch to divert flood water into the upstream pond. There would be a second overflow located downstream. There would be an overflow spillway. The upstream ponds would function as sediment settling basins, and access for heavy equipment for sediment removal would be incorporated into the design.

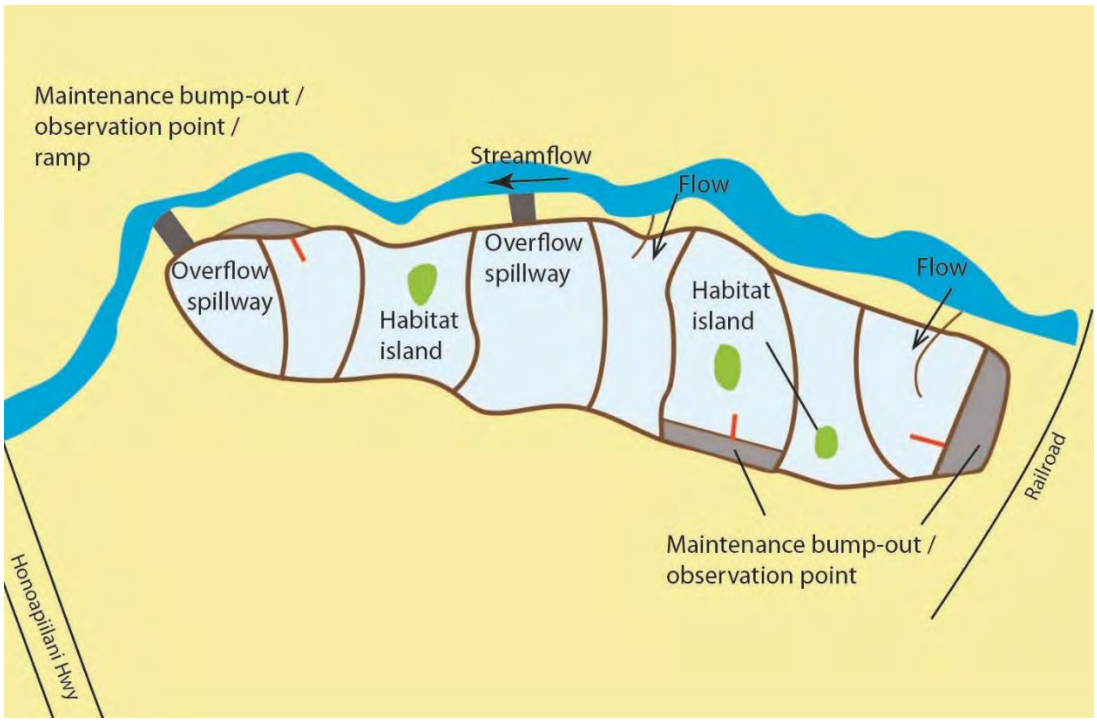


Figure 6-3: Sediment Capture and Groundwater Recharge Basins Complex Combined with Recreational Open Space at Wahikuli Gulch and Hāhākea Gulch Concept Sketch



Figure 6-4: Sediment Capture and Groundwater Recharge Basins Complex Combined with Recreational Open Space at Wahikuli Gulch and Hāhākea Gulch Concept Sketch over Aerial Photo

This measure could be implemented along Wahikuli Gulch and Hāhākea Gulch (Figure 6-3, Figure 6-4). It would be preferable because this measure does not include vertical construction, only excavation up to four feet in depth may be necessary to optimize the site's recharge capabilities. From a cursory site investigation, it appears that the top three feet of sediment is silt, with gravels below. It may be advantageous to remove this layer of silt to improve recharge, however, the benefits of additional flow storage will have to be balanced against the risk of disturbing the existing loose soils. Currently, there are existing homeless encampments in this area.

This measure would need regular inspection and maintenance of the inlet and outlet works, as well as the sediment basins. Typical maintenance activities would include trash and debris removal, vegetation management, and removal of accumulated sediment. Paid staff would likely need to perform tasks requiring heavy equipment, but volunteers could potentially conduct vegetation management and trail maintenance.

The West Maui R2R has recommended the following measures concurrent to this study:

Gulch buffers adjacent to Wahikuli Gulch and Hāhākea Gulch. The West Maui R2R proposes measures to be implemented in the agricultural fields and above areas surrounding stream valleys. The following erosion control measures are intended to create a buffer around the gulches and are intended to reduce transport of sediments and other pollutants from the agricultural fields up above into the adjacent stream valleys below. In particular, these measures have been proposed in the mid-watershed areas of Wahikuli and Honokōwai and could potentially be proposed at additional watersheds to the north.

- Ripping: Deep tilling roads and fields to three feet to remove compaction and increase infiltration.
- Terraforming: Re-shape the contours of the land to optimize hydrology in favor of keeping runoff on the land.
- Micro-basins: Series of small depressions positioned to receive and settle out sediment from runoff.
- Key lining/ripping on contour: Deep plowing to remove soil compaction and direct water from wetter to drier parts of the landscape.

- Vetiver eyebrows in kickouts: Planting tight arcs of vetiver on contours in the channels directed off of a series of practices designed to clear water from roads during rainfall.
- Contour planting vetiver: Working across the topographic lines of the landscape, close planting vetiver slips to create a living check dam for water and sediment.
- Native plant establishment: Planting species native to Hawai'i adapted to the conditions and likely to thrive without maintenance after establishment.
- Hydro-mulching: Coating bare landscapes with a sprayed-on combination of seeds, fertilizer and tackifier to achieve coverage of large areas in a relatively short time period.
- Check dams: A small dam that can be created by various materials including debris, sandbags, coconut coir logs etc. to reduce the velocity of water and therefore rain-driven erosion.

Gulch Buffer Stacked Practices via optimal combinations of the aforementioned erosion control measures. The West Maui R2R needs to determine the optimal suite of actions to take within the 100-foot gulch buffer zones of the mid-elevation lands in the Wahikuli and Honokōwai watersheds that will best meet the objectives of keeping sediment on the land, deliver some community benefit, improve water retention, and increase ecosystem integrity. Ideally, once the best suite of actions is determined, this decision will form the path forward, and only require updating when there is new science or lessons learned that would prompt a new course of action. Decisions on awarding of grants and which actions to pursue are spread between non-profit organizations and agencies. There is urgency around determining the best suite of erosion control actions to take because the coral reefs receiving the turbid water from these drainages are in rapid decline, and this has resulted in a temporary focus on priority grant funding for the area.

6.1.3 Structural Measures Developed by USACE to Address In-Stream Erosion of Historic Fill Terraces

USACE formulated measures that would expound upon the measure recommended by the 2016 Watershed Assessment Plan: *Measures to address in-stream sediment deposits and prevent transport downstream e.g., Micro basins in Ka'ōpala or Wahikuli, Lo'i terraces in Honolua or Honokōwai, Basin modifications at Ka'ōpala, Kahana and Honokōwai*. USACE intended that the effort to formulate such sediment management measures would address a substantial pollutant source that pervades all of West Maui and accordingly would substantially improve coral reef health. Documentation

of that plan formulation is provided below. For full description of each measure, see Appendix C.

Plan Formulation Strategies Watershed Management strategies were formulated that provide a means to address the watershed problem and meet the study objectives. The main problem is land-based pollution conveyance via streamflow to nearshore coral reefs. The study objective is to propose measures that reduce pollution sources and conveyance to coral reefs, the implementation of which increases coral reef resistance and resiliency. To guide development of management measures, strategies to address the problem could be implemented at the following general locations throughout the West Maui watershed:

- Upstream of the source
  - Hold or slow storm flows
  - Divert storm flows
- At the source
  - Stabilize sediments in place
  - Remove sediment source
  - Modify the pollutant
- Downstream of the source
  - Capture sediments in transport

Strategy: Structural Measures Proposed Upstream of the Source

Addressing the conveyance of fine-grain sediments to the ocean above the source would involve management of flows i.e., slow/entrain or divert storm flows, that erode the historic fill terraces and mobilize sediments for transport to West Maui's coral reefs. The following strategies derived measures proposed to address the problem upstream of the source:

- Upstream Detention Basin/Dam
- Retrofit Existing Irrigation Ditch System

Upstream Detention Basin/ Dam. The upstream detention basin/dam measure features a holding structure of concrete or earthen construction intended to capture flows in the upper watershed and lower flow conditions in the channel, which could minimize in-stream erosion. An upstream detention basin could be constructed at one or multiple

upstream locations across the study area. The more water the basin can hold, the more effective the basin is at slowing stream velocity downstream. Greater holding capacity equates to greater structural footprint (either individually or in series).

This measure would meet the study objective to reduce conveyance of pollutants. Construction of a new detention basin or dam would be a challenge for buildability due to limited accessibility(most of the upper watershed is inaccessible), significant construction cost due to size (capable of holding back storm flows), would be challenging to permit and meet both USACE and State of Hawai‘i dam safety criteria, could result in significant adverse environmental effect, and likely would not be acceptable to the West Maui community, some of whom are against any type of water diversion due to historic and current strife related to water diversion in West Maui. When presented to the FAST, the R2R Working Group and the West Maui community, this measure received no positive feedback. Construction of an Upstream Detention Basin/Dam was ultimately eliminated and “not recommended” for further consideration as a management measure.

Retrofit Existing Irrigation Ditch System. The utilization of existing irrigation ditch system measure proposes to modify the existing and extensive agricultural irrigation ditch system to re-route flow across multiple watersheds into a single stream during large flow events (Figure 6-5:). This measure would effectively and efficiently address sediment conveyance by concentrating the problem to a single culmination point. New construction would be focused at the central flow point which could be a sedimentation basin and would require modifications to existing infrastructure to route to the central basin.

Similar to the aforementioned proposed measure, retrofitting the existing irrigation system and rerouting flow from multiple sub-watersheds to a central sedimentation basin would be costly, very large in scale, would also be challenging to permit, and likely would result in significant adverse direct and indirect environmental effects by significantly altering the flow and sediment regime across multiple drainage basins. Likewise, when presented to the stakeholders, this measure received no positive feedback. Retrofitting



Figure 6-5 Retrofit Existing Irrigation Pipe System. USACE concept illustration.

the existing irrigation ditch system and rerouting flows to a central sedimentation basin was ultimately eliminated and not recommended for further consideration as a management measure.

Strategy: Structural Measures Proposed at the Source

Addressing the pollutant and conveyance of pollutants at the source would involve stabilization of the sediments in place, removal of the source in its entirety, or modification of the pollutant. This strategy would completely and effectively prevent mobilization of fine-grade sediments to the ocean that have the potential to degrade coral reef health. The following strategies derived measures proposed to address the problem at the source:

- Bank stabilization
- Manually excavate or remove sediment source
- Flocculation

Bank stabilization. The primary source of in-stream sediment pollution, as identified by USGS, is historic fill terraces deposited by agricultural practices during the plantation era (USGS, Stock, 2021). In situ stabilization of the fill terraces that comprise the bed and banks of streams and gulches in West Maui would prevent sediments from being conveyed by stream transport out to West Maui coral reefs.

Stabilization techniques could involve environmentally acceptable alternatives such as planting or the less desirable hard alternative: armoring. However, the magnitude of this proposed solution is reflective of the pervasiveness of the problem throughout the study area and would likely render implementation of this measure infeasible. These deposits are extensive, comprising the bed and banks of approximately 40% of the stream length of streams and gulches (over 247,000 meters or 154 miles of total stream length) throughout the Agricultural District across all five watersheds of the study area (USGS, Stock, 2021). Even if the West Maui community proposed to target stabilization of the stream with the greatest sediment budget, Kahana Stream—annual load of 285 metric tons, the effort would require planting or armoring 54,992 meters or 34 miles of stream length (doubled, to account for left and right banks, and perhaps tripled to account for the stream bed).

When presented to the FAST, the R2R Working Group and the West Maui community, this measure received mixed reviews. Addressing the pollutant at the source rather than managing flows once sediment is mobilized was preferred. It was estimated that the initial cost to construct would likely be less than the measures proposing new construction above the source, however, the maintenance requirements would be significant and the scale of this effort in areas where much of the fill terraces are inaccessible could quickly inflate costs. Planting, as a means of stabilizing the sediment, was the preferred, environmentally acceptable alternative, however, plantings across such a vast area generated concern for potential adverse secondary impacts regarding ecology and biodiversity. Due to the uncertainty of the practicality of implementing this measure, stabilization of fill terraces in place was ultimately eliminated by the PDT based on stakeholder and sponsor feedback and not recommended for further consideration as a management measure.

Remove sediment source. The study group considered manual excavation or removal of the sediments from its source. Manually removing in-stream sediments would eliminate the pollutant from the equation. However, similar to the proposed stabilization of sediments in situ, the magnitude of this effort would likely render implementation of this measure infeasible. According to the USGS sediment budget for the study area, West Maui contributes 922 metric tons of sediment every year. This is a massive amount of sediment that further highlights the issue of limited accessibility. Options of excavation would require use of many, large heavy machinery and equipment or pneumatic removal by shovels and buckets or a vacuum apparatus e.g. “dry dredging” to overcome limited access to these areas. The extent of the total volume of sediment that would need to be excavated is unknown. Additionally, once excavated, the disposition of the excavated material would need to be decided and the disturbed areas stabilized to prevent further erosion. Options for disposition include upland disposal, ocean disposal or beneficial reuse. Regardless of the selected disposition, the volume of excavated material is significant and would likely require a combination in order to handle all excavated material.

When presented to members of the West Maui R2R and West Maui community, this measure received mixed reviews from the stakeholders. Addressing the pollutant at the source and removing it from the equation was a preferable strategy to managing flows before or after sediment is mobilized. However, this management measure was eliminated from further consideration based on feasibility concerns regarding cost to mobilize, remove and dispose and implementation e.g. access, scope, geotechnical stability and disposal options.

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Flocculation. Fine sediment, such as clays and fine silts, require a long time to settle. Accordingly, targeting clay and fine silts is generally not practical. Coarse to medium size silt particles settle more quickly and can be realistically targeted for sediment trapping. However, these fine particles that are suspended in the water can be encouraged to stick together with the help of a coagulant chemical. Flocculation, a gentle mixing stage, further increases the particle size and thereby also reduces the time required for settlement. This

measure compliments previously proposed measures that rely upon capturing sediment through detention.

When initially proposed at the public meeting in August 2018, there was some uncertainty regarding the impact that coagulant chemicals would have on the environmental system. Coagulation and flocculation are commonly used in water treatment facilities but have a limited performance history in Hawaii for addressing sedimentation issues in natural river systems. The measure was generally met with hesitancy by the public.

However, since the time of the public meeting, further research has revealed there are sources of biodegradable, natural flocculants that perform on a wide array of soil types and pH ranges; and have demonstrated no harm to aquatic organisms based on toxicity testing at recommended dosages (Dober). One example of this is Chitosan, a natural biopolymer derived from chitin, recycled from the shells of crustaceans like shrimp, crabs, and lobsters.

Flocculants would prove a challenge to implement singularly as a management measure given flashy, high velocity flow events characteristic of West Maui, potential for labor-intensive operations and maintenance demand, and dosing requirements. Accordingly, this management measure was eliminated from further consideration based on feasibility concerns. However, flocculants show promise as an additive measure used in conjunction with another management measure to increase efficiency of trapping fine sediments by inducing aggregation and promoting fallout.

Strategy: Structural Measures Proposed Downstream of the Source

Addressing the conveyance of pollutants downstream of the pollutant source would involve capturing diverting or filtering streamflow to reduce conveyance or volume of conveyed sediments from the stream channel. This strategy would prevent mobilization or minimize volume of conveyed fine-grade sediments and filter or slow down stream velocity. The following strategies derived measures proposed to address the problem downstream of the source:

- Improve existing sedimentation measures
- Send flows offshore, past coral reefs

- Filter sediment-laden flow
- Micro Basins
- Loʻi Terraces

Retrofit/re-design existing sedimentation basins. Kaʻōpala Gulch, Kahana Stream and Honokōwai Stream all contain a sediment retention or desilting basin along their stream channel. The purpose of a desilting basin is to temporarily store storm flow, thereby increasing slowing velocity and increasing residence time, allowing for sediment to settle out within the basin. A portion of the sediment in suspension is removed from the stream flow prior to conveyance downstream and out to the ocean.

The study team, the West Maui R2R Watershed Coordinator and USGS discussed at great length the variation in settling rates among different size sediments, with large boulders, gravel and coarse grain sands settling out immediately to within minutes, and fine clay particles settling out in hours, under still water conditions. During a storm event, continuous stream flow agitates the water column suspending and resuspending fine-grained sediments throughout the water column. Water that spills over the basin (by design) and flows downstream carries with it fine sediments that were not able to settle out in the basin. Sedimentation basins reduce, but do not necessarily eliminate in-stream pollution conveyance. With every flow event, sediment is captured in the basin and accumulates over time, requiring maintenance by the landowner to routinely remove accumulated sediments and restore the holding capacity of the basin.

This measure proposes improvements to the existing sediment retention basins at the three aforementioned locations. Kahana Stream and Kaʻōpala Gulch basins, as constructed, are undersized. Honokōwai Stream basin is not operating at full capacity. The basin improvements measure proposes modifying existing detention basins to improve their effectiveness in capturing sediment. Improvements to the existing basins would meet the study objective to effectively and efficiently reduce pollutant conveyance. The reduced footprint associated with modification to existing structures is preferable to new construction and likely would cause no more than minimal environmental effects. The proposed measure, improve existing basins, received positive feedback from

stakeholders. The measure proposing to improve existing basins completely, effectively, efficiently and acceptably met the study objective to reduce conveyance of land-based pollutants to the ocean and accordingly, was carried forward.

Stormwater Discharge Pipe. This measure proposes the construction of a large pipe originating in the streams and with end terminus in deep offshore waters (Figure 6-6). The pipe would collect and convey sediment-laden storm flows past nearshore coral reefs via an outfall pipe. In-stream erosion of legacy agricultural deposit would continue through natural processes before being captured and diverted into the deep ocean.

There are several challenges associated with this measure, including its technical complexity, high cost of construction, requirements for land acquisition or easement rights, anticipated significant environmental impacts, extensive permitting requirements, and increased maintenance requirements post-construction. A similar project in the reverse was proposed offshore of Waikiki and ultimately was not approved for construction or otherwise abandoned. In addition, the measure would not reduce sediment pollution, only relocate it past the coral reefs to deeper marine ecosystems that would be adversely affected. When presented at the August 2018 public meeting, this measure was strongly opposed by the public



Figure 6-6: Stormwater Discharge Pipe. USACE concept illustration.

Geotextile Filtration/Silt Bags. USACE proposed installation of pumps upstream of existing sedimentation basins to divert flows into temporary geotextile bag structures that would effectively filter storm flow to remove fines, but not impede flow to the downstream basin (Figure 6-7). This measure would require minimal new construction and expansion of the existing maintenance plan to remove filtered sediments and operate and maintain the pump system.



Figure 6-7 Geotextile Filtration. USACE concept image.

Geotextile filtration bags are versatile and used for many applications, however, large scale, long-term use for this purpose would be novel and without precedent locally. Diversion of flow into the filtration system would also pose potential adverse environmental effects associated with entrainment, aquatic life movements, etc. This measure received mixed reviews when presented to the FAST, the R2R Working Group, and the West Maui community. While the overall footprint appeared minimal and the concept sounded promising, increasing maintenance demands on the County's underfunded and undermanned maintenance program was undesirable and the uncertainty of the practicality and secondary impacts was questionable. Due to the uncertainty associated with this measure, installation of a Geotextile Filtration System was ultimately eliminated and not recommended for further consideration as a management measure. However, geotextile filtration shows promise as an additive measure used in conjunction with another management measure to increase efficiency of trapping fine sediments prior to flow into siltation basins.

Micro Basins. The offset micro basins measure proposes the construction of new micro basins adjacent to streams and gulches. Rather than one large sediment retention basin positioned within the stream channel, excess streamflow i.e., above a set stage height, would be diverted during a storm event into a series of smaller basins sited adjacent to the main channel. Flow into the micro basin system would enter on the upstream end and follow natural topography overflowing downstream into the next micro basin in series.



Source: CORAL, 2018

Figure 6-8 Micro Basins at Wahikuli Stream. Concept design by Coral Reef Alliance

Continuous streamflow in the main channel would be maintained. These basins would be designed to slow flows and increase residence time to allow settling of sediment out of suspension for a portion of stormwater flow before confluence with the main channel downstream. The greater the holding capacity, the more successful this measure would be at trapping sediment. In addition, earthen basins promote groundwater recharge.

Proposals for a series of smaller basins would allow for greater versatility in site selection. The Coral Reef Alliance (CORAL) furthered this measure to conceptual design

at Wahikuli Stream, upstream of Honoapi‘ilani Highway, incorporating recreational, cultural, and educational opportunities (Figure 6-8). This measure was not formally presented to the West Maui community by USACE. The high potential for success in meeting the study objective, opportunity to provide multiple secondary benefits, and likelihood for less than significant adverse environmental impacts may outweigh the anticipated relatively moderate to high construction and operation/maintenance costs. For these reasons, the study partners recommend Micro Basins for further consideration and was carried forward.

Lo‘i Terraces. Traditional Hawaiian cultivation of taro or *kalo* (*Colocasia esculenta*) involved the use of a connected, terraced, wetland agricultural system called lo’i, typically located adjacent to a flowing stream. This concept, as it relates to sediment retention, is akin to the micro basins concept. While lo‘i successfully traps sediment, they are not engineered to withstand storm flows.



Source: Maui Cultural Lands, Maui No Ka Oi Magazine, 2006

Photo 6-2 Project Mālama Honokōwai Lo‘i Restoration in Honokōwai Valley

This measure would differ in that it would focus on the cultivation of flooded agriculture, requiring continuous flow of water and heavy soil capable of impounding water without much loss through percolation. This measure proposes the restoration of lo‘i at historical sites or new lo‘i strategically placed within the study area. Restoration of

historic loʻi and construction of new loʻi were considered "feasible" because of the community support behind its implementation. Construction costs would be relatively low. Daily operation and maintenance costs and post-storm repairs, in terms of manpower, would be high (i.e. labor intensive). Restoration of cultural sites and practices would benefit the West Maui community. There is a history of loʻi in Honolua and Honokōwai, where this measure is being proposed (Photo 6-2). This measure was well received by the FAST agencies, the R2R Working Group, and the West Maui community and accordingly was recommended for further consideration as a management measure and carried forward.

6.1.4 Comprehensive Management Measures

The following table lists the compiled management measures described in Section 6.1.1-6.1.3 above and evaluates each measure against the study objectives of reducing sources of land-based pollutants and reducing conveyance of land-based pollutants to the ocean. Measures that meet the study objectives and with expert judgement from the West Maui R2R and PDT are carried forward for further consideration.

Table 6-1: Screening of Comprehensive Management Measures

	Measure	Reduce Pollutant Source? (Yes/No)	Reduce Conveyance? (Y/N)	Carry Forward? (Y/N)
2012 Watershed Assessment Measures	Road and Trail Inventory Assessment and Pollution Source Minimization Practices	Y	N	N Implementation complete
	Fallow Agricultural Field Inventory Assessment and Pollution Source Minimization Practices	Y	N	N Irrelevant, fallow fields no longer exist
	Lāhaina Wastewater Reclamation Facility Alternate Disposal e.g. Increase production of R-1 water for reuse	N	N	N Lacks legal nexus; USEPA is lead agency
	Engineering Analysis and Retrofit Design at Honokōwai Structure #8	N	Y	Y
	Engineering Analysis and Stabilization Designs at Wahikuli Gulch	N	Y	Y
	Fertilizer Management Plan	Y	N	N Implemented to Date
	Burn Area Emergency Response Plan	Y	N	Y
	Urban Pollution Control: Baffle Box	N	Y	N Sited location is ineffective
	Urban Pollution Control: Bioretention Cell e.g. Rain Garden	N	Y	Y
2016 Watershed Assessment Measures	County Storm Water Management Plan	N	Y	Y
	Enforcement of Temporary Construction Storm water BMPs	N	Y	Y
	Post Construction Storm water Ordinance: Drainage Master Plan Requirement	N	Y	Y
	Requirement for BMP Management Plans and Reporting by Large Scale Nutrient and Pesticide Users	Y	N	Y
	Water Quality Monitoring Program	N	N	Y
	Agricultural Conservation Plan Requirement for Ag Lands	Y	Y	Y
	Establish Storm Water Fees	N	N	Y

Table 6-2 (cont.): Screening of Comprehensive Management Measures

	Measure	Reduce Pollutant Source? (Yes/No)	Reduce Conveyance? (Y/N)	Carry Forward? (Y/N)
2016 Watershed Assessment Measures (continued)	Low Impact Development Requirement for development, redevelopment and improvement projects > 1 acre (State, County and private sector) to incorporate LID measures into design and construction	N	N	Y
	Golf Courses and Landscaping BMP Management Plans	Y	N	Y
	Pool and Vehicle Wash Water Discharge Policy	Y	N	Y
	Storm Water Management Asset Mapping	N	N	Y
	Regional Drainage Analysis	N	N	Y
	Stop sediment from entering streams and gulches via -Push pile assessment and stabilization -Stream crossings stabilization -Access road improvements	Y	Y	Y
	Stop future sediment sources via -Construction best management practices (BMPs) -Grazing BMPs -"Go Time" Wildfire Plan	Y	N	N Irrelevant and/or ineffective at watershed scale
	Stop existing in-stream sediment deposits from transporting sediments downstream to the ocean via -Identification of sediment terraces in streams and gulches -Researching, piloting and implementation of stream/gulch bank management measures -Restoration of traditional lo'i kalo	Y	Y	Y
	Address current in-stream sediment movement via -Kahana desilting basin maintenance -Desilting basin monitoring and analysis -Desilting basin retrofits -Potential new desilting/sediment basins	N	Y	Y *These measures were furthered to conceptual design as documented in Section 7 and 8 and Appendix C.*
	Increase groundwater recharge and slow surface flows via -Conservation boundary fencing -Active ungulate & invasive weed management -Landscape restoration	N	N	Y
	Monitor and assess roadside erosion at Honoapi'ilani Highway and Lower Road	Y	Y	Y

Table 6-3 (cont.): Screening of Comprehensive Management Measures

	Measure	Reduce Pollutant Source? (Yes/No)	Reduce Conveyance? (Y/N)	Carry Forward? (Y/N)
2016 Watershed Assessment Measures (continued)	Cesspool Identification and Conversion	Y	N	N Identification complete. Irrelevant, not a significant pollution source.
	Urban Storm Water Management Retrofits	Y	Y	Y
	Continue to fund existing outreach initiatives and outreach coordinators	N	N	Y
Stakeholder Proposed Measures	Community Water Quality Monitoring Program (Hui O Ka Wai Ola)	N	N	Y
	Multiple Sediment Capture and Groundwater Recharge Basins at Wahikuli and Hāhākea Gulches (Coral Reef Alliance)	N	Y	Y
	Sediment Capture and Groundwater Recharge Basins Complex Combined with Recreational Open Space at Wahikuli Gulch and Hāhākea Gulch (Coral Reef Alliance)	N	Y	Y
	Gulch buffers adjacent to Wahikuli Gulch and Hāhākea Gulch(Coral Reef Alliance)	N	Y	Y
	Gulch Buffer Stacked Practices via optimal combinations of the following: -Ripping, Terraforming, Micro-basins, Key lining/ripping on contour, Vetiver eyebrows in kickouts, Contour planting vetiver, Native plant establishment, Hydro-mulching and Check dams (West Maui R2R)	N	Y	Y
	Ocean-Friendly Landscaper Outreach Program (West Maui R2R)	Y	N	Y
	Wildland Fire Management Measures e.g. Fire breaks (West Maui R2R)	N	N	Y
USACE Proposed Measures	Upstream Detention Basin/Dam	N	Y	N No public support, too costly, significant environmental concerns
	Retrofit Existing Irrigation Pipe System	N	Y	N No public support, too costly, significant environmental concerns

Table 6-4 (cont.): Screening of Comprehensive Management Measures

	Measure	Reduce Pollutant Source? (Yes/No)	Reduce Conveyance? (Y/N)	Carry Forward? (Y/N)
USACE Proposed Measures (continued)	Bank stabilization	Y	N	N Infeasible, inaccessible, impractical
	Manually excavate or remove sediment source	Y	N	N Infeasible, inaccessible, impractical
	Flocculation	N	N	N Ineffective at watershed scale
	Improve existing sedimentation measures	N	Y	Y
	Send flows offshore, past coral reefs	N	Y	N No public support, too costly, significant environmental concerns
	Filter sediment-laden flow	N	N	N Ineffective at watershed scale, potential safety concern
	Micro Basins	N	Y	Y
	Lo‘i Terraces	N	Y	Y

Although ultimately eliminated from further consideration under this study, based on a literature review, flocculants showed promise as a possible additive measure to increase the sediment trap efficiency of sediment management measures by promoting coagulation of fine grain sediments into coarser grains that readily settle out of suspension. Implementation of flocculants for the purpose of sediment management, and on a watershed scale, is not common, if at all attempted. Uncertainty exists surrounding the feasibility, practicality, scalability and also, potential for adverse physical, chemical and ecological impacts if applied in the real world, especially in or upstream of any of

Hawai'i's sensitive ecosystems. Further research would need to be conducted to better understand the feasibility of this measure, in conjunction with other measures recommended by this study for implementation.

Similarly, geotextile filtration could be further studied to better form a proposal for feasible implementation. Such a measures used in conjunction with another sediment management measure proposed by this study could increase trap efficiency and thus effectiveness of the implemented measure. More information is required to further define the logistics and mechanics of implementing geotextile filtration for this application.

This study proposes to carry forward the measures above that have not been eliminated based on an evaluation against the Water Council's National Evaluation Criteria. All viable measures carried forward are listed in the table below (Table 6-2:) and in Section 9.

Table 6-5: Viable Measures Carried Forward

Engineering Analysis and Retrofit Design at Honokōwai Structure #8^
Engineering Analysis and Stabilization Designs at Wahikuli Gulch
Burn Area Emergency Response Plan
Urban Pollution Control: Bioretention Cell e.g. Rain Garden
County Storm Water Management Plan
Enforcement of Temporary Construction Storm water BMPs
Post Construction Storm water Ordinance: Drainage Master Plan Requirement
Requirement for BMP Management Plans and Reporting by Large Scale Nutrient and Pesticide Users
Water Quality Monitoring Program
Agricultural Conservation Plan Requirement for Ag Lands
Establish Storm Water Fees
Low Impact Development Requirement for development, redevelopment and improvement projects > 1 acre (State, County and private sector) to incorporate LID measures into design and construction
Golf Courses and Landscaping BMP Management Plans
Pool and Vehicle Wash Water Discharge Policy
Storm Water Management Asset Mapping
Regional Drainage Analysis
Stop sediment from entering streams and gulches via - Push pile assessment and stabilization - Stream crossings stabilization - Access road improvements
Stop existing in-stream sediment deposits from transporting sediments downstream to the ocean via - Identification of sediment terraces in streams and gulches - Researching, piloting and implementation of stream/gulch bank management measures - Restoration of traditional loʻi kalo
Address current in-stream sediment movement via - Kahana desilting basin maintenance - Desilting basin monitoring and analysis - Desilting basin retrofits - Potential new desilting/sediment basins

Table 6-6 (cont.): Viable Measures Carried Forward

Increase groundwater recharge and slow surface flows via - Conservation boundary fencing - Active ungulate & invasive weed management - Landscape restoration
Monitor and assess roadside erosion at Honoapi‘ilani Highway and Lower Road
Urban Storm Water Management Retrofits
Continue to fund existing outreach initiatives and outreach coordinators
Community Water Quality Monitoring Program (Hui O Ka Wai Ola)
Multiple Sediment Capture and Groundwater Recharge Basins at Wahikuli and Hāhākea Gulches (Coral Reef Alliance)*
Sediment Capture and Groundwater Recharge Basins Complex Combined with Recreational Open Space at Wahikuli Gulch and Hāhākea Gulch (Coral Reef Alliance)
Gulch buffers adjacent to Wahikuli Gulch and Hāhākea Gulch(Coral Reef Alliance)
Gulch Buffer Stacked Practices via optimal combinations of the following: Ripping, Terraforming, Micro-basins, Key lining/ripping on contour, Vetiver eyebrows in kickouts, Contour planting vetiver, Native plant establishment, Hydro-mulching and Check dams (West Maui R2R)
Ocean-Friendly Landscaper Outreach Program (West Maui R2R)
Wildland Fire Management Measures e.g. Fire breaks (West Maui R2R)
Improve existing sedimentation measures*
Micro Basins*
Lo‘i Terraces*

Measures proposed by CORAL and USACE (annotated with an ‘*’, in Table 6-2:) and that were not eliminated by this evaluation were carried forward to conceptual design alternatives to further define effectiveness and efficiency in meeting the study objectives, leveraging hydrologic, hydraulic, sediment and marine transport dynamics modelling efforts by USACE and USGS, as discussed in Section 7, below. Measures annotated with a ‘^’ in Table 6-2 are synonymous with the USACE proposed measures to improve existing sediment measures and accordingly are not repeated as recommendations in Section 9.

7 Formulating Alternative Plans to Address Terrestrial Sediment

The intent of the West Maui Watershed Study is to contribute to the restoration, enhancement and resilience of West Maui coral reefs and nearshore waters through the reduction of land-based pollution threats – specifically, terrestrial sediment being discharged into the marine environment. This section presents the various management measures proposed by USACE to meet the study objectives that passed the initial screening evaluation and recommended to be carried forward to conceptual design (Table 6-2:).

Sediment management measures that were carried forward were sited across the study area, based on land area available, stakeholder support, and with consideration towards other existing measures in the watershed. Detailed information on site-specific conditions, recommendations, effectiveness, and costs associated with each sited measure are included in Appendix C.

7.1 Initial Array of Alternatives

This section describes the initial array of conceptual alternatives proposed to address terrestrial sediment contributions by riverine systems. The different alternatives listed and discussed below are specifically scoped and scaled to meet the needs of the watershed conditions in which it is sited. The reported efficacy is not necessarily applicable in general or transferrable to all watersheds. None of the listed alternatives are meant to be utilized alone or as perfect solutions, but as part of a larger watershed management plan and sediment mitigation framework. A summary description of the initial array of alternatives is provided at Table 7-11.

7.1.1 Alternative A: No Action

Serving as the base alternative, there are no action measures proposed under this alternative. The No Action alternative serves as a means to capture efforts already underway and to establish a baseline condition to compare to action alternatives. Existing detention basins remain unmodified. The goal of this alternative is to provide a basis to compare the other alternatives' sediment flux (load) to the ocean. The current sediment load contributed by each watershed to the nearshore environment is presented in Table 7-1.

Table 7-1: Alternative A Sediment Load, 50% Annual Exceedance Probability (AEP) Event

Watershed	Peak Flow (ft^3/s)	Sediment Load (metric tons)				
		Total	Clay	Silt	Sand	Gravel
Honolua	227	30.2	4.92	12.10	11.10	2.09
Kaʻōpala	80.8	7.79	7.68	0	0	0
Kahana	464	57.8	23.9	33.9	0	0
Honokōwai	646	6.87	1.35	3.18	2.05	0.19
Wahikuli	1,270	11.3	1.93	4.89	3.98	0.36

7.1.2 Alternative B: Honolua Loʻi

This alternative proposes the construction of five new loʻi along Honolua Stream, covering a total area of approximately one acre. The trap efficiency of the implemented measure(s) and the resulting amount of sediment removed from the system by this alternative are presented in Table 7-2. The ROM construction cost estimate is $1.7 million. The annual O&M cost is high ($150,000-170,000).

Table 7-2: Alternative B Performance Metrics, 50% AEP Event

Watershed	Trap Efficiency (%)				
	Total	Clay	Silt	Sand	Gravel
Honolua	0.12	0.06	0.13	0.13	0.13
Watershed	**Sediment Removed (metric tons)**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Honolua	0.03	0.00	0.02	0.01	0.00

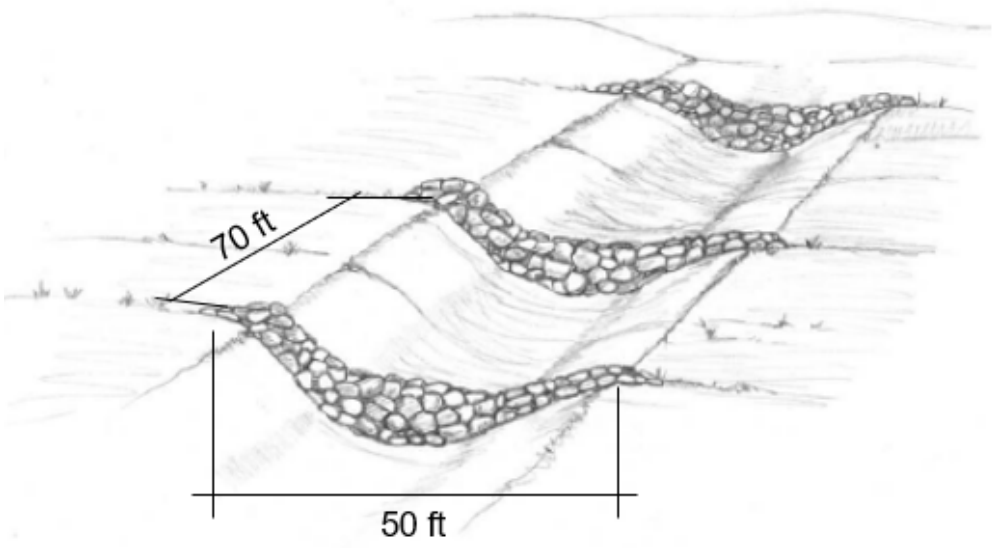
7.1.3 Alternative C: Pāpua Gulch Micro Basins

This alternative proposes that ten micro basins be constructed in series along Pāpua Stream. Each micro basin would be approximately 70 feet long, 50 feet wide, and include a 4-foot-high rock weir on the downstream end. As sediment-laden water flows down Pāpua Stream, the widened channel and physical barrier of the rock weir would slow down the flow (Figure 7-1, Figure 7-2). The rock weir, constructed of loose riprap

with partial grouting, would maintain flow continuity in the stream[8] as a pervious structure. As the capacity of the first micro basin is exceeded, waters would flow over the rock weir and enter the next micro basin. Each micro basin creates an opportunity for sediment to settle before continuing downstream. The trap efficiency of the implemented measure and the resulting amount of sediment removed from the system by this alternative are presented in Table 7-3. The ROM construction cost estimate is $3,044,775. The annual O&M cost is moderate ($5k to $25k/year).

Table 7-3: Alternative C Performance Metrics, 50% AEP Event

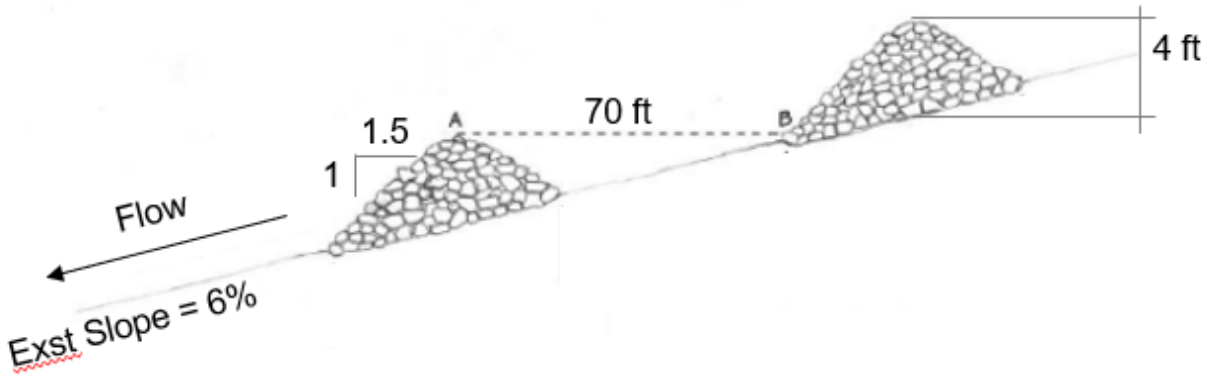
Watershed	Trap Efficiency (%)				
	Total	Clay	Silt	Sand	Gravel
Honolua	83	0.15	100	100	100
Watershed	**Sediment Removed (metric tons)**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Honolua	49.61	0.01	23.7	21.8	4.1



Original figure source: USACE, ERDC/CRREL TR-14-26, 2014

Figure 7-1: Pāpua Gulch Micro Basin Design

[8] Flow continuity is maintained during the flood event; streamflow in Pāpua Stream is intermittent. It does not have continuous flow throughout the year, even under existing conditions.



Original figure source: USACE, ERDC/CRREL TR-14-26, 2014

Figure 7-2: Section View Along Stream Profile

7.1.4 Alternative D: Ka‘ōpala Basin Outlet Modification

An open outlet pipe, located near the bottom of the Ka‘ōpala Basin, allows for sediment-laden water to pass through freely. This alternative proposes modifying the existing Ka‘ōpala Basin outlet works with sluice gates to provide the dam operator with the option to retain water for longer periods or release flow from the top-down. A similar outlet works modification was made to the Nāpili 4-5 Basin in 2011. The trap efficiency of the implemented measure and the resulting amount of sediment removed from the system by this alternative are presented in Table 7-4.

Table 7-4: Alternative D Performance Metrics, 50% AEP Event

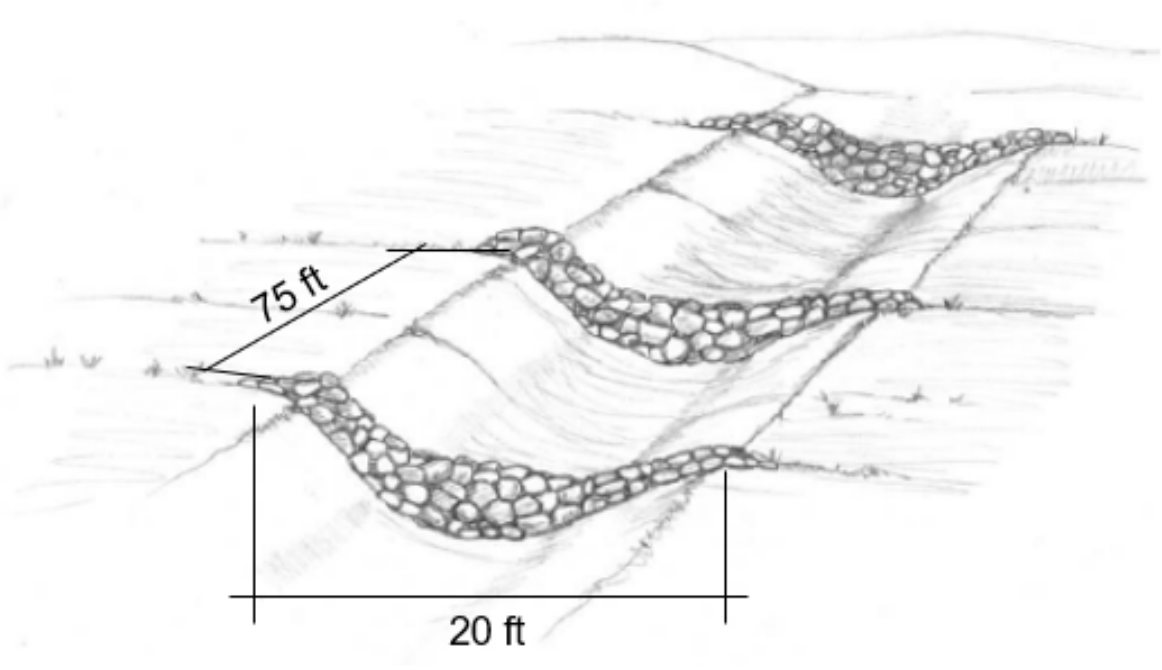
Watershed	Trap Efficiency (%)				
	Total	Clay	Silt	Sand	Gravel
Ka‘ōpala	-5	22	-22	--	--
Watershed	**Sediment Removed (metric tons)**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Ka‘ōpala	-3.21	2.23	-4.82	--	--

The existing Ka‘ōpala Basin is relatively effective at capturing sediment, essentially capturing all silt, sand, and gravel particles during the design flow event. However, it still releases about 8.5 tons of clay annually. The proposed modification increases the amount of clay that is captured by the management measure. However, the trap efficiency of silt is reduced as the principal spillway is activated earlier due to the higher pool elevation created from storing more water in the reservoir. Sand and gravel are still completely

captured by the basin under the modified conditions for the design flow (50% AEP) event. The ROM construction cost estimate is $144k. The annual O&M cost is moderate (between $5,000 and $25,000 per year).

7.1.5 Alternative E: Ka‘ōpala Rock Weirs

This alternative proposes the construction of four, short rock weirs in the channel to trap sediment. The location for siting this measure along Ka‘ōpala Stream, downstream of Ka‘ōpala Basin and Honoapi‘ilani Highway was requested by West Maui R2R to be evaluated for trap efficiency. The rock weirs are short (3-feet-high), as wide as the existing and natural channel (~20 feet) and spaced 75 feet apart from one another (Figure 7-3).



Original figure source: USACE, ERDC/CRREL TR-14-26, 2014

Figure 7-3: Ka‘ōpala Rock Weirs

The trap efficiency of the implemented measure and the resulting amount of sediment removed from the system by this alternative are presented in Table 7-5.

Table 7-5: Alternative E Performance Metrics, 50% AEP Event

Watershed	Trap Efficiency (%)				
	Total	Clay	Silt	Sand	Gravel
Ka'ōpala	0	0.01	0	0	0
Watershed	**Sediment Removed (metric tons)**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Ka'ōpala	0.01	0.01	--	--	--

This alternative was not effective at reducing sediment because the only type of residual sediment released by the upstream basin during the design flow (50% AEP) event was clay. The ROM construction cost estimate is $495,183. The annual O&M cost would be moderate ($5k - $25k / year).

7.1.6 Alternative F: Annual Excavation of Kahana Basin

This alternative recommends regular excavation of Kahana Basin to its design limits. This excavation should occur every 1-2 years to ensure maximum basin capacity available to maximize volume of sediment retained in the basin. This sediment management measure would maximize the design capacity of the basin to maximize sediment trapping efficiency while also increasing the volume of sediments removed from the system. The increased trap efficiency of the basin and the resulting amount of sediment removed from the system by this alternative are presented in Table 7-6. There is no construction cost for this alternative (as no new construction is proposed). However, the annual O&M cost is high, doubling the current COM annual budget of approximately $32,000 to a ROM annual cost estimate of $70,630.

Table 7-6: Alternative F Performance Metrics, 50% AEP Event

Watershed	Trap Efficiency (%)				
	Total	Clay	Silt	Sand	Gravel
Kahana	13	0.01	32	--	--
Watershed	**Sediment Removed (metric tons)**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Kahana	20.6	0.20	20.4	--	--

7.1.7 Alternative G: Honokōwai Loʻi

This alternative proposes the construction of ten new loʻi along Honokōwai Stream, covering a total area of approximately 2 acres. The trap efficiency of the implemented measure and the resulting amount of sediment removed from the system by this alternative are presented in Table 7-7. The ROM construction cost estimate is $3.4 million. The annual O&M cost is moderate (between $5,000 and $25,000 per year). Note, this alternative would only be viable if low-flow stream standards returned some baseline water flow to the stream.

Table 7-7: Alternative G Performance Metrics, 50% AEP Event

Watershed	Trap Efficiency (%)				
	Total	Clay	Silt	Sand	Gravel
Honokōwai	0.08	0.04	0.09	0.09	0.09
Watershed	**Sediment Removed (metric tons)**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
$Honokōwai	0.01	0.00	0.01	0.00	0.00

7.1.8 Alternative H: Honokōwai Basin Riser Structure Modification

This alternative recommends modifying the existing Honokōwai concrete riser to allow for controlled release of flow from the top-down via stoplog panels (Figure 7-4). 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.

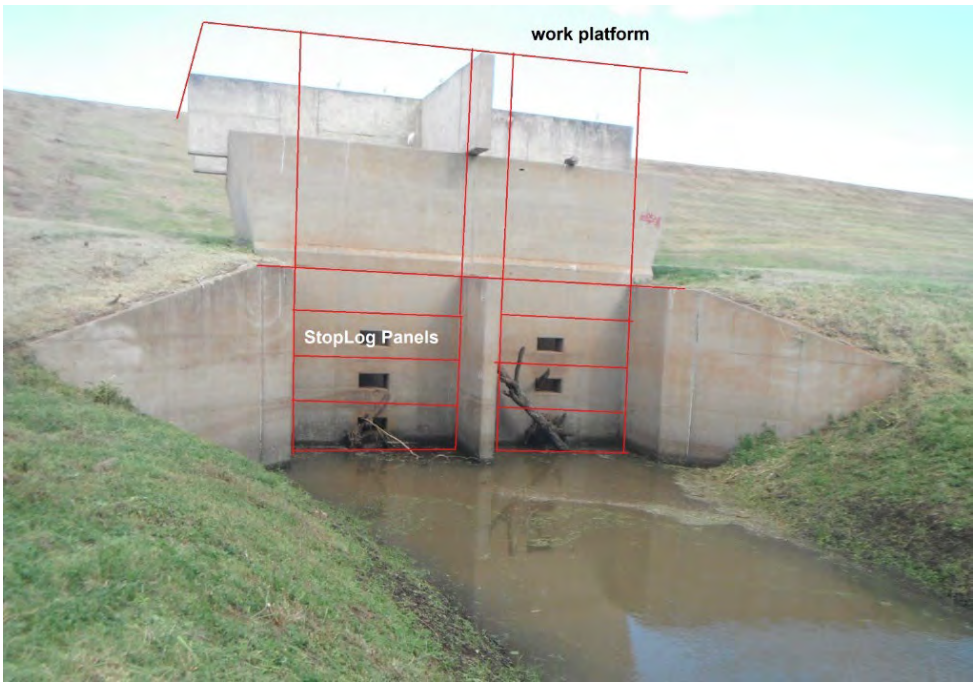


Figure 7-4: StopLog Panels and Work Platform at Honokōwai Riser

Construction of the stoplog panels would slightly increase the surface area of the reservoir, but most importantly reduce the rate of flow leaving the reservoir. Increased retention time allows for increased settlement and a greater trap efficiency. The increased trap efficiency of the basin and the resulting amount of sediment removed from the system by this alternative are presented in Table 7-8. The ROM construction cost estimate is $1.8 million. The annual O&M cost is low (less than $5,000 per year).

Table 7-8: Alternative H Performance Metrics, 50% AEP Event

Watershed	Trap Efficiency (%)				
	Total	Clay	Silt	Sand	Gravel
Honokōwai	3	1	8	--	--
Watershed	**Sediment Removed (metric tons)**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Honokōwai	0.51	0.12	0.39	--	--

7.1.9 Alternative I: Upper Wahikuli Micro Basin

This alternative proposes that moderate to low flows in Hāhākea Stream be diverted to an offset micro basin to facilitate settlement of fine particles before returning

flow to the main channel. By spreading the flow across a wide area, the water depth is reduced significantly, and sediments will only have to travel a short vertical distance before settling to the bottom. A site map is provided as Figure 7-5.

A short (4-foot-high), diversion weir embankment will be constructed across Hāhākea Stream about 80 ft downstream of the existing road crossing and at about a 45° angle. This purpose of this rock weir is to divert moderate to low flows into the adjacent micro basin. The proposed micro basin is located on the right bank of Hāhākea Stream. The footprint is approximately 20,000 ft^2. The recommended depth is 3 feet. Grassy vegetation in the basin will aid in slowing down flows, but woody vegetation would make it difficult to remove the captured sediment. A second rock weir embankment is proposed at the downstream end of the micro basin to restrict the rate of flow leaving to 75 ft^3/s. The height of the embankment is flush with the surrounding floodplain (about 3 ft). A 32-inch culvert should also be installed at the basin invert and sloped to return flows to the main channel (2% slope minimum, 45° angle).

The trap efficiency of the implemented measure and the resulting amount of sediment removed from the system by this alternative are presented in Table 7-9: Alternative I Performance Metrics, 50% AEP Event. The ROM construction cost estimate is $1.0 million. The annual O&M cost is high (greater than $25,000 per year).

Table 7-9: Alternative I Performance Metrics, 50% AEP Event

Watershed	**Trap Efficiency (%)**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Wahikuli	80	0.06	43	100	100
Watershed	**Sediment Removed (metric tons)**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Wahikuli	3.07	0	0.71	1.33	0.17

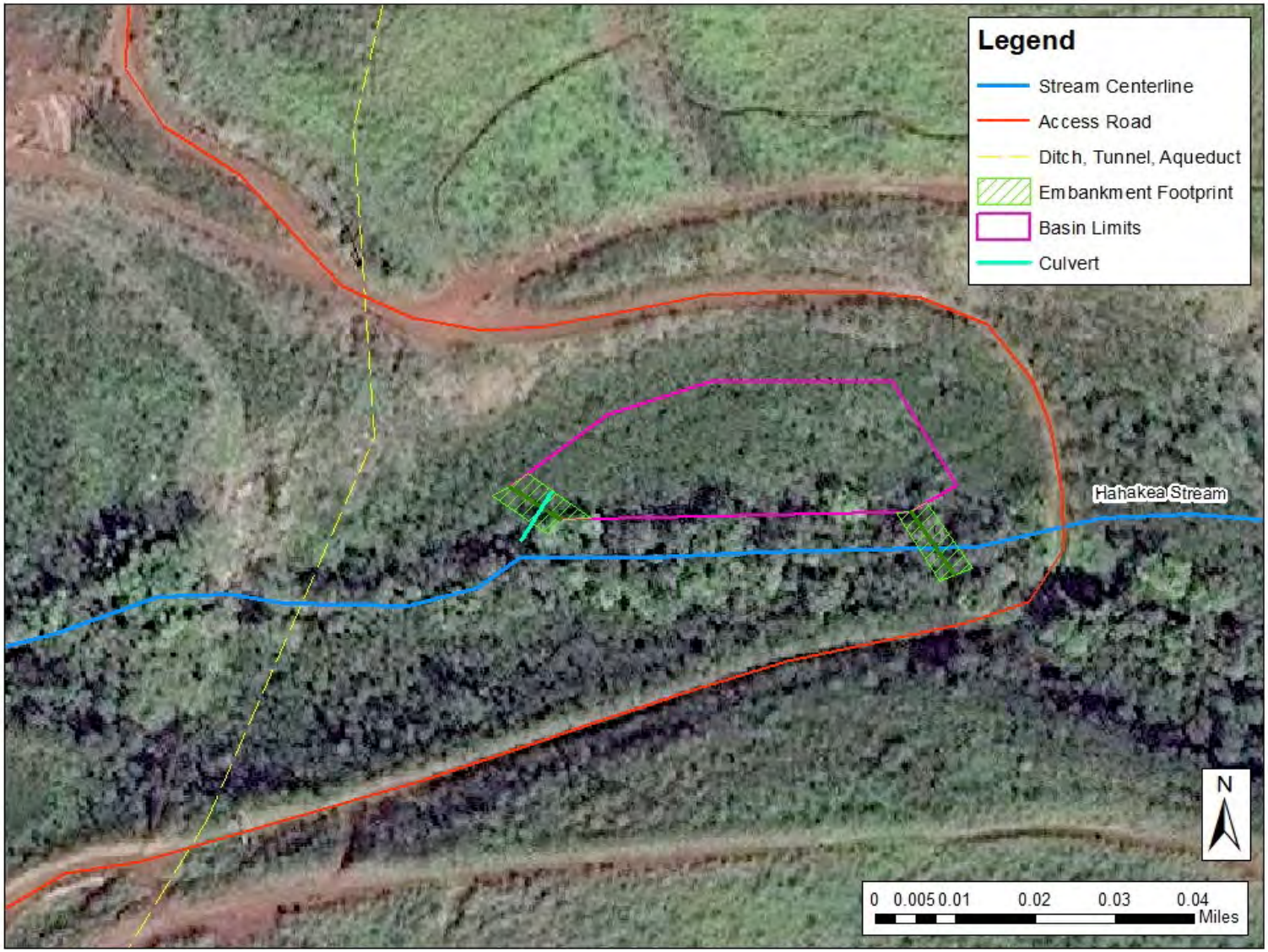


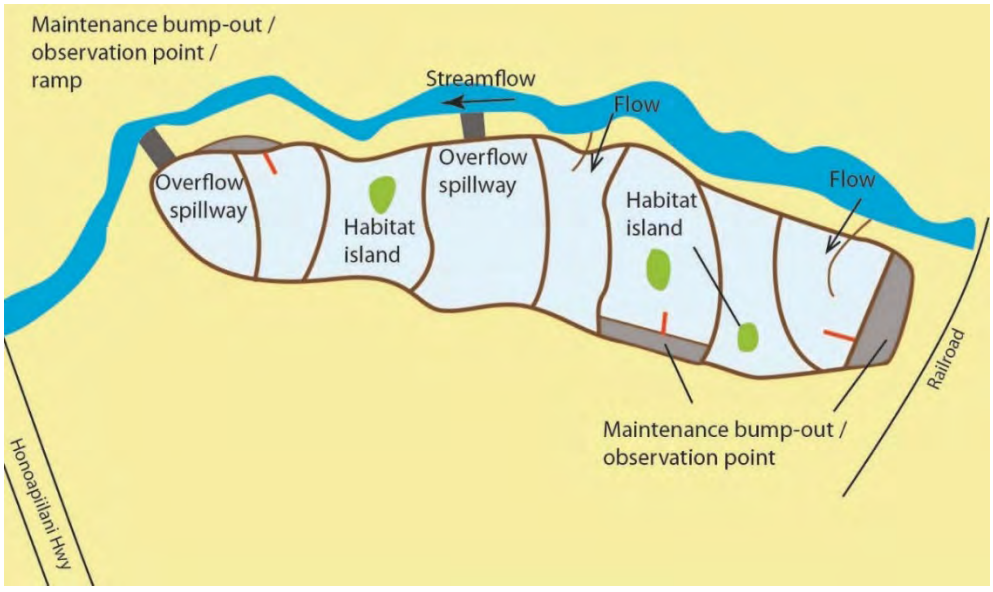
Figure 7-5: Site Map for Proposed Micro Basin at Upper Wahikuli

7.1.10 Alternative J: Middle Wahikuli Micro Basin

This alternative includes one in-stream micro basin (identical to Alternative K), sited in Wahikuli just upstream of Old Stuart Road. The flow, load, and trap efficiency would essentially be the same (14% trap efficiency for silt). If both sites implemented this measure (a 180-ft long, 160-ft wide area of micro basins), the trap efficiency would be doubled (28% trap efficiency for silt). The ROM construction cost estimate is $445,799 with annual O&M costs estimated at >$25k/year.

7.1.11 Alternative K: Lower Wahikuli Micro Basin

This alternative includes an offset micro basin in Lower Wahikuli, just upstream of Honoapi'ilani Highway. The proposed design is a series of small detention basins that cover an area approximately 820 feet long and 160 feet wide on the south overbank of Wahikuli Stream. This design is based on earlier proposals by the Coral Reef Alliance for offset micro basins that could also be used for groundwater recharge, habitat, and recreation. The concept sketch and rendering for this measure, originally included in the 2017 technical solutions report prepared by Christy Chung (Section 4.5), are included as Figure 7-6 and Figure 7-7.



Source: West Maui R2R, Coral Reef Alliance, and U.C. Berkeley (2017)

Figure 7-6: Concept Sketch for Lower Wahikuli Micro Basins



Source: West Maui R2R, Coral Reef Alliance, and U.C. Berkeley (2017)

Figure 7-7: Bird's Eye View Rendering of Lower Wahikuli Micro Basins

The trap efficiency of the implemented measure and the resulting amount of sediment removed from the system by this alternative are presented in Table 7-. The ROM construction cost estimate is $3.6 million. The annual O&M cost is high (greater than $25,000 per year).

Table 7-10: Alternative I Performance Metrics, 50% AEP Event

Watershed	**Trap Efficiency (%)**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Wahikuli	43	0.02	14	100	100
Watershed	**Sediment Removed (metric tons)**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Wahikuli	5.02	0	0.68	3.98	0.36

The following table summarizes the facts and figures of the sediment management initial array of alternatives (Table 7-11).

Table 7-11 Initial Array of Alternatives

Alternative	A: No Action	B: Honolua Lo‘i	C: Pāpua Gulch Instream Micro Basins (10)	D: Ka‘ōpala Basin Outlet Modification	E: Ka‘ōpala Rock Weirs	F: Annual Excavation of Kahana Basin	G: Honokōwai Lo‘i	H: Honokōwai Basin Riser Structure Modification	I: Upper Wahikuli Offset Micro Basin	J: Middle Wahikuli In-Stream Micro Basin	K: Lower Wahikuli Offset Micro Basin
Description	Status quo. No new construction. No basin modification.	Construct five (5) off-channel basins similar to a traditional lo‘i system; no retention of flows	Construct ten (10) off-channel micro basins in series, no retention of flows	Modify existing Ka‘ōpala Basin outlet with sluice gates, releases flow from the top-down	Construct four (4) rock weirs along Ka‘ōpala Stream, downstream of Ka‘ōpala Basin and Honoapi‘ilani Highway.	Modify maintenance frequency of Kahana Basin; regular excavation every 1-2 years	Construct ten (10) off-channel basins similar to a traditional lo‘i system	Modify existing Honokōwai Basin concrete riser via stoplog panels, releases flow from the top-down	Construct a single off-channel basin	Construct a series of offset micro basins	Construct a series of offset micro basins
Sediment Management Design	n/a	Divert high flows to lo‘i system to increase sediment settling capacity	Divert high flows to micro basins system to increase sediment settling capacity	Increases residence time in basin with siphoning of storm flows off top of basin, allowing for increased settling at bottom of basin	Create settling basins within the stream to allow sediments to settle	Increased frequency and volume of sediment removal to maximize efficiency of existing settling basin	Divert high flows to lo‘i system to increase sediment settling capacity	Increases residence time in basin with siphoning of storm flows off top of basin, allowing for increased settling at bottom of basin	Divert high flows to micro basin to increase sediment settling capacity	Divert high flows to micro basins to increase sediment settling capacity	Divert high flows to micro basins to increase sediment settling capacity
Location (Affected Waterway)	n/a	Honolua Stream, Honolua Watershed	Papua Stream, Honolua Watershed	Ka‘ōpala Stream, Kahana Watershed	Ka‘ōpala Stream, Kahana Watershed	Kahana Basin, Kahana Watershed	Honokōwai Stream, Honokōwai Watershed	Honokōwai Basin, Honokōwai Watershed	Hāhākea Stream, Wahikuli Watershed	Hāhākea Stream, Wahikuli Watershed	Hāhākea Stream, Wahikuli Watershed
Land Ownership	n/a	Private	Private	Public	Private	Public	Private	Public	Public	Private	Private
Structural Footprint	n/a	1-acre total area	Each basin is 70’Lx50’W or 3,500 sqft	n/a	Each rock weirs 3’ high and spans the 20’ channel width, spaced 75’ apart	n/a	2-acre total area, 1.25’depth	Eight (8) panels, 4’W x 3’H each	20,000 sqft area, 3’ depth	series of small detention basins with a total area of 820’Lx160’W	series of small detention basins with a total area of 820’Lx160’W
Construction Cost	n/a	$1.7M	$3M	$144K	$495k	$0	$3.4M	$1.8M	$1M	$446k	$3.6M

Table 7-12 (cont.) Initial Array of Alternatives

Alternative	A: No Action	B: Honolua Lo‘i	C: Pāpua Gulch Instream Micro Basins (10)	D: Ka‘ōpala Basin Outlet Modification	E: Ka‘ōpala Rock Weirs	F: Annual Excavation of Kahana Basin	G: Honokōwai Lo‘i	H: Honokōwai Basin Riser Structure Modification	I: Upper Wahikuli Offset Micro Basin	J: Middle Wahikuli In-Stream Micro Basin	K: Lower Wahikuli Offset Micro Basin
Annual O&M Cost	n/a	$150-170k	<$5k	$5-25k	$5-25k	$73K	$5-25k	<$5k	>$25K	>$25K	$5-25k
Fine Grain Trap Efficiency	n/a	0.12%	83%	-5%	0%	13%	0.08%	3%	80%	14%	14%
Reduction of Fine Grain Load	n/a	0.02 tons	24 tons	-2.6 tons	0.01 tons	20.6 tons	0.01 tons	0.51 tons	0.71 tons	0.68 tons	0.68 tons

8 Evaluating and Comparing Alternatives

USACE follows the *Principles, Requirements, and Guidelines for Water and Land Related Resources Implementation Studies* (PR&G) as a common framework for evaluating water resource investments. This includes assessing alternatives against four screening criteria: completeness, effectiveness, efficiency and acceptability.

8.1 Screening Criteria

These four screening criteria were subdivided into nine specific evaluation criteria that are reflective of the project's objectives or constraints. Each alternative was assigned a rating of how well it met the criteria using the appropriate metric (i.e., high, medium, low, yes, or no). These metrics were defined for each alternative based on best professional judgment of the project delivery team members and are presented in Table 8-1: Evaluation of Alternatives.

. Color coding of Table 8-1 provides visual aid in communicating evaluation of the alternatives analyzed by the PDT.

The standards established for each criterion are:

1. Technical Feasibility (Completeness): Technical feasibility evaluates whether the alternative can be adequately constructed and will perform as intended. To be complete, an alternative must not rely on other activities to function. Response is yes or no; preferred response is Yes.

2. Trap Efficiency of Fine Sediments (Effectiveness): This criterion reflects how efficient the proposed alternative is at trapping fine sediments (clay and silt). For this criterion, the alternative was rated "High" if trapping efficiency was greater than 70% and "Low" if trapping efficiency was less than 30%. Preferred response is High.

3. Reduction of Fine Sediment Load (Effectiveness): Reduction of Fine Sediment Load reflects the total mass of fine sediments (clay and silt) trapped by the measure, in metric tons. For this criterion, the alternative was rated "High" if it reduced the fine sediment load by more than 5 metric tons, and "Low" if it reduced the fine sediment load by less than 1 metric ton. Preferred response is High.

4. Potential for Reducing Terrestrial Sediment Impacts to Coral Reefs (Effectiveness): This criterion reflects the potential for impacting the nearshore marine

environment based on the watershed(s) within which the proposed alternative is sited. It does not reflect impacts based on trap efficiency or reduced sediment loads, which are represented by separate criteria. It takes into consideration how many reefs are likely affected by the proposed alternative, and the reef's baseline vulnerability to sedimentation and turbidity. Alternatives sited in Honolua and Kahana are rated "High," alternatives sited in Honokōwai and Wahikuli are rated "Medium," and alternatives sited in Ka'ōpala are rated "Low." Preferred response is High.

The data USACE used to develop this criterion is the result of a concurrent study and partnership with USGS simulating the marine transport dynamics of sediment outputs from the five watersheds into the nearshore environment and the eventual deposition on West Maui coral reefs. Additional information regarding this study is provided in Section 8.2.

5. Overall Effectiveness: Given the trap efficiency of each alternative within the geographic context in which alternative is sited, a qualitative overall effectiveness rating was assigned. This criterion reflects the overall effectiveness of each alternative relative to the study objective to reduce the source and conveyance of land-based sediments to improve West Maui coral reef health. Each alternative was rated "High", "Medium" or "Low". Preferred response was "high".

6. Construction Cost (Efficiency): Construction Cost reflects the cost of constructing the features associated with the proposed alternative. For this criterion, the alternative was rated "High" if its construction cost was estimated to be greater than $3 million, and "Low" if it was estimated to be less than $1 million. Preferred response is Low.

7. Annual O&M Cost (Efficiency): This criterion reflects the annual cost of operation and maintenance (O&M), based on professional judgment and consideration of other O&M costs in the area. For this criterion, the alternative was rated "High" if the annual O&M costs were estimated to be greater than $25,000 per year, and "Low" it was estimated to be less than $5,000 per year. Preferred response is Low.

8. Overall Efficiency: Given the estimated costs to construct and maintain each alternative, and the overall effectiveness, an overall efficiency rating was assigned. This criterion reflects the overall efficiency of each alternative relative to the study objective in

consideration of the cost to achieve varying rates of effectiveness across the array of alternatives. Each alternative was rated “High”, “Medium” or “Low”. Preferred response was “high”.

9. Stakeholder Engagement (Acceptability): Stakeholder Engagement reflects the likelihood that the stakeholder will support the proposed alternative, based on past engagement with the West Maui R2R Initiative. For this criterion, the alternative was rated “Yes” if they have previously expressed support for a measure being implemented, or “No” if they either have no past engagements with West Maui R2R or have previously expressed opposition towards implementing measures that they would be directly responsible for or impacted by. The preferred response is Yes.

10. Regulatory Compliance (Acceptability): This criterion reflects the relative complexity to achieve regulatory compliance to construct and operate each of these alternatives based on past USACE experience as a construction agency. Alternatives with considerable environmental impact and involving new construction or other significant hydrology/hydraulics manipulation were rated “High”, alternatives with varying environmental impact and not requiring new construction or modification to existing hydrology/hydraulics were rated “Medium” and alternatives that do not propose new construction or waterway manipulation and do not anticipate particularly complex regulatory compliance requirements were rated “Low”. Preferred response is “Low”.

Based on the qualitative evaluation of the alternatives by the USACE, FAST, and West Maui Watershed Coordinator, and an analysis of the overall criteria ratings, alternatives were screened for recommendation potential. Those alternatives that generally scored favorably across several criteria are recommended for implementation. A summary of the results of that evaluation is provided at Table 8-1.

Table 8-1: Evaluation of Alternatives

Description of Alternatives		Alternative A	Alternative B	Alternative C	Alternative D	Alternative E	Alternative F	Alternative G	Alternative H	Alternative I	Alternative J	Alternative K
Evaluation Criteria		No Action	Honolua Lo‘i	Pāpua Gulch Instream Micro Basins	Ka‘ōpala Basin Outlet Modification	Ka‘ōpala Rock Weirs	Annual Excavation of Kahana Basin	Honokōwai Lo‘i	Honokōwai Basin Riser Structure Modification	Upper Wahikuli Offset Micro Basin	Middle Wahikuli Offset Micro Basin	Lower Wahikuli Offset Micro Basin
Completeness	**Technical Feasibility** (Yes*/No)	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Effectiveness	**Trap Efficiency of Fine Sediments** (High*, Medium, Low)	Low	Low	High	Low	Low	Low	Low	Low	Medium	Low	Low
	Reduction of Fine Sediment Load (High*, Medium, Low)	Low	Low	Medium	Low	Low	High	Low	Medium	Medium	Low	Low
	Potential for Benefit to Coral Reefs (High*, Medium, Low)	Low	Low	Medium	Low	Low	High	Low	Medium	Medium	Medium	Medium
	Overall Effectiveness (High*, Medium, Low)	Low	Low	Medium-High	Low	Low	High	Low	Medium	Medium	Low	Low
Efficiency	**Construction Cost** (High, Medium, Low*)	Low	Medium	High	Low	Low	Low	High	Medium	Medium	Low	High
	Annual O&M Cost (High, Medium, Low*)	Low	High	Medium	Medium	Medium	High	Medium	Low	High	High	Medium
	Overall Efficiency (High*, Medium, Low)	Low	Low	Medium	Medium	Low	Medium	Low	Medium	Medium	Medium	Medium
Acceptability	**Stakeholder Engagement** (Yes*/No)	No	Yes (ML&P, Living Pono Project)	Yes (ML&P, Living Pono Project)	Yes (COM)	Yes (Pineapple Ridge, LLC)	Yes (COM)	Yes (Maui Cultural Land, KLMC)	Yes (COM)	Yes (State)	Yes (KLM)	Yes (KLM)
	Regulatory Compliance (High, Medium, Low)	Low	Medium	Medium	Low	Low	Low	Medium	Low	Medium	Medium	Medium
Recommended? (Yes/No)		**No**	**No**	**Yes**	**No**	**No**	**Yes**	**No**	**Yes**	**Yes**	**Yes**	**Yes**

Note: light gray shading indicates favorable condition for implementation, dark gray shading indicates less favorable condition for implementation.

8.2 USGS Marine Transport Dynamics Analysis

The USGS marine transport dynamics analysis combined observational data and model simulations to understand how ocean waves and currents influence the transport, dispersal, settling, and removal of sediment from West Maui coral reef areas. Of particular interest is the disposition of terrestrial sediments and residence times over nearshore coral reefs during a during a low frequency flood event (~50% AEP) (USGS, Storlazzi, 2023).

A qualitative summary on the impacts that each stream has on the nearshore reef areas is provided in the table below. The data and recommendation for watershed prioritization was subjectively determined by USACE based on the numerical modeling results by USGS. Based on the data presented in Table 8-2, Kahana Stream and Honolua Stream have the greatest negative impact to coral reefs and accordingly management measures proposed in these watersheds should be prioritized for implementation.

Table 8-2 Summary of Impacts to West Maui Coral Reefs by Stream

	Honolua Stream	**Ka‘ōpala Stream**	**Kahana Stream**	**Honokōwai Stream**	**Wahikuli Stream**
Number of Affected Reefs	1	3	3	2	1
Sedimentation	Large	Small	Large	Moderate	Large
Exposure (>10 mg/m^2)	Limited	Limited	Small	Limited	Limited
Suspended Sediment Concentration	Large	Limited	Small	Small	Small
Exposure (>10 mg/L/m^2)	Moderate	Limited	Moderate	Limited	Limited
Overall Potential for Impact:	**High**	**Low**	**High**	**Medium**	**Medium**

8.3 Final Array of Sediment Management Alternatives

The conceptual Alternatives C, F, H, I, J and K meet the study objectives, providing more benefit than harm, and are accordingly recommended for implementation by this study.

Alternative C ranked medium-high on overall effectiveness, showing particularly high trap efficiency of fine grain sediments, in particular. Overall efficiency and acceptability were also medium, lending to a positive recommendation for Alternative C.

Likewise, Alternative F , also technically feasible, was very effective at reducing sediment load and trapping fine sediments in particular, for no construction cost and an increase in maintenance costs. This alternative also ranked well for acceptability and ultimately is recommended by USACE as an effective, efficient, acceptable means to managing sediment in West Maui.

Alternative H was generally positively effective, efficient and acceptable, with no particular negative factor that would lend to justifying elimination. Accordingly, Alternative H is recommended by this study.

Alternatives I, J and K rank fairly in effectiveness individually, however in combination of two or three of these alternatives, the effectiveness increases linearly. Accordingly, these alternatives are recommended by this study.

Alternatives A, B, D, E and G are not recommended because they are not effective at meeting the study objectives.

The no action alternative, Alternative A, the No Action alternative, is not recommended because it is not effective at meeting the study objective of reducing the source and conveyance of land-based pollutants that degrade coral health to the marine environment.

Alternative D, Kaʻōpala Basin Outlet Modification, was proposed because of its demonstrated success at Nāpili 4-5 Basin. However, the same effectiveness did not materialize at Kaʻōpala Basin, rather increasing the fine sediment load downstream. While not successful at Kaʻōpala Basin, the outlet modifications could be successful at reducing fine sediment transport at another basin or with modification to the design.

Alternative E, Kaʻōpala Rock Weirs is also not effective at reducing fine sediment transport and is not efficient given the cost. Additionally, construction of the rock weirs requiring significant earth-moving work, could result in generation of more fine sediment.

Alternatives B and G propose traditional loʻi structures. Based on the sediment modelling results, loʻi are not effective at reducing sediment transport during the 50% AEP i.e. storm conditions; the volume of flow overburdens the loʻi system and renders them ineffective. Sediment and flow modelling results indicate loʻi are approximately 90% effective at reducing fine grain sediment transport, however, this is only under flow conditions of less than 1 cfs. Such flow conditions are not causing turbidity plumes in the

nearshore environment. Accordingly, these alternatives do not meet the study objectives. Alternatively, offset micro basins recommended for Wahikuli are, in essence, larger scale lo‘i and have demonstrated effective fine-grain sediment reduction and meet the study objectives.

The elimination of measures in Section 6 and alternatives in Section 8 is based on the criteria set forth by this study as a means of measuring technical feasibility, effectiveness, efficiency, and acceptability. Elimination by this study is not intended to be absolute. Rather, eliminated measures and alternatives may in fact be viable under other parameters, considerations and objectives that differ from this study.

9 Recommendations and Conclusions

9.1 Study Recommendations

The following comprehensive list of measures (from Table 6-2), including sediment management alternative measures furthered to conceptual design (Table 8-1), is recommended by the study to be implemented strategically across the West Maui watershed. Information provided in this study should be used by local planning and decisionmakers to inform future planning decisions.

- Engineering Analysis and Stabilization Designs at Wahikuli Gulch
- Burn Area Emergency Response Plan
- Urban Pollution Control: Bioretention Cell e.g. Rain Garden
- County Storm Water Management Plan
- Enforcement of Temporary Construction Storm water BMPs
- Post Construction Storm water Ordinance: Drainage Master Plan Requirement
- Requirement for BMP Management Plans and Reporting by Large Scale Nutrient and Pesticide Users
- Water Quality Monitoring Program
- Agricultural Conservation Plan Requirement for Ag Lands
- Establish Storm Water Fees
- Low Impact Development Requirement for development, redevelopment and improvement projects > 1 acre (State, County and private sector) to incorporate LID measures into design and construction
- Golf Courses and Landscaping BMP Management Plans
- Pool and Vehicle Wash Water Discharge Policy
- Storm Water Management Asset Mapping
- Regional Drainage Analysis
- Stop sediment from entering streams and gulches via gulch buffers
    - Push pile assessment and stabilization
    - Stream crossings stabilization
    - Access road improvements

- Stop existing in-stream sediment deposits from transporting sediments downstream to the ocean via
  - Identification of sediment terraces in streams and gulches
  - Researching, piloting and implementation of stream/gulch bank management measures
  - Restoration of traditional loʻi kalo
- Increase groundwater recharge and slow surface flows via
  - Conservation boundary fencing
  - Active ungulate & invasive weed management
  - Landscape restoration
- Monitor and assess roadside erosion at Honoapiʻilani Highway and Lower Road
- Urban Storm Water Management Retrofits
- Continue to fund existing outreach initiatives and outreach coordinators
- Community Water Quality Monitoring Program (Hui O Ka Wai Ola)
- Multiple Sediment Capture and Groundwater Recharge Basins at Wahikuli and Hāhākea Gulches (Coral Reef Alliance)*
- Sediment Capture and Groundwater Recharge Basins Complex Combined with Recreational Open Space at Wahikuli Gulch and Hāhākea Gulch (Coral Reef Alliance)
- Gulch buffers adjacent to Wahikuli Gulch and Hāhākea Gulch(Coral Reef Alliance)
- Gulch Buffer Stacked Practices via optimal combinations of the following:
  - Ripping, Terraforming, Micro-basins, Key lining/ripping on contour, Vetiver eyebrows in kickouts, Contour planting vetiver, Native plant establishment, Hydro-mulching and Check dams (West Maui R2R)
- Ocean-Friendly Landscaper Outreach Program (West Maui R2R)
- Wildland Fire Management Measures e.g. Fire breaks (West Maui R2R)
- Improve existing sedimentation measures*
  - Alternative F and H
- Micro Basins*
  - Alternatives C, I, J and K

9.2 Implementation Strategy

9.2.1 Sequencing

In terms of implementation sequence, in the near term (0-5 years), any opportunity to gather data and initiate monitoring programs necessary to inform planning decisions should be prioritized. Data gathering is relatively low cost and typically does not require permits and permissions necessary for construction and can be funded through grants or other federal technical assistance opportunities such as through the USACE Planning Assistance to States program or the USEPA Water Quality Management Grans Program. Likewise, development of any community plans such as for wastewater, low-impact development and hazard mitigation to inform planning and development decisions should also be pursued in the near term, as costs are relatively low and can be developed in partnership with local and federal government entities and local organizations. Lastly, any education or outreach programs could begin immediately upon funding. Funding sources through USACE include the Silver Jackets program that could support outreach initiatives.

Should the County of Maui or State of Hawai‘i determine desire to pursue any of the drainage improvements to existing structures recommended, obtaining necessary permits and approvals and completing environmental compliance documentation, coordination and consultation should be pursued immediately. From planning to design and construction, anticipate no less than three years from inception to begin construction, and a year or two of construction thereafter. Planning for any measures that requires new construction, especially with impacts to waters of the U.S. e.g. in-stream microbasins and lo‘i terracing should begin in the near term, anticipating permits, approvals, planning and environmental documents, design and contracting would not be complete until after five years, conservatively. Construction could begin thereafter and take two to three years, or more, for completion. Smaller scale construction not involving impacts to waters of the U.S., e.g. gulch buffers in agricultural fields, could be completed in a relatively shorter timeframe of less than five years from inception to completion.

Further information regarding federal funding opportunities is at Section 9.4.

9.2.2 Prioritization

The sediment management measures furthered to conceptual design and sited in West Maui watersheds by USACE have demonstrated watershed scale applicability to addressing the benchmark low frequency flood event (50% AEP). These measures were formulated specifically to address the legacy agricultural sediments demonstrated by USGS to contribute the greatest volumes of terrestrial sediments that have the greatest potential for causing the greatest adverse impacts to nearshore coral reef ecosystems. Accordingly, implementation of the recommended sediment management measures, Alternatives C, F, H, I, J and K, should be prioritized for implementation.

Utilizing the results of the USGS marine hydrodynamics analysis, recommended sediment management measures sited in Honolua or Kahana watersheds i.e. Alternatives C and F, Pāpua Gulch Instream Micro Basins and Increased Annual Excavation at Kahana Basin, respectively, should be prioritized for implementation.

Success of any one of these measures is dependent upon interrelated and associated measures within and adjacent to the sited location that synergistically work to address pollution of the West Maui watershed from mauka to makai. Per the West Maui R2R, emphasis should be on the ongoing practices that require constant investment and active management, including ungulate control, stabilizing open areas with native seed hydro-mulch, stream bank stabilization with native plantings, push pile stabilization along with the other ongoing programs in the conservation areas. Real success in managing erosion/sediment export across the landscape comes from sustained maintenance by an established management entity. In the case of Honolua, sustaining the ongoing efforts of the Living Pono Project team who are managing the area, now completely in conservation from mauka to makai, is anticipated by the West Maui R2R to yield more long-term success than any one discrete project.

9.2.3 Real Estate

The implementation of any of the recommended structural alternatives would likely require real estate acquisition by the implementing party, either in title or other formal agreement with the landowner, in perpetuity, to support construction and operation of the sediment management measure. Due to limited availability of land on an island that is further restricted as over half of the land is held in conservation designations, the cost of

available land for purchase and development in Hawai'i is exorbitant, relative to the rest of the U.S. The average price of farms, ranches and other land for sale in Maui County is $3 million per sale (LandWatch, 2022). Due to high cost of real estate, land use will likely be highly scrutinized by the landowner. The decision to use private or public land for the purpose of common sediment management will be taken into consideration by the landowner and therefore the implementation and success of the recommended measures is highly dependent upon support by the landowner or willingness and funding available to acquire necessary real estate, at a relatively high cost.

9.2.4 Risk and Uncertainty

The purpose of a USACE watershed study is to collaborate with stakeholders, the community and other local, state and federal agencies and partners to identify strategies for solving the identified problems in a given watershed. Recommended strategies are broad, conceptual at best, and not intended for immediate implementation. Measures are not intended to be implemented individually and anticipated that strategic implementation of multiple measures across the West Maui watershed would provide greater synergy in effectively addressing transport of terrestrial sediments to West Maui coral reefs. Parametric, rough order of magnitude cost estimates are based on broad assumptions to guide prioritization and planning and lack the specific detail necessary to inform budget decisions, especially for implementation purposes.

From the onset of the study, it became readily apparent that baseline hydrology, hydraulics and sediment data was lacking, incomplete or nonexistent. USACE partnered with CWRM and USGS to install certain meters and sensors to help expand the knowledge base, however much of the model inputs and calibration for both USACE and USGS was based on several assumptions to help overcome the lack of site-specific data. A description of risk and uncertainty associated with the USACE engineering analysis, including recommendations to mitigate risk and reduce such uncertainty, is provided at Table 9-1. Spin-off studies that would provide additional validation or further expand the knowledge base to better inform planning decisions is provided in Section 9.3.

Recommended strategies were formulated based on available information and expert judgement, however the overall risk of such uncertainty to the West Maui

community is low given the purpose of a USACE watershed study to inform planning decisions, and not for immediate construction.

Table 9-1 Risk and Uncertainty in the Engineering Analysis

Product	Data Input	Source	Risk / Uncertainty	Recommendation to Reduce Uncertainty
Peak Flow Estimates (Hydrology)	Rainfall Data	West Maui R2R Climate Stations	Medium / High – some difficult in calibrating the rainfall-runoff model due to having a limited record and having different climates across the study area. Peak flow estimates are a best guess for the data available, but still has some uncertainty (may be over- or under-estimated).	Continue monitoring precipitation. Add a climate station in the middle or upper watershed of Honolua.
	Stream Data	USGS, CWRM Stream Gages	Medium – USGS stream gages were most helpful (long record, reliable). CWRM gages somewhat helpful, but great uncertainty in the stage-discharge relationship (converting water surface elevation data to flow).	Improve confidence in the stage-discharge rating curve by taking additional flow measurements during higher stage events.
	Land Cover	PAC-RISA	Low – Existing conditions representative of 2017. Additional urban development in the future likely, but not likely to affect final recommendations or reduce their benefits. Used to estimate transform parameters (lag time) in the rainfall-runoff model.	Although a hypothetical future development scenario predicted by PAC-RISA was evaluated under this study comprehensively, a site-specific analysis of an area that is being developed could be done to understand its specific impact. However, it is not likely to significantly affect the final recommendations which address in-stream bank erosion.
	Geology and Soil	Hawai'i Soil Data Atlas	Low – Soil permeability rate in rainfall-runoff model corresponds with field measurements	Additional field tests to determine soil infiltration rates could be done but are probably not necessary (not likely to change results).
Floodplain Modeling (Hydraulics)	Elevation Data	NOAA, USGS	High – only coastal LiDAR data was available for this study, which was very limiting. There is still some uncertainty regarding whether the agricultural fields are hydrologically connected to the streams during smaller flow events. They are assumed not to be connected, as suggested by USGS, for events smaller than the 10% AEP event. If they are connected, there could be a much greater amount of sediment entering the streams, and the recommended measures would be undersized / incomplete.	Comprehensive LiDAR has already been collected across the study area. When it becomes available, create a 2D hydraulic River Analysis System(RAS) model with precipitation on grid as another method of analysis for better understanding the extent of hydrologic connectivity in each watershed for different events.
	As-Built Drawings, Design Documents	County of Maui, DLNR	Low – most drawings and design documents were available as a reference for this study, and then verified in the field and with stakeholders. It is still possible that the model does not actually reflect existing conditions if the design documents are not the latest representation of the site / feature.	Surveys, field measurements, photographs, as needed. However, there are currently no suspected misrepresentations of the physical site to investigate.
	Land Cover	PAC-RISA	Low – Existing conditions representative of 2017. Additional urban development in the future likely, but not likely to affect final recommendations or reduce their benefits. Used to represent roughness (Manning's n) in the hydraulic model.	Although a hypothetical future development scenario predicted by PAC-RISA was evaluated under this study comprehensively, a site-specific analysis of an area that is being developed could be done to understand its specific impact. However, it is not likely to significantly affect the final recommendations which address in-stream bank erosion.
Sediment Transport Analysis	Total Load Estimate	USGS SIR 2020-5133	Medium – Sediment baseline conditions are based off the total annual sediment load estimated by USGS for each watershed. While this estimate was determined by reasonable science, there is a lot of weight being put on this estimate.	Collect additional data to support the total annual sediment load and event-based sediment load. This includes suspended sediment concentration (SSC) time series data, or field measurements that might pair turbidity and SSC data.
	Event-Based Load Estimate	USACE	High – A continuous flow simulation was used to approximate the total load for various frequency events. This is a very simple approach that gives a rough estimate. There is still reasonable uncertainty regarding the total load that is created / transported for various frequency events.	See above.
	Sediment Samples	UH, USGS	Medium – Three samples were collected by UH, two of which were in a detention basin, but it is unknown if the basin was recently cleared, a storm had just occurred, or it was a random collection. These samples were not used directly in this study. Cohesive strength meter (jet) testing was performed by USGS on historic fill terraces that provides reasonable particle size distribution.	Collect additional samples and approximate volume of sediment collected in the detention basin immediately after a large event. Continue to maintain record of sediment removal from the basins.
	Frequency of Plume Events	USGS Coastal Cameras	Low – Coastal cameras show when plumes are occurring, but there are gaps in the record that leaves some uncertainty in the frequency. These images suggested an appropriate frequency of plumes that occur each month, which can be calibrated to in the rainfall-runoff model.	Continue to maintain the record.
	Turbidity	Hui o Ka Wai Ola	Medium – The turbidity samples collected in the nearshore environment seem to imply that certain reefs are more susceptible to resuspension.	Take turbidity – SSC measurements to distinguish between general turbidity and sediment.

9.3 Spin-off studies and future work

This study, proposed measures and recommended strategies that are based on data available at the time of this study. Limited data sets resulted in drawing conclusions based upon assumptions to develop model inputs and objectively evaluate measures and alternatives. Efforts to increase the knowledge base, update and expound upon data sets to increase the confidence rating and reduce uncertainty of the model results, as well as ground truth and validate model results would increase the overall value of the study. Example studies are as follows:

1. Suspended Sediment Concentration Time Series Data.

Additional information is needed on the suspended-sediment particle-size distribution and concentration data from one or multiple reaches in the study area. Currently, the rainfall-runoff model is automatically distributing the total annual sediment load previously estimated by USGS over a one-year period in a continuous flow simulation. Calibrating the model to an observed record of suspended sediment concentration over time would better define the flow-sediment relationship and improve confidence in related estimates (total sediment load and suspended sediment concentration).

2. Rating Curve

The stream gages installed at Honokōwai (CWRM 6-124) and Honolua (CWRM 6-158) measure stage (the height of the water surface above the gage datum). To convert stage to flow (discharge), a stage-discharge rating curve must be defined by measuring discharge at a wide range of river stages at each gage site. CWRM has already begun this process by measuring the corresponding flow for several smaller stages (baseflow or low flow events). However, the resulting rating curve does not provide reasonable estimates for larger flood events (where stage and flow are much higher). To improve the rating curve, additional flow measurements must be taken when the stage is higher. This data could then be used to improve the calibration of the rainfall-runoff model.

3. A continuous stream flow gage sited just upstream of Honokōwai Basin.

Stream gages were installed in upper Honokōwai (CWRM 6-124) and below the dam (CWMR 6-156). These gages were strategically placed to analyze and monitor

typical low flow conditions throughout the entire reach. For analyzing flow frequency, however, it would have been better sited at the former USGS gage site (USGS 16630200), located just upstream of Honokōwai Basin. Data from a stream gage at this site would have moderately improved calibration of the rainfall-runoff model, depending on the range of events recorded.

4. A climate station within or near the Honolua watershed.

The rainfall data provided by the various climate stations in the Honokōwai watershed (operated by West Maui R2R) proved to be incredibly valuable to this study. It was used for the continuous flow simulation and can also be used in improving the calibration of the rainfall-runoff model in the future once the stage-discharge relationship at Honokōwai (CWRM 6-124) is better defined. However, these climate stations are a reasonable distance away from the northernmost watershed in the study area, Honolua. An additional climate station in the middle of the Honolua watershed would provide valuable data on the different hydrology the northern watersheds in the study area may be experiencing.

9.4 Programs, grants and other opportunities available to the West Maui Planning Community

Table 9-2 below features a non-exhaustive list of federal agencies' grants, programs and funding opportunities, some cost-shared, that can assist the West Maui Community in a range of watershed planning initiatives including further technical assistance and implementation of watershed management projects and goals.

Table 9-2 Federal Watershed Funding Opportunities

Agency	Name	Description	Link	Cost Share
Federal Emergency Management Agency (FEMA)	Hazard Mitigation Assistance Grants	FEMA's hazard mitigation assistance provides funding for eligible mitigation measures that reduce disaster losses. Hazard mitigation is any sustainable action that reduces or eliminates long-term risk to people and property from future disasters. Mitigation planning breaks the cycle of disaster damage, reconstruction and repeated damage. Hazard mitigation includes long-term solutions that reduce the impact of disasters in the future.	https://fema.gov/grants/mitigation	No
FEMA	Building Resilient Infrastructure and Communities &Capability- and Capacity-Building Activities	The Building Resilient Infrastructure and Communities program aims to categorically shift the federal focus away from reactive disaster spending and toward research-supported, proactive investment in community resilience against —natural hazards, such as sea level rise, droughts, tornadoes, hurricanes, floods, wildfires, and earthquake. Through BRIC, FEMA continues to invest in a variety of mitigation activities with an added focus on infrastructure projects and Community Lifelines.	https://fema.gov/grants/mitigation/building-resilient-infrastructure-communities	No
FEMA	National Dam Safety Program (NDSP) See also: Rehabilitation Of High Hazard Potential Dam (HHPD) Grant Program	This program provides financial assistance to the States for strengthening their dam safety programs The HHPD Grant awards provide technical, planning, design and construction assistance in the form of grants for rehabilitation of eligible high hazard potential dams. A state or territory with an enacted dam safety program, the State Administrative Agency, or an equivalent state agency, is eligible for the grant.	https://www.fema.gov/national-dam-safety-program See also: https://.fema.gov/emergency-managers/risk-management/dam-safety/rehabilitation-high-hazard-potential-dams	
U.S. Army Corps of Engineers (USACE)	USACE Environmental Laboratory	This program provides guidance for implementing environmental programs as ecosystem restoration and reuse of dredged materials.	http://erdc.usace.army.mil/Locations/EL.aspx	
USACE	Flood Plain Management Services	This program provides technical support for effective flood plain management.	http://nae.usace.army.mil/Missions/Public-Services/Flood-Plain-Management-Services/	No; 100% federal funds
USACE	Continuing Authorities Program	The Continuing Authorities Program (CAP) is a collection of water resource authorities issued under several different laws. Congress delegated its authority to approve certain projects, up to specified dollar amounts (subject to availability of funds) to the Chief of Engineers.	http://nae.usace.army.mil/Missions/Public-Services/Continuing-Authorities-Program/	Yes
USACE	International and Interagency Support	Interagency and International Services (IIS) is the USACE program providing technical assistance to non-Department of Defense (DoD) Federal agencies, State and local governments, Tribal nations, private U.S. firms, international organizations, and foreign governments. Most IIS work is funded on a reimbursable basis. The Corps provides engineering and construction services, environmental restoration and management services, research and development assistance, management of water and land related natural resources, relief and recovery work and other management and technical services.	http://usace.army.mil/Missions/Military-Missions/Interagency-International-Support/	No
USACE	Emergency Operations	Under the Flood Control and Coastal Emergency Act, the USACE provides disaster preparedness and response services and advanced planning measures designed to reduce the amount of damage caused by an impending disaster. The USACE is prepared and ready to respond to natural and man-made disasters.	http://usace.army.mil/Missions/Emergency-Operations/	
USACE	Planning Assistance to States	States, local governments and Native American Tribes often have needs in planning for water and related resources of a drainage basin or larger region of a State, for which the Corps of Engineers has expertise. The needed planning assistance is determined by the individual States and Tribes. Typical studies are only undertaken at the planning level of detail; they do not include detailed design for project construction. The studies generally involve the analysis of existing data for planning purposes using standard engineering techniques although some data collection is often necessary. Most studies become the basis for State or Tribal and local planning decisions.	https://iwr.usace.army.mil/Portals/70/docs/frmp/PAS	Yes

Table 9-3 (cont.) Federal Watershed Funding Opportunities

Agency	Name	Description	Link	Cost Share
Natural Resources Conservation Service (NRCS)	Landscape Planning - Watershed and Flood Prevention Operations (WFPO) Program	The WFPO Program helps units of federal, state, local and tribal of government (project sponsors) protect and restore watersheds up to 250,000 acres. NRCS offers financial and technical assistance through this program for the following purposes: - Erosion and sediment control - Watershed protection - Flood prevention - Water quality Improvements - Rural, municipal and industrial water supply - Water management - Fish and wildlife habitat enhancement - Hydropower sources	https://nrcs.usda.gov/wps/portal/nrcs/detail/national/programs/landscape/wfpo/?cid=nrcs143_008271	No
NRCS	Landscape Planning - Emergency Watershed Protection (EWP) Program	The EWP Program is a federal emergency recovery program that helps local communities recover after a natural disaster strikes. The program offers technical and financial assistance to help local communities relieve imminent threats to life and property caused by floods, fires, windstorms and other natural disasters that impair a watershed. The EWP Program allows communities to quickly protect infrastructure and land from additional flooding and soil erosion. EWP does not require a disaster declaration by federal or state government officials for program assistance to begin. The NRCS State Conservationist can declare a local watershed emergency and initiate EWP program assistance.	https://nrcs.usda.gov/wps/portal/nrcs/main/national/programs/landscape/ewpp/	No
NRCS	Landscape Planning – Watershed Surveys and Planning	The purpose of the program is to assist Federal, State, and local agencies and tribal governments to protect watersheds from damage caused by erosion, floodwater, and sediment and to conserve and develop water and land resources. Resource concerns addressed by the program include water quality, opportunities for water conservation, wetland and water storage capacity, agricultural drought problems, rural development, municipal and industrial water needs, upstream flood damages, and water needs for fish, wildlife, and forest-based industries. Types of surveys and plans include watershed plans, river basin surveys and studies, flood hazard analyses, and flood plain management assistance. The focus of these plans is to identify solutions that use land treatment and nonstructural measures to solve resource problems.	https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/landscape/wsp/	
U.S. Environmental Protection Agency (USEPA)	Targeted Watersheds Grants (TWG)	EPA's TWG program is a competitive grant program that provides funding to community-driven watershed projects. The TWG program provides watershed organizations and practitioners with resources to examine water-related problems in the context of the watershed in which they exist; to develop creative solutions to those problems; and to restore and preserve water resources through strategic planning and coordinated project management that include public and private sector partners.	https://www.epa.gov/nps/nonpoint-source-tribal-current-grant-information	Yes
USEPA	Environmental Justice Small Grants Program	The Environmental Justice Small Grants (EJSG) Program provides funding directly to community-based organizations for projects that help residents of underserved communities understand and address local environmental and public health issues. For purposes of this announcement, the term "underserved community" refers to a community with environmental justice concerns and/or vulnerable populations, including minority, low income, rural, tribal, indigenous, and homeless populations that may be disproportionately impacted by environmental harms and risks.	https://www.grants.gov/web/grants/view-opportunity.html?oppId=310477	No
U.S. Fish and Wildlife Service	Coastal Program	The USFWS Coastal Program delivers habitat conservation in coastal watersheds (i.e., headwaters to nearshore) on both public and private lands. USFWS works on public and private lands and with a diversity of partners which is necessary for implementing a coastal habitat conservation strategy, especially in coastal watersheds where land ownership is often a mosaic of private and public entities. This ability also creates a unique opportunity for the Service to deliver landscape conservation, maintain habitat connectivity and continuity, and to connect and engage partners with the Service's conservation priorities and objectives. Habitat protection is an important component of the Service's landscape-scale conservation strategy. Coastal Program fulfills a unique role by providing both technical and financial assistance for third-party land acquisitions to protect habitats. This practice allows the Service to complement its land holdings and expand its conservation efforts beyond the boundaries of the National Wildlife Refuges System. For habitat improvement projects, our average financial leveraging ratio is $8 partner to $1 Coastal Program.	https://fws.gov/program/coastal	Yes
U.S. Bureau of Reclamation (USBR)	WaterSMART Drought Response Program: Drought Resiliency Projects	Reclamation will provide funding for projects that will help communities prepare for and respond to drought. Typically, these types of projects are referred to as "mitigation actions" in a drought contingency plan. Reclamation will fund projects that will build resiliency to drought by -Increasing the reliability of water supplies -Improving water management -Providing benefits for fish and wildlife and the environment	https://www.usbr.gov/drought/projects.html	Yes

Table 9-4 (cont.) Federal Watershed Funding Opportunities

Agency	Name	Description	Link	Cost Share
USBR	WaterSMART Cooperative Watershed Management Program and Environmental Water Resources Projects Funding Opportunity	The Cooperative Watershed Management Program (CWMP) contributes to the WaterSMART strategy by providing funding to watershed groups to encourage diverse stakeholders to form local solutions to address their water management needs. Funding is provided on a competitive basis for Watershed Group Development and Watershed Restoration Planning and Implementation of Watershed Management Projects through the Environmental Water Resources Projects funding opportunity.	https://usbr.gov/watersmart/cwmp/index.html See also: https://usbr.gov/watersmart/ewrp/index.html	Yes

9.5 Conclusion

This comprehensive five-watershed management plan builds upon the 2012 and 2016 watershed plans prepared for West Maui. It incorporates the best available scientific information and reflects extensive collaboration with federal, state and local partners and community organizations. The study recommendations ensure the problems are addressed, opportunities for secondary benefits are explored, study objectives are met and within the context and constraint of the study area. Targeting land-based pollution will increase the resistance and resiliency of West Maui coral reef health thereby improving the local West Maui economy.

The purpose of the watershed management plan and its prioritized list of conceptual recommendations is to assist the West Maui community and its leaders in strategic planning and future decision-making. The prioritized list of conceptual recommendations can be incorporated into an implementation strategy, to offer the West Maui community a roadmap to take each recommendation to implementation. This watershed management plan can be used to execute follow-on studies or projects in the areas that meet the community of West Maui's greatest needs and can be leveraged to secure funding sources and project opportunities to implement the recommendations.

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LIST OF ACRONYMS & ABBREVIATIONS

BMP	best management practice
COM	County of Maui
CORAL	Coral Reef Alliance
CPA	Conservation Planning Assistance
CRE	Committee on River Engineering
CTAHR	College of Tropical Agriculture and Human Resources
CWB	Clean Water Branch
CWRM	Commission on Water Resource Management (CWRM)
DAR	Division of Aquatic Resources
DLNR	Department of Land and Natural Resources
DOFAW	Division of Forestry and Wildlife
DOH	Department of Health
DPW	Department of Public Works
DWS	Department of Water Supply
EPA	Environmental Protection Agency
FAST	Funding and Agency Support Team
KHFMA	Kahekili Herbivore Fisheries Management Agency
KUA	Kua‘āina Ulu ‘Auamo
LID	low impact development
MCL	Maui Cultural Lands
MKWP	Mauna Kahālāwai Watershed Partnership
ML&P	Maui Land & Pineapple Company
MLCD	Marine Life Conservation District
MNMRC	Mau Nui Marine Resource Council
NBBF	Nāpili Bay and Beach Foundation
NFWF	National Fish and Wildlife Foundation
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NREM	Natural Resources and Environmental Management
OCM	Office for Coastal Management
OFR	Open-File report

PacIOOS	Pacific Islands Ocean Observing System
R2R	West Maui Ridge to Reef Initiative
State	State of Hawaii
TNC	The Nature Conservancy
TNCH	The Nature Conservancy of Hawaii
UH	University of Hawai'i
USACE	U.S. Army Corps of Engineers
USCRTF	U.S. Coral Reef Task Force
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Survey
USGS	U.S. Geological Survey
WMSWCD	West Maui Soil & Water Conservation District
WRRC	Water Resources Research Center

1 Collaborative Partnerships

1.1 West Maui Ridge to Reef Initiative

In 2012, initiated by local agency and community partners, the West Maui Ridge to Reef (R2R) Initiative was formalized. The primary objective of the West Maui R2R Initiative is to restore and enhance the health and resiliency of West Maui coral reefs and nearshore waters through the reduction of land-based pollution threats from the summit of Puʻu Kukui to the outer reef, the efforts of which, will be guided by the values and traditions of the West Maui community. The goals of the West Maui R2R Initiative align with the goals of this U.S. Army Corps of Engineers (USACE) West Maui watershed study.

Website: https://www.westmauir2r.com/

1.1.1 Watershed and Coastal Management Coordinator

The West Maui R2R Initiative is supported by a grant funded Watershed and Coastal Management Coordinator (herein referred to as the "R2R Coordinator"), who has been funded by various entities, including DLNR-DAR with funds from the National Oceanic and Atmospheric Administration (NOAA) and the State of Hawaiʻi Department of Health (DOH) with funds from the U.S. Environmental Protection Agency (EPA), National Fish and Wildlife Foundation (NFWF), and Castle Foundation. This individual oversees all the R2R initiatives and remains in close contact with each of the R2R partners' independent initiatives, as they relate to the health and welfare of the West Maui watershed. The R2R Coordinator illuminates overlap between initiatives to identify strategic opportunities for collaboration and furtherance of R2R objectives towards the bigger pollution reduction and reef enhancement and restoration picture.

Throughout this study, the R2R Coordinator often acted as a liaison between USACE, other R2R members, and the West Maui community. The R2R Coordinator has guided this study towards success by 1) ensuring incorporation of independent and interrelated initiatives occurring beyond the purview of USACE and DLNR-DAR and 2) providing insight into the community and its goals.

1.1.2 Funding and Agency Support Team (FAST)

The leadership body for the West Maui R2R Initiative is the Funding and Agency Support Team (FAST). This group is formed by several partner agencies and organizations, including:

- NFWF
- State of Hawai'i, DOH, Clean Water Branch
- State of Hawai'i, Department of Land and Natural Resources (DLNR), Commission on Water Resource Management (CWRM)
- State of Hawai'i, DLNR, Division of Aquatic Resources (DAR)
- State of Hawai'i, DLNR, Division of Forestry and Wildlife (DOFAW)
- U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS)
- U.S. Department of Commerce, NOAA, National Marine Fisheries Service (NMFS)
- U.S. Department of Defense, U.S. Army Corps of Engineers (USACE)
- U.S. Department of the Interior, U.S. Fish and Wildlife Service (USFWS)
- U.S. Department of the Interior, U.S. Geological Survey (USGS)
- EPA

FAST meets at regular intervals to provide oversight in managing funds and prioritization of activities and developing strategies to achieve the R2R goals. USACE participated in the quarterly FAST meetings to provide an update on the West Maui Watershed Study, as needed, and to obtain feedback from agency partners.

1.1.3 R2R Working Group

Led by a representative from DAR, the Working Group is comprised of members representing local interests in agriculture, land development, resort operation, soil conservation, traditional Native Hawaiian knowledge, non-profit marine conservation, recreational ocean users, and fishing. The Working Group supports the R2R Initiative by serving as a local body liaison between the community and FAST partners.

1.1.4 R2R Hui

The R2R Hui includes all additional agencies, non-profits, community groups, individuals, businesses, and landowners who support the goals of the West Maui R2R Initiative.



Figure 1-1: West Maui Ridge to Reef Teams and Functions

2 Partner Agencies and Organizations

2.1 Coral Reef Alliance (CORAL)

The Coral Reef Alliance (CORAL) is an international organization who works with local communities to protect their coral reefs. In West Maui, CORAL works with the community to prevent land-based pollution from degrading reefs by restoring the natural filtration processes within the watershed (Coral Reef Alliance, 2016). The CORAL team on Maui works in the Wahikuli and Honokōwai watersheds[1]. Some of their ongoing projects include:

- Restoration and stabilization of decommissioned agricultural roads. In the Agricultural District, highly compacted, unvegetated dirt roads run parallel to the stream gulches. Sheet flow accumulates and moves very quickly on these paths, picking up sediment and other pollutants. To reduce the risk of these pollutants entering the adjacent stream valley, CORAL has installed physical barriers to slow down flow and create opportunities for the suspended sediments to settle.
- Experimentation of different Best Management Practices (BMPs). Different BMPs to reduce the risk of sediment and pollutants entering the adjacent stream valley have been tested by CORAL, including vetiver rows, native grass rows, coconut coirs, check dams, living check dams, sandbag rows, living sandbag rows, living plant rows, and native plant restoration. Vetiver rows with a small slope was the most efficient at trapping sediment (Coral Reef Alliance, 2022).

In 2017, CORAL published a report identifying possible solutions for addressing terrestrial sediment contributions to the nearshore environment in the Wahikuli and Honokōwai watersheds. Their report, *Stream Restoration Technical Solutions, Wahikuli and Honokōwai Watersheds, West Maui*, refines some of the recommendations made in the *Wahikuli-Honokowai Watershed Management Plan* published by NOAA in 2012, and proposes new solutions for specific use in West Maui. They have also developed several

[1] As defined by the U.S. Coral Reef Task Force, which includes the Wahikuli, Hanakaʻōʻō, Honokōwai, and Māhinahina watersheds, as defined by USACE in this study.

resource documents related to rain gardens, traditional Hawaiian agriculture, and low impact design (LID).

Website: http://coral.org/

2.2 County of Maui

The County of Maui is the local government agency of Maui Nui. Relative to this watershed study, the following departments of the County of Maui have been actively engaged to ensure recommendations comport with County plans and operations.

Website: http://www.co.maui.hi.us/

2.2.1 Department of Planning

Among other responsibilities, the County of Maui, Department of Planning proposes zoning legislation, presents reports and recommendations on development proposals, and oversees programs on cultural resources, census and geographic information, floodplain permits and other special projects and permits. Residential development projects are tracked by the Department's Long-Range Planning Division. In October 2021, the Planning Departmtne published a draft version of the update to the *West Maui Community Plan*, which guides future development and revitalization in West Maui.

Website: https://westmaui.wearemaui.org/

2.2.2 Department of Public Works (DPW)

The County of Maui, Department of Public Works (DPW) is the local government agency who is responsible for the maintenance of the Nāpili 2-3 Basin, Nāpili 4-5 Basin, Honokeana Basin, Ka'ōpala Basin, Pōhakukā'anapali Basin, Māhinahina Basin, and the Honokōwai Basin, along with County roads, storm water drainage systems, and flood control channels.

Website: https://www.mauicounty.gov/124/Public-Works

2.2.3 Department of Water Supply (DWS)

The County of Maui, Department of Water Supply (DWS) is tasked with "providing adequate source storage, transmission, distribution and fire protection flows to meet County needs, and with protecting water resources at the County level" (Pu'u Kukui Watershed Preserve, 2014). In support of its mission to "provide clean water efficiently," DWS spends over $1 million per year on resource protection and monitoring. DWS is also

a participant and sponsor of the West Maui Mountains Watershed Partnership (Section 1.2).

Website: www.mauiwater.org/

2.3 Department of Health (DOH)

One goal of the State of Hawai'i, DOH is to preserve a healthy and natural environment. This includes protecting and enhancing water quality. The EPA has delegated authority to DOH to enforce many federal environmental acts including the Clean Water Act. DOH also sets the limits for pollutants.

Website: https://health.hawaii.gov/

2.3.1 Clean Water Branch

DOH's Clean Water Branch (CWB) protects the public health of residents and tourists who enjoy playing in and around Hawai'i's coastal and inland water resources. The CWB also protects and restores inland and coastal waters for marine life and wildlife. This is accomplished through statewide coastal water surveillance and watershed-based environmental management through a combination of permit issuance, monitoring, enforcement, sponsorship of polluted runoff control projects, and public education. Hui O Ka Wai Ola (Section 3.1), a citizen science program, provides CWB with additional samples that can be used to assess changes in water quality.

Website: https://health.hawaii.gov/cwb/

2.4 Department of Land and Natural Resources (DLNR)

The State of Hawai'i, DLNR is responsible for managing, administering, and exercising control over public lands, water resources, ocean waters, navigable streams, coastal areas (except commercial harbors), minerals, and all interests therein. The DLNR is the local sponsor for this study.

2.4.1 Commission on Water Resource Management (CWRM)

The Commission on Water Resource Management (CWRM or "the Commission") of DLNR is comprised of seven members whose primary responsibilities are to implement and administer the provisions of the State Water Code by planning, surveying, regulating, monitoring, and conserving the State's water resources within established plans that have

already been adopted by the Commission. Additional responsibilities include the following:

1. Administer the Hawaii Water Plan and its constituent parts, except the Water Quality plan which will be administered by DOH.
2. Regulate the use of water resources in water management areas, and coordinate activities necessary to ensure the protection of native Hawaiian water rights;
3. Recommend appropriate interim and final instream flow standards;
4. Receive and process water-related citizen complaints;
5. Recommend dispute resolutions by mediation or other procedures;
6. Retain hearings officers and consultants for the conduct of special administrative proceedings by the Commission;
7. Receive and process permit applications for stream channel alterations, well drilling, pump installations, and diversion works construction; and
8. Conduct hydrologic investigations and recommend appropriate action regarding designation of water management areas.

In partnership with West Maui R2R, the Commission installed three stream gages within the study area in 2017. The gages are in the upper Honokōwai valley (6-124[2]), lower Honokōwai below the dam (6-156), and lower Honolua (6-158). These stream gages provide instantaneous data on stream stage (the height of the water above the gage datum).

Website: http://dlnr.hawaii.gov/cwrm/

2.4.2 Division of Aquatic Resources (DAR)

The non-federal sponsor for the West Maui Watershed Study is the State of Hawai‘i, as represented by its DLNR, Division of Aquatic Resources (DAR). DAR manages the State’s aquatic resources and ecosystems through programs in ecosystem management, place-based management, and fisheries management. It is the mission of DAR to work with the people of Hawai‘i to manage, conserve and restore the State’s unique aquatic resources and ecosystems for present and future generations. Some of the work they do

[2] 6-124 refers to the site number assigned to the stream gage by the Commission

includes chairing the West Maui R2R Working Group (Section 1.1.3), working to develop and implement community-based subsistence fishing area rules to grow the Kā‘anapali Makai Watch program (Section 3.2), and supporting the Coral Reef Assessment and Monitoring Program (CRAMP) research program.

Website: http://dlnr.hawaii.gov/dar/

2.4.3 Division of Forestry and Wildlife (DOFAW)

DLNR's Division of Forestry and Wildlife (DOFAW) is responsible for managing and protecting watersheds, native ecosystems, and cultural resources. DOFAW holds various parcels of land within the recognized study area that are recognized as either a Natural Area Reserve or Forest Reserve.

Website: https://dlnr.hawaii.gov/forestry/

2.5 Mauna Kahālāwai Watershed Partnership (MKWP)

The Mauna Kahālāwai Watershed Partnership (MKWP) is a non-profit organization created in 1998. It was formed for the long-term protection and preservation of the West Maui Mountains. There are 10 partners in the MKWP:

- County of Maui
- Kahoma Land Company LLC
- Kamehameha Schools
- Kā'anapali Land Management Corp.
- Makila Land Company LLC
- Maui County Board of Water Supply
- Maui Land & Pineapple Co. Ltd.
- DLNR
- The Nature Conservancy of Hawai‘i
- Wailuku Water Company LLC

While the members of the partnership have different priorities, mandates, and constituencies, they all share a common value of protecting large areas of forested watersheds for water recharge and conservation values.

Website: https://www.maunakahalawai.org/

2.6 Kā'anapali Moku

The Kā'anapali Moku is part of the Na Hono A'o Pi'ilani Council, which is part of the larger Aha Moku System. The Aha Moku System promotes the integration of traditional natural resource management practices into the existing resource management policies of state and county agencies. The purpose is to ensure ecological health, sustainability of natural resources, and to honor the ancestral past and wisdom of the Native Hawaiian elders. There is an emphasis on self-governance and community empowerment through education, consultation, and local regulations.

Website: http://www.ahamoku.org/

2.7 Maui Cultural Lands (MCL)

Maui Cultural Lands, Inc. (MCL) is a grassroots land trust organization whose mission is to stabilize, protect, and restore Hawaiian cultural resources. Their mission focuses on reforestation, archaeological stabilization, and education. One of their major project sites is Honokōwai Valley, where volunteers have cleared more than 10 acres of the valley, planted thousands of native plants and trees, restored lo'i for dryland taro, planted vegetable gardens, and built a simple hale (house).

Several of the West Maui R2R climate stations and the CWRM 6-124 stream gage are located on property owned by MCL, with their support.

Website: http://mauiculturallands.org/

2.8 Maui Land & Pineapple Company (ML&P)

Maui Land & Pineapple Company (ML&P) is a land holding and operating company historically dedicated to agriculture, resort operation, and the creation and management of holistic communities. After the opening of Kapalua Resort in 1978, Honolua Bay and Mokulē'ia Bay were designated a Marine Life Conservation District (MLCD) and became protected from fishing and harvesting. ML&P has dedicated 3,300 acres of its coastal land around these bays to the MLCD. ML&P historically managed the Pu'u Kukui Watershed Preserve, but now has arranged for management under the Living Pono Project.

Website: https://mauiland.com/

2.8.1 Pu‘u Kukui Watershed Preserve

In 1992, ML&P granted to The Nature Conservancy of Hawai‘i a permanent conservation easement of 8,405 acres, creating the largest private nature preserve in Hawai‘i. ML&P now contracts the Living Pono Project to employ a team of conservationists who take care of the land. Honolua Wao Kele Native Plant Reforestation Project is a volunteer-based, grass-roots effort instigated by ML&P conservationists to restore native plants and trees to former pineapple field lands.

Website: https://www.puukukui.org

2.9 Kā‘anapali Operators Association, Inc.

In 1995, 11 resort properties in Kā‘anapali formed a non-profit organization, the Kā‘anapali Operators Association that stewards the common grounds and navigates common issues for its members and properties. As large private landowners in West Maui representing the Kā‘anapali resort and transient visitor community the Kaanapali Operators Association are an important stakeholder concerning Watershed Management of West Maui. The Kā‘anapali Operators Association recently partnered with Roth Ecological Design International to pilot a project funded by NFWF to install two floating wetlands in a resort lagoon in West Maui intended to improve water quality.

Website: none

2.10 Maui Nui Marine Resource Council (MNMRC)

Maui Nui Marine Resource Council (MNMRC) is a volunteer-based council and non-profit organization, with a mission to preserve, protect and enhance the coral reefs of Maui Nui. The MNMRC’s goal is to raise awareness about the status of Maui County’s coral reefs and develop community-based solutions to reverse local coral reef declines.

In 2010, the MNMRC brought sixteen of Hawai‘i’s most widely recognized coral reef management experts, scientific researchers, and community representatives to Maui to form the Maui Coral Recovery Team. As a result of their collaboration and dedication to improve reef health, water quality, and native fish populations, the *Maui Coral Recovery Plan* was published in 2012. This document provides recommendations on priority recovery sites and restoration strategies, including cultural and traditional management and partner/community engagement.

Additionally, MNMRC is one of three partner organizations committed to sustained water quality monitoring (Section 3.1, Hui O Ka Wai Ola), promotes sustainable fishing, supports community-based sustainable management actions, and works with others to improve local wastewater management.

Website: https://www.mauireefs.org/

2.11 Nāpili Bay and Beach Foundation

The Nāpili Bay and Beach Foundation (NBBF) is a non-profit community organization aimed at improving the health of Nāpili Bay and Nāpili Beach. Some of their past accomplishments include restoration of Nāpili Stream and improvements to the Nāpili 4-5 desilting basin. Volunteers continue to remove non-native vegetation from the streambed and banks of Nāpili Stream and take care of native plantings. In 2011, with support from the NRCS, NFWF, and the County of Maui, DPW, the NBBF installed a tri-level outlet valve on the Nāpili 4-5 desilting basin and a grassed waterway to slow and filter runoff from the basin.

Website: http://www.napilibayfoundation.org/

2.12 National Fish and Wildlife Foundation (NFWF)

The NFWF is an American foundation that was chartered by Congress in 1984 to increase resources available for the conservation of the nation's fish, wildlife, plants, and habitats. The NFWF Coral Reef Conservation Fund has supported various restoration projects in West Maui, such as the work done by CORAL (Section 2.1) to plant native plants along stream banks and decommissioned agricultural roads.

Website: https://www.nfwf.org/

2.13 National Oceanic and Atmospheric Administration (NOAA)

The U.S. Department of Commerce, NOAA is the federal agency responsible for daily weather forecasts, severe storm warnings, climate monitoring, fisheries management, coastal restoration, and supporting marine commerce. NOAA regional staff actively engaged on this study and other interrelated West Maui inititatives

Website: http://www.noaa.gov/

2.13.1 Office for Coastal Management (OCM)

NOAA's Office for Coastal Management (OCM) was founded to work with a variety of partners, from all sectors, to deliver the products, services, and programs most needed by the nation's coastal communities.

2.13.1.1 Coral Reef Conservation Program

The Coral Reef Conservation Program brings together expertise from across NOAA for a multidisciplinary approach to studying coral reef ecosystems. The program focuses on impacts from the top three recognized global threats to coral reefs: climate change, land-based sources of pollution, and unsustainable fishing practices. Under the Coral Reef Conservation Program, NOAA sponsored the development of the *Wahikuli-Honokōwai Watershed Management Plan* in 2012. In collaboration with DLNR-DAR, NOAA also sponsors the West Maui R2R Watershed and R2R Coordinator.

Website: http://coralreef.noaa.gov/

2.13.1.1 National Coastal Zone Management Program

The National Coastal Zone Management Program comprehensively addresses the nation's coastal issues through a unique federal and state partnership. Major components of the national program include federal consistency, program enhancements, and nonpoint pollution control. The program establishes a set of management measures for states to use in controlling runoff from five main sources: agriculture, forestry, urban areas, marinas and hydromodification (shoreline and stream channel modification).

Website: https://coast.noaa.gov/czm/

2.13.2 NOAA National Marine Fisheries Service (NMFS or Fisheries)

NOAA Fisheries is responsible for the stewardship of the nation's ocean resources and their habitat. Using the Magnuson-Stevens Fishery Conservation and Management Act as the guide, NOAA Fisheries assess and predicts the status of fish stocks, set catch limits, ensures compliance with fisheries regulations, and reduces bycatch. Under the Marine Mammal Protection Act and the Endangered Species Act, NOAA Fisheries works to recover protected marine species while allowing economic and recreational opportunities.

Website: https://www.fisheries.noaa.gov/contact/pacific-islands-regional-office

2.14 Natural Resources Conservation Service (NRCS)

The U.S. Department of Agriculture, NRCS provides technical and financial assistance for projects that help to protect, enhance, or preserve the Nation's soil, water, air, plants, and animals. They partner with Conservation Districts, such as the West Maui Soil & Water Conservation District (Section 3), farmers, and private landowners. NRCS also collects and shares information on the nation's soil, water, air, and plants.

NRCS has previously dedicated funding specifically to West Maui for the implementation of water quality related conservation practices designed to prevent the loss of excessive nutrients, pesticides, and sediment from the land.

Website: https://www.nrcs.usda.gov/

2.15 Project S.E.A.-Link

Project S.E.A.-Link is a Maui-based non-profit organization focused on promoting marine science, education, and awareness. This organization is a sponsor of the Kā'anapali Makai Watch program (Section 3.2) and the West Maui Kumuwai campaign (Section 3.3).

Website: http://www.projectsealink.org/

2.16 Save Honolua Coalition

The Save Honolua Coalition is a volunteer-based organization whose mission is to maintain open space, public access, and revitalize the ecosystem of the Honolua ahupua'a through community-based resource management utilizing Hawaiian practices and values. Their current focus is on restoring Honolua's ecosystem and promoting community-based resource management that utilizes Native Hawaiian practices and values. They also co-sponsor the Turbidity Task Force before there was a comprehensive water quality monitoring program.

Website: http://www.savehonolua.org/

2.17 The Nature Conservancy of Hawaii (TNCH)

Established in 1980, The Nature Conservancy of Hawaii (TNCH) is a local affiliate of The Nature Conservancy, a leading international, nonprofit organization that works to protect the most ecologically important lands and waters around the world. Kapunakea Preserve is a state-funded Nature Conservancy of Hawaii, located within the Wahikuli

and Honokōwai watersheds. TNCH helped to found the MKWP (Section 1.2) and continues to play an active role in the partnership. They work closely together with MKWP to remove ungulates (hoofed mammals), maintain infrastructure, and provide access to researchers (The Nature Conservance of Hawaii, 2015). TNC also joined forces with local and state partners to launch Hui O Ka Wai Ola (Section 3.1).

Website: http://www.nature.org/hawaii

2.18 University of Hawai'i (UH)

Founded in 1907, the University of Hawai'i (UH) is the state's public system of higher education and includes three universities, seven community colleges, and community-based learning centers across Hawai'i.

2.18.1 College of Tropical Agriculture and Human Resources (CTAHR)

2.18.1.1 Department of Natural Resources and Environmental Management

In the UH at Mānoa's CTAHR, Department of Natural Resources and Environmental Management (NREM) emphasizes the science and management of natural resources and their links to environmental quality. In May 2017, with funding provided by USACE, Kirsten Oleson and Megan Barnes completed a report, *Evaluating potential solutions to West Maui's Coral Reef Decline: Feasibility of ecological models to evaluate solutions*. Several models were created under this effort, including a landscape erosion model, bank erosion model, and landscape nutrient model. In 2017, with funding provided by USGS, UH revised the bank erosion model to estimate sediment reduction from implementing specific management measures, such as pig removal and repairing stream crossings. It was also updated in April 2017 to include data provided by USGS.

Website: https://cms.ctahr.hawaii.edu/nrem/

2.18.2 School of Ocean and Earth Science and Technology (SOEST)

2.18.2.1 Hawai'i Sea Grant

UH's Sea Grant College Program (Hawai'i Sea Grant) supports an innovative program of research, education, and extension services directed to the improved understanding and stewardship of coastal and marine resources of the state, region, and nation. Hawai'i Sea Grant works in partnership with the University of Hawai'i's prestigious School of Ocean and Earth Science and Technology (SOEST) and NOAA to identify

Hawai'i's critical resource management issues and guide cutting-edge scientific research to address these challenges.

Website: https://seagrant.soest.hawaii.edu/

2.18.2.2 Pacific Islands Ocean Observing System (PacIOOS)

Based within SOEST at UH at Mānoa, the Pacific Islands Ocean Observing System (PacIOOS) believes that ocean data and information can help save lives and resources. PacIOOS collects real-time data on ocean conditions, forecasts future events, and develops user-friendly tools to access this information. With funding from NOAA's Regional Coastal Resiliency Grants Program, PacIOOS has developed a high resolution, real-time wave run-up forecast and notification system for West Maui's coastline. They have also modeled a suite of inundation planning scenarios that take rising sea levels and increasing wave energies into account.

Website: http://www.pacioos.hawaii.edu/

2.18.3 Water Resources Research Center (WRRC)

The UH at Mānoa's Water Resources Research Center (WRRC) concentrates on addressing the unique water and wastewater management problems facing people in the Pacific. The main focuses of the center are to coordinate and conduct research to identify, characterize and quantify water-related problems in Hawai'i; assist Pacific Island and Asian governments facing water problems similar to those in Hawai'i; and facilitate access to interdisciplinary expertise within the university to enhance understanding of environmental problems and to identify effective solutions.

With funding provided by DLNR-DAR, researchers from the WRRC analyzed the sediment retention performance of the existing outlet structure at Honokōwai Basin under as-built conditions and assumed conditions of legacy sediment accumulation in the basin (Babcock Jr., et al., 2016). They also analyzed the improved trapping efficiency of the basin under different modification scenarios.

2.19 U.S. Army Corps of Engineers (USACE)

The USACE is a component of the Department of the Army, with a mission "to deliver vital engineering solutions, in collaboration with our partners, to secure our Nation, energize our economy, and reduce disaster risk." Through its Civil Works Program and in

cooperation with local nonfederal sponsors, USACE plans and implements water resource projects, authorized by Congress, in principally three core mission areas: 1) flood and coastal storm risk management, 2) commercial navigation, and 3) aquatic ecosystem restoration. In conducting watershed planning, the USACE uses its planning capability in a broader sense to meet the challenging water resources needs of the nation.

As part of the West Maui Watershed Study, USACE and the State of Hawai'i (through DLNR-DAR), co-sponsored the *West Maui Watershed Plan: Kahana, Honokahua, and Honolua Watersheds*, prepared by Group 70 International, Inc. in 2016. As a continuation of this study, USACE provided funding to USGS (Section 2) for field work that led to the development of a sediment budget for West Maui and the development of a marine sediment transport model to improve understanding of sediment dynamics in the West Maui nearshore environment.

USACE was one of the first members of the West Maui R2R Initiative (Section 1.1) and still maintains membership on the FAST (Section 1.1.2), in support of common goals to contribute to the restoration, enhancement, and resiliency of West Maui coral reefs.

2.19.1 Committee on River Engineering

In August 2019, the USACE Committee on River Engineering (CRE) visited several sites in West Maui to provide recommendations on effective management strategies for reducing in-stream erosion, technical modeling, and next steps in the planning process.

2.20 U.S. Coral Reef Task Force (USCRTF)

The U.S. Coral Reef Task Force (USCRTF) was established in 1998 to lead, coordinate, and strengthen the U.S. Government's actions to better preserve and protect coral reef ecosystems. In 2002, the USCRTF, in collaboration with the State of Hawai'i, created Local Action Strategies to address threats to coral reefs in U.S. jurisdictions with coral reefs. The Fisheries Local Action Strategy for Hawai'i (FLASH) addresses fishing-related impacts to coral reefs in the main Hawaiian Islands and coordinates with partners in other non-fisheries sectors to ensure a balanced approach to coral reef conservation.

Within the USCRTF, there is a Watershed Working Group that focuses its efforts on the reduction of land-based sources of pollution, including sediments and nutrients, in support of the USCRTF's mission to protect and enhance coral reef ecosystems. In 2011,

the USCRTF designated Wahikuli and Honokōwai as priority watersheds[3], later extending to include Kahana Honokahua, and Honolua.

Website: http://www.coralreef.gov/

2.21 U.S. Environmental Protection Agency (EPA)

The EPA protects people and the environment from significant health risks, sponsors and conducts research, and develops and enforces environmental regulations. EPA's Pacific Southwest (Region 9) implements and enforces federal environmental laws in Hawai'i. EPA regularly awards grants to the State of Hawai'i, DOH who it has delegated authority to enforce many federal environmental acts, including the Clean Water Act. As a result, the DOH provides low-cost loans to the counties to upgrade their drinking water and wastewater facilities (Higuchi, 2016). The USEPA actively engages on this study and other West Maui initiatives as a member of the FAST.

Website: https://www.epa.gov/hi

2.22 U.S. Fish and Wildlife Service (USFWS)

The USFWS is at the forefront of applying the best-known science to their conservation work. Within the USFWS, the Aquatic Ecosystem Conservation program falls under the broad umbrella of Conservation Planning Assistance (CPA). The mission of CPA is to work collaboratively with state and federal agencies, the private sector, and other stakeholders to achieve development of infrastructure projects in ways that maximize the conservation of fish and wildlife resources, and their associated aquatic habitats.

Website: https://www.fws.gov/program/conservation-planning-assistance

2.23 U.S. Geological Survey (USGS)

The USGS is a scientific agency of the United States government. As the Nation's largest water, earth, and biological science and civilian mapping agency, USGS collects, monitors, analyzes, and provides science about natural resource conditions, issues, and problems. There are USGS-operated climate stations and stream gages within the West

[3] USCRTF uses the term "watersheds," but is actually referring to the five hydrologic units (Wahikuli, Honokōwai, Kahana, Honokahua, and Honolua), as delineated by the State of Hawai'i and inclusive of eleven watersheds.

Maui study area. Elevation data is also provided for the study area through the USGS National Geospatial Program.

Through extensive mapping, field experiments, monitoring, and data analysis, USGS created a sediment budget that estimates the annual export of fine sediment (clays, silts, and sands) from the West Maui watersheds. Most of the fieldwork occurred between 2014-2016. An Open-File Report (OFR), *Reconnaissance Sediment Budget for Selected Watersheds of West Maui, OFR 2015-1190*, was published in 2015 to provide immediate information (preliminary findings) to stakeholders. The Scientific Investigations Report (SIR), *Sediment Budget for Watersheds of West Maui, Hawaii, SIR 2020-5133*, was published in 2020 and includes the final documentation on this investigation.

As part of the West Maui Watershed Study, USGS also analyzed how terrestrial sediment from the West Maui watersheds is dispersed into the marine environment and the associated residence time over nearshore coral reefs.

Website: https://www.usgs.gov/centers/pacific-islands-water-science-center

2.24 West Maui Soil & Water Conservation District (WMSWCD)

The West Maui Soil & Water Conservation District (WMSWCD) is a self-governing entity under the State of Hawai‘i, organized for the protection and conservation of soil and water resources. WMSWCD is focused on minimizing the negative impacts of agriculture on natural resources.

Several of the existing detention basins and flood risk reduction structures in West Maui were constructed under the Honolua Watershed Project, sponsored by the WMSWCD and the County of Maui. Contrary to its name, the Honolua Watershed Project spans across the Wahikuli, Honokōwai, and Kahana watersheds. The implemented project features include eight desilting basins, about 0.8 miles of floodwater diversions, about 0.7 miles of floodwater channels, land treatment measures on about 24,000 acres, four bridges, relocation of three water mains, and controlled use of flood plain areas.

The WMSWCD has also functioned as a fiscal agent for the West Maui Watershed and Coastal Management role since 2015.

Website: http://www.mauicountysoilandwater.org/

2.25 2.24 Ridge to Reefs, LLC.

Ridge to Reefs (RTR) is a non-profit incorporated in 2011 with the mission to work with communities to achieve tangible outcomes creating permanent sustainability for people and the planet. RTR currently has projects in the Chesapeake Bay, Hawai'i, Puerto Rico, Palau, and American Samoa. Through the process of identifying environmental and social challenges, designing innovative solutions, and working with local partners and community members, we catalyze local capacity and implement nature-based solutions to support communities where connected human and natural systems thrive. RTR has been working in West Maui since 2015 as key implementation partners bringing green innovations such as nutrient curtains, vetiver eyebrow sediment capture, gulch buffer concepts, wastewater solutions, planning support for sustainable agriculture, and much more.

Website: https://www.ridgetoreefs.org/

3 Community Campaigns and Programs

3.1 Hui O Ka Wai Ola

Hui O Ka Wai Ola is a community-based water quality monitoring program to measure nutrients in coastal waters. It was launched in 2016 through a partnership of Maui Nui Marine Research Council, The Nature Conservancy, and the West Maui R2R Initiative. Volunteers collect ocean water samples at 17 sites in West Maui every three weeks to supplement DOH water quality monitoring.

Website: http://www.huiokawaiola.com/

3.2 Kāʻanapali Makai Watch

The Makai Watch program is a collaborative, statewide program where citizens and non-government organizations become directly involved with the State of Hawaiʻi, DLNR in the management of marine resources through promoting compliance to rules, education, and monitoring. This program trains communities to accurately report violations and to conduct outreach and monitoring.

The Kāʻanapali Makai Watch volunteer program is coordinated jointly by Project S.E.A.-Link (2.13) and the DAR, with the support of many other groups, community members and volunteers. This program trains communities to accurately report violations within the Kahekili Herbivore Fisheries Management Area (KHFMA) and to conduct outreach and monitoring. KHFMA is a protected area that was established to maintain the population of algae-eating fish and sea urchins to help control overgrowth and degradation of coral reefs (Osher, 2011). It extends from Honokōwai Beach Park to Hanakaʻōʻō Beach.

Website: http://kaanapalimakaiwatch.com/

3.3 West Maui Kumuwai

West Maui Kumuwai is a locally managed campaign, comprised of community members and representatives from local, state, and federal agencies. The effort was funded by NOAA's Coral Reef Conservation Program (see Section 2.12.1.1) with strategic support provided by SeaWeb during the campaign development process. The focus of West Maui Kumuwai is on reducing land-based sources of pollution through personal

action and community collaboration. They empower residents to reduce their individual contribution of polluted runoff, such as by using fertilizer wisely, and encourage them to lend a hand in community projects organized by partner agencies.

Website: http://westmauikumuwai.org/

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Appendix B

Hydrology and Hydraulics

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EXECUTIVE SUMMARY

The final event-based sediment load and distribution time series data at the outlet of eleven watersheds within the study area were determined by flood frequency analysis, use of rainfall-runoff modeling, calibration of event-based sediment loads to previous investigations, and analysis of the trap efficiency of existing detention basins. The eleven watersheds are: Wahikuli, Hanakaʻōʻō, Honokōwai, Māhinahina, Kahana, Kaʻōpala, Honokeana, Nāpili 4-5, Nāpili 2-3, Honokahua, and Honolua.

The flood frequency analysis included stream gage analysis, application of regional regression equations, and development of a rainfall-runoff model using HEC-HMS software. The rainfall-runoff model was initially calibrated to replicate specific historical storms; however, the limited number of sites and storm events that could be used for calibration proved this method to be ineffectual. However, a Bulletin 17C stream gage analysis on two sites in the Honokōhau and Honokōwai watershed provided a strong level of confidence based on long periods of record and the rainfall-runoff model was calibrated to match these results. The final peak flow estimates adopted by this study are presented in Section 5.3.6.

The annual sediment load previously estimated by USGS was used as input for the rainfall-runoff model, paired with historical rainfall data from 1 November 2014 to 1 November 2015, to provide a reasonable estimate of typical flows and sediment loads produced by the various low flow events throughout the year. Reservoir elements in the rainfall-runoff model helped determine approximate trap efficiencies of existing detention basins within the watershed, based on Chen's sediment trap method of analysis. These results are presented in Section 6.3. The level of accuracy of these results is commensurate with the level of data that was available during this study

The output of the calibrated rainfall-runoff model was used as input for the two-dimensional, unsteady flow hydraulic model that was developed using HEC-RAS software. Models were created that are representative of the lower reaches within the Wahikuli, Honokōwai, Kahana, Kaʻōpala, and Honolua watersheds.

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Note: Photos were taken by USACE unless otherwise noted

LIST OF ACRONYMS & ABBREVIATIONS

2D	two-dimensional
AEP	annual exceedance probability
cfs	cubic feet per second
CN	curve number
CSM	cohesive strength meter
CWRM	Commission on Water Resource Management
DA	drainage area
DAR	Division of Aquatic Resources
DCIA	directly connected impervious area
DLNR	Department of Land and Natural Resources
DPW	Department of Public Works
DEM	digital elevation model
DTM	digital terrain model
ECB	Engineering and Construction Bulletin
ENSO	El Niño-Southern Oscillation
ER	Engineer Regulation
FEMA	Federal Emergency Management Agency
FIS	Flood Insurance Study
GIS	geographic information system
GMSL	global mean sea level
HEC	Hydrologic Engineering Center
HMS	Hydrologic Modeling Software
IPCC	Intergovernmental Panel on Climate Change
L	length
LMSL	local mean sea level
MHHW	mean higher high water
MLLW	mean lower low water
MSL	mean sea level
n	Manning's roughness coefficient
NCEI	National Centers for Environmental Information
NED	National Elevation Dataset

NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
OCM	Office for Coastal Management
PAC-RISA	Pacific Regional Integrated Sciences and Assessments
PFDS	Precipitation-Frequency Data Server
PRF	Peak rating factor
R2R	Ridge to Reef
RAS	River Analysis Software
RC	rating curve
S	potential maximum retention
SCS	Soil Conservation Service
SIR	Scientific Investigation Report
SLC	sea level change
State	State of Hawaii
SSP	Statistical Software Package
SWCD	Soil and Water Conservation District
t_L	lag time
TR-55	Technical Release 55
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
VLM	vertical land movement
Y	The average subbasin slope

1 Introduction

This appendix describes the existing site conditions in West Maui with regards to its hydrology, hydraulics, and sediment transport potential. It describes the methodology used to determine peak flow estimates and the approximate sediment load contributed to the nearshore marine environment by each watershed in the study area.

1.1 Study Purpose

The intent of the West Maui Watershed Study is to contribute to the restoration, enhancement and resiliency of West Maui coral reefs and nearshore waters through the reduction of land-based pollution threats. Several alternatives that have potential to reduce the amount of terrestrial sediment being discharged into the marine environment will be proposed and evaluated as part of this study. The results of this study will be shared with key stakeholders and local decision-makers to provide them with additional information to rely upon in the future.

1.2 Authority

The authority for the West Maui Watershed Study is provided by Section 729 of the Water Resources Development Act (WRDA) of 1986, Public Law 99-662, as amended (33 U.S.C. 2267a; hereinafter “Section 729”). Section 729 authorizes the development of watershed plans that are multi-purpose and multi-objective in scope and developed in cooperation with federal, state, and local government entities.

1.3 Project Sponsor

The non-federal sponsor for the West Maui Watershed Study is the State of Hawai‘i, as represented by its Department of Land and Natural Resources (DLNR), Division of Aquatic Resources (DAR).

1.4 Study Area

The study area encompasses a collection of about eleven adjacent watersheds (Figure 1-1) on the leeward side of the West Maui Mountains, north of the town of Lahaina, Maui. These watersheds are grouped by the State of Hawai‘i into five surface water

hydrologic units: Wahikuli (6009[1]), Honokōwai (6010), Kahana (6011), Honokahua (6012), and Honolua (6013).

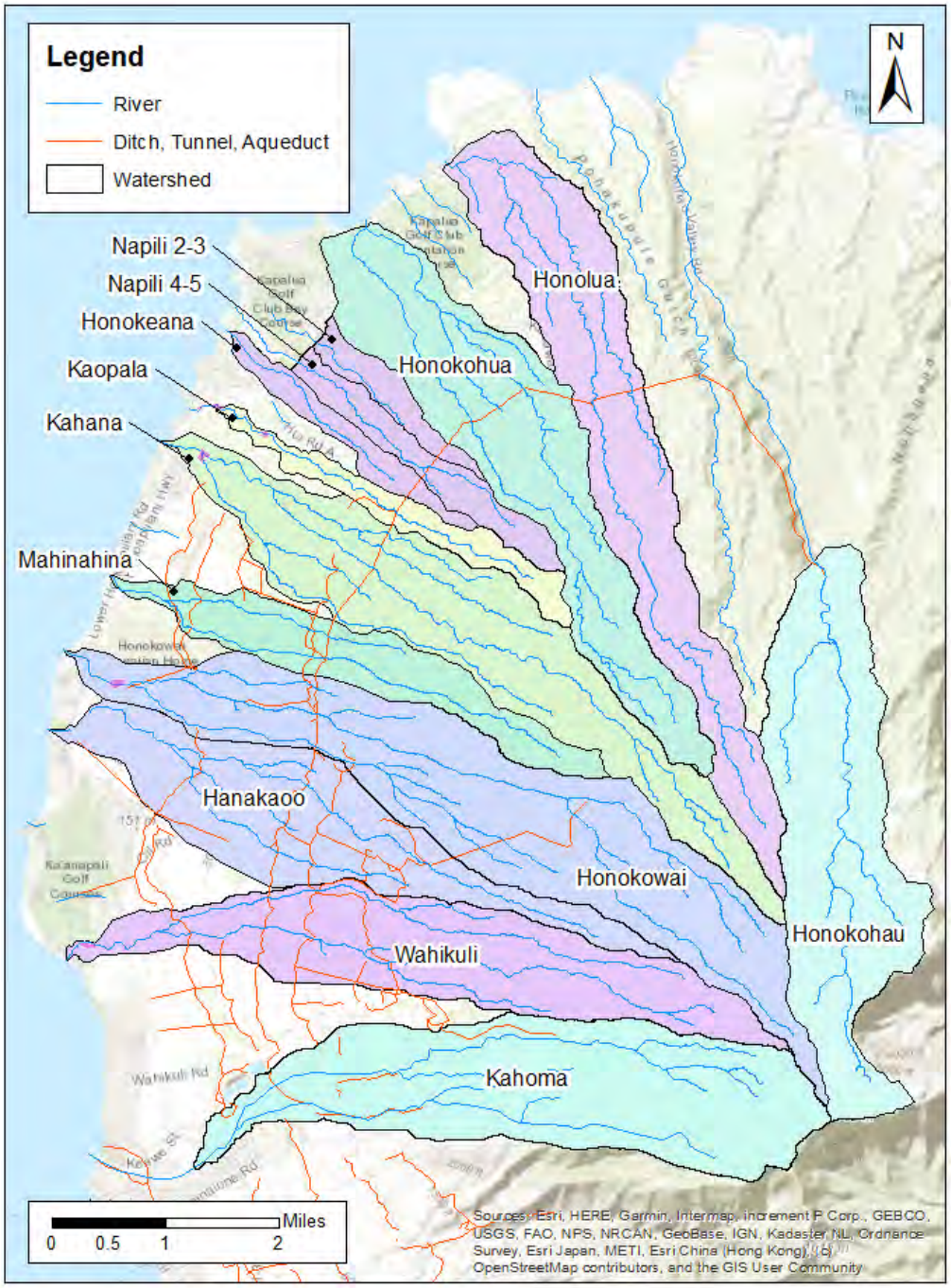


Figure 1-1: Watershed Map, West Maui, Hawai'i

[1] Each surface water hydrologic unit has a unique 4-digit code assigned by the State's Commission on Water Resource Management.

1.5 Previous Investigations and Reports

A list of previous work completed by the U.S. Army Corps of Engineers (USACE) and others is provided below, including a summary of key findings directly relevant to this study:

- *Wahikuli-Honokōwai Watershed Management Plan*, *Volume 1: Watershed Characterization* (National Oceanic and Atmospheric Administration, Coral Reef Conservation Program, 2012).
- *Wahikuli-Honokōwai Watershed Management Plan*, *Volume 2: Strategies and Implementation* (Coral Reef Conservation Program, 2012).
- *Low-Flow Characteristics of Streams in the Lahaina District, West Maui, Hawaii.* Scientific Investigations Report 2014-5087, (U.S. Department of the Interior, U.S. Geological Survey [USGS], 2014).
- *Spatially Distributed Groundwater Recharge Estimated Using a Water-Budget Model. for the Island of Maui, Hawai'i, 1978-2007.* Scientific Investigations Report 2014-5168, (USGS, 2014).
- *Reconnaissance Sediment Budget for Selected Watersheds of West Maui, Hawai'i.* Open-File Report 2015-1190. (USGS, 2015).
    - Streambank erosion of historic terraces of sands, silts, and clays, are likely the primary source of sediment in the channel system, resulting in annual plume generation in the nearshore waters of West Maui, Hawai'i.
    - Treatments of former agricultural fields, roads, and reserve forests are not likely to measurably affect sediment pollution from smaller, more frequent storms.
    - As a reconnaissance budget, erosion-rate estimates were based on work elsewhere in the Hawaiian Islands and have great uncertainties.
- *West Maui Watershed Plan: Kahana, Honokahua and Honolua Watersheds, Characterization Report* (USACE and DLNR, 2016).
- *West Maui Watershed Plan: Kahana, Honokahua and Honolua Watersheds, Strategies and Implementation Report* (USACE and DLNR, 2016).

- *West Maui Wahikuli & Honokōwai Priority Watershed Area, Reef Condition Report* (DAR, 2016).
- *Sediment Budget for Watersheds of West Maui, Hawaii*. Scientific Investigation Report 2020-5133. (USGS, 2020).
    - Coastal sediment plumes occur at least 3-5 times per year in source watersheds.
        - Although total rainfall has decreased since the 1970s, more of it now occurs during short, intense storms capable of causing runoff and erosion.
    - Historic fill terraces (the primary source of sediment) are found only downstream of historic agricultural fields and are composed of silt and fine sand.
    - Several field experiments were conducted, including a survey of historic fill terraces, the installation and periodic monitoring of erosion pins, and cohesive strength meter (CSM) testing, which are described in Section 4.3.
    - Bank erosion of fill terraces from a few watersheds likely dominates the current annual fine sediment load to the nearshore, with Kahana producing the largest annual input of 285 metric tons, the equivalent of 29 dump-truck loads every year.
    - The storms capable of generating widespread runoff from agricultural fields are decadal events.
- *Instream Flow Standard Assessment Report, Island of Maui, Hydrologic Unit 6010, Honokōwai*. Draft PR-2019-01. (CWRM, 2019)
- *Instream Flow Standard Assessment Report, Island of Maui, Hydrologic Unit 6013, Honolua*. Draft PR-2019-02. (CWRM, 2019)
- *Instream Flow Standard Assessment Report, Island of Maui, Hydrologic Unit 6014, Honokōhau*. Draft PR-2019-03. (CWRM, 2019)
- *Observations of coastal circulation, waves, and sediment transport along West Maui, Hawai'i (November 2017–March 2018), and modeling effects of potential*

watershed restoration on decreasing sediment loads to adjacent coral reefs. Open-File Report 2022–1121. (USGS, 2023)

1.5.1 **USACE Committee on River Engineering**

In August 2019, the USACE Committee on River Engineering (CRE) visited several sites in West Maui to provide recommendations on effective management strategies for reducing in-stream erosion, technical modeling, and next steps in the planning process. Their recommendations include the following:

- Develop a Water Budget using HEC-HMS, identifying sources of water supply and diversion.
- Verify the Sediment Budget developed by USGS; verify the assumption that sediment is primarily sourced from in-stream erosion versus overland sources.
- A sediment model analyzing trap efficiency would be helpful in evaluating the effectiveness of the alternatives currently proposed. The existing field data available does not support detailed erosion modeling (e.g. BSTEM, MUSLE).
- Determine the sediment tolerance of the reefs; understand the types and amounts of sediment that the reefs can tolerate by either conducting a thorough literature search on this subject or working with local experts to develop this information.

There were several different approaches considered by CRE to address in-stream erosion: 1) stabilizing the problematic banks, 2) removing the erosive bank material directly, 3) capturing the sediment with an in-stream feature, 4) diverting all or some portion of the flow to a side-channel feature (e.g. offset stilling basin), 5) altering the flow regime (reducing the amount of flow in the channel with an upstream feature), and 6) flocculation. Generally, capturing the sediment with an in-stream feature or diverting flow to a side-channel feature seemed to be the most promising. Removal of the erosive bank material, altering the flow regime, and flocculation were not recommended.

- At Honolua, one alternative was considered that included lowering the floodplain and arranging boulders at constrictions to generate floodplain residence time to encourage sediment settlement. For this type of alternative,

a two-dimensional (2D) hydraulic model would be useful in computing a change in velocity field and residence time.

- In Wahikuli, two sediment stilling basin site proposals were considered. A simple sediment model could investigate the value of different configurations.

2 Watershed Description

2.1 Location

The entire study area is approximately 36 square miles (mi^2) and encompasses a collection of eleven adjacent watersheds (Figure 1-1) on the leeward side of the West Maui Mountains, north of the town of Lahaina, Maui. A watershed is an area of land that drains all the streams and rainfall to a common outlet. Whereas previously, the West Maui study area has been referred to as a "five-watershed priority area," the study area includes at least eleven watersheds with streams that discharge into the Pacific Ocean independently of each other. These eleven watersheds have been identified as Wahikuli, Hanakaʻōʻō, Honokōwai, Māhinahina, Kahana, Kaʻōpala, Honokeana, Nāpili 4-5, Nāpili 2-3, Honokahua, and Honolua. The adjacent watershed of Honokōhau was also included in this study as it provides a long record of continuous streamflow data (streamflow data within the study area itself is very limited).

The State of Hawai'i's classification system groups these individual watersheds into just five surface water hydrologic units: Wahikuli (6009[2]), Honokōwai (6010), Kahana (6011), Honokahua (6012), and Honolua (6013). These five hydrologic units are likely what the U.S. Coastal Reef Task Force was referring to when they designated Wahikuli, Honokōwai, Kahana, Honokahua, and Honolua as priority watershed areas in 2011.

2.2 Terminology

Watershed: A watershed is an area of land that drains all the streams and rainfall to a common outlet.

Drainage Basin: In this report, the watershed is often referred to as a *basin*, and sub-divided into individual *subbasins*. Use of this term is standard practice, especially in developing the hydrologic model and completing the hydrologic analysis.

Detention Basin: A *detention basin* is an excavated area or facility that is designed to temporarily store surface runoff and release it gradually until completely drained. There

[2] Each surface water hydrologic unit has a unique 4-digit code assigned by the State's Commission on Water Resource Management.

are existing detention basins in the study area that are very large, such as the Honokōwai Basin.

2.3 Topography

The summit of Puʻukukui is the highest point in the study area at 5,785 feet above mean sea level (ft MSL). The steep river profile originating in the mountains results in each basin having an oblong shape as water travels west-northwest toward the Pacific Ocean with limited meandering. Watershed lengths range from 3.6 miles (mi) for Kaʻōpala to 8.2 mi for Honokōwai. Honokōwai is the steepest basin, with an average basin slope of about 53 percent (%). Wahikuli, Kahana, Honokahua, and Honolua are also steep with an average basin slope between 40-50%. The smaller watersheds that originate at a lower elevation (e.g. Hanakaʻōʻō, Māhinahina, Kaʻōpala, Honokeana, and Nāpili) have an average basin slope between 15-30%.

2.4 Geology and Soils

The West Maui Mountains were formed through at least three series of major volcanic eruptions during its shield building period: the Wailuku volcanic series, the Honolua volcanic series, and the Lahaina volcanic series. Following the cessation of West Maui volcanism 500,000 years ago, the rapid erosion and valley incision of West Maui has produced broad alluvial fans with unconsolidated dunes of lithified to semi-lithified calcareous sand on the western slopes.

2.5 Climate

Hawaiʻi has a subtropical climate with temperatures that are mild and fairly uniform throughout the year. The mean annual temperature at Kahului[3], based on data collected over the last fifty years (1971 – 2021), is 76.1° Fahrenheit (F), with an average maximum of 78.6°F and average minimum of 74.0°F (Honolulu Weather Forecast Office, 2020).

The climate of the Hawaiian Islands is characterized by a two-season year; a 5-month summer or dry season and a 7-month winter or wet season; mild and uniform temperatures, strikingly marked geographic differences in rainfall, generally humid conditions, and prevailing dominance of trade wind flow from the northeast. During the 5-

[3] *Kahului AP*, located in Kahului, is the closest National Weather Service station to the study area

month summer from May through September, trade winds prevail 80-95 percent of the time. During the 7-month winter from October through April, the prevalence of the trade winds decreases to 50-80 percent. Although the northeasterly trade winds produce most of the annual rainfall over the Hawaiian Islands, it is during the absence of these winds that the flood producing rainfall occurs. In particular, southerly winds bring moist warm air that creates “Kona” storms which produce the damaging floods in Hawai‘i. These storms usually occur during the winter months. The climate of the West Maui watersheds is tropical with cooler and wetter areas at higher elevations in the belt of the northeasterly trade winds. The average monthly precipitation ranges from 3.35 inches in the wettest month (December) to 0.2 inches in the driest month (June) (U.S. Climate Data, 2017).

2.6 Dams and Reservoirs

As part of the Honolua Watershed Project, sponsored by the West Maui Soil and Water Conservation Districts (SWCD) and the County of Maui, eight desilting basins were constructed within the West Maui study area.

2.6.1 **Nāpili 2-3 Basin**

National Dam ID: HI00128

State Dam ID: MA-0128

Location: 20°59'38.31"N, 156°39'44.49"W

The Nāpili 2-3 Basin, "Structure #1," was constructed in 1988 and is currently maintained by the County of Maui, Department of Public Works (DPW). The basin has been adapted to serve as a golf course water feature. It is operated to retain water at all times and has not been dredged for several years. There are indications that sediment/silt deposition is 8 feet thick near the outlet, tapering to 1.5 feet thick at the inlet. Discharges from Nāpili 2-3 consistently break into Nāpili Bay two hours before any discharge occurs from Nāpili 4-5, presumably because there is less active storage volume in the Nāpili 2-3 basin (NRCS, 2011).



Source: State of Hawaii, DLNR, Dam Inventory System

Photo 2-1: Aerial photo of the Nāpili 2-3 basin

2.6.2 Nāpili 4-5 Basin

National Dam ID: HI00127

State Dam ID: MA-0127

Location: 20°59'32.56"N, 156°39'55.09"W

The Nāpili 4-5 Basin, "Structure #2," was constructed in 1985 for watershed protection (reduction of sediment and debris transport) and flood prevention. The basin is owned by the County of Maui, who has designated its Department of Public Works as the agency responsible for maintenance.

The basin was modified in 2011, under the direction of the Nāpili Bay and Beach Foundation and funding provided by the National Fish and Wildlife Foundation. The modification included a tri-level outlet valve for flow management and a grassed waterway to slow and filter runoff released from the outlet. During small storm events the valve can be set to allow longer retention time, which allows more sediment to settle out of the water column and prevent sediments from being discharged into nearshore waters. During larger storm events the valve can be adjusted and water can pass through. Since this modification, there has reportedly been no visible plumes near the outlet except for the runoff caused by Hurricane Olivia in September 2018 (Napili Bay and Beach Foundation). The Nāpili 4-5 dam is being considered for removal from the State Dam Safety Program because of its small size.



Source: State of Hawai'i, DLNR, Dam Inventory System

Photo 2-2: Aerial photo of the Nāpili 4-5 basinHonokeana Basin

Location: 20°59'24.60"N, 156°40'1.11"W

Honokeana Basin, "Structure #3," was constructed in 1997 for watershed protection (reduction of sediment and debris transport) and flood prevention. It is not regulated by the DLNR Dam Safety Program. The basin is owned by the County of Maui, who has designated its Department of Public Works as the agency responsible for maintenance. This basin has acceptable functioning to reduce sediment transport to

nearshore waters as it is appropriately sized for its drainage area. Below the outlet, water is causing erosion adjacent to Lower Honoapi‘ilani Road.



Source: Google Earth

Photo 2-3: Aerial photo of the Honokeana Basin

2.6.3 Ka‘ōpala Basin

National Dam ID: HI00134

State Dam ID: MA-0134

Location: 20°58'55.22"N, 156°40'13.45"W

The Kaʻōpala Basin, "Structure #4," was constructed in 1998 for watershed protection (reduction of sediment and debris transport) and flood prevention. The basin is owned by the County of Maui, who has designated its Department of Public Works as the agency responsible for maintenance. This basin is considered undersized and is constrained by site topography. The open outlet (Photo 2-5), located near the bottom of the reservoir basin, allows for sediment-laden water to pass through easily.

In September 2014, the University of Hawaiʻi at Mānoa, Water Resources Research Center collected sediment samples from Kaʻōpala Basin as part of an *Engineering Analysis and Development of Retrofit Designs for Sediment Retention at Honokōwai Structure #8*. The sample showed a relatively high percentage of gravel (23%), sand (57%) and much smaller amounts of silt and clay (20%). The composition may reflect gravel contributions from ridge activities or perhaps only the large sediments are settling out of the water. It is unclear when these samples were taken (if the basin was recently cleared, following a large storm event, or randomly).



Photo 2-4: Looking upstream at Ka‘ōpala Basin



Source: State of Hawai‘i, DLNR, Dam Inventory System

Photo 2-5: Upstream end of outlet intake, Ka‘ōpala Basin



Photo 2-6: Looking downstream at Ka‘ōpala Basin

2.6.4 Kahana Basin

National Dam ID: HI00126

State Dam ID: MA-0126

Location: 20°58'32.50"N, 156°40'19.04"W

The Kahana Basin, “Structure #5,” was constructed in 1984 for watershed protection (reduction of sediment and debris transport) and flood prevention. It has a 50-foot-high earthen dam and a maximum storage capacity of 73 million gallons. The basin outlet consists of a concrete structure with ports for trapping coarse debris. An emergency spillway south of the dam conveys water from high flow storm events to prevent overtopping of the earthen dam structure. The basin is considered undersized for its drainage area.

The basin is owned by the County of Maui, who has designated its Department of Public Works as the agency responsible for maintenance. Buried outlet pipes have previously prevented complete drying of the basin, which in turn prevented equipment from being able to remove sediments and results in significantly decreased retention volume. However, the basin was recently cleared out and the old valve accessed with funding provided by the National Fish and Wildlife Foundation. DPW has continued with the excavation work and is currently pursuing retrofitting the valve to improve operability.



Photo 2-7: Looking upstream at Kahana Basin

2.6.5 Pōhakukā‘anapali Basin

Location: 20°57'57.64"N, 156°40'42.65"W

Pōhakukā‘anapali Gulch is a small watershed located between the larger Kahana and Māhinahina watersheds. It empties a drainage area of approximately 0.6 mi^2 into the ocean south of Pōhaku Park. Upstream of Honoapi‘ilani Hwy, there is an earthen embankment dam similar in design to the Māhinahina Dam: the Pōhakukā‘anapali Basin, “Structure #5.” This impoundment is maintained by the County and is not regulated by the DLNR Dam Safety Program. Pōhakukā‘anapali Gulch is not one of the primary watersheds being evaluated under this study.

2.6.6 Māhinahina Basin

Location: 20°57'29.54"N, 156°40'51.61"W

Māhinahina Basin, “Structure #7” (Photo 2-8) was constructed in 1995 as part of the larger Honolua Watershed Project. It is owned by the County of Maui, who has designated its Department of Public Works (DPW) as the agency responsible for maintenance. It is not regulated by the State Dam Safety Program. The basin is effective at trapping fine sediments due to a long retention time and the orifice sizing of the outlet.

The dam was also designed to overtop during large storm events, as evidenced by the reinforced concrete dam face at the downstream side of the structure.

DPW mows the basin approximately once or twice per month. Sediment typically accumulates within the basin near the concrete embankment and is removed with a backhoe and loader approximately two or three times per year. The sediment level typically ranges between 1.5 to 2 feet at the time of removal but does not exceed 3 feet due to regular maintenance. An estimated 250 – 500 cubic yards (CY) of sediment is removed annually (this is roughly equivalent to a 6 inch deep layer of sediment covering between 13,500 – 27,000 square feet [ft^2] of land area). To alleviate berm erosion and subsequent sediment deposition that had been occurring on the perforated drainage pipe, a riprap wall was constructed around the pipe.



Photo 2-8: Māhinahina Basin, Looking northeast from the top of the embankment



Photo 2-9: Māhinahina Basin, inlet pipe



Photo 2-10: Māhinahina Basin, twin culverts under Honoapi‘ilani Hwy

2.6.7 Honokōwai Basin

National Dam ID: HI00130

State Dam ID: MA-0130

Location: 20°56'46.78"N, 156°41'0.50"W

Honokōwai Dam, Structure #8, is located in the Honokōwai watershed, approximately 2,600 ft from the Honokōwai shoreline. The facility is owned by the County of Maui, who has designated its Department of Public Works (DPW) as the agency responsible for maintenance. It was constructed in 1995 with the primary objective of reducing the sediment load transported to the ocean. The basin was sized for trap

efficiency and not for sediment volume over a period of time (requiring periodic removal of the sediment after each major storm event).

The basin outlet consists of a concrete structure with ports for trapping coarse debris cast incrementally in height along one side of the structure and larger overflow ports at the top of the structure that discharge into the principal outlet channel. An emergency spillway south of the dam conveys water at high flow storm events to prevent overtopping of the earthen dam structure.

DPW mows the basin and berm area on an as needed basis, with more mowing necessary during the winter months. Debris is removed from the concrete outlet structure an average of three times per year depending on the frequency of debris deposition form large storm events. Debris has been observed as mostly large, woody, and vegetative, as opposed to fine or coarse sediment. The water level has not been observed overtopping the dam, and debris has been observed on top of the concrete outlet structure approximately six times over a period of 20 years.



Photo 2-11: Aerial photograph of Honokōwai Dam Structure #8



Photo 2-12: Honokōwai Intake Structure

3 Geographic Information Systems Data

3.1 Datum and Projection

The datum and projection for this study is as follows:

Horizontal projection: State Plane Zone 2 (US Survey Feet)

Horizontal datum: NAD83 (PA11)

Vertical Datum for Land Applications: Local Tidal Datum – MSL

Tidal Epoch: 1983 – 2001

Geoid: 2012B

3.2 Elevation

The following sources of elevation data were used in this study:

Table 3-1: Elevation Data Type and Sources

Survey year	Agency	Data type	Location
2005 - 2013	State of Hawai'i	DTM	about 1.0 mi inland from coast
2013	USGS	DEM	United States

Light Detection and Ranging (LiDAR) data were provided by an online GIS database under the Hawai'i Statewide GIS Program. This database reflects a multi-agency effort to establish and promote the use of GIS technology in Hawai'i State Government, led by the State of Hawai'i, Office of Planning. A digital terrain model (DTM) was available to download, based on LIDAR collected by various agencies between 2005 and 2013 along the coast of West Maui.

Areas within the study area that were not covered by LIDAR were supplemented using an elevation raster from the USGS National Elevation Dataset (NED). The NED was developed by merging the highest resolution, best quality Digital Elevation Model (DEM) data available across the United States into a seamless raster format. Across the study area, digital elevation data was available at resolutions of 1/3 arc-second (approx. 10 meters). These data are distributed in geographic coordinates in units of decimal degrees, and in conformance with NAD83 (USGS).

3.3 Imagery

High resolution imagery used for background mapping of the study area is from DigitalGlobe, the National Geospatial-Intelligence Agency and the USGS. World Imagery, provided by Esri, was used for larger scale background mapping, such as when it was necessary to show the entire island of Maui.

3.4 Basin, subbasin and river delineation

GIS data were used to delineate the basins (Table 5-10), subbasins (Table 5-11) and rivers. Each basin was divided into subbasins based on key locations in the watershed (e.g. the location of a streamflow gage, junction, or existing detention basin).

Table 3-2: Basin identification and information

Basin ID	Basin name	Drainage area (mi^2)	Centroid location	
			Latitude	Longitude
1	Wahikuli	3.89	20.911475	-156.639656
2	Hanakaʻōʻō	3.37	20.928895	-156.657939
3	Honokōwai	5.80	20.929811	-156.632436
4	Māhinahina	1.80	20.948749	-156.650262
5	Kahana	4.35	20.952354	-156.635833
6	Kaʻōpala	0.812	20.967475	-156.642701
7A	Honokeana	0.554	20.978622	-156.652712
7B	Nāpili 4-5	0.814	20.974488	-156.640926
7C	Nāpili 2-3	0.433	20.983515	-156.646616
8	Honokahua	4.13	20.975677	-156.629628
10	Honolua	4.28	20.976841	-156.615055
12	Honokōhau	4.32	20.927803	-156.585456

Table 3-3: Subbasin identification and information

Subbasin ID	Basin name	Drainage area (mi^2)	Centroid location	
			Latitude	Longitude
1A	Wahikuli	0.237	20.914075	-156.68211
1B	Wahikuli	2.28	20.909011	-156.635398
1C	Wahikuli	1.37	20.915133	-156.639399
2A	Hanakaʻōʻō	0.679	20.929989	-156.673387
2B	Hanakaʻōʻō	2.69	20.928619	-156.654040
3A	Honokōwai	0.243	20.947352	-156.683530
3B	Honokōwai	1.56	20.930424	-156.641111
3C	Honokōwai	1.77	20.941118	-156.650151
3D	Honokōwai	2.23	20.918459	-156.606669
4A	Māhinahina	1.80	20.948749	-156.650262
5A	Kahana	0.060	20.97671	-156.673711
5B	Kahana	1.36	20.956836	-156.648874
5C	Kahana	2.92	20.949757	-156.628927
6A	Kaʻōpala	0.812	20.967475	-156.642701
7A	Honokeana	0.554	20.978622	-156.652712
7B	Nāpili 4-5	0.814	20.974488	-156.640926
7C	Nāpili 2-3	0.433	20.983515	-156.646616
8A	Honokahua	2.60	20.971047	-156.629524
8B	Honokahua	1.53	20.983527	-156.629806
10A	Honolua	0.386	21.008828	-156.632857
10B	Honolua	2.78	20.965825	-156.611664
10C	Honolua	1.11	20.993317	-156.617362
12A	Honokōhau	4.32	20.927803	-156.585456

3.5 Land Cover and Land Use

A general land cover and land use raster was developed by NOAA's Office for Coastal Management (OCM) in 2005 based upon high resolution (1 to 5 meter) aerial and satellite imagery. This raster was used to compute the directly connected impervious areas for the rainfall-runoff model (Section 5.3.2). A detailed land cover raster was also developed in 2010 by OCM but was not used in this study.

A detailed land cover raster was also provided by the Pacific Regional Integrated Sciences and Assessments (PAC-RISA) program, which provides land cover data representative of 2017 conditions and "future" land cover for four different scenarios: 1) a conservation-focused future, 2) a status-quo future, 3) a development-focused future, and 4) a future in which high native forest restoration and high urban development coexist. When comparing the "existing" 2017 land cover with "future" scenario 2 (status-quo), the change in land cover is not significant except for the extensive fallow agricultural lands becoming slightly grassed. There is also a reduction in agricultural lands in the lower Hanakaʻōʻō watershed, and a slight increase in agricultural lands in the lower Honokōwai lands (Brewington, 2018). The "existing" land cover raster, representative of 2017 conditions, was used to create the Manning's n layer in the hydraulic model (Section 8.2.3).

3.6 Soil Data

A water permeability shapefile provided by the Hawai'i Soil Data Atlas was used to determine initial loss rates for the hydrologic model, as described in Section 5.3.2 (University of Hawai'i, 2014). A soil classification survey raster was provided by the NRCS's Web Soil Survey (NRCS) and used to determine initial loss and transform parameters for the hydrologic model.

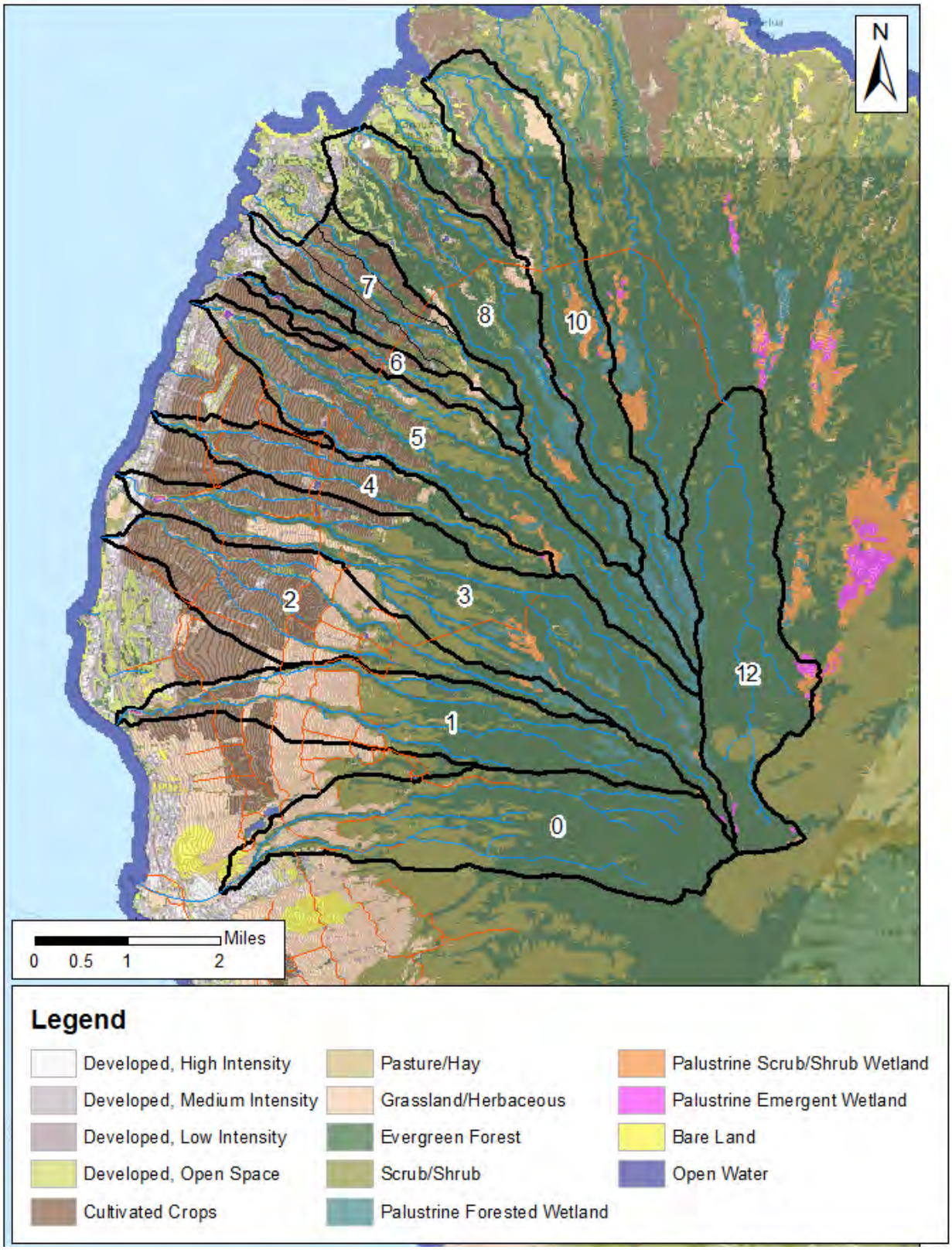


Figure 3-1: Land Cover Types in West Maui, Hawai‘i (OCM, 2005)

4 Data Collection

This section describes available climate, stream, and sediment data within the study area and the adjacent watersheds of Kahoma and Honokōhau. Due to the limited availability of streamflow records within the study area, the adjacent watersheds of Kahoma and Honokōhau were also included in the hydrologic analysis for comparative purposes.

4.1 Climate

Climate data (e.g. rainfall) was available at one USGS and four National Oceanic and Atmospheric Administration (NOAA) rain gages within or near the study area (NCEI). There are also four other rainfall stations located within the study area that are monitored by West Maui Ridge to Reef (R2R). These gages are listed in Table 4-1, identified in Figure 4-1, and each provide instantaneous data in either 5 or 15-minute intervals. Historical, instantaneous data were used to calibrate the hydrologic model (see Section 5.3.4).

Point precipitation data for annual exceedance rainfall was obtained from the National Weather Service's (NWS) NOAA Atlas 14 Precipitation-Frequency Data Server (PFDS). This source presents rainfall frequencies from recurrence intervals of 1 to 500 years (100% to 0.2% AEP) at various locations across the study area (NWS, 2014). The location points used to extract PFDS data were the approximate centroid locations for each subbasin (Table 5-11). This data was put into the calibrated hydrologic model to compute the peak flow estimates for various recurrence intervals.

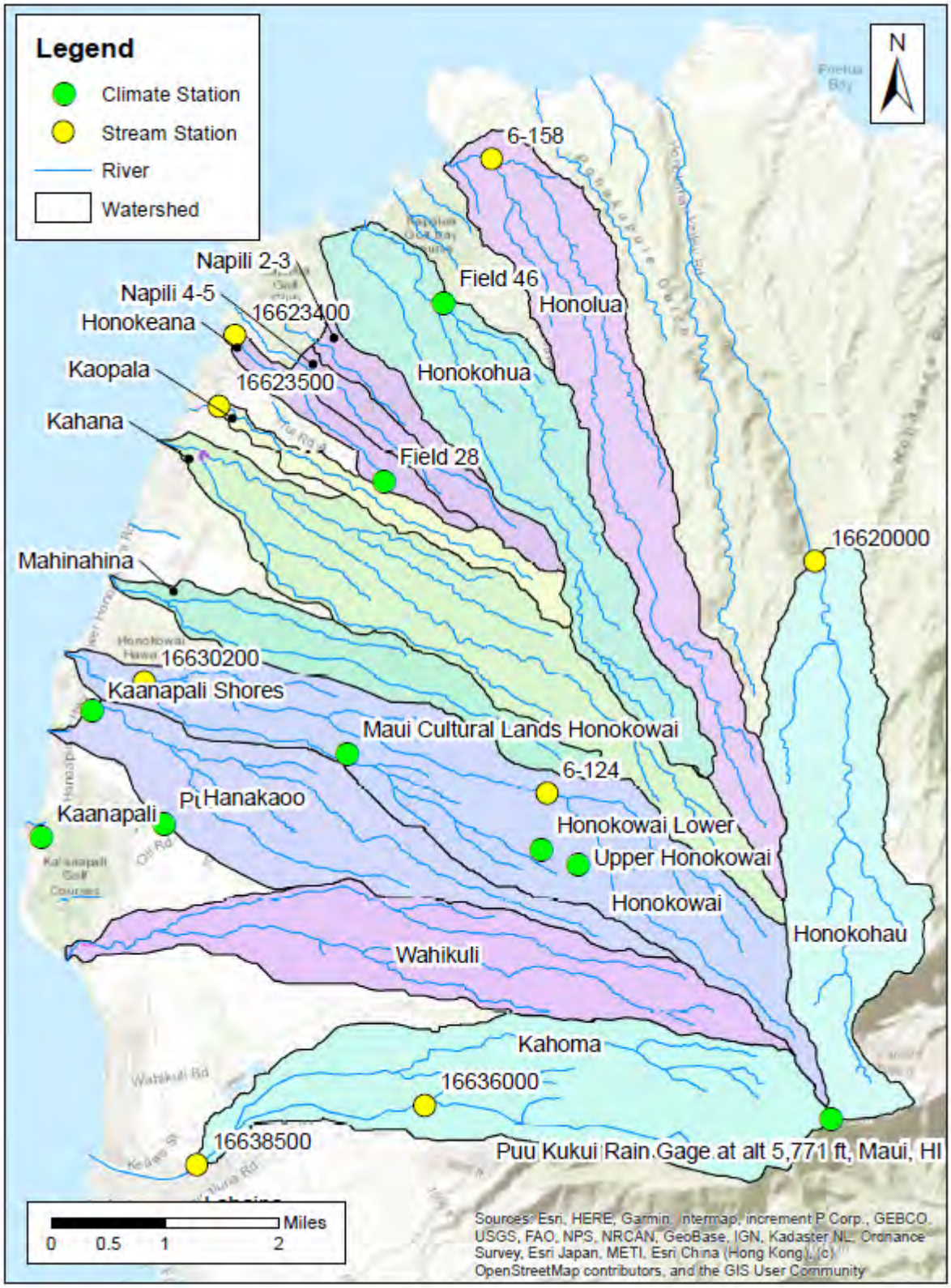


Figure 4-1: Climate and Stream Station Map

Table 4-1: Climate Station Inventory

Agency	Site Number / Network:ID	Site Name	Period of Record	Datum of gage (ft above LMSL[1])	Latitude	Longitude
USGS	2053271 56351102	380.0 Puʻu Kukui Rain Gage at alt 5,771 ft, Maui, HI	2005 – 2020	5,771	20.89083	-156.58638
NOAA	COOP:510530	Field 28 Reservoir 474.2, HI US	2006 – 2014	1,157	20.96722	-156.63750
NOAA	COOP:510541	Field 46 474, HI US	1978 – 2005	1,050	20.98888	-156.62750
NOAA	COOP:518407	Puʻukoliʻi 457.1, HI US	2002 – 2014	421	20.92861	-156.67361
NOAA	COOP:515177	Lahaina 361, HI US	1977 – 2001	11.6	20.8788	-156.6741
West Maui R2R	--	Upper Honokōwai	2016 –2020	2,951	20.92333	-156.62083
West Maui R2R	--	Maui Cultural Lands Honokōwai	2016 – 2020	900	20.93750	-156.65222
West Maui R2R	--	Kāʻanapali Shores	2016 –2018	19.6	20.94305	-156.68694
West Maui R2R	--	Honokōwai Lower	2016 –2020	2,602	20.92527	-156.62583

[1]: local mean sea level

4.2 Stream

There are three USGS stream gages within the study area: 16630200 in Honokōwai, 16623500 in Ka‘ōpala, and 16623400 in Honokahua. These crest-stage gages provide peak flow data at each site. However, the stream gage in Ka‘ōpala has only a single peak flow that is usable in its very short period of record (four years); and the stream gage at Honokahua is an older record (1965 – 1985).

There is, however, an instantaneous streamflow gage in one of the watersheds adjacent to the study area: 16620000 in Honokōhau. This gage provides continuous streamflow data in 5-minute intervals, with a period of record of 30 years (1990 to 2020). It also provides peak flow data for a period of record of 101 years (1914 – 2019, intermittently). All stream monitoring stations referenced in this study are identified in Table 4-2 and Figure 4-1.

Due to the limited availability of streamflow records within the study area, new stream monitoring stations (Figure 4-1; Photo 4-1) were installed at three sites in 2017, in partnership with West Maui R2R and the State of Hawai‘i, Department of Land and Natural Resources (DLNR), Commission on Water Resource Management (CWRM). These stations are still operated and maintained by CWRM today (as of March 2020). 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 (the water surface level in the stream) only. Rating curves (RCs) were developed by CWRM and USACE using different methods to compute the relation between stage and streamflow (discharge). CWRM’s rating curve was developed by taking periodic measurements of flow. As field measurements are not typically taken by personnel during significant events, the resulting RCs are biased towards smaller flows (the largest flow recorded at Honokōwai was 94.0 ft^3/s; and 89.1 ft^3/s at Honolua). CWRM’s RCs had reasonable accuracy for predicting flows of smaller events, but overpredicted flows for large events. Using the cross-section survey data taken in the field, USACE developed a simple, steady flow hydraulic model (Section 8.1) and tested it against twenty five (25) different flow profiles (0.1 to 20,000 ft^3/s). This method provided more reasonable flow estimates for larger events (applicable to stages 1-8 ft) but does not represent lower flow events well due to the type of model used and very simple

geometry it relies upon (four to five cross sections). In summary, the CWRM RC should be used to estimate low flow events or the annual flow simulation; and the USACE RC should be used to estimate medium flow events. Additional information regarding development of the USACE RC is provided in Section 8.1.



Photo 4-1: Stream monitoring station, Pāpua Gulch, Honolua Watershed (2017)

Table 4-2: Stream Station Inventory

Agency	Site Number	Site Name	Period of Record	Drainage Area (mi^2)	Latitude	Longitude
USGS	16630200	Honokōwai Stream at Honokōwai, Maui, HI	Peak Flow: 1961 – 2009	5.74	20°56'48"	-156°40'47"
USGS	16623500	Ka'ōpala Gulch near Nāpili, Maui, HI	Peak Flow: 2016 – 2020[1]	0.86	20°58'55"	-156°40'11"
USGS	16623400	Honokeana Gulch near Honokahua, Maui, HI	Peak Flow: 1965 – 1985	0.75	20°59'27"	-156°40'03"
USGS	16620000	Honokōhau Stream near Honokōhau, Maui, HI	Peak Flow: 1914 – 2019 Instantaneous: 1990 – 2021	4.18	20°57'44"	-156°35'19"
CWRM	6-124	Honokōwai Below Confluence	Instantaneous: 2017 – 2021		20.932457	-156.624945
CWRM	6-156	Honokōwai Below Dam	Instantaneous: 2017 – 2021[1]	unknown	unknown	unknown
CWRM	6-158	Honolua Above Highway	Instantaneous: 2017 – 2021		21.013493	-156.632455

[1]: usable data is very limited

4.2.1 **Significant Past Flow Events**

Figure 4-2 shows the annual peak flow record at the stream flow gaging station with the longest period of record: USGS 16620000, Honokōhau Stream. The historic maximum flow recorded at this gage was 12,200 ft^3/s on September 12, 2018, during Tropical Storm Olivia. This storm was the first tropical cyclone to make landfall on Maui in recorded history. There were no other events of significance in the recent past (within the last 30 years) at this site, with the second greatest peak flow occurring on January 28, 1988 (7,260 ft^3/s).

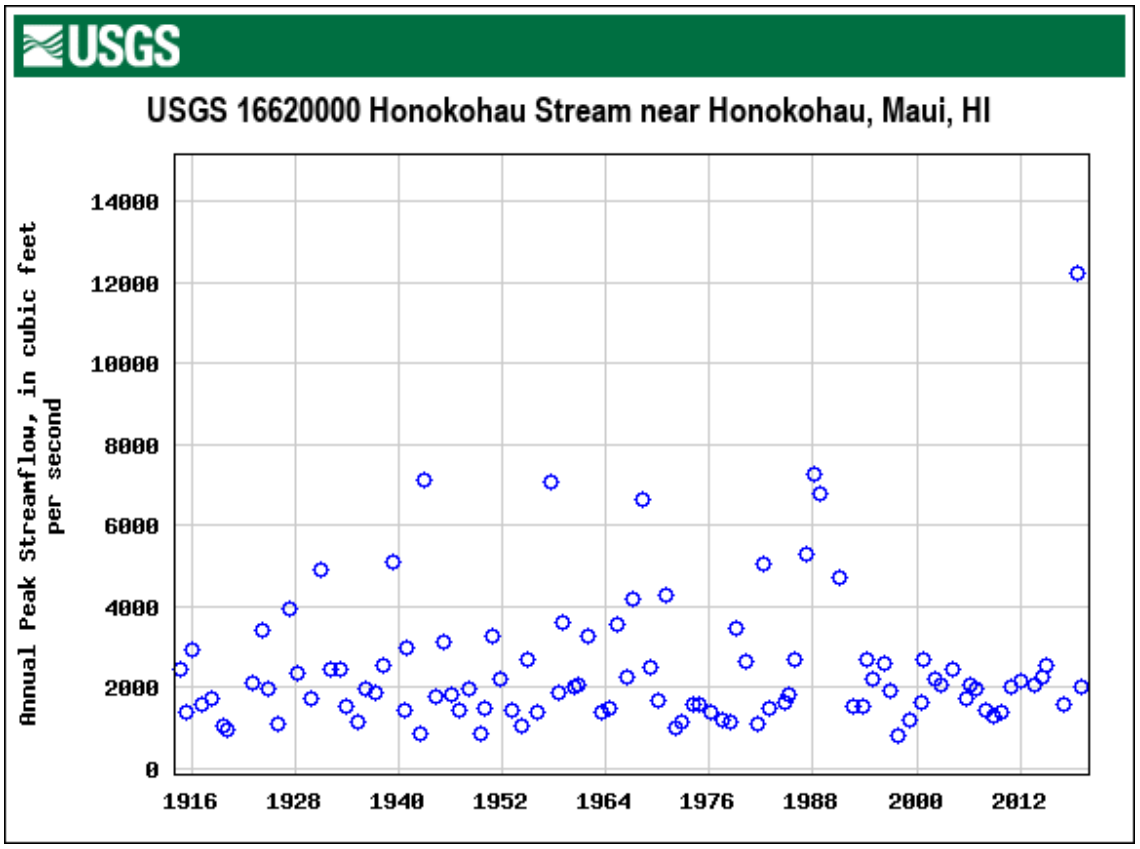


Figure 4-2: Peak stream flow at USGS 16620000

Stream gages were also installed at Honolua and Honokōwai in 2017 to provide continuous streamflow data for the study (Section 4.2). The peak events identified for calibration during this period are 24 October 2017, 20 December 2017, 24 August 2017, and 12 September 2018. Additional information on these events and model calibration is provided in Section 5.3.4, Reservoir Modeling.Sediment

4.2.2 **Sediment Impacts to Coral Reefs**

From a 2011 publication, *Impacts on Sediment on Coral Reefs*, there are essentially three ways in which sediments stress corals: 1) decreasing the available light and thereby also reducing the amount of energy supplied by the zooxanthellae to the coral host; 2) draining their metabolic system as the corals try to rid themselves of the sediment by ciliary action, tentacle waving, or mucus sheet secretion; and 3) increasing bacterial activity and the virulence of disease (Risk & Edinger, pp. 578 - 579). Different sediments exert greatly contrasting levels of stress on the corals, depending on the grain size, organic content, and geochemistry. Clay- and silt-sized sediments have a greater negative impact to corals as they settle more slowly and are more susceptible to resuspension thereby reducing light transmission for a longer period (Storlazzi, Norris, & Rosenberger, 2015). Tissue damage under a layer of sediment increases with decreasing grain size (Risk & Edinger, 2011, p. 579). Additionally, finer-grained sediments can be more difficult for coral to remove. A study by Weber et al. (2006) found that photophysiological stress was measurable after 36 hours of exposure to most of the silt-sized sediments, and coral recovery was incomplete after 48 to 96 hours recovery time. In contrast, sandy sediment types caused no measurable stress at the same concentration for the same exposure time. Fine-grained sediments, such as clays and silts, should be targeted for removal for the greatest impact to improving coral health.

4.2.3 **Frequency of Sediment Plumes**

4.2.3.1 Rainfall Analysis

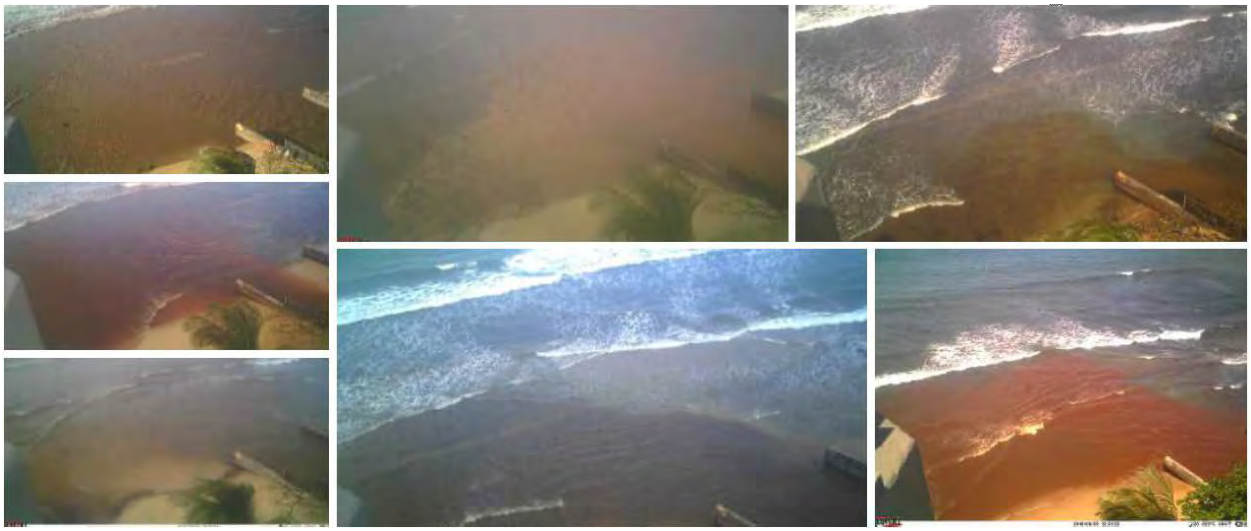
A rainfall analysis was performed by the USGS to evaluate the frequency of rainfall events that resulted in coastal sediment plumes. Such events were predicted to occur when two or more hours of rain falls at rates greater than 10-20 mm/hr (0.4-0.8 in/hr) in source watersheds. Based on the average rainfall record at the Field 46 and Lahaina climate stations (Table 4-1), two-hour intensities above 10 mm/hr (0.4 in/hr) happened about three times a year in the northern wet side (at Field 46) and about once a year to the south (at Lahaina). These values are slightly lower than the 4-5 times/year recurrence interval suggested by the recent record (2014 – 2016) of the various West Maui R2R

climate stations (Table 4-1), located in the southern watersheds. This suggests that West Maui can expect rainfalls that generate plumes to occur between 3 and 5 times a year.

A small number of these storms also have higher rainfall intensities capable of eroding agricultural fields for an hour or longer. These occurred four to five times per decade during the 1980s and 2000s, but only twice during the 1990s. Although past large storms have contributed to sediment loading, annual plume generation is now caused by smaller rainfalls eroding near-stream terrace deposits, a legacy of historic agriculture (Stock & Cerovski-Darriau, 2020).

4.2.3.2 Coastal Camera Analysis

In 2017, cameras were installed along the West Maui shoreline to capture daily photos at the river outlets of Wahikuli, Honokōwai, Kahana, and Kaʻōpala Stream (Photo 4-2). This data was reviewed by West Maui R2R who provided the following summary of how often plumes occurred during the period of record (Table 4-3). There are significant data gaps in the period of record (Table 4-4), 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.



Source: West Maui R2R

Photo 4-2: Plume events captured by coastal cameras at the Honokōwai outlet

Table 4-3: Summary of Observed Sediment Plumes at Various Locations in West Maui

Year	Wahikuli		Honokōwai		Kahana		Ka‘ōpala		Averages	
	# of Events	# of Months	# of Events	# of Months	# of Events	# of Months	# of Events	# of Months	# of Events	# of Months
2017	6	3	25	3	7	1	6	3	11	2.5
2018	28	12	65	10	24	12			39	11.3
2019	7	9	20	11	12	9			13	7.25
2020	1	9	25	12	4	2			7.5	5.75
2021	1	2	14	5	3	3				
	43	35	149	41	50	27				

# of Events = the number of days a sediment plume was observed

# of Months = the number of months included in the record

Table 4-4: Summary of Data Gaps for the Coastal Camera Period of Record

Camera #	Site	Period of Record	Data Gaps
1	Wahikuli	28 Sep 2017 to present	22 March 2019 to 21 June 2019; 4 October 2019 to 10 January 2020; 15 May 2020 to 6 November 2020
3	Honokōwai	25 Sep 2017 to 23 March 2021	6 June 2018 to 27 July 2018; 28 June 2019 to 8 August 2019; 24 March 2021 to 2 August 2021
7	Kahana	27 Sep 2017 to present	4 October 2019 to 24 January 2020; 3 March 2020 to 6 November 2020; 31 April 2021 to 19 May 2021
5	Ka‘ōpala	26 Sep 2017 to 6 July 2018	

4.2.4 **Land-Based Sediment Characteristics**

4.2.4.1 Field Survey of Historic Fill Terraces

As documented in Scientific Investigation Report (SIR) 2020-5133 by USGS, *Sediment Budget for Watersheds of West Maui, Hawaii*, the extent of bank erosion was estimated by surveying the extent of historic fill terraces in four valleys: Honokōwai Stream, Ka‘ōpala Gulch, lower Honolua Stream, and Pāpua Gulch (a tributary of Honolua Stream). Surveys showed that fill terraces occupy approximately forty percent (40%) of streambank length (Stock & Cerovski-Darriau, 2020).

4.2.4.2 Erosion Pin Test

As documented in the 2019 Scientific Investigation Report (SIR) by USGS, *Sediment Budget for Watersheds of West Maui, Hawaii*, 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. 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 4-5). The median lowering rate for all three sites on the "wet side" was estimated to be 14 mm/yr (Stock & Cerovski-Darriau, 2020).

Table 4-5: 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

4.2.4.3 Cohesive Strength Meter "Jet" Test

In 2017, USACE requested assistance from USGS in performing 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 (Table 4-6). 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 (Table 4-7). 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).

Table 4-6: CSM test site locations

Location	Latitude	Longitude
Wahikuli Stream	20.913024	-156.688887
Honokōwai Stream	20.946716	-156.681593
Māhinahina Gulch	20.958245	-156.679406
Honolua Stream	21.014066	-156.634614
Lower Pāpua	21.012899	-156.630574
Upper Pāpua	21.012746	-156.62797



Source: USGS, SIR 2019

Photo 4-3: The Cohesive Strength Meter test deployed at a fill terrace in Wahikuli

Table 4-7: Bank material cohesion

Location	Cohesion							
	90%		75%		50%		25%	
	PSI	kPA	PSI	kPA	PSI	kPA	PSI	kPA
Wahikuli Stream	0.04	0.3	0.09	0.6	0.11	0.8	0.16	1.1
Honokōwai Stream	0.06	0.4	0.10	0.7	0.17	1.2	0.36	2.5
Māhinahina Gulch	0.17	1.2	0.29	2.0	0.38	2.6	0.38	2.6
Honolua Stream	0.02	0.2	0.05	0.3	0.22	1.5	0.54	3.7
Lower Pāpua	0.10	0.7	0.21	1.4	0.22	1.5	0.40	2.7
Upper Pāpua	0.14	1.0	0.30	2.1	0.30	2.1	0.49	3.4
Average	0.09	0.61	0.17	1.18	0.24	1.62	0.39	2.68

After testing, sediment at each site were analyzed for particle size distribution (Table 4-8; Table 4-9). At some sites, two samples were analyzed.

Table 4-8: Mean and median (D_{50}) particle sizes of fill terrace sediments

Site	Classification	Mean (mm)	Median (mm)	Standard deviation (mm)
Wahikuli	Loam	0.73	0.42	1.09
Honokōwai	Silt loam	0.73	0.32	1.22
		0.75	0.31	1.36
Māhinahina	Sandy loam	1.14	0.57	1.63
		0.92	0.48	1.29
Honolua	Silt loam	0.74	0.33	1.29
		0.66	0.34	1.01
Lower Pāpua	Gravelly sandy loam	0.96	0.48	1.50
Upper Pāpua	Sandy loam	1.43	0.68	2.30

Table 4-9: Particle size distribution of fill terrace sediment samples by soil classification

Site	Soil texture	Clay	Silt	Very fine sand	Fine sand	Medium sand	Coarse sand	Very coarse sand	Gravel
		< 0.002 mm	0.002-0.05 mm	0.05-0.1 mm	0.1-0.25 mm	0.25-0.5 mm	0.5-1 mm	1-2 mm	> 2 mm
Wahikuli	Loam	7.37	46.00	23.46	14.66	3.49	1.38	0.06	3.58
Honokōwai	Silt loam	9.16	52.18	17.25	11.69	4.25	2.15	0.25	3.07
		8.85	51.84	17.81	11.88	4.47	2.05	0.02	3.07
Māhinahina	Sandy loam	6.38	39.77	20.67	20.81	7.64	4.08	0.32	0.33
		6.88	44.19	20.74	19.07	6.45	2.20	0.14	0.33
Honolua	Silt loam	8.93	50.26	19.16	13.34	3.65	2.08	0.21	2.37
		9.06	50.34	20.60	12.65	3.84	1.13	0.02	2.37
Lower Pāpua	Gravelly sandy loam	5.67	36.91	18.57	14.42	5.15	2.19	0.34	16.75
Upper Pāpua	Sandy loam	4.85	33.49	21.76	20.94	5.96	4.69	2.11	6.21
	Mean	7.46	45.0	20.0	15.5	4.99	2.43	0.386	4.23

4.2.4.4 Sediment Deposit Samples

Three surface (0 – 5 cm) soil samples were collected in July 2014 and analyzed for particle size distribution for the *Engineering Analysis and Development of Retrofit Designs of Honokōwai Structure #8* (Babcock, et al.). The first sample was collected from within the Māhinahina Basin; the second from a kickout area of an agricultural road above on the Lahaina side of Honokōwai Stream; and the third sample was collected from the Ka‘ōpala Basin. The particle size distribution of the collected samples are provided in Table 4-10.

Table 4-10: Particle Size Distribution of Collected Samples

Sample #	Location	Gravel	Sand	Medium Silt	Small Silt	Clay
1	Māhinahina Basin	5.0	17.2	14.0	15.5	48.3
2	Honokōwai Agricultural Road	3.4	23.6	24.7	21.7	26.6
3	Ka‘ōpala Basin	23.0	57.4	6.2	1.4	12.0

4.2.5 **Sediment Budget**

The final sediment budget estimated by USGS (Table 4-11) 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, 2020).

Table 4-11: USGS sediment budgets for West Maui watersheds

USACE Basin / Subbasin ID	USGS Basin ID	Watershed name	Total area (km^2)	Estimate of annual storm mass load from bank erosion[1] (metric tons/yr)	Hypothetical decadal storm mass load annualized[1] (metric tons/yr)	Hypothetical decadal storm mass load[1] (metric tons)
10	2	Honolua	11.00	91	180	1800
8A	9	Honokahua	6.65	45	37	370
8B	8	Honokahua	4.03	46	33	330
7A	16	Honokeana	1.94	43	25	250
7B	14	Nāpili 4-5	2.41	56	28	280
7C	13	Nāpili 2-3	1.98	44	21	210
6	20	Kaʻōpala	2.36	62	27	270
5	22	Kahana	11.68	285	125	1250
4	26	Māhinahina	5.00	45	60	600
3	28	Honokōwai	15.20	62	106	1060
2A	30	Hanakaʻōʻō	5.94	26	63	630
2B	31	Hanakaʻōʻō	1.65	25	22	220
1	35	Wahikuli	10.42	42	70	700
1: assumes 1300 kg/m^3 bulk density						

5 Flood Frequency Analysis

Methods for estimating the peak flow for the 99%, 50%, 20%, 10%, 4%, 2%, 1%, 0.4%, and 0.2% AEP (1- 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-year) flood events (9 profiles) include the following:

1. Stream gage analysis
2. Regional regression equations
3. Rainfall-runoff model

Other peak flow estimates previously published (for reference):

1. 2015 Flood Insurance Study (FIS)

5.1 Stream Gage Analysis

Annual peak flow data from three stream gages in or near the study area were analyzed individually using methodology from Bulletin 17C (USGS, 2019) as applied by the Hydrologic Engineering Center's Statistical Software Package (HEC-SSP) program (version 2.2, HEC, 2019). A Bulletin 17C analysis offers the opportunity to use intervals or thresholds to represent the magnitudes of flood peaks that might be known with less precision, such as historical flood data. There is no known additional historical flood data to add to the record. Thresholds were added to indicate all other floods that may have occurred during data gaps in the record. The weighted skew option was used, which weights the computed station skew with the generalized regional skew. A generalized skew value of -0.05 and mean-square error of 0.302 was used per the national map in Bulletin 17B and verified by USGS in 2010 (Oki, Rosa, & Yeung). Table 5-1 contains the number and names of the stream-gaging stations upon which a Bulletin 17C analysis was performed. Table 5-2, Table 5-3, and Table 5-4 contain the results from completing the analysis.

Table 5-1: Relevant stream gages

Site Number	Site Name	Period of record	No. years of usable record	Drainage area (mi^2)
16630200	Honokōwai Stream at Honokōwai, Maui, HI	1961 – 2009	47	5.74
16623400	Honokeana Gulch near Honokahua, Maui, HI	1965 – 1985	22	0.75
16620000	Honokōhau Stream near Honokōhau, Maui, HI	1914 – 2019	101	4.18

Table 5-2: Peak flow estimates computed using Bulletin 17C methodology for USGS 16630200, Honokōwai Watershed

Annual Exceedance Probability (AEP)	Computed Curve Flow in ft^3/s	Variance Log	Confidence Limits	
			0.05	0.95
1/500	6,469	0.03554	20,009	3,796
1/200	4,805	0.02506	12,084	3,044
1/100	3,784	0.01857	8,185	2,533
1/50	2,932	0.01329	5,498	2,069
1/25	2,226	0.00917	3,655	1,648
1/10	1,476	0.00538	2,087	1,155
1/5	1,022	0.00364	1,328	826
1/2	530	0.00251	645	438
Station Skew: 0.516 | Regional Skew: -0.050 | Weighted Skew: 0.330				

Table 5-3: Peak flow estimates computed using Bulletin 17C methodology for USGS 16623400, Honokahua Watershed

Annual Exceedance Probability (AEP)	Computed Curve Flow in ft^3/s	Variance Log	Confidence Limits	
			0.05	0.95
1/500	2,764	0.13327	37,422	1,000
1/200	1,918	0.10166	17,437	781
1/100	1,412	0.08062	9,527	625
1/50	1,004	0.06207	4,941	484
1/25	683	0.04607	2,460	357
1/10	371	0.02917	914	214
1/5	206	0.02054	408	124
1/2	64.2	0.02226	103	16.9
Station Skew: -0.564 | Regional Skew: -0.050 | Weighted Skew: -0.169				

Table 5-4: Peak flow estimates computed using Bulletin 17C methodology for USGS 16620000, Honokōhau Watershed

Annual Exceedance Probability (AEP)	Computed Curve Flow in ft^3/s	Variance Log	Confidence Limits	
			0.05	0.95
1/500	14,305	0.01374	27,722	10,198
1/200	11,133	0.00934	18,943	8,380
1/100	9,127	0.00668	14,137	7,148
1/50	7,409	0.00456	10,502	6,024
1/25	5,935	0.00295	7,758	4,998
1/10	4,300	0.00155	5,140	3,767
1/5	3,250	0.00096	3,704	2,912
1/2	2,018	0.00061	2,221	1,838
Station Skew: 0.796 | Regional Skew: -0.050 | Weighted Skew: -0.422				

5.2 Regional Regression Equations

In 2010, the U.S. Geological Survey published *Flood Frequency Estimates for Streams on Kaua'i, O'ahu, Moloka'i, Maui, and Hawaii, State of Hawaii*, which includes regional regression equations for estimating peak flow for the 50%, 20%, 10%, 4%, 2%, 1%, and 0.2% AEP (2-, 5-, 10-, 25-, 50-, 100-, and 500-year) flood events (7 profiles). The Wahikuli, Hanaka'ō'ō, and Honokōwai watersheds are located in the central-southwestern region of Maui, *Region 7*, and the other watersheds in the study area are located in the eastern-northwestern region of Maui, *Region 8*. The equations for each region are presented in Table 5-5 and Table 5-6, respectively. Results of using these equations to estimate peak flow at each subbasin are presented in Table 5-7 through Table 5-8.

Table 5-5: Regional regression equations for peak flow estimates in Region 7

Regression equation	Range of explanatory variables	Standard error of prediction, in percent	R^2	Standard model error, in percent
$Q_2=55.46\ (DA^{0.506})$	$0.45 \leq DA \leq 18.6$	320	0.07	270
$Q_5=162.9(DA^{0.638})$	$0.45 \leq DA \leq 18.6$	99	0.50	87
$Q_{10}=276.7(DA^{0.691})$	$0.45 \leq DA \leq 18.6$	62	0.73	52
$Q_{25}=463.4(DA^{0.731})$	$0.45 \leq DA \leq 18.6$	55	0.80	44
$Q_{50}=638.3(DA^{0.750})$	$0.45 \leq DA \leq 18.6$	59	0.79	48
$Q_{100}=843.3(DA^{0.764})$	$0.45 \leq DA \leq 18.6$	67	0.76	54
$Q_{500}=1{,}459(DA^{0.787})$	$0.45 \leq DA \leq 18.6$	89	0.71	73

Q_T = peak discharge for T-year recurrence interval
DA = drainage area, in square miles
$a < DA < b$ = the drainage area may be greater than or equal to a and less than or equal to b

Table 5-6: Regional regression equations for peak flow estimates in Region 8

Regression equation	Range of explanatory variables	Standard error of prediction, in percent	R^2	Standard model error, in percent
$Q_2=602.6(DA^{0.885})$	$0.09 \leq DA \leq 17.2$	93	0.64	90
$Q_5=1038(DA^{0.831})$	$0.09 \leq DA \leq 17.2$	70	0.71	68
$Q_{10}=1380(DA^{0.804})$	$0.09 \leq DA \leq 17.2$	66	0.72	64
$Q_{25}=1875(DA^{0.776})$	$0.09 \leq DA \leq 17.2$	65	0.72	63
$Q_{50}=2280(DA^{0.759})$	$0.09 \leq DA \leq 17.2$	67	0.71	65
$Q_{100}=2716(DA^{0.744})$	$0.09 \leq DA \leq 17.2$	70	0.69	67
$Q_{500}=3,828(DA^{0.717})$	$0.09 \leq DA \leq 17.2$	79	0.64	76

Q_T = peak discharge for T-year recurrence interval

DA = drainage area, in square miles

$a < DA < b$ = the drainage area may be greater than or equal to a and less than or equal to b

Table 5-7: Peak flow estimates at various basin outlets, computed using regional equations

Basin ID	Watershed	Drainage area (mi^2)	Region	Peak flow (ft^3/s)[1]						
				1/2	1/5	1/10	1/25	1/50	1/100	1/500
1	Wahikuli	3.89	7	110	388	707	1,250	1,770	1,800	4,250
2	Hanakaʻōʻō	3.37	7	103	354	641	1,130	1,590	1,610	3,800
3	Honokōwai	5.80	7	135	500	932	1,680	2,390	2,450	5,820
4	Māhinahina	1.80	8	74.7	237	415	712	992	1,000	2,320
5	Kahana	4.35	8	117	416	764	1,360	1,920	1,960	4,640
6	Kaʻōpala	0.812	8	49.9	143	240	398	546	544	1,240
7	Honokeana	1.80	8	74.7	237	415	712	992	1,000	2,320
8	Nāpili 4-5	4.13	8	114	403	737	1,310	1,850	1,890	4,450
10	Nāpili 2-3	4.28	8	116	412	756	1,340	1,900	1,940	4,580
12	Honokahua	4.32	8	2,200	3,500	4,480	5,840	6,920	8,070	10,900

[1]: rounded to three significant figures

Table 5-8: Subbasin peak flow estimates, computed using regional equations

Subbasin ID	Drainage area (mi^2)	Peak flow (ft^3/s)[1]						
		1/2	1/5	1/10	1/25	1/50	1/100	1/500
1A	0.237	26.8	65.0	102	162	217	212	470
1B	2.28	84.2	276	489	846	1,180	1,200	2,790
1C	1.37	65.0	199	344	583	808	812	1,870
2A	0.679	45.6	127	212	349	477	475	1,080
2B	2.69	91.5	306	548	955	1,340	1,360	3,180
3A	0.243	27.1	66.1	104	165	221	217	479
3B	1.56	69.5	216	376	641	891	897	2,070
3C	1.77	74.0	234	411	703	980	987	2,290
3D	2.23	83.2	272	482	833	1,160	1,180	2,740
4A	1.80	1,010	1,690	2,210	2,960	3,560	4,210	5,830
5A	0.060	50.0	100	144	211	269	335	509
5B	1.36	791	1,340	1,770	2,380	2,880	3,410	4,770
5C	2.92	1,560	2,530	3,270	4,310	5,140	6,030	8,250
6A	0.812	501	873	1,170	1,600	1,950	2,330	3,300
7A	0.554	357	635	858	1,190	1,460	1,750	2,510
8A	2.60	1,400	2,300	2,980	3,940	4,710	5,530	7,590
8B	1.53	878	1,480	1,940	2,610	3,150	3,730	5,190
10A	0.386	260	471	642	896	1,110	1,340	1,930
10B	2.78	1,490	2,430	3,140	4,150	4,950	5,810	7,970
10C	1.11	661	1,130	1,500	2,030	2,470	2,940	4,130
12A	4.32	2,200	3,500	4,480	5,840	6,920	8,070	10,900

[1]: rounded to three significant figures

Table 5-9: Peak flow estimates for key locations in the study area, computed using regional equations

HMS Element	Location	Drainage area (mi^2)	Region	Peak flow (ft^3/s)[1]						
				1/2	1/5	1/10	1/25	1/50	1/100	1/500
CWRM 6-124	Stream gage at Upper Honokōwai	2.23	7	83.2	272	482	833	1,160	1,180	2,740
CWRM 6-158	Stream gage at Honolua	3.89	8	110	388	707	1,250	1,770	1,800	4,250
Wahikuli Junction	Lower confluence at Wahikuli	3.65	7	107	372	677	1,190	1,690	1,720	4,040
Honokōwai Dam	Honokōwai Basin Inflow	5.56	7	132	487	905	1,620	2,310	2,370	5,630
Kahana Dam	Kahana Basin Inflow	4.28	8	116	412	756	1,340	1,900	1,940	4,580
USGS -0000	Stream gage Honokōwai	4.18	8	114	406	743	1,320	1,870	1,900	4,500
USGS -0200	Stream gage at Honokōhau	5.74	7	134	497	926	1,660	2,370	2,430	5,770
USGS -3400	Stream gage at Honokeana	0.75	8	47.9	136	227	376	514	512	1,160
[1]: rounded to three significant figures										

5.3 Rainfall-Runoff Model

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, Hanaka'ō'ō, Honokōwai, Māhinahina, Kahana, Ka'ōpala, 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 watershed (Section 5.1) 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 and are presented in Section 5.3.

5.3.1 **Basin Characteristics**

GIS data were used to delineate the basins (Table 5-10), subbasins (Table 5-11) and rivers. Each basin was divided into subbasins based on key locations in the watershed (e.g. the location of a streamflow gage, junction, or existing detention basin). The basin model layout created in HEC-HMS is provided in Figure 5-1.

Table 5-10: Basin identification and information

Basin ID	Basin name	Drainage area (mi^2)	Centroid location	
			Latitude	Longitude
1	Wahikuli	3.89	20.911475	-156.639656
2	Hanakaʻōʻō	3.37	20.928895	-156.657939
3	Honokōwai	5.80	20.929811	-156.632436
4	Māhinahina	1.80	20.948749	-156.650262
5	Kahana	4.35	20.952354	-156.635833
6	Kaʻōpala	0.812	20.967475	-156.642701
7A	Honokeana	0.554	20.978622	-156.652712
7B	Nāpili 4-5	0.814	20.974488	-156.640926
7C	Nāpili 2-3	0.433	20.983515	-156.646616
8	Honokahua	4.13	20.975677	-156.629628
10	Honolua	4.28	20.976841	-156.615055
12	Honokōhau	4.32	20.927803	-156.585456

Table 5-11: Subbasin identification and information

Subbasin ID	Basin name	Drainage area (mi^2)	Centroid location	
			Latitude	Longitude
1A	Wahikuli	0.237	20.914075	-156.68211
1B	Wahikuli	2.28	20.909011	-156.635398
1C	Wahikuli	1.37	20.915133	-156.639399
2A	Hanakaʻōʻō	0.679	20.929989	-156.673387
2B	Hanakaʻōʻō	2.69	20.928619	-156.654040
3A	Honokōwai	0.243	20.947352	-156.683530
3B	Honokōwai	1.56	20.930424	-156.641111
3C	Honokōwai	1.77	20.941118	-156.650151
3D	Honokōwai	2.23	20.918459	-156.606669
4A	Māhinahina	1.80	20.948749	-156.650262
5A	Kahana	0.060	20.97671	-156.673711
5B	Kahana	1.36	20.956836	-156.648874
5C	Kahana	2.92	20.949757	-156.628927
6A	Kaʻōpala	0.812	20.967475	-156.642701
7A	Honokeana	0.554	20.978622	-156.652712
7B	Nāpili 4-5	0.814	20.974488	-156.640926
7C	Nāpili 2-3	0.433	20.983515	-156.646616
8A	Honokahua	2.60	20.971047	-156.629524
8B	Honokahua	1.53	20.983527	-156.629806
10A	Honolua	0.386	21.008828	-156.632857
10B	Honolua	2.78	20.965825	-156.611664
10C	Honolua	1.11	20.993317	-156.617362
12A	Honokōhau	4.32	20.927803	-156.585456

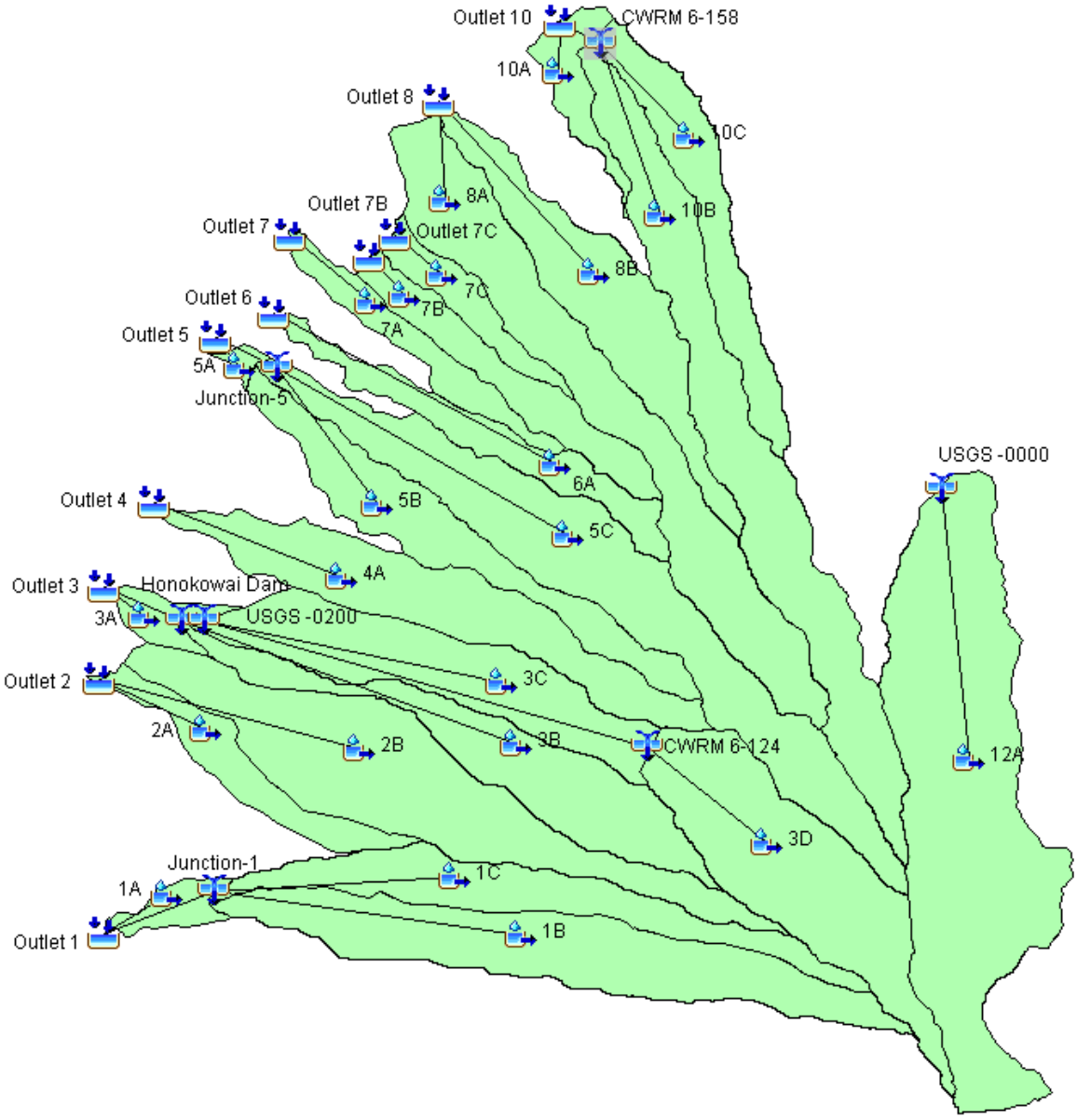


Figure 5-1: HEC-HMS Basin Model Layout

5.3.2 **Initial estimation for loss parameters**

The initial and constant loss methods were applied to the model to account for precipitation loss due to infiltration. This approach uses three parameters: initial loss, constant rate, and percent impervious area. The initial loss, the amount of precipitation lost to the soil at the beginning of the rainfall event, depends on the saturation of the soil and varies for each event. 0.1 inches of precipitation was assumed to be the initial loss due to absorption of the soil.

The constant loss rates were determined using soil data from the Hawai'i Soil Data Atlas, an interactive and online tool for providing basic information about each soil type (University of Hawai'i, 2014). Each soil type had previously been classified by their saturated hydraulic conductivity (Ksat) as either slow (< 3 micrometers per second; µm/s), moderate (3 to 10 µm/s), fast (10 to 100 µm/s), or very fast (> 100 µm/s). Only fast and moderate soil types were found in the study area. A geospatial shapefile provided by the Hawai'i Soil Data Atlas was used to compute a weighted average Ksat for each subbasin, and then converted to the appropriate units – inches per hour (in/hr). Results are provided in Table 5-12.

Table 5-12: Initial constant loss rates

Subbasin ID	Saturated hydraulic conductivity, Ksat (µm/s)	Constant loss rate (in/hr)
1A	9.47	1.34
1B	20.7	2.93
1C	22.1	3.13
2A	13.9	1.96
2B	17.8	2.52
3A	13.0	1.84
3B	15.2	2.15
3C	12.7	1.80
3D	39.9	5.65
4A	14.8	2.10
5A	13.7	1.95
5B	19.0	2.70
5C	29.4	4.17
6A	19.1	2.71
7A	13.0	1.84
7B	17.1	2.43
7C	15.7	2.22
8A	30.4	4.31
8B	25.5	3.61
10A	18.4	2.60
10B	36.0	5.10
10C	25.8	3.65
12A	29.2	4.13

NRCS's Technical Release 55 (TR-55) identifies typical percentages of directly connected impervious areas (DCIA) for various land cover types. A land cover raster (Section 3.5) was used to compute the weighted average DCIA based on the various land cover classifications (Table 5-13) within each subbasin. Results are provided in Table 5-14.

Table 5-13: Directly connected impervious areas by land cover type

Land cover	Directly connected impervious area (%)
Developed, Open Space	< 20
Developed, Low Intensity	20 – 49
Developed, Medium Intensity	50 – 79
Developed, High Intensity	80 – 100

Table 5-14: Directly connected impervious areas for each subbasin

Subbasin ID	Directly connected impervious area (%)
1A	7.87
1B	0.443
1C	0.150
2A	4.55
2B	1.52
3A	18.74
3B	0.827
3C	1.80
3D	0.031
4A	3.02
5A	24.8
5B	2.35
5C	0.809
6A	1.71
7A	10.7
7B	14.6
7C	22.7

Table 5-15 (cont.): Directly connected impervious areas for each subbasin

Subbasin ID	Directly connected impervious area (%)
8A	3.27
8B	1.69
10A	5.32
10B	0.417
10C	0.583
12A	0.017

5.3.3 Initial estimation for transform parameters

The excess precipitation in each subbasin was transformed into surface runoff by applying the SCS Unit Hydrograph method in the hydrologic model. This method was selected because it requires only a single parameter (Lag time, t_L) that could easily be determined based on the GIS data available for the study area. Other transform methods, such as Clark's Unit Hydrograph, would be difficult to apply as it relies upon distinguishing between sheet, shallow, and channel flow using elevation data that does not define channels clearly in the middle and upper watershed. t_L represents the time between the center of the mass of rainfall excess (about in the middle of the rainfall event) to the peak discharge (when there is the greatest amount of flow in the channel) and was estimated using the SCS lag equation, given as:

$$t_L = \frac{L^{0.8}(S+1)^{0.7}}{1900\,(Y)^{0.5}}$$

where: t_L = lag time in hours (hrs)

L = length of the longest drainage path in feet (ft)

S = potential maximum retention in inches, (1000/CN)-10

CN = the average curve number for the subbasin

Y = the average subbasin slope in percent (%)

The average curve number for the subbasin, CN, was determined by using the general land cover and land use raster (Section 3.5) and soil properties shapefile (Section 3.6). Individual curve numbers were assigned to specific areas based on their land cover classification and hydrologic soil group, as presented in Table 5-15 (NRCS, 1986).

The average subbasin slope was determined by creating a slope raster from the USGS NED raster (Section 3.2) and then applying the "Zonal Statistics" tool to calculate the average slope for each subbasin.

Table 5-16: Representative curve numbers for various land cover types

NLCU ID	Land cover description	CN ID	CN description	Hydrologic soil group			
				A	B	C	D
2	Developed, High Intensity	2	Urban: commercial	89	92	94	95
3	Developed, Medium Intensity	3	Residential: 1/8 acre lot	61	75	83	87
4	Developed, Low Intensity	4	Residential: 1/3 acre lot	57	72	81	86
5	Developed, Open Space	5	Open space, fair condition	49	69	79	84
6	Cultivated Crops	6	Fallow: crop residue cover	76	85	90	93
20	Bare Land	20	Fallow: bare soil	77	86	91	94
7	Pasture / Hay	7	Pasture, grassland, or range	49	69	79	84
8	Grassland / Herbaceous						
12	Scrub / Shrub						
10	Evergreen Forest	10	Woods	30	48	65	73
13	Palustrine Forested Wetland	13	Water / wetland	0	0	0	0
14	Palustrine Scrub / Shrub Wetland						
15	Palustrine Emergent Wetland						
21	Open Water						

The computed lag times for each subbasin are presented in Table 5-16, along with selected peak rating factors (PRFs). Steep terrain and urban areas tend to produce higher and earlier peaks than flat, swampy regions. The default PRF of 484 can be adjusted in the hydrologic model to something more representative of the basin. Table 5-17 provides some guidance for the selection of this parameter (NWS, 2005). Generally, the average watershed slope (Y) and general land cover classification influenced the PRF selected for each subbasin.

Table 5-17: Lag time estimates for each subbasin

Subbasin ID	L	CN	S	Y	t_L	PRF
1A	5,640	87.4	1.44	11.7	0.288	400
1B	33,576	64.4	5.53	48	1.18	484
1C	31,178	66	5.15	41.7	1.14	484
2A	16,941	89.3	1.20	7.25	0.82	400
2B	34,408	79.6	2.56	21.5	1.18	484
3A	3,953	91.8	0.89	7.32	0.229	400
3B	27,599	68	4.71	33.7	1.1	484
3C	23,514	79.9	2.52	39.5	1.74	484
3D	21,747	41.1	14.33	82.7	3.13	550
4A	27,940	81.2	2.32	21.6	0.946	484
5A	2,756	85.6	1.68	8.35	0.205	400
5B	27,456	76.6	3.05	22.9	1.04	400
5C	40,729	58.8	7.01	50	1.56	500
6A	17,965	71.5	3.99	28.6	0.768	400
7A	15,869	86.1	1.61	16.9	0.575	400
7B	16,810	74.4	3.44	24.3	1.93	400
7C	10,825	80.3	2.45	19.3	1.22	400
8A	36,527	55.1	8.15	44.5	1.66	484
8B	25,659	60.3	6.58	34.2	1.25	484
10A	6,097	80.8	2.38	17.5	0.315	400
10B	44,438	45.2	12.12	53.4	2.28	500
10C	21,561	57.9	7.27	41.3	1.05	484
12A	32,282	46.8	11.37	87.8	1.33	550

Table 5-18: Hydrograph peaking factors and recession limb ratios:

General description	Peaking factor	Limb ratio (recession to rising)
Urban areas; steep slopes	575	1.25
Typical SCS	484	1.67
Mixed urban/rural	400	2.25
Rural, rolling hills	300	3.33
Rural, slight slopes	200	5.5
Rural, very flat	100	12.0

5.3.4 **Reservoir Modeling**

Reservoir elements were included in the rainfall-runoff model representative of the basins in Honokōwai, Māhinahina, Kahana, Kaʻōpala, and Nāpili 4-5. As-built drawings were used to define the outflow structures (i.e. outlets, spillways, and dam tops) at each of these sites. Elevation-area curves for each basin were estimated by running various flow profiles across the digital terrain in a two-dimensional hydraulic model.

5.3.5 **Model Calibration – Event-Based Simulation**

Traditionally, the rainfall-runoff model would be calibrated to replicate the observed hydrograph from a stream gage for several large and recent flood events. Calibrating subbasin 3D (upper Honokōwai) to the observed record at CWRM 6-124 was possible but had limited application (only the upper watershed was calibrated well). It was not possible to calibrate subbasins 10B and 10C (Honolua) to the observed record at CWRM 6-158 effectively as there was reasonable uncertainty in the stage-flow relationship at this station and no nearby rainfall gage to provide reliable paired data. Additionally, it was not possible to calibrate subbasin 12A (upper Honokōhau) to the observed record at USGS 16620000, *Honokōhau Stream near Honokōhau, Maui, HI* effectively. In several instances, the observed rainfall record did not pair well with the corresponding streamflow record. For example, USGS 16620000 recorded its largest peak flow in its 102-year record on 12 September 2018, however, the nearest rainfall gage (USGS 205327156351102, *380.0 Puʻu Kukui Rain Gage at alt 5,771 ft, Maui, HI*) showed light, continuous rainfall.

As an alternative approach, the model was calibrated to replicate the peak flow estimates determined through the Bulletin 17C stream gage analysis (Section 5.1) for USGS 16630200, *Honokōwai Stream at Honokōwai, Maui, HI* (Table 5-2) and USGS 16620000, *Honokōhau Stream near Honokōhau, Maui, HI* (Table 5-4). This approach to calibration builds confidence in the model's ability to replicate the peak flow as both sites have long periods of record to rely upon. Precipitation frequency data was added to the model and the loss and transform parameters were adjusted in Honokōwai (subbasins 3C and 3D) and Honokōhau (subbasin 12A), as needed.

5.3.5.1 Precipitation Frequency Data

Point precipitation data was obtained from the National Weather Service's (NWS) NOAA Atlas 14 Precipitation-Frequency Data Server (PFDS). This source presents the estimated total rainfall from recurrence intervals of 1 to 1000 years (100% to 0.1% annual exceedance probabilities) for various durations (5 minutes to 60 days) within or adjacent to the study area (NOAA, 2017). The location points used to extract PFDS data were the approximate centroid locations for each subbasin (Table 3-3).

5.3.5.2 Calibrated Parameters

The peak flow at the HEC-HMS element representing the USGS stream gage in Honokahua (USGS 16620000) is dependent on the parameters of subbasin 12A, and the peak flow at the element representing the USGS stream gage at Honokōwai (USGS 16630200) is dependent on the parameters of subbasin 3C and 3D. The *constant loss* parameters of these subbasins were adjusted until the model was able to closely match the estimated peak flow for each frequency event (e.g. the 1/100 AEP event) as determined by the corresponding Bulletin 17C results. Calibrated values for the constant loss parameter, as presented in Table 5-18 and Table 5-19, varied for each frequency event and were characterized by the percent change from its initial value.

The percent change of each calibrated "constant loss" value from its initial estimate in Honokōhau and Honokōwai were used to adjust the initial estimates of other subbasins in the study area. With "0" representing the percent change value at the dry, western subbasins of Honokōwai, and "1" representing the percent change value at the wet, northern subbasin of Honokōhau, a scale factor was assigned to each subbasin based on the azimuths from a central point (the highest peak in the Honokōhau watershed) to

the centroid of each subbasin (Table 3-2). For the Wahikuli and Hanakaʻōʻō watersheds, which are beyond this range (Honokōwai to Honokōhau), the same scale factor and percent change that were used for Honokōwai were also applied to these watersheds. Final adjusted constant loss values for each subbasin are presented in Table 5-21.

Table 5-19: Calibrated "constant loss" parameter for subbasin 12A

AEP Event	Constant loss (in/hr)		Peak flow (ft^3/s)	
	Value	Percent change	Calibrated	Bulletin 17C
Initial	4.13	0.0	--	--
1/500	1.72	-58.4	14,921	14,305
1/200	2.10	-49.2	11,061	11,133
1/100	2.23	-46.0	9,138	9,127
1/50	2.35	-43.1	7,408	7,408
1/25	2.41	-41.6	5,932	5,935
1/10	2.51	-39.2	4,296	4,300
1/5	2.59	-37.3	3,255	3,250
1/2	2.65	-35.8	2,021	2,018

Table 5-20: Calibrated "constant loss" for subbasins 3C and 3D

AEP Event	Constant loss (in/hr)			Peak flow (ft^3/s)	
	3C Value	3D Value	Percent change	Calibrated	Bulletin 17C
Initial	1.80	5.65	0.0	--	--
1/500	0.347	1.091	-80.7	6,473	6469
1/200	0.540	1.70	-70.0	4,683	4805
1/100	0.652	2.05	-63.8	3,783	3783
1/50	0.743	2.33	-58.7	2,934	2932
1/25	0.833	2.62	-53.7	2,228	2226
1/10	0.943	2.96	-47.6	1,476	1476
1/5	1.035	3.25	-42.5	1,022	1022
1/2	1.242	3.90	-31.0	530	530

Table 5-21: Assigned scale factors and percent changes for each subbasin

Subbasin ID	Azimuth (º)	Scale factor	Percent change from initial value (%)							
			1/500	1/200	1/100	1/50	1/25	1/10	1/5	1/2
1A	165.3279	0.00	-80.7	-70.0	-63.8	-58.7	-53.7	-47.6	-42.5	-31
1B	158.1414	0.00	-80.7	-70.0	-63.8	-58.7	-53.7	-47.6	-42.5	-31
1C	153.7315	0.00	-80.7	-70.0	-63.8	-58.7	-53.7	-47.6	-42.5	-31
2A	154.2448	0.00	-80.7	-70.0	-63.8	-58.7	-53.7	-47.6	-42.5	-31
2B	149.092	0.00	-80.7	-70.0	-63.8	-58.7	-53.7	-47.6	-42.5	-31
3A	148.1117	0.00	-80.7	-70.0	-63.8	-58.7	-53.7	-47.6	-42.5	-31
3B	142.2301	0.00	-80.7	-70.0	-63.8	-58.7	-53.7	-47.6	-42.5	-31
3C	139.8578	0.00	-80.7	-70.0	-63.8	-58.7	-53.7	-47.6	-42.5	-31
3D	124.422	0.00	-80.7	-70.0	-63.8	-58.7	-53.7	-47.6	-42.5	-31
4A	135.909	1.53	-87.9	-76.7	-69.5	-63.7	-57.6	-50.3	-44.2	-29.5
5A	133.6208	1.50	-86.5	-75.4	-68.4	-62.7	-56.8	-49.8	-43.8	-29.8
5B	131.5655	1.48	-85.2	-74.2	-67.4	-61.8	-56.1	-49.3	-43.5	-30.0
5C	124.0752	1.40	-80.5	-69.8	-63.6	-58.5	-53.6	-47.5	-42.4	-31.0
6A	124.5628	1.40	-80.8	-70.1	-63.9	-58.8	-53.7	-47.6	-42.5	-31.0
7A	125.3171	1.41	-81.3	-70.5	-64.2	-59.1	-54.0	-47.8	-42.6	-30.9
7B	121.4476	1.37	-78.8	-68.3	-62.3	-57.4	-52.7	-46.9	-42.1	-31.4
7C	121.3696	1.37	-78.8	-68.2	-62.3	-57.4	-52.7	-46.9	-42.1	-31.4
8A	116.7817	1.31	-75.9	-65.5	-60.0	-55.4	-51.1	-45.8	-41.4	-32.0
8B	113.7432	1.28	-74.0	-63.8	-58.5	-54.0	-50.1	-45.1	-40.9	-32.4
10A	110.309	1.24	-71.9	-61.8	-56.7	-52.5	-48.9	-44.3	-40.4	-32.9
10B	107.585	1.21	-70.1	-60.2	-55.4	-51.3	-48.0	-43.6	-40.0	-33.3
10C	105.8733	1.19	-69.1	-59.2	-54.5	-50.6	-47.4	-43.2	-39.8	-33.5
12A	88.8366	1.00	-58.4	-49.2	-46.0	-43.1	-41.6	-39.2	-37.3	-35.8

Table 5-22: Adjusted constant loss values for each subbasin

Subbasin ID	Initial	Constant loss (in/hr)							
		1/500	1/200	1/100	1/50	1/25	1/10	1/5	1/2
1A	1.34	0.259	0.402	0.485	0.553	0.620	0.702	0.771	0.925
1B	2.93	0.565	0.879	1.061	1.210	1.357	1.535	1.685	2.022
1C	3.13	0.604	0.939	1.133	1.293	1.449	1.640	1.800	2.160
2A	1.96	0.378	0.588	0.710	0.809	0.907	1.027	1.127	1.352
2B	2.52	0.486	0.756	0.912	1.041	1.167	1.320	1.449	1.739
3A	1.84	0.355	0.552	0.666	0.760	0.852	0.964	1.058	1.270
3B	2.15	0.415	0.645	0.778	0.888	0.995	1.127	1.236	1.484
3C	1.8	0.347	0.540	0.652	0.743	0.833	0.943	1.035	1.242
3D	5.65	1.090	1.695	2.045	2.333	2.616	2.961	3.249	3.899
4A	2.1	0.254	0.489	0.640	0.762	0.890	1.043	1.172	1.482
5A	1.95	0.264	0.480	0.616	0.727	0.842	0.979	1.095	1.370
5B	2.7	0.400	0.697	0.881	1.031	1.185	1.369	1.524	1.889
5C	4.17	0.814	1.259	1.517	1.729	1.936	2.188	2.400	2.875
6A	2.71	0.521	0.811	0.979	1.118	1.253	1.419	1.558	1.870
7A	1.84	0.345	0.542	0.658	0.753	0.846	0.960	1.056	1.272
7B	2.43	0.514	0.771	0.916	1.035	1.150	1.290	1.408	1.667
7C	2.22	0.471	0.706	0.838	0.947	1.051	1.179	1.286	1.523
8A	4.31	1.038	1.485	1.725	1.924	2.107	2.336	2.526	2.929
8B	3.61	0.938	1.308	1.500	1.660	1.803	1.983	2.132	2.439
10A	2.6	0.732	0.994	1.125	1.235	1.329	1.449	1.549	1.745
10B	5.1	1.522	2.032	2.276	2.483	2.653	2.875	3.058	3.403
10C	3.65	1.129	1.491	1.660	1.804	1.920	2.072	2.198	2.427
12A	4.13	1.718	2.098	2.230	2.350	2.412	2.511	2.590	2.651

5.3.6 **Final Peak Flow Estimates**

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. These estimates are provided in Table 5-22 through Table 5-24.

Table 5-23: 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	8,870
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	5,520
6	Kaʻōpala	182	396	584	887	1,180	1,500	1,860	2,400
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	3,230	4,210	5,960
10	Honolua	227	467	717	1,160	1,560	2,050	2,670	3,820
[1]: rounded to three significant figures									

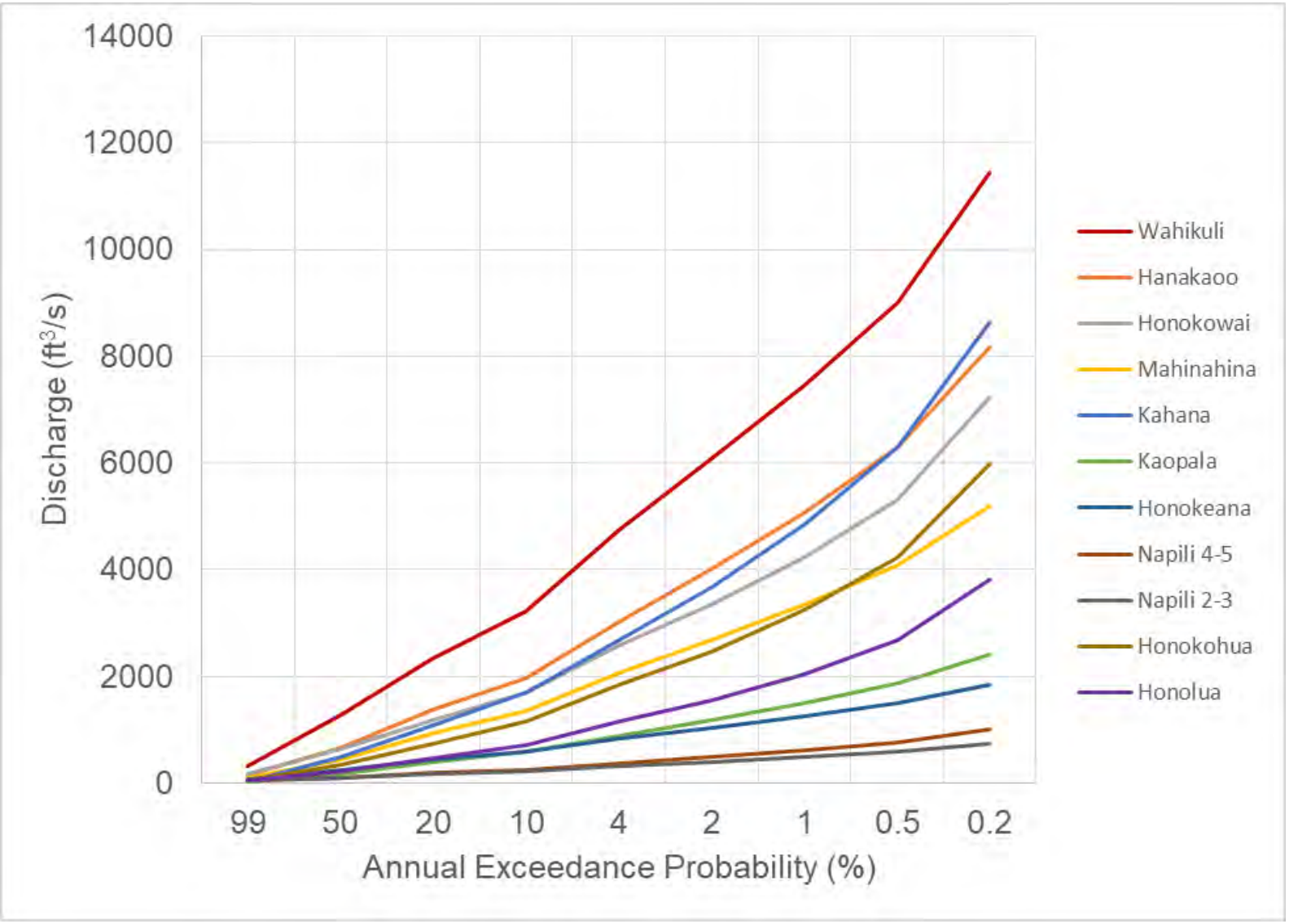


Figure 5-2: Flow Duration Curves for West Maui Basins

Table 5-24: Peak flow estimates for each subbasin

Sub-basin ID	Peak flow (ft^3/s)[1]							
	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500
1A	173	297	392	530	639	755	879	1,060
1B *Hāhākea*	855	1,530	2,100	3,050	3,860	4,680	5,620	7,060
1C	407	787	1,100	1,650	2,150	2,680	3,270	4,200
2A	178	355	503	755	972	1,200	1,460	1,840
2B	515	1,070	1,550	2,390	3,190	4,060	5,040	6,580
3A	198	343	457	621	755	900	1,060	1,290
3B	497	912	1,300	1,930	2,460	3,020	3,660	4,630
3C	311	586	854	1,310	1,700	2,130	2,630	3,400
3D	284	562	801	1,170	1,560	2,060	2,650	3,650
4A	453	933	1,360	2,070	2,690	3,340	4,090	5,180
5A	56	95	125	168	204	243	285	344
5B	228	510	763	1,190	1,620	2,090	2,630	3,460
5C	300	657	1,040	1,650	2,250	3,020	4,010	5,620
6A	182	396	584	889	1,180	1,500	1,860	2,410
7A	241	434	597	839	1,050	1,260	1,500	1,840
7B	128	224	306	442	574	725	898	1,190
7C	117	196	260	365	457	564	679	857
8A	203	430	663	1,080	1,450	1,910	2,510	3,600
8B	149	324	504	811	1,080	1,430	1,840	2,540
10A	182	342	486	692	860	1,040	1,240	1,540
10B	140	308	478	797	1,090	1,440	1,910	2,770
10C *Pāpua*	142	285	438	696	913	1,190	1,520	2,080
12A	1,780	2,870	3,800	5,250	6,570	8,130	9,860	12,800

[1]: rounded to three significant figures

Table 5-25: Peak flow estimates at key locations

Junction Name	Peak flow (ft^3/s)[1]							
	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500
CWRM 6-124 *Stream gage at Honokōwai*	284	562	801	1,170	1,560	2,060	2,650	3,650
CWRM 6-158 *Stream gage at Honolua*	217	458	705	1,150	1,540	2,030	2,640	3,750
Junction-1 *Lower confluence at Wahikuli*	1,260	2,310	3,200	4,690	6,000	7,350	8,880	11,300
Junction-2 *Lower confluence in Hanakaʻōʻō*	667	1,370	1,980	3,030	5,080	5,080	6,290	8,170
Junction-3 *Honokōwai Basin Inflow*	845	1,580	2,280	3,450	5,620	5,620	6,970	9,150
Honokōwai Dam *Outflow*	699	1,560	2,270	3,440	5,610	5,610	6,970	8,780
Junction-5 *Kahana Basin Inflow*	493	1,090	1,690	2,670	3,650	4,820	6,270	8,600
Kahana Basin *Outflow*	250	712	1,090	1,720	3,080	3,080	4,000	5,490
Kaʻōpala Basin *Outflow*	80.8	370	574	887	1,500	1,500	1,860	2,400
Māhinahina Dam *Outflow*	452	933	1,350	2,060	3,340	3,340	4,090	4,190
Nāpili 4-5 Basin *Outflow*	128	224	306	442	725	725	898	1,190
USGS -0000 *Stream gage at Honokōwai*	1,780	2,870	3,800	5,250	6,570	8,130	9,860	12,800
USGS -0200 *Stream gage at Honokōwai*	513	988	1,430	2,160	2,840	3,650	4,620	6,200

[1]: rounded to three significant figures

5.3.7 **Sensitivity Analyses**

The calibrated loss and transform parameters in the rainfall-runoff model were increased and decreased by 20% to improve our understanding regarding the sensitivity of the model. The degree of change (20%) was based on engineering judgment. How much does the peak flow change when these inputs are slightly adjusted higher or lower? This section describes all sensitivity tests performed on the rainfall runoff model. Results specific to climate change are further described in Section 7, Climate Change. Six sensitivity tests were performed on the existing rainfall-runoff model:

- Increase Constant Loss 20%
- Decrease Constant Loss 20%
- Increase Impervious by 20%
- Decrease Impervious by 20%
- Increase Lag Time 20%
- Decrease Lag Time 20%

The results of these tests are provided in the tables that follow. A sensitivity test on the hydrologic parameters was determined to not be necessary for this study. Mean annual rainfall averages are trending down across the state and in the study area. Resulting peak flow estimates may be slightly conservative.

Table 5-26: Peak flow estimates at each basin outlet when Constant Loss is changed +/- 20%

HMS Element	Peak flow (ft^3/s)[1]							
	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500
Outlet 1 *Wahikuli*	1,270 1,060 – 1,550	2,330 2,070 – 2,670	3,220 2,880 – 3,710	4,750 4,260 – 5,290	6,080 5,590 – 6,570	7,460 7,020 – 7,910	9,010 8,620 – 9,430	11,400 11,200 – 11,700
Outlet 2 *Hanakaʻōʻō*	667 558 – 821	1,370 1,190 – 1,570	1,980 1,780 – 2,250	3,030 2,730 – 3,400	4,020 3,680 – 4,370	5,080 4,770 – 5,400	6,290 6,090 – 6,650	8,170 7,970 – 8,370
Outlet 3 *Honokōwai*	646 531 – 915	1,190 1,370 – 1,830	2,280 2,020 – 2,630	3,460 3,120 – 3,840	4,490 4,150 – 4,890	5,640 5,270 – 6,070	7,020 6,650 – 7,390	7,230 8,630 – 9,180
Outlet 4 *Māhinahina*	453 385 – 554	933 835 – 1,060	1,360 1,220 – 1,530	2,060 1,900 – 2,240	2,680 2,530 – 2,840	3,340 3,200 – 3,480	4,090 3,980 – 4,200	5,180 5,130 – 5,250
Outlet 5 *Kahana*	252 151 – 371	1,100 599 – 867	1,690 948 – 1,270	1,720 1,550 – 1,960	2,340 2,120 – 2,630	3,090 2,840 – 3,400	4,030 3,750 – 4,310	8,630 5,310 – 5,750
Outlet 6 *Kaʻōpala*	182 34.3 – 154	396 298 – 454	584 510 – 660	887 804 – 991	1,180 1,080 – 1,280	1,500 1,410 – 1,590	1,860 1,780 – 1,940	2,410 2,350 – 2,460
Outlet 7 *Honokeana*	241 210 – 283	434 396 – 479	597 552 – 650	839 790 – 891	1,050 1,000 – 1,090	1,260 1,220 – 1,300	1,500 1,460 – 1,530	1,840 1,820 – 1,860
Outlet 7B *Nāpili 4-5*	128 116 – 144	190 201 – 248	258 283 – 337	442 408 – 491	574 529 – 632	725 674 – 779	898 852 – 954	1,190 1,140 – 1,230
Outlet 7C *Nāpili 2-3*	117 108 – 130	168 180 – 213	222 244 – 283	365 340 – 397	457 427 – 490	564 535 – 594	679 654 – 708	857 837 – 878
Outlet 8 *Honokahua*	341 273 – 446	751 613 – 904	1,130 956 – 1,380	1,830 1,590 – 2,090	2,450 2,190 – 2,780	3,235 2,910 – 3,630	4,210 3,870 – 4,650	5,980 5,590 – 6,370
Outlet 10 *Honolua*	227 189 – 295	467 382 – 583	717 598 – 882	1,160 993 – 1,360	1,560 1,380 – 1,790	2,050 1,830 – 2,330	2,670 2,410 – 2,990	3,820 3,530 – 4,190

the top number indicates the original peak flow estimate; the bottom number shows the range resulting from increasing or decreasing the variable

[1]: rounded to three significant figures

Table 5-27: Peak flow estimates at key locations when Constant Loss is changed +/- 20%

	Peak flow (ft^3/s)[1]

Junction Name	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500
CWRM 6-124	284 234 – 357	562 466 – 672	801 701 – 921	1,170 1,050 – 1,370	1,560 1,380 – 1,820	2,060 1,830 – 2,320	2,650 2,440 – 2,870	3,650 3,450 – 3,890
CWRM 6-158	217 167 – 288	458 373 – 573	705 586 – 869	1,150 978 – 1,340	1,540 1,360 – 1,770	2,030 1,810 – 2,300	2,640 2,390 – 2,940	3,750 3,480 – 4,100
Junction-1	1,260 1,050 – 1,540	2,310 2,050 – 2,650	3,200 2,860 – 3,670	4,690 4,220 – 5,220	6,000 5,510 – 6,480	7,350 6,920 – 7,800	8,880 8,500 – 9,290	11,300 11,000 - 11,500
Junction-2	667 558 – 821	1,370 1,190 – 1,570	1,980 1,780 – 2,250	3,030 2,730 – 3,400	4,020 3,680 – 4,370	5,080 4,770 – 5,400	6,290 6,090 – 6,650	8,170 7,970 – 8,370
Junction-3	845 707 – 1,010	1,580 1,400 – 1,830	2,280 2,020 – 2,620	3,450 3,110 – 3,830	4,480 4,130 – 4,880	5,620 5,260 – 6,040	6,970 6,620 – 7,340	9,150 8,840 – 9,550
Honokōwai Dam	699 526 – 908	1,560 1,360 – 1,820	2,270 2,010 – 2,620	3,440 3,110 – 3,820	4,460 4,130 – 4,870	5,610 5,250 – 6,030	6,970 6,610 – 7,330	8,780 8,550 – 9,080
Junction-5	493 393 – 624	1,090 914 – 1,330	1,690 1,450 – 1,960	2,670 2,390 – 3,040	3,650 3,290 – 4,100	4,820 4,420 – 5,300	6,270 5,850 – 6,710	8,600 8,280 – 8,960
Kahana Basin	250 150 – 369	712 595 – 863	1,090 943 – 1,270	1,720 1,540 – 1,950	2,330 2,110 – 2,620	3,080 2,830 – 3,390	4,000 3,740 – 4,290	5,490 5,290 – 5,720
Ka‘ōpala Basin	80.8 34.3 – 154	370 298 – 454	574 510 – 660	887 804 – 991	1,180 1,080 – 1,280	1,500 1,410 – 1,590	1,860 1,780 – 1,940	2,400 2,350 – 2,460
Māhinahina Dam	452 385 – 554	933 835 – 1,060	1,350 1,220 – 1,530	2,060 1,900 – 2,240	2,680 2,530 – 2,840	3,340 3,200 – 3,480	4,090 3,980 – 4,200	4,190 5,130 – 5,250
Nāpili 4-5 Basin	128 116 – 144	224 201 – 248	306 283 – 336	442 408 – 491	574 528 – 632	725 674 – 779	898 851 – 954	1,190 1,140 – 1,230
USGS -0000	1,780 1,480 – 2,180	2,870 2,490 – 3,300	3,800 3,390 – 4,350	5,250 4,700 – 6,050	6,570 5,870 – 7,480	8,130 7,330 – 9,080	9,860 9,010–10,800	12,800 12,000–13,500
USGS -0200	513 427 – 625	988 856 – 1,160	1,430 1,260 – 1,650	2,160 1,930 – 2,440	2,840 2,580 – 3,180	3,650 3,340 – 4,010	4,620 4,320 – 4,930	6,200 5,940 – 6,520

Table 5-28: Peak flow estimates at each basin outlet when Impervious is changed +/- 20%

HMS Element	Peak flow (ft^3/s)[1]							
	1/2	**1/5**	**1/10**	**1/25**	**1/50**	**1/100**	**1/200**	**1/500**
Outlet 1 *Wahikuli*	1,270 1,270 – 1,270	2,330 2,330 – 2,330	3,220 3,220 – 3,230	4,750 4,740 – 4,750	6,080 6,070 – 6,080	7,460 7,450 – 7,460	9,010 9,010 – 9,010	11,400 11,400 – 11,400
Outlet 2 *Hanakaʻōʻō*	667 659 – 675	1,370 1,360 – 1,380	1,980 1,970 – 1990	3,030 3020 – 3,040	4,020 4010 – 4,030	5,080 5070 – 5,090	6,360 6,350 – 6,360	8,170 8170 – 8,180
Outlet 3 *Honokōwai*	646 697 – 711	1,190 1,560 – 1,570	2,280 2,280 – 2,290	3,460 3,450 – 3,470	4,490 4,480 – 4,490	5,640 5,630 – 5650	7,020 7,010 – 7,030	7,230 8,870 – 8880
Outlet 4 *Māhinahina*	453 447 – 459	933 926 – 939	1,360 1,350 – 1,360	2,060 2060 – 2,070	2,680 2,680 – 2,690	3,340 3,330 – 3,340	4,090 4,080 – 4,090	5,180 5,190 – 5,190
Outlet 5 *Kahana*	252 246 – 261	1,100 710 – 722	1,690 1,090 – 1,100	1,720 1,720 – 1,730	2,340 2,340 – 2,350	3,090 3090 – 3,100	4,030 4,020 – 4,030	8,630 5,510 – 5,520
Outlet 6 *Kaʻōpala*	182 75.5 – 85	396 367 – 372	584 571 – 576	887 885 – 889	1,180 1,180 – 1,180	1,500 1490 – 1,500	1,860 1,850 – 1,860	2,400 2,400 – 2,400
Outlet 7 *Honokeana*	241 233 – 248	434 427 – 441	597 590 – 604	839 833 – 846	1,050 1,040 – 1,050	1,260 1,250 – 1,260	1,500 1,490 – 1,500	1,840 1,840 – 1,850
Outlet 7B *Nāpili 4-5*	128 118 – 138	190 213 – 235	258 293 – 318	442 429 – 455	574 561 – 587	725 713 – 738	898 887 – 909	1,190 1,180 – 1,200
Outlet 7C *Nāpili 2-3*	117 107 – 127	168 185 – 207	222 249 – 272	365 353 – 376	457 446 – 468	564 554 – 574	679 670 – 688	857 851 – 863
Outlet 8 *Honokahua*	341 332 – 350	751 722 – 743	1,130 1120 – 1,140	1,830 1,820 – 1,840	2,450 2,430 – 2,460	3,235 3220 – 3,250	4,210 4,200 – 4,230	5,980 5,950 – 5970
Outlet 10 *Honolua*	227 223 – 232	467 464 – 470	717 713 – 720	1,160 1160 – 1,170	1,560 1,560 – 1,570	2,050 2050 – 2,050	2,670 2,670 – 2,680	3,820 3,810 – 3820

the top number indicates the original peak flow estimate; the bottom number shows the range resulting from increasing or decreasing the variable

[1]: rounded to three significant figures

Table 5-29: Peak flow estimates at key locations when Impervious is changed +/- 20%

Junction Name	Peak flow (ft^3/s)[1]							
	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500
CWRM 6-124	284 284 – 285	562 562 – 562	801 801 – 801	1,170 1,070 – 1,170	1,560 1,560 – 1,560	2,060 2,060 – 2,060	2,650 2,650 – 2,650	3,650 3,650 – 3,650
CWRM 6-158	217 216 – 219	458 456 – 460	705 702 – 707	1,150 1,140 – 1,150	1,540 1,540 – 1,550	2,030 2,020 – 2,030	2,640 2,640 – 2,650	3,750 3,750 – 3,750
Junction-1	1,260 1,260 – 1,260	2,310 2,310 – 2,320	3,200 3,190 – 3,200	4,690 4,680 – 4,690	6,000 5,990 – 6,000	7,350 7,350 – 7,350	8,880 8,880 – 8,880	11,300 11,300 - 11,300
Junction-2	667 659 – 675	1,370 1,360 – 1,380	1,980 1,970 – 1,990	3,030 3,020 – 3,040	4,020 4,010 – 4,030	5,080 5,070 – 5,090	6,290 6,350 – 6,360	8,170 8,170 – 8,180
Junction-3	845 841 – 849	1,580 1,580 – 1,590	2,280 2,280 – 2,280	3,450 3,440 – 3,450	4,480 4,470 – 4,480	5,620 5,260 – 5,630	6,970 6,970 – 6,980	9,150 9,150 – 9,150
Honokōwai Dam	699 693 – 704	1,560 1,550 – 1,560	2,270 2,270 – 2,280	3,440 3,440 – 3,450	4,460 4,460 – 4,470	5,610 5,610 – 5,620	6,970 6,970 – 6,970	8,780 8,780 – 8,780
Junction-5	493 487 – 500	1,090 1,080 – 1,100	1,690 1,680 – 1,700	2,670 2,660 – 2,680	3,650 3,640 – 3,650	4,820 4,820 – 4,830	6,270 6,260 – 6,280	8,600 8,600 – 8,600
Kahana Basin	250 244 – 259	712 707 – 717	1,090 1,090 – 1,100	1,720 1,710 – 1,720	2,330 2,330 – 2,340	3,080 3,080 – 3,090	4,000 4,000 – 4,010	5,490 5,480 – 5,490
Ka‘ōpala Basin	80.8 75.5 – 85	370 367 – 372	574 571 – 576	887 885 – 889	1,180 1,180 – 1,180	1,500 1,490 – 1,500	1,860 1,850 – 1,860	2,400 2,400 – 2,400
Māhinahina Dam	452 447 – 459	933 926 – 939	1,350 1,350 – 1,360	2,060 2,060 – 2,070	2,680 2,680 – 2,690	3,340 3,330 – 3,340	4,090 4,080 – 4,090	4,190 5,190 – 5,190
Nāpili 4-5 Basin	128 118 – 137	224 212 – 235	306 293 – 318	442 429 – 455	574 561 – 587	725 713 – 738	898 887 – 909	1,190 1,180 – 1,200
USGS -0000	1,780 1,780 – 1,780	2,870 2,870 – 2,870	3,800 3,800 – 3,800	5,250 5,250 – 5,250	6,570 6,570 – 6,570	8,130 8,130 – 8,130	9,860 9,860–9,860	12,800 12,800–12,800
USGS -0200	513 510 – 516	988 985 – 991	1,430 1,430 – 1,430	2,160 2,160 – 2,160	2,840 2,830 – 2,840	3,650 3,640 – 3,650	4,620 4,620 – 4,620	6,200 6,200 – 6,200

Table 5-30: Peak flow estimates at each basin outlet when Lag Time is changed +/- 20%

HMS Element	Peak flow (ft^3/s)[1]							
	1/2	**1/5**	**1/10**	**1/25**	**1/50**	**1/100**	**1/200**	**1/500**
Outlet 1 *Wahikuli*	1,270 1,120 – 1,570	2,330 1,960 – 2,870	3,220 2,710 – 3,950	4,750 4,030 – 5,740	6,080 5,210 – 7,270	7,460 6,430 – 8,860	9,010 7,820–10,600	11,400 10,000 – 13,300
Outlet 2 *Hanakaʻōʻō*	667 562 – 817	1,370 1,160 – 1,680	1,980 1,670 – 2,420	3,030 2,580 – 3,680	4,020 3,450 – 4,820	5,080 4,390 – 6,040	6,360 5,540 – 7,480	8,170 7,200 – 9,520
Outlet 3 *Honokōwai*	646 587 – 873	1,190 1,320 – 1,930	2,280 1,920 – 2,810	3,460 2,930 – 4,210	4,490 3,820 – 5,440	5,640 4,810 – 6,810	7,020 6,030 – 8,240	7,230 7,920 – 10,100
Outlet 4 *Māhinahina*	453 383 – 555	933 791 – 1,140	1,360 1,150 – 1,650	2,060 1,780 – 2,470	2,680 2,340 – 3,180	3,340 2,930 – 3,920	4,090 3,610 – 4,770	5,180 4,610 – 6,000
Outlet 5 *Kahana*	252 217 – 306	1,100 605 – 875	1,690 927 – 1,350	1,720 1,450 – 2,110	2,340 1,990 – 2,860	3,090 2,630 – 3,750	4,030 3,450 – 4,830	8,630 4,770 – 6,540
Outlet 6 *Kaʻōpala*	182 70.1 – 94.7	396 317 – 444	584 492 – 696	887 757 – 1,070	1,180 1,020 – 1,400	1,500 1,300 – 1,760	1,860 1,630 – 2,170	2,400 2,130 – 2,780
Outlet 7 *Honokeana*	241 206 – 288	434 373 – 517	597 517 – 706	839 737 – 981	1,050 925 – 1,210	1,260 1,120 – 1,450	1,500 1,340 – 1,720	1,840 1,650 – 2,110
Outlet 7B *Nāpili 4-5*	128 110 – 153	190 192 – 270	258 261 – 370	442 377 – 536	574 489 – 696	725 619 – 876	898 768 – 1,080	1,190 1,030 – 1,410
Outlet 7C *Nāpili 2-3*	117 102 – 139	168 170 – 234	222 225 – 311	365 314 – 436	457 395 – 542	564 489 – 667	679 591 – 800	857 752 – 1,000
Outlet 8 *Honokahua*	341 288 – 419	751 618 – 904	1,130 954 – 1,400	1,830 1,540 – 2,260	2,450 2,060 – 3,020	3,235 2,730 – 3,980	4,210 3,560 – 5,160	5,980 5,060 – 7,220
Outlet 10 *Honolua*	227 193 – 278	467 391 – 581	717 600 – 891	1,160 973 – 1,440	1,560 1,310 – 1,940	2,050 1,720 – 2,550	2,670 2,240 – 3,320	3,820 3,190 – 4,740

the top number indicates the original peak flow estimate; the bottom number shows the range resulting from increasing or decreasing the variable

[1]: rounded to three significant figures

Table 5-31: Peak flow estimates at key locations when Lag Time is changed +/- 20%

Junction Name	Peak flow (ft^3/s)[1]							
	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500
CWRM 6-124	284 238 – 354	562 469 – 699	801 669 – 998	1,170 979 – 1,460	1,560 1,310 – 1,940	2,060 1,730 – 2,550	2,650 2,230 – 3,280	3,650 3,090 – 4,460
CWRM 6-158	217 182 – 270	458 383 – 569	705 590 – 875	1,150 960 – 1,420	1,540 1,290 – 1,910	2,030 1,700 – 2,510	2,640 2,220 – 3,270	3,750 3,150 – 4,640
Junction-1	1,260 1,110 – 1,560	2,310 1,950 – 2,840	3,200 2,700 – 3,910	4,690 3,990 – 5,670	6,000 5,150 – 7,170	7,350 6,350 – 8,730	8,880 7,710–10,500	11,300 9,880 – 13,100
Junction-2	667 562 – 817	1,370 1,160 – 1,680	1,980 1,670 – 2,420	3,030 2,580 – 3,680	4,020 3,450 – 4,820	5,080 4,390 – 6,040	6,290 5,540 – 7,480	8,170 7,200 – 9,520
Junction-3	845 709 – 1,050	1,580 1,330 – 1,960	2,280 1,920 – 2,810	3,450 ,2930 – 4,200	4,480 3,810 – 5,420	5,620 4,800 – 6,780	6,970 5,990 – 8,360	9,150 7,940 – 10,900
Honokōwai Dam	699 582 – 867	1,560 1,310 – 1,910	2,270 1,910 – 2,790	3,440 2,920 – 4,190	4,460 3,800 – 5,400	5,610 4,790 – 6,760	6,970 5,980 – 8,170	8,780 7,840 – 10,000
Junction-5	493 415 – 608	1,090 917 – 1,350	1,690 1,420 – 2,080	2,670 2,250 – 3,280	3,650 3,080 – 4,460	4,820 4,100 – 5,850	6,270 5,360 – 7,540	8,600 7,440 – 10,200
Kahana Basin	250 216 – 304	712 602 – 870	1,090 922 – 1,340	1,720 1,450 – 2,100	2,330 1,980 – 2,850	3,080 2,620 – 3,730	4,000 3,430 – 4,810	5,490 4,750 – 6,500
Ka‘ōpala Basin	80.8 70.1 – 94.7	370 317 – 444	574 492 – 696	887 757 – 1,070	1,180 1,020 – 1,400	1,500 1,300 – 1,760	1,860 1,630 – 2,170	2,400 2,130 – 2,780
Māhinahina Dam	452 383 – 555	933 791 – 1140	1,350 1,150 – 1,650	2,060 1,780 – 2,470	2,680 2,340 – 3,180	3,340 2,930 – 3,920	4,090 3,610 – 4,770	4,190 4,610 – 6,000
Nāpili 4-5 Basin	128 110 – 153	224 192 – 270	306 261 – 370	442 377 – 536	574 489 – 696	725 619 – 876	898 768 –1,080	1,190 1,030 – 1,410
USGS -0000	1,780 1,490 – 2,210	2,870 2,410 – 3,550	3,800 3,190 – 4,690	5,250 4,310 – 6,460	6,570 5,540 – 8,060	8,130 6,880 – 9,900	9,860 8,390–11,900	12,800 10,900–15,300
USGS -0200	513 430 – 637	988 827 – 1,230	1,430 1,200 – 1,770	2,160 1,810 – 2,660	2,840 2,390 – 3,490	3,650 3,080 – 4,470	4,620 3,930 – 5,610	6,200 5,330 – 7,450

The results of the sensitivity tests show that the model is not strongly affected by changes to the *directly connected impervious areas* parameter and slightly affected by changes in the *constant loss* parameter. *Constant Loss* primarily reflects our assumptions regarding the infiltration rate of the overland areas. Small changes in the *Lag Time* parameter, however, had a moderate impact to the overall peak flow estimates. This parameter represents the temporal difference between the peak in the hyetograph (rainfall) and the peak in the hydrograph (stream flow). Watersheds affected by wildfires or with a large amount of fallow land, where water would travel more quickly across the landscape, would have a shorter lag time and higher peak flow than a typically forested or grassy landscape of the same shape and size.

5.4 Reference Flows

5.4.1 2015 Flood Insurance Study

In 2015, the Federal Emergency Management Agency (FEMA) published peak flow estimates for various streams in West Maui (FEMA, 2015). These flow estimates are included here:

Table 5-32: Summary of Peak Flow Estimates by FEMA

Flooding Source and Location	Drainage Area (mi^2)	Peak Flow (ft^3/s)			
		1/10	1/50	1/100	1/500
Honokahua Stream at mouth	3.8	1,670	3,360	4,300	7,020
Honokeana Bay Gulch at mouth	0.6	350	670	830	1,300
Honokōwai Stream at mouth	6.0	2,000	4,000	5,200	8,200
Kahana Stream at mouth	4.6	2,000	4,000	5,100	8,400
Kahoma Stream at mouth	5.3	2,600	5,100	6,400	10,200
Kaʻōpala Gulch at mouth	0.95	550	1,100	1,300	2,100
Māhinahina Gulch at mouth	1.9	930	1,800	2,300	3,700
Nāpili Gulch 2-3 at mouth	0.8	420	810	1,020	1,600
Nāpili Gulch 4-5 at mouth	0.9	540	1,000	1,300	2,000

6 Continuous Flow Simulations

6.1 Background and Purpose

To evaluate terrestrial sediment dynamics in the nearshore environment (Appendix D), flow and sediment load time series data representative of a specific event (i.e. the 50% AEP flood) were needed as input for the hydrodynamic-sediment transport model. This data was provided to USGS in September 2020. The initial estimation of this data was determined by using flow and shear stress time series data outputs from the two dimensional (2D) hydraulic model for the 50% AEP event, and then applying the excess shear equation in Microsoft Excel to calculate the total sediment time series data (Section 8.2.5, Sediment Transport Analysis). This method assumed that the total sediment load for the 50% AEP event would be approximately equal to the total annual sediment load divided by 4.5 (the estimated number of plume-triggering events occurring over a one-year period). There is less confidence in this assumption now, after reviewing the frequency of plumes created at each outlet and finding that they occur much more frequently (Section 4.3.2.2, Coastal Camera Analysis). This assumption also assumes that each plume-triggering event had relatively the same amount of sediment in the system when the total sediment load for each event likely varies quite a bit. Finally, the flow and shear stress time-series data taken from the 2D hydraulic model is also based on a limited number of sites along the reach, and not necessarily representative of the downstream boundary conditions (at a basin or outlet).

The methodology for determining event-based flow and sediment loads was later updated to rely more 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.

For additional information comparing the baseline data from the first methodology (using the 2D hydraulic model and excess shear equation) and the second methodology (continuous flow simulation in the rainfall-runoff model), refer to Section 8.2.5, Sediment Transport Analysis.

6.2 Methodology

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 (Table 6-1). The period 1 November 2014 to 1 November 2015 was selected because it did not include any significant flow events and seemed to be the best representation of typical flows and sediment loads experienced in any given year. The complete record (hyetograph) for all rainfall gages relevant to Honokōwai is provided as Figure 6-1. The *Upper Honokōwai* rainfall gage was a critical record to include that began on 31 October 2014. However, the record in 2016 seemed unusually high. There was no corresponding flood event or news of intense rainfall found; it was determined to not be a reliable period of the record and possibly an error as other nearby gages did not record a similar intensity. There were significant flood events in 2017 and 2018 (see Section 4.2.1, Significant Past Flow Events) that excluded these years from the usable record for a representation of typical, low flow events. 2019 was a particularly hot year in Hawaii, with the rainfall record representing atypical drought-like conditions. These exclusions left the 1 November 2014 to 1 November 2015 period for use in the continuous flow simulation.

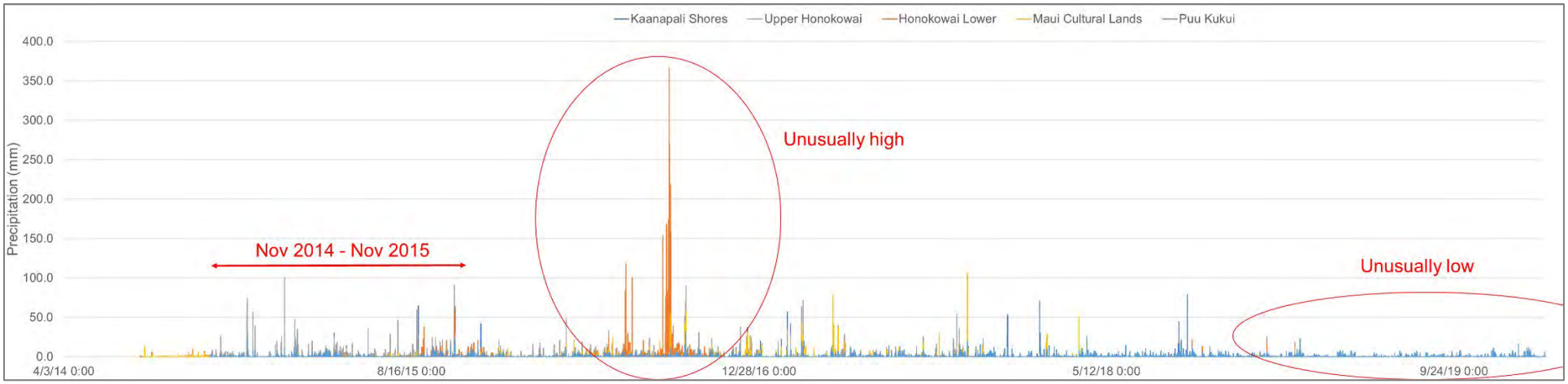


Figure 6-1: Honokōwai Rainfall Record, Multiple Gages

Table 6-1: USGS sediment budgets for West Maui watersheds

USACE Basin / Subbasin ID	USGS Basin ID	Watershed name	Total area (km^2)	Estimate of annual storm mass load from bank erosion[1] (metric tons/yr)
10	2	Honolua	11.00	91
8A	9	Honokahua	6.65	45
8B	8	Honokahua	4.03	46
7A	16	Honokeana	1.94	43
7B	14	Nāpili 4-5	1.98	56
7C	13	Nāpili 2-3	2.41	44
6	20	Ka‘ōpala	2.36	62
5	22	Kahana	11.68	285
4	26	Māhinahina	5.00	45
3	28	Honokōwai	15.20	62
2A	30	Hanaka‘ō‘ō	5.94	26
2B	31	Hanaka‘ō‘ō	1.65	25
1	35	Wahikuli	10.42	42
1: assumes 1300 kg/m^3 bulk density				

A separate basin model was created to run simulations with sediment. These annual sediment loads were entered into the rainfall-runoff model as a source element, with the results from the flow-only simulation as the corresponding discharge data. The locations of the source elements were selected based on representative locations for the total annual sediment load estimated by USGS (Table 6-1) or upstream of a critical feature, such as an existing detention basin. An example of the basin model layout is provided as Figure 6-2 for Hanaka‘ō‘ō (subbasin 2) Honokōwai (subbasin 3). The reservoir elements introduced earlier in Section 5.3.4 were also modified to perform *Chen’s Sediment Trap* method of analysis.

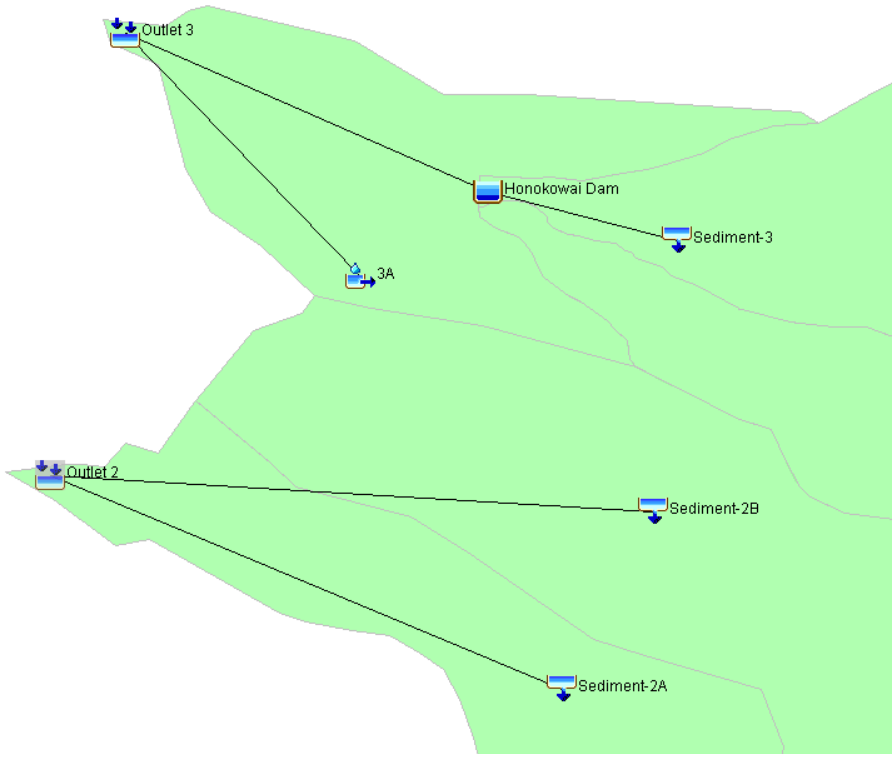


Figure 6-2: HMS Basin Model for Hanakaʻōʻō and Honokōwai

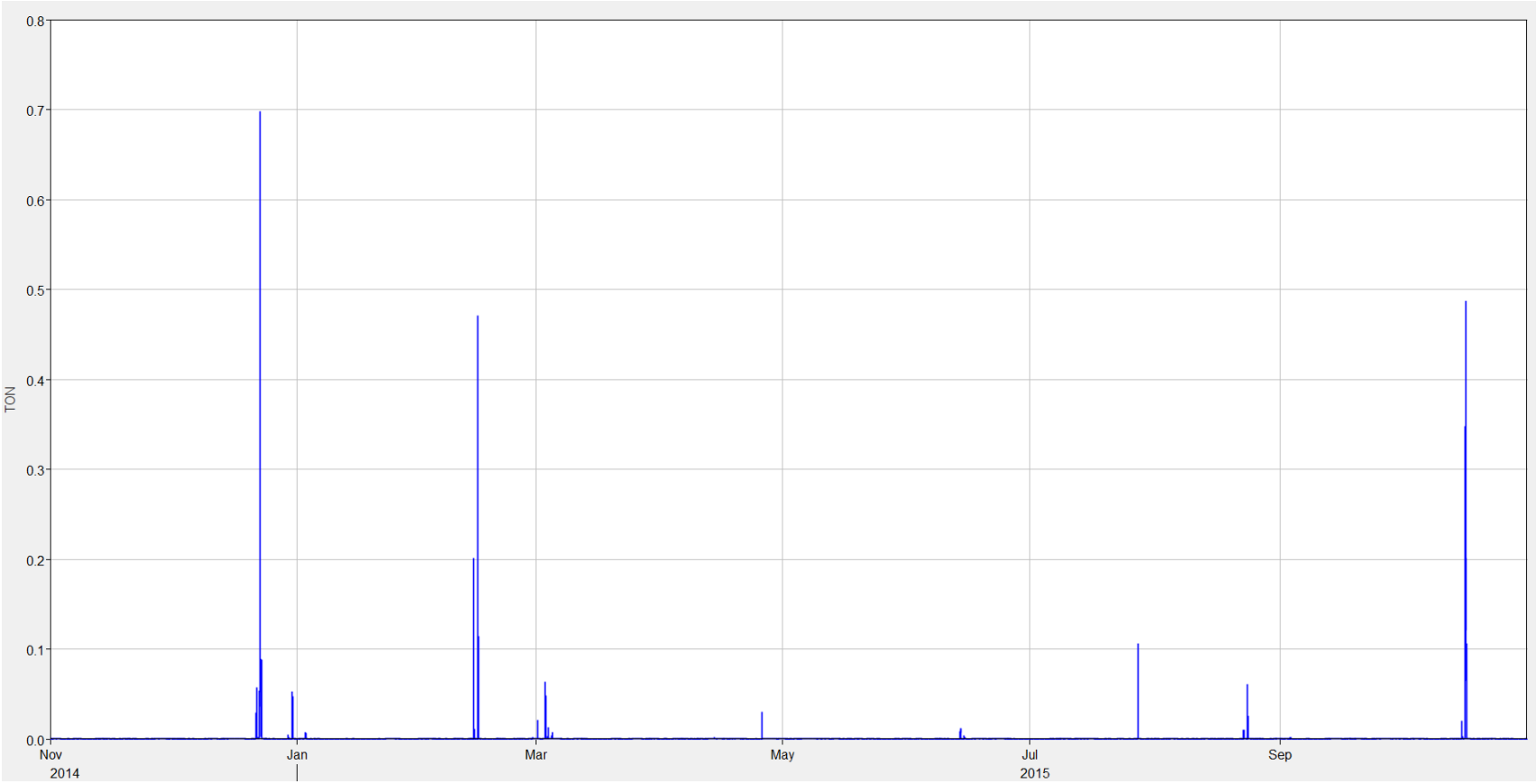
There was a strong attempt by the modeler to further calibrate the rainfall-runoff model to the continuous streamflow records at CWRM 6-124 and CWRM 6-158, but ultimately the effort was not productive. There was too much uncertainty in the stage-discharge relationship at these sites. After calibrating subbasin 3D (upper Honokōwai) within reasonable limits, extrapolating the changes in the constant loss and lag time parameters to the rest of the watershed resulted in flows at the outlet that were unrealistically high. For example, annual rainfall data produced flows expected for the 1% AEP flood. Therefore, the calibrated parameters selected for the 50% (1/2) AEP basin model (presented in Section 5.3.5.2, Calibrated Parameters) were used in the simulation runs for the annual flow event. The results (the frequency of flow events occurring throughout the year and the corresponding peak flows) were much more reasonable.

6.3 Results

By distributing the annual sediment load over a one-year period (Figure 6-3), it was possible to estimate typical sediment loads for the various low flow events occurring throughout the year (Figure 6-4, Table 6-2). The approximate AEP for each peak flow that occurred in each watershed during the continuous flow simulation is included in Table 6-2. As this simulation uses historical rainfall data, there is understandably some variability in the frequency of the peak flow events. However, the variability is still considered to be within a reasonable range (based on engineering judgment), considering the limited data available for calibration of the model. The AEPs range from >100% (likely to occur more than once a year) to 20% (likely to occur once every five years).

Additionally, the trap efficiencies of the existing detention basins were also computed. The results from this method (applying Chen's Sediment Trap in the rainfall-runoff model) are presented in Table 6-3.

Figure 6-3: Sediment Load entering Honokōwai Basin, 1 November 2014 – 1 November 2015 Simulation



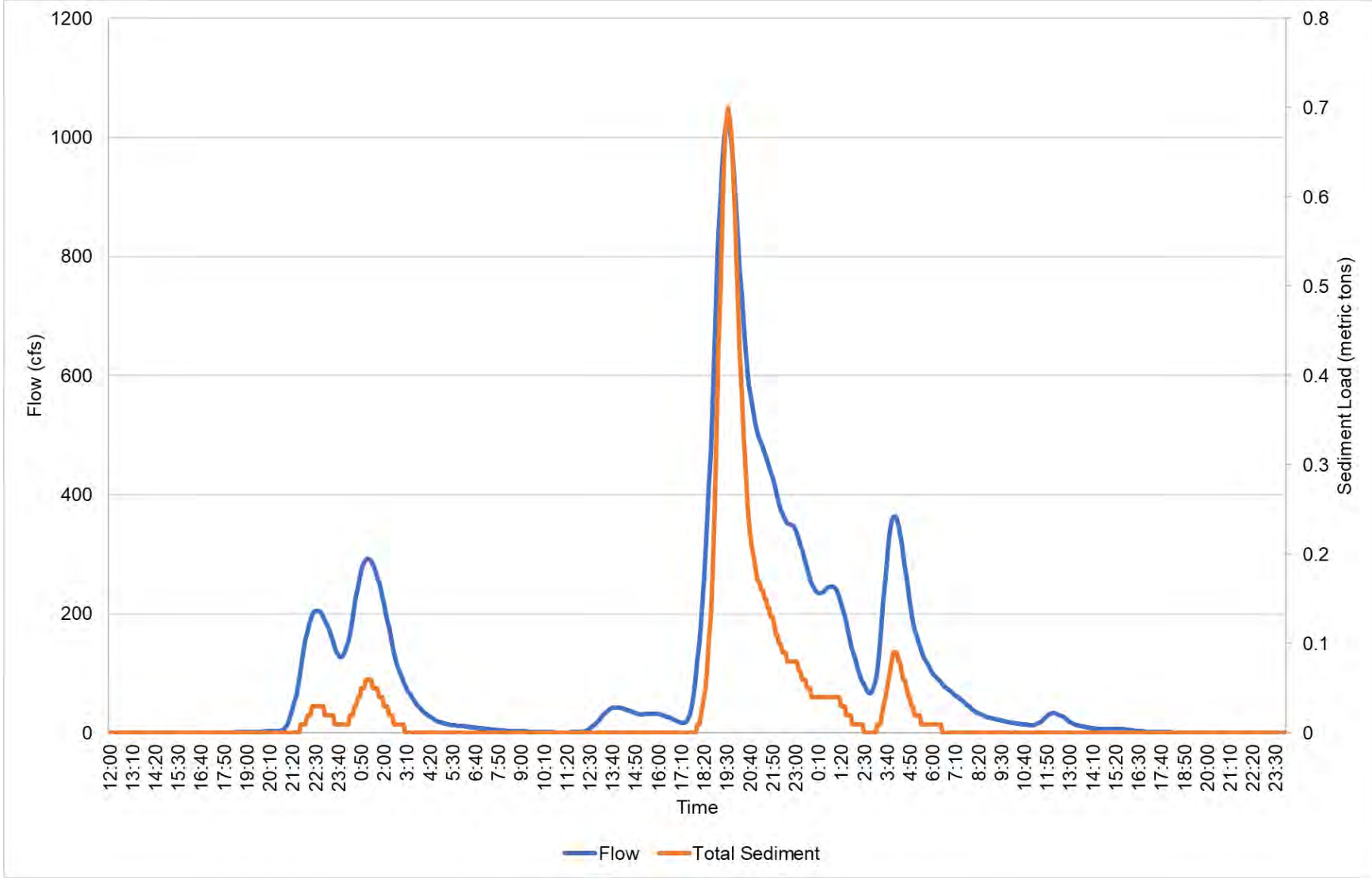


Figure 6-4: Hydrograph and Sedigraph for Flow and Sediment Load entering Honokōwai Basin, 22-24 December 2014

Table 6-2: Peak Flows and Total Sediment Loads for Typical Low Flow Events in West Maui

Watershed	Annual Sediment Load (tons)	Event: 22 December 2014			Event: 13-14 February 2015		
		Peak Flow (cfs)	AEP	Sediment Load (tons)	Peak Flow (cfs)	AEP	Sediment Load (tons)
Wahikuli	42	1,876	27%	20.2	1,625	33%	11.5
Hanakaʻōʻō	51	121	>100%	2.78	311	~100%	18.9
Honokōwai[1]	62	1,023	43%	19.6	840	50%	12.2
Honokōwai[2]	31	928		11.4	632		6.57
Māhinahina[1]	45	389	34%	3.94	905	21%	30.0
Māhinahina[2]	22	388		1.73	901		14.2
Kahana[1]	285	190	>100%	10.7	475	54%	201
Kahana[2]	89.5	131		1.10	464		61.5
Kaʻōpala[1]	62	--	--	--	155	36%	55.3
Kaʻōpala[2]	8.62	--		--	31		7.19
Honokeana	43	--		--	142	>100%	22.3
Nāpili 4-5[1]	56	27	>100%	8.00	59	>100%	31.1
Nāpili 4-5[2]	8.73	27		0.50	58		1.69
Nāpili 2-3	44	--		--	62	>100%	9.37
Honokahua	91	21	>100%	8.55	23	>100%	3.22
Honolua	91	105	>100%	4.85	448	22%	59.5

[1]: representative of flow and sediment load entering the detention basin
[2]: representative of flow and sediment load leaving the detention basin

6.3.1 Trap Efficiency of Existing Detention Basins

The trap efficiency estimated by the rainfall-runoff model during the continuous flow simulation is presented in Table 6-3.

Table 6-3: Trap Efficiency of Existing Detention Basins

Honokōwai Basin			
	Trap Efficiency		
	Annual	Event: 23 Dec 2014	Event: 14 Feb 2015
Total Sediment	49%	42%	46%
Clay	1%	1%	1%
Silt	34%	33%	38%
Sand	100%	100%	100%
Gravel	100%	100%	100%
Māhinahina Basin			
	Trap Efficiency		
	Annual	Event: 23 Dec 2014	Event: 14 Feb 2015
Total Sediment	51%	56%	53%
Clay	3%	10%	10%
Silt	13%	24%	16%
Sand	100%	100%	100%
Gravel	100%	100%	100%
Kahana Basin			
	Trap Efficiency		
	Annual	Event: 23 Dec 2014	Event: 14 Feb 2015
Total Sediment	68%	95%	62%
Clay	35%	79%	27%
Silt	65%	100%	59%
Sand	100%	100%	100%
Gravel	100%	100%	100%
Ka‘ōpala Basin			
	Trap Efficiency		
	Annual	Event: 23 Dec 2014	Event: 14 Feb 2015
Total Sediment	86%	--	88%
Clay	11%	--	25%
Silt	100%	--	100%
Sand	100%	--	100%
Gravel	100%	--	100%
Nāpili 4-5 Basin			
	Trap Efficiency		
	Annual	Event: 23 Dec 2014	Event: 14 Feb 2015
Total Sediment	84%	94%	95%
Clay	12%	60%	71%
Silt	96%	100%	98%
Sand	100%	100%	100%
Gravel	100%	100%	100%

6.4 Magnitude-Frequency Analysis of Suspended Sediment Loads

What is the relationship between flow and sediment load for each watershed? This section begins to make that comparison with a magnitude-frequency analysis of the suspended sediment load. The continuous flow simulation introduced at the beginning of this section provides estimated sediment loads for various low flow events experienced in 2014 and 2015. Additionally, USGS provided an estimate for the decadal storm load in SIR 2020-5133. This was paired with the estimated peak flow for the 10% AEP "decadal" event, as presented earlier in Section 5.3.6. Together, a sediment-frequency curve can be developed to provide approximate loads for events up to and including the 10% AEP flood event. These estimates are provided in Table 6-4.

Table 6-4: Magnitude-Frequency Estimates of Suspended Sediment Load, Wahikuli Watershed Outlet

AEP		Peak Flow, cfs[1]	Sediment Load, tons[1]
0.5	1/2	1,270	11.3
0.2	1/5	2,330	247
0.1	1/10	3,220	700

[1]: rounded to three significant figures

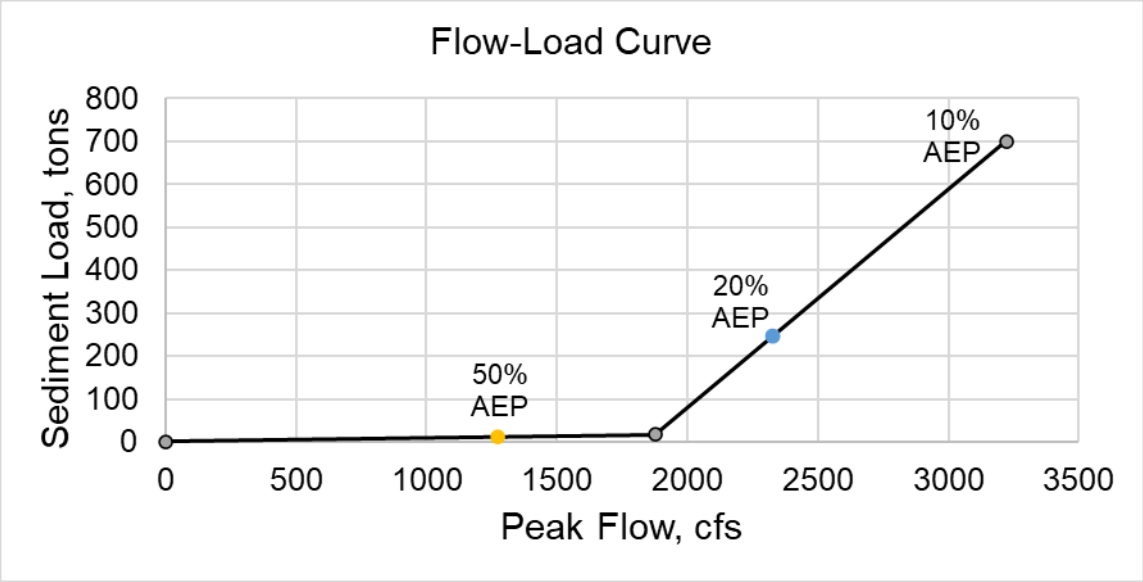


Figure 6-5: Peak Flow vs Sediment Mass Load, Wahikuli Watershed Outlet

Table 6-5: Magnitude-Frequency Estimates of Suspended Sediment Load Entering Honokōwai Detention Basin

AEP		Peak Flow, cfs[1]	Sediment Load, tons[1]
0.5	1/2	845	8.99
0.2	1/5	1,580	518
0.1	1/10	2,280	1,060

[1]: rounded to three significant figures

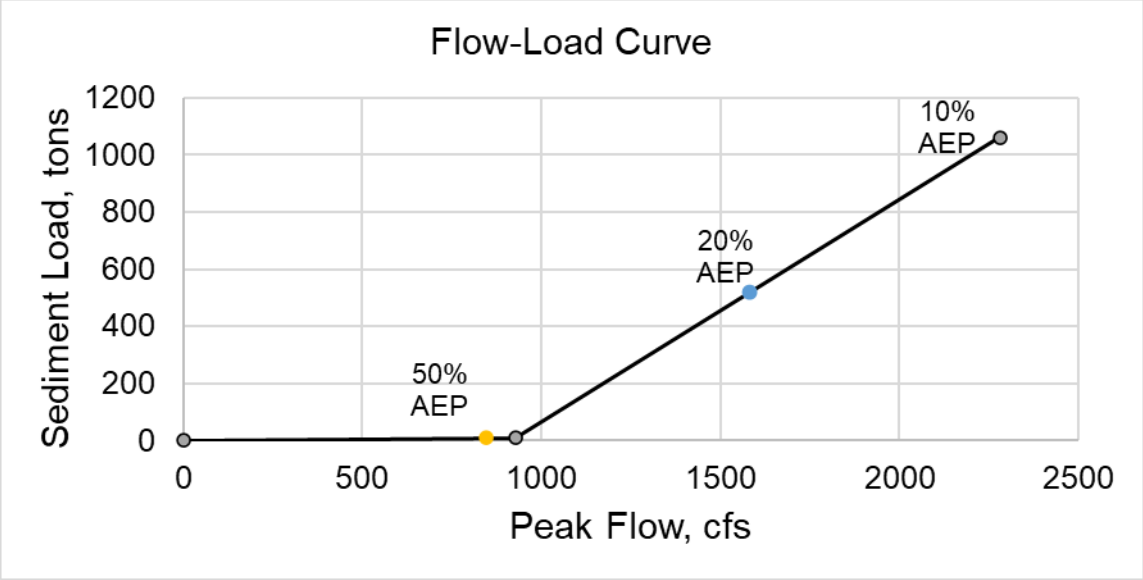


Figure 6-6: Peak Flow vs Sediment Mass Load Entering Honokōwai Detention Basin

Table 6-6: Magnitude-Frequency Estimates of Suspended Sediment Load Entering Kahana Detention Basin

AEP		Peak Flow, cfs[1]	Sediment Load, tons[1]
0.5	1/2	493	178
0.2	1/5	1,090	714
0.1	1/10	1,690	1,250

[1]: rounded to three significant figures

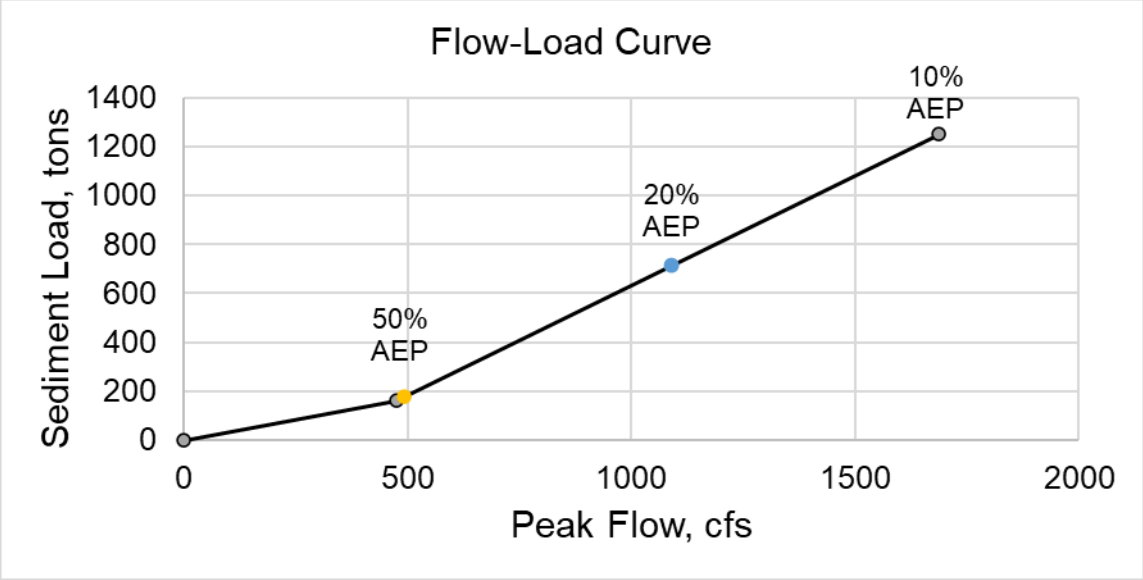


Figure 6-7: Peak Flow vs Sediment Mass Load Entering Kahana Detention Basin

Table 6-7: Magnitude-Frequency Estimates of Suspended Sediment Load Entering Ka‘ōpala Detention Basin

AEP		Peak Flow, cfs[1]	Sediment Load, tons[1]
0.5	1/2	182	78.5
0.2	1/5	396	180
0.1	1/10	583	270

[1]: rounded to three significant figures

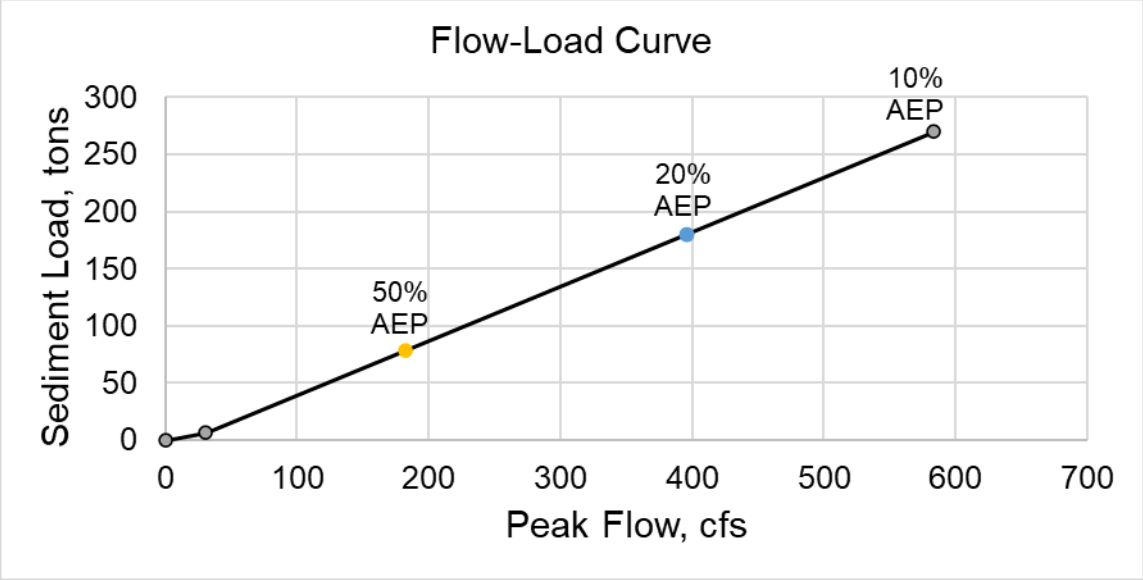


Figure 6-8: Peak Flow vs Sediment Mass Load Entering Ka‘ōpala Detention Basin

Table 6-8: Magnitude-Frequency Estimates of Suspended Sediment Load, Honolua Watershed Outlet

AEP		Peak Flow, cfs[1]	Sediment Load, tons[1]
0.5	1/2	227	30.2
0.2	1/5	497	378
0.1	1/10	717	1,800

[1]: rounded to three significant figures

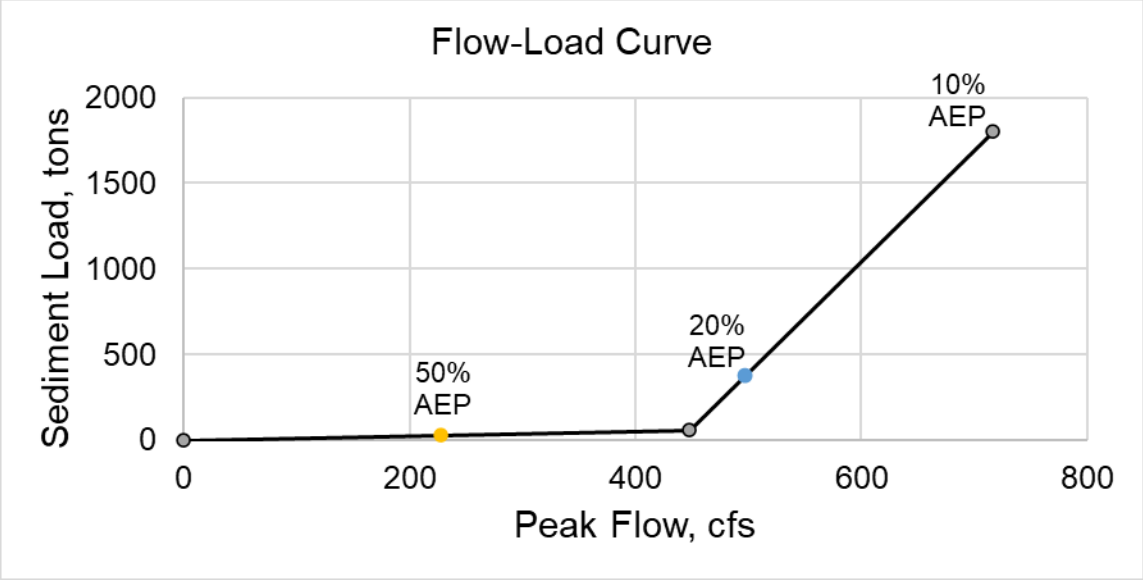


Figure 6-9: Peak Flow vs Sediment Mass Load, Honolua Watershed Outlet

7 Climate Change

A qualitative analysis on climate and hydrology was conducted in accordance with Engineering and Construction Bulletin (ECB) 2018-14, *Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects*.

7.1 Literature Review

A comprehensive literature review was completed to support this assessment, which includes, but is not limited to, review of the following key resources:

7.1.1 **Wahikuli-Honokōwai Watershed Management Plan**

A section on climate change was included in the 2012 *Wahikuli-Honokōwai Watershed Management Plan*, *Volume 1: Watershed Characterization* report. The narrative highlights the following:

- Sea level rise is expected to alter the location of the shoreline and impact infrastructure layout;
- Sea level rise will impact the water table of aquifers currently in contact with the ocean, and in some locations may increase the salinity level of the groundwater, reducing availability for fresh water uses;
- Changes to the flood regime, including its frequency and the extent of land impacted under future climatic conditions are unknown;
- Channel conveyance near the outlet may be reduced as a result of sea level rise;
- Global warming is likely to impact the Hawaiian trade wind regime and may have negative impacts on Hawaiian rainfall; and
- The most likely scenario for Hawai‘i is a 5 to 10% reduction of wet-season rainfall and a 5% increase of dry-season rainfall as a result of changes in the wind field.

7.1.2 **West Maui Watershed Plan: Climate Change**

In 2013, USACE published the report, *Applying a Risk Informed Decision-Making Framework for Climate Change to Integrated Water Resource Management Planning –*

West Maui Watershed Plan. Using a Shared Vision Process, USACE worked with several federal and state agencies, the County of Maui, and key non-governmental organizations to develop a decision framework to guide the West Maui R2R Initiative. One of the key lessons from this process was incorporating climate change early in the planning process to provide broader context for understanding of the key problems, constraints, and opportunities.

Of the physical changes in hydrology and sea level rise, the greatest concern for the West Maui areas is the potential impact of changing precipitation in the watershed. A primary root of the problems within the watershed is fragmented water systems with increasing demands on water for all uses. Drought conditions are likely to increase in frequency with climate change. While smaller storm events are expected to decrease in frequency, the large storm events are expected to increase in both frequency and intensity. Additionally, there is a significant amount of uncertainty around how species and ecosystems will respond to climate change shifts in Hawai‘i.

7.1.3 **West Maui Watershed Plan: Kahana, Honokahua and Honolua Watersheds**

In 2014, USACE completed a climate change analysis for the *West Maui Watershed Plan: Kahana, Honokahua and Honolua Watersheds, Characterization Report*. The analysis modeled climate impacts of rainfall amount, frequency, and intensity in addition to sea-level rise by downscaling available state level projections and other relevant sources. A time horizon of 50 years was used with an end year of 2065. The analysis examines and acknowledges many studies with climate change modeling. Based on the results of the various studies, the report concludes rainfall amounts, frequency and intensity would remain at current levels.

For the report, three sea-level rise scenarios were modeled per USACE ER 1100-2-8162 *Incorporating Sea Level Change in Civil Works Programs*. The sea-level rise projections ranged from 6 to 18 inches, with 12 inches (a 1-foot rise) in the middle of the range. Sea-level rise will change the shoreline and impact the aquifer water table. Ground water may increase in salinity, thereby reducing freshwater availability. Drainage channels may back up at outlets due to higher sea-level elevation. This would reduce the ability of channels to convey water and increase amount and time of runoff water in channels.

The impacts of sea-level rise can also be considered by looking at the Flood Zone maps where the VE zone is identified. These are low lying areas where ocean effects are the greatest during storm events and may eventually be impacted similarly by sea-level rise.

7.1.4 **National Climate Assessment**

The Fourth National Climate Assessment (NCA4) was first published in 2018 by the U.S. Global Change Research Program (USGCRP, 2018). Volume II, Chapter 27 provides a regional-specific assessment on the current and future risks posed by climate change and what can be done to minimize risk in Hawaii and U.S.-affiliated Pacific Islands. This document includes six key messages focusing on 1) water supplies, 2) ecosystems and biodiversity, 3) coastal communities, 4) marine resources, 5) indigenous peoples, and 6) impacts and adaptation.

7.1.4.1 Climate Change and Pacific Islands: Indicators and Impacts

In 2012, the *Climate Change and Pacific Islands: Indicators and Impacts* report was published as one of a series of technical inputs for the National Climate Assessment. This report was developed by the Pacific Islands Regional Climate Assessment (PIRCA) and aimed at assessing the state of knowledge about climate change indicators, impacts, and adaptive capacity of the Hawaiian Archipelago and the U.S.-affiliated Pacific Islands (Keener, Marra, Finucane, Spooner, & Smith, 2012). Key findings of this assessment suggest multiple concerns for human and natural communities in the Pacific Islands region:

- Low islands, coral reefs, nearshore and coastal areas on high islands, and high-elevation ecosystems are most vulnerable to climatic changes.
- Freshwater supplies will be more limited on many Pacific Islands, especially low islands, as the quantity and quality of waters in aquifers and surface catchments change in response to warmer, drier conditions coupled with increased occurrences of saltwater intrusion.
- Rising sea levels will increase likelihood of coastal flooding and erosion, damaging coastal infrastructure and agriculture, negatively impacting tourism,

reducing habitat for endangered species, and threatening shallow reef systems.

- Extreme water levels will occur when sea-level rise related to longer-term climate change combines with seasonal high tides, interannual and interdecadal sea-level variations (e.g. ENSO, Pacific Decadal Oscillation, mesoscale eddy events), and surge and/or high runup associated with storms.
- Higher sea-surface temperatures will increase coral bleaching, leading to a change in coral species composition, coral disease, coral death, and habitat loss.
- Rising ocean acidification and changing carbonate chemistry will have negative consequences for the insular and pelagic marine ecosystems; although potentially dramatic, the exact nature of the consequences is not yet clear. Distribution patterns of coastal and ocean fisheries will be altered, with potential for increased catches in some areas and decreased catches in other areas, but open-ocean fisheries being affected negatively overall in the long term.
- Increasing temperatures, and in some areas reduced rainfall, will stress native Pacific Island plant and animal populations and species, especially in high-elevation ecosystems, with increased exposure to non-native biological invasions and fire, and with extinctions a likely result.
- Threats to traditional lifestyles of indigenous communities in the region (including destruction of coastal artifacts and structures, reduced availability of traditional food sources and subsistence fisheries, and the loss of the land base that supports Pacific Island cultures) will make it increasingly difficult for Pacific Island cultures to sustain their connection with a defined place and their unique set of customs, beliefs, and languages.
- Mounting threats to food and water security, infrastructure, and public health and safety will lead increasingly to human migration from low islands to high islands and continental sites.

7.1.5 State Climate Summary

In 2022, NOAA published its State Climate Summaries to provide each state with up-to-date information on observed changes in climate, including both long-term trends and extreme weather events relevant to that state. Its key messages for Hawai'i include the following:

1) Temperatures in Hawai'i have risen by about 2°F since 1950, with a sharp increase in warming over the last decade. Under a high emissions pathway, historically unprecedented warming is projected during this century.
2) Annual rainfall has decreased throughout Hawai'i since the early 1980s, with uncertain projections for the future. The frequency and magnitude of extreme precipitation events have changed in recent years, but these changes are not uniform across the island chain. Extreme precipitation events have become less frequent for Kaua'i and O'ahu but more frequent for the island of Hawai'i.
3) Sea level rise will continue to be a major threat to the state's coastline through inundation and erosion.

7.1.6 Hawai'i's Climate Commission

In response to the Paris Agreement, the State of Hawaii created the Hawaii Climate Change Mitigation and Adaptation Commission. The Commission's priorities are captured in two statements, on ground transportation emissions reduction and adaptation to sea level rise, including disaster recovery preparedness. Among other projects, their work includes the development of Sea Level Rise online tools, highlighting nature-based solutions in Hawai'i and characterizing climate vulnerabilities in Hawaii (Hawai'i Climate Change Mitigation and Adaptation Commission, 2021).

7.1.7 Hawai'i's Changing Climate

In 2010, Dr. Chip Fletcher published a briefing sheet on *Hawai'i's Changing Climate* funded by the University of Hawai'i's Sea Grant College Program. This document highlights some of the climate change indicators trending in Hawaii, where:

- Air temperature has risen;
- Rainfall and stream flow have decreased;
- Rain intensity has increased;

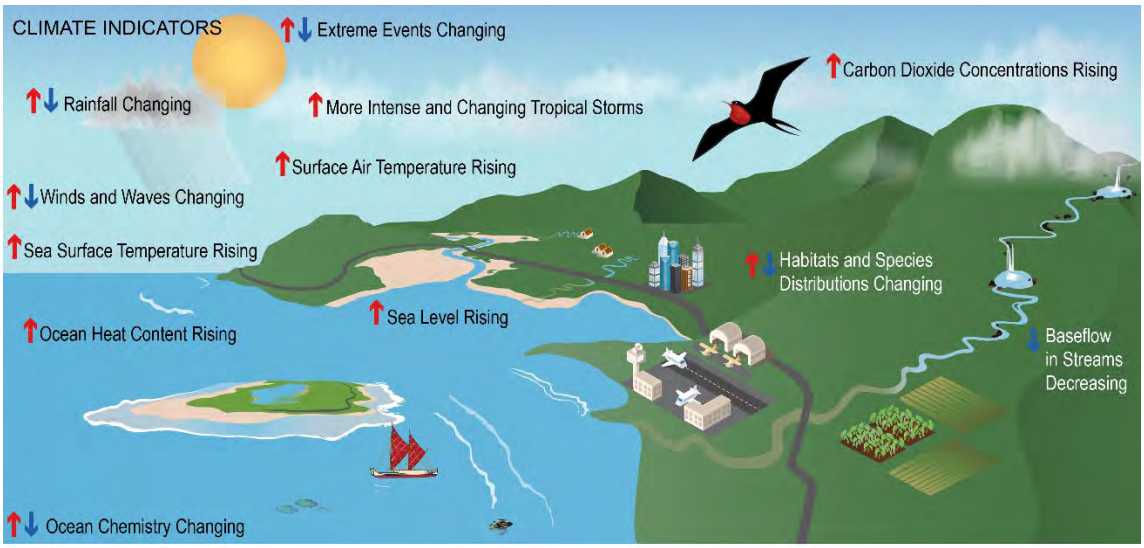
- Sea level and sea surface temperature have increased; and
- The ocean is acidifying.

7.2 Climate Indicators

Regionally and within the study area, the following climate change indicators are relevant to this project:

- Rising surface air temperatures
- Rising sea surface temperatures
- Winds changing
- More frequent El Niño-Southern Oscillation occurrences
- Less frequent, but more intense rainfall;
- More frequent and more intense tropical cyclones;
- Declining base flow in streams;
- Ocean acidification
- Rising sea levels

These indicators and others were also identified by NCA4, as portrayed in Figure 7-1. The sections that follow provide additional information on climate indicators for West Maui and the region.



Source: NCA4, 2018

Figure 7-1: Climate Indicators in Hawai‘i

7.2.1 Rising Surface Air Temperature

The surface air temperature in Hawai‘i is rapidly rising (averaging 0.3°F per decade), but less than the global rate of warming (0.36°F per decade). At low elevations (below 2,600 ft), the rate of temperature rise is much lower (0.16°F per decade). At high elevations (above 2,600 ft), however, the rate of temperature rise is 0.48°F per decade – much higher than the global rate of warming (Fletcher, 2010). For reference, the *Lower Honokōwai* rainfall gage (located deep in Honokōwai valley) is at an elevation of 2,602 ft.

7.2.2 Rising Sea Surface Temperatures

Sea surface temperatures in the region are rising at a rate of 0.22°F per decade according to marine researchers at the University of Hawai‘i. Continued warming of Hawaiian surface waters potentially expose coral reefs and other marine ecosystems to negative impacts related to temperature increases. (Fletcher, 2010). Warmer waters mean less oxygen in the water, making it hard for corals and beneficial algae to survive (Hawai'i Climate Change Mitigation and Adaptation Commission, 2021).

7.2.3 Winds Changing

Trade winds are expected to change in the future, but there is still great uncertainty regarding the extent of these changes. Performing climatological studies in the region of Hawaii are challenging due to 1) the steadiness of the trade winds over the Pacific Ocean,

2) orography and diurnal cycles over the islands, and 3) natural variability which include ENSO and the Pacific Decadal Oscillation (PDO). Generally, winds over the Hawaiian Island region are expected to change direction (from northeast to east) and wind speed is expected to increase (Garza, Chu, Norton, & Schroeder, 2012). Persistent northeasterly trade winds are important to Hawaii because they affect wave height, cloud formation, and precipitation over specific areas of the region.

7.2.4 More Frequent El Niño-Southern Oscillation Occurrences

Every 3 to 7 years, climate conditions over the Pacific Ocean basin change dramatically because of the El Niño-Southern Oscillation (ENSO). The extremes of this oscillation are referred to as El Niño and La Niña. As summarized by NOAA's Pacific ENSO Applications Climate Center, an El Niño event would typically result in the following climate impacts in Hawai'i:

- More rain the beginning of the season, then rapidly less;
- Weaker trade winds, with occasional westerly winds;
- Near to slightly above normal sea level;
- High run-up from distant swells;
- Much warmer temperatures at and below the sea surface; and
- Increased risk of tropical cyclones (storms form closer and move towards the islands).

The strength of these ENSO-related patterns in the short term can make it difficult to detect the more gradual, long-term trends of climatic change. It is unknown how the timing and intensity of ENSO will continue to change in the coming decades, but recent climate model results suggest a doubling in frequency of both El Niño and La Niña extremes in the 21st century as compared to the 20th century under scenarios with more warming (Keener, et al., 2018).

7.2.5 Less Frequent, but More Intense Rainfall

Rainfall in Hawai'i is strongly affected by climate-driven variations, such as the El Niño-Southern Oscillation (which oscillates every 3-7 years) and the Pacific Decadal Oscillation (which produces strings of wet or dry years lasting decades in the region). El Niño events are typically associated with lower than normal rainfall during winter months

in Hawai‘i. Positive phases of the PDO are also generally associated with lower rainfall in Hawai‘i. In addition to natural variations, mean rainfall in Hawaii has slowly declined overall as a result of long-term trends that might be caused by global warming.

Despite this downward trend in mean annual rainfall, rainfall events in Hawai‘i are becoming more extreme. Heavy rainfall events and droughts are becoming more common. The number of consecutive wet days and the number of consecutive dry days are both increasing in Hawai‘i (Keener, et al., 2018).

7.2.5.1 Nonstationarity Analysis

To investigate whether a trend of changing peak annual flow is occurring, West Maui gage records were tested using the Nonstationarity Detection Tool in accordance with ETL 1110-2-3. Two USGS streamflow gages (16630200 and 16620000) were used in this study, as previously introduced in Section 4.2, Table 4-2.

The gage record for USGS 16630200, Honokōwai Stream at Honokōwai, Maui, HI includes peak annual stream flow from 1961 to 2009 and has a 47-year period of record. This period of record has a missing data point, which can sometimes result in potential issues with the changepoints detected. The missing data point is for 1964. The gage captures a drainage area of 5.74 square miles and is located about 60 ft above local mean sea level (LMSL). The tool did not detect any statistically significant changes. The average peak streamflow observed over the period of record is 753.0 ft^3/s with a standard deviation of 772.2 ft^3/s and a variance of 596,262 ft^3/s. Monotonic trend analysis of this period did not detect a statistically significant trend using the Mann-Kendall Test at a 0.05 level of significance (exact p-value of 0.140) or using the Spearman Rank Order Test at the 0.05 level of significance (exact p-value of 0.174). No trends were detected using parametrical statistical methods or Sens's Slope method. No nonstationarities or monotonic trends are detected within the streamflow record for USGS 16630200, Honokōwai Stream at Honokōwai, Maui, HI.

The gage record for USGS 16620000, Honokōhau Stream near Honokōhau, Maui, HI includes peak annual stream flow from 1914 to 2020, which is a 102-year period of record. This period of record has missing data points, which can sometimes result in potential issues with the changepoints detected. The missing data points are 1921-1922,

1929, 1990, and 2016. The gage captures a drainage area of 4.18 square miles and is located about 940 ft above LMSL. A nonstationarity detector and trend analysis was performed on the period from 1914 to 2015 (the record was truncated due to the missing data point on the tail end of the complete record). The tool detected three possible nonstationiarities based on a change in distributional characteristics in 1957, 1986, and 1991 (Figure 7-3). However, each changepoint was supported by only one of the four distributional changepoint tests (lack of consensus). Additionally, there was one possible nonstationarity based on a statistically significant change in variance in 1998 (Figure 7-3). This was also only supported by one of the two variance changepoint tests (lack of consensus). The average peak streamflow observed over the period of record is 2,409 ft^3/s with a standard deviation of 1,574 ft^3/s and a variance of 2,476,978 ft^3/s. Monotonic trend analysis of this period did not detect a statistically significant trend using the Mann-Kendall Test at a 0.05 level of significance (exact p-value of 0.729) or using the Spearman Rank Order Test at the 0.05 level of significance (exact p-value of 0.757). No trends were detected using parametrical statistical methods or Sens's Slope method.

These two analyses indicate that no statistically significant changes in the basin hydrology have occurred during the period of record.

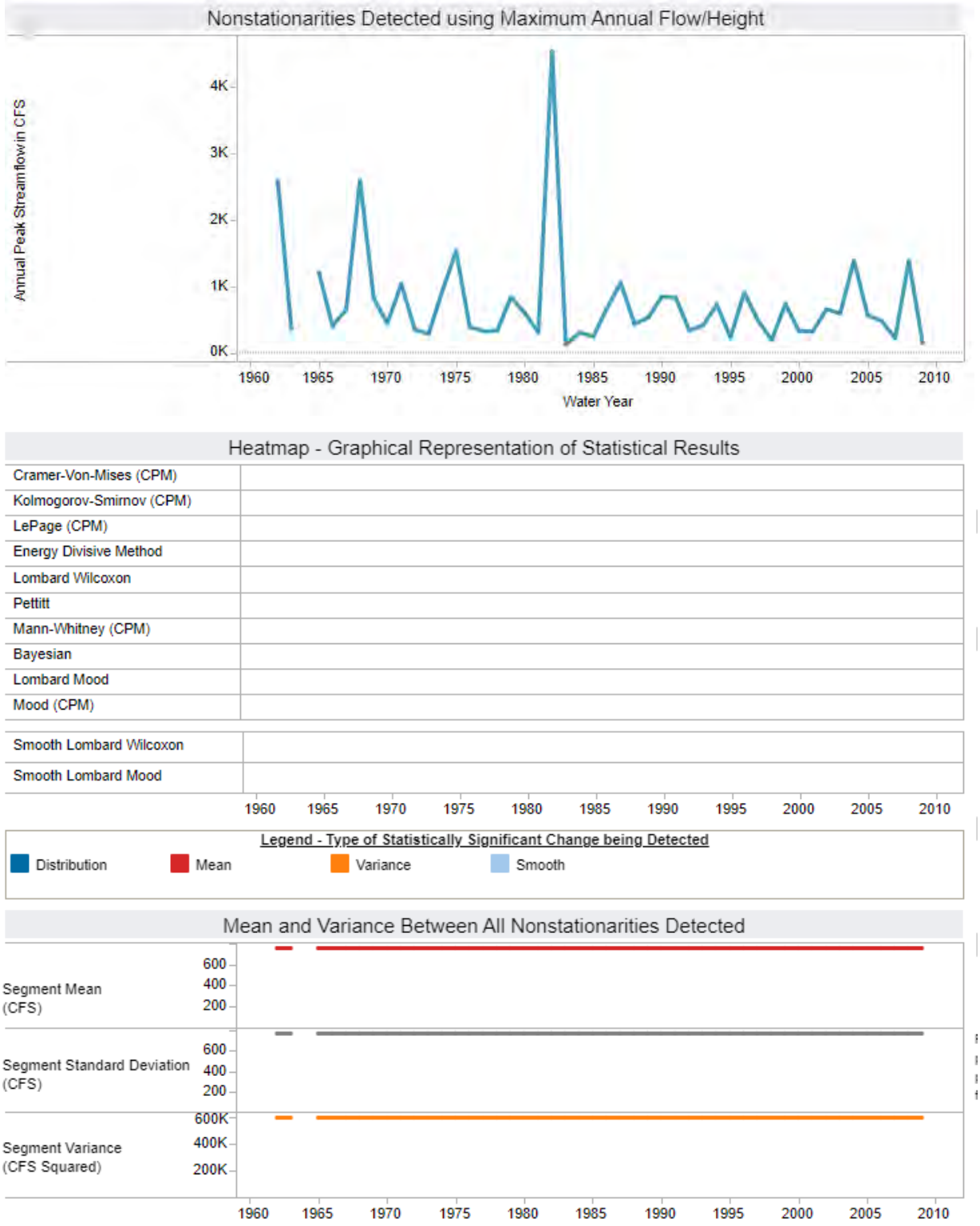


Figure 7-2: Nonstationarity Detector Charts – USGS 16630200

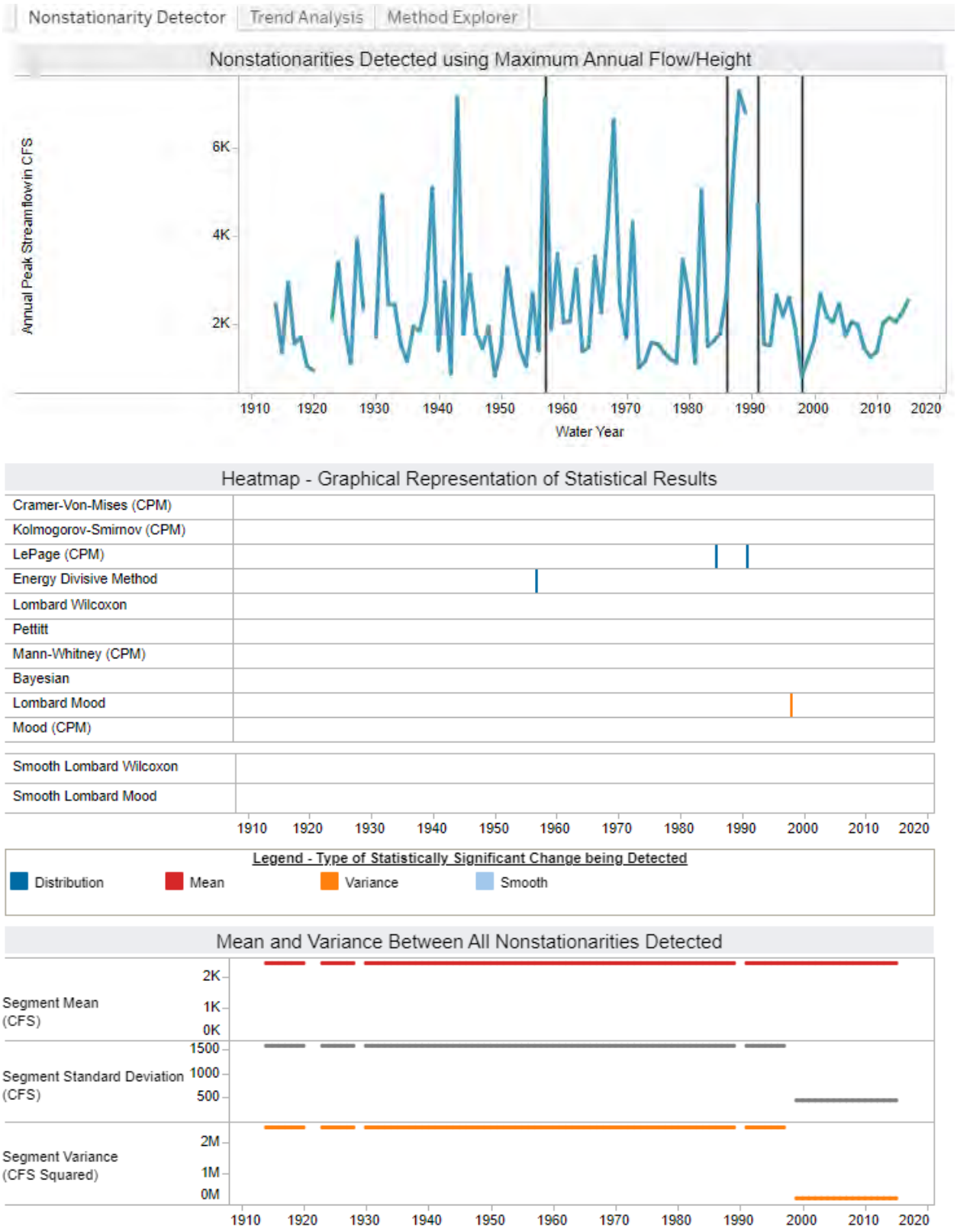


Figure 7-3: Nonstationarity Detector Charts – USGS 16620000

7.2.6 More Frequent, and More Intense Tropical Cyclones

The way climate change alters the frequency and intensity of tropical cyclones is complex. However, tropical cyclone frequency and intensity in the central Pacific are expected to increase. This is in part due to:

1) changes in tropical cyclone tracks
2) increased formation of tropical cyclones near Hawai‘i
3) weakening of the vertical wind shear that typically tears tropical cyclones apart as they approach the islands
4) Greater frequency of ENSO occurrences (Keener, et al., 2018).

A physically based empirical model analysis in 2013 revealed that the primary cause for an increased tropical cyclone frequency around the Hawaiian Islands was due to storm tracks shifting northward in the open ocean southeast of the island (Murakami, Wang, Li, & Kitoh, 2013). The study also found other causes for an increased frequency of tropical cyclone occurrences 1) tropical cyclone formation in the open ocean east of the Hawaiian domain is expected to increase and 2) a projected change-in-track effect off the coast of Mexico (tropical cyclones that form there are more likely to propagate into the Hawaiian domain).

Tropical cyclones are expected to landfall more frequently and with greater intensity in Hawai‘i due to the loss of a “vertical wind shear” that typically tears them apart as they approach the islands. In Hawai‘i, strong northeasterly trade winds flow in the opposite direction of the westerly winds aloft in the upper atmosphere. The effect – a “vertical wind shear” – essentially tears apart approaching tropical cyclones before they can make landfall. However, this wind shear is simulated to weaken. Under the assumption that CO_2 concentrations are doubled, model simulations show an approximate doubling of the risk of landfalling tropical cyclones in Hawai‘i (Grabowski M. , 2020).

El Niño events typically result in an increased risk of tropical storms landfalling, as storms form closer and move towards the islands more easily. The number of ENSO occurrences is also expected to increase, as discussed in Section 7.2.4. The most active hurricane season on record in the Central Pacific was 2015 (a strong ENSO season), with 8 hurricanes and 6 additional tropical storms (NCEI, 2022).

7.2.7 **Declining Base flow in Streams**

Oki (2004) indicated that a long-term reduction in base flow (groundwater discharge to streams) in Hawaii during the 20th century is consistent with a reduction in rainfall. Decadal variability in base flow appears to be related to the PDO, although the PDO cannot fully explain the downward trend in base flow. The downward trend in base flow is generally consistent with documented trends in other factors (rainfall, frequency of trade-wind inversion, and temperature) that indicate a drying climate and reflect the vulnerability of streamflow to climate change (Bassiouni & Oki, 2012).

7.2.8 **Ocean Acidification**

Ocean acidification is the process by which ocean waters have become more acidic (have a lower pH) due to the absorption of human-produced carbon dioxide. Ocean acidification reduces the ability of corals to build and maintain reefs. Nutrient input can substantially exacerbate acidification of reef erosion.

A study by Henson et al. (2016) found that the climate change-driven trend in pH already exceeds the range in natural seasonal variability over most of the ocean. Analysis of the trend suggests that ocean acidification is likely to be anthropogenically driven.

7.2.9 **Rising Sea Levels**

USACE requires that planning studies and engineering designs consider alternatives that are formulated and evaluated for the entire range of possible future rates of sea level change (SLC). Designs must be evaluated over the project life cycle and include evaluations for three scenarios of *low*, *intermediate*, and *high* sea level change. According to Engineer Regulation (ER) 1100-2-8162 (USACE, 2019) and Engineer Pamphlet 1100-2-1 (USACE, 2019), the SLC *low* rate is the historic SLC. The *intermediate* and *high* rates are computed by:

- Estimating the *intermediate* rate of local mean sea level change using the modified National Research Council (NRC) Curve I, the NRC equations, and correcting for the local rate of vertical land movement (VLM).
- Estimating the *high* rate of local mean sea level change using the modified NRC Curve III, NRC equations, and correcting for the local rate of VLM. This *high* rate exceeds the upper bounds of the Intergovernmental Panel on

Climate Change (IPCC) estimates from both 2001 and 2007 to accommodate the potential rapid loss of ice from Antarctica and Greenland.

The 1987 NRC described these three scenarios using the following equation:

$$\boldsymbol{E(t) = 0.0012t + bt^2}$$ Equation 1

in which *t* represent years, starting in 1986, *b* is a constant, and *E(t)* is the eustatic sea level change, in meters, as a function of *t*. The NRC committee recommended, "projections be updated approximately every decade to incorporate additional data." At the time the NRC report was prepared, the estimate of global mean sea-level (GMSL) change was approximately 1.2 mm/year. Using the current estimate of 1.7 mm/year for GMSL change, as presented by the IPCC, results in this equation being modified to be:

$$\boldsymbol{E(t) = 0.0017t + bt^2}$$ Equation 2

The three scenarios proposed by the NRC result in global eustatic sea level rise values (by the year 2100) of 0.5 meters, 1.0 meters, and 1.5 meters. Adjusting the equation to include the historic GMSL change rate of 1.7 mm/year and the start date of 1992 (which corresponds to the midpoint of the current National Tidal Datum Epoch of 1983-2001), results in updated values for the variable b being equal to 2.71E-5 for modified NRC Curve I, 7.00E-5 for modified NRC Curve II, and 1.13E-4 for modified NRC Curve III.

Manipulating the equation to account for it being developed for eustatic sea level rise starting in 1992, while project will be constructed at some date after 1992, results in the following equation:

$$\boldsymbol{E(t_2) - E(t_1) = 0.0017(t_2 - t_1) + b({t_2}^2 - {t_1}^2)}$$ Equation 3

where t_1 is the time between the project's construction date and 1992 and t_2 is the time between a future date at which one wants an estimate for sea-level change and 1992 (or

t_2 = t_1 + the number of years after construction). Using the three *b* scenarios required by ER 1100-2-8162 (United States Army Corps of Engineers, 2019) results in the following three GMSL rise scenarios depicted in Figure 7-5.

An analysis of the potential sea level rise was performed in the projected area. The gage at Kahului Harbor (NOAA ID: 1615680) was used for the analysis. This gage was established in 1946 and in its present location since 1989. It is located on the northwest corner of Pier #2 at Kahului Harbor, approximately 1.5 miles southeast of the Wailuku River outlet. The relative sea level trend for this tidal gauge is 2.26 mm/year (0.007415 ft/yr) with a 95% confidence interval of +/- 0.39 mm/yr based on monthly mean sea level data from 1947 to 2021, which is equivalent to a change of 0.74 feet in 100 years.

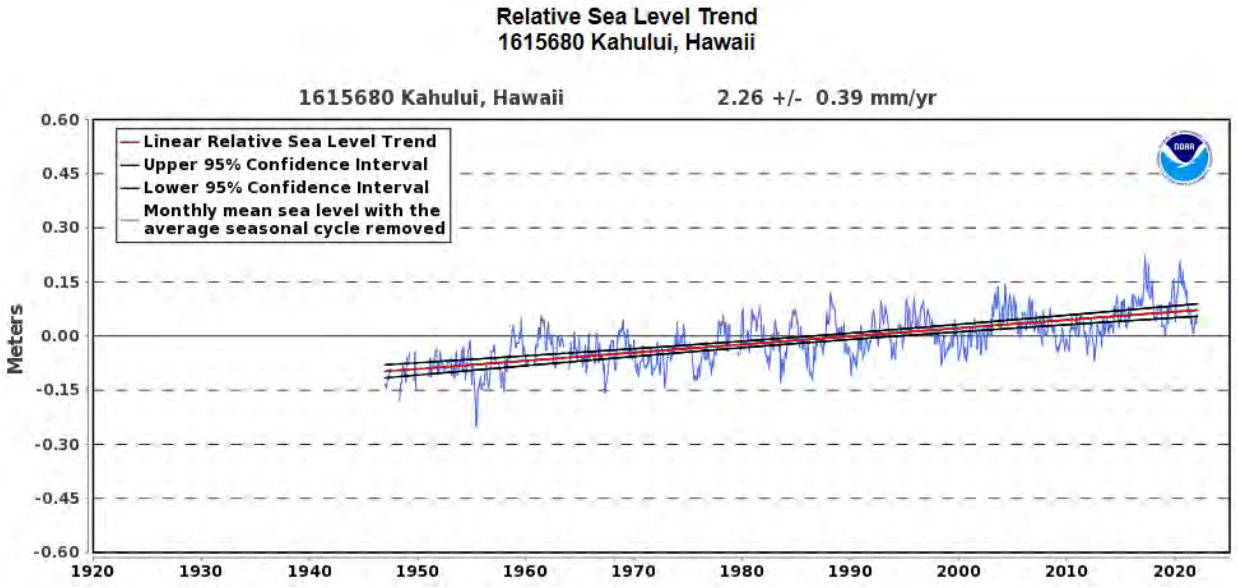


Figure 7-4: Relative Sea Level Trend for Station 1615680 Kahului, Hawaii

This gage site was input into the USACE Sea Level Change Calculator (Version 2019.21). The result of the calculation indicates a relative sea level change of 5.15 feet was determined in the year 2100 at the *high* condition. For the *intermediate* condition, the change is 1.86 feet, and the *low* condition shows an increase of 0.82 feet. These values are relative to Local Mean Sea Level (LMSL) as the calculator states NAVD88 datum is not available for this station. The resulting sea level rise curve is shown in Figure 7-5. This curve is based on the 2006 NOAA sea level change rate of 0.00761 ft/yr, which is

higher than the 2021 rate (0.007415 ft/yr) and is therefore a conservative assumption of sea level rise.

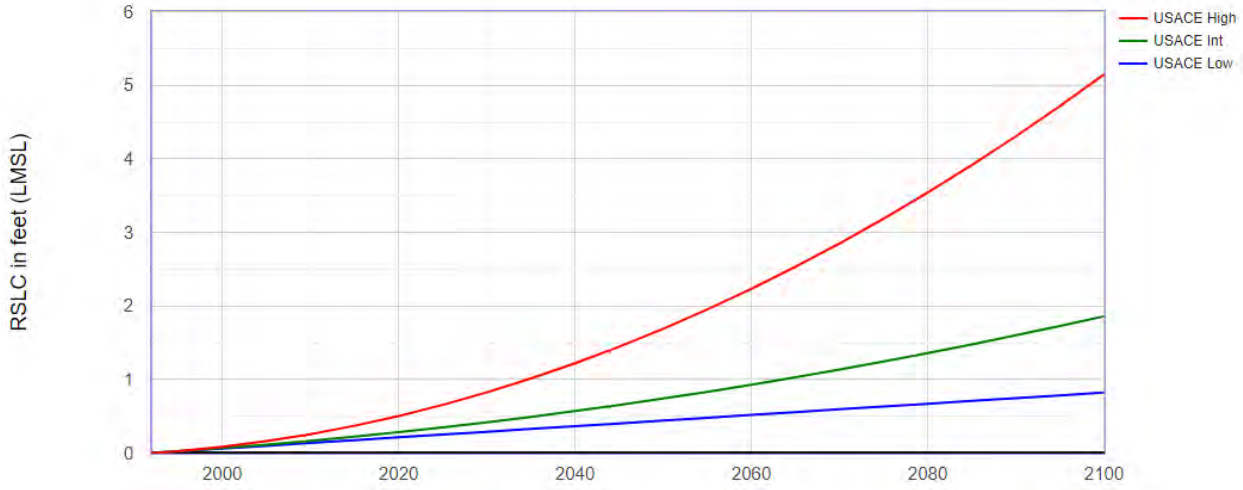


Figure 7-5: Estimated Relative Sea Level Change Projections – Gauge: 1615680, Kahului: Kahului Harbor, HI

The calculator also outputs a table showing the progression of sea level rise. This table was derived in 5-year increments and is shown below.

Table 7-1: Sea Level Rise by Year

Year	USACE		
	Low	***Intermediate***	***High***
1992	0.00	0.00	0.00
1995	0.02	0.02	0.03
2000	0.06	0.07	0.09
2005	0.10	0.11	0.16
2010	0.14	0.17	0.26
2015	0.18	0.22	0.37
2020	0.21	0.28	0.50
2025	0.25	0.35	0.66
2030	0.29	0.42	0.83
2035	0.33	0.49	1.01
2040	0.37	0.57	1.22
2045	0.40	0.65	1.45
2050	0.44	0.74	1.69
2055	0.48	0.83	1.95
2060	0.52	0.93	2.23
2065	0.56	1.03	2.53
2070	0.59	1.14	2.85
2075	0.63	1.24	3.19
2080	0.67	1.36	3.54
2085	0.71	1.48	3.91
2090	0.75	1.60	4.31
2095	0.78	1.73	4.72
2100	0.82	1.86	5.15

The calculator also provides extreme water levels expected across several datums. These datums and their respective values are shown in the table and figure below:

Table 7-2: Tidal Datums and Extreme Water Levels

Datum / EWL	Reference Datum	
	LMSL	***MLLW***
HAT	1.98 ft	3.09
MHHW	1.14 ft	2.25
MHW	0.78 ft	1.89
MSL	0.00 ft	1.11
MLW	-0.79 ft	0.32
MLLW	-1.11 ft	0
NAVD88	--	
EWL Type	NOAA GEV	
1/100 AEP	2.55 ft	3.66
1/50 AEP	2.50 ft	3.61
1/20 AEP	2.42 ft	3.53
1/10 AEP	2.35 ft	3.46
1/5 AEP	2.27 ft	3.38
½ AEP	2.11 ft	3.22
Yearly	1.78 ft	
Monthly	--	
From	1947	
To	2007	
Years of Record	60	

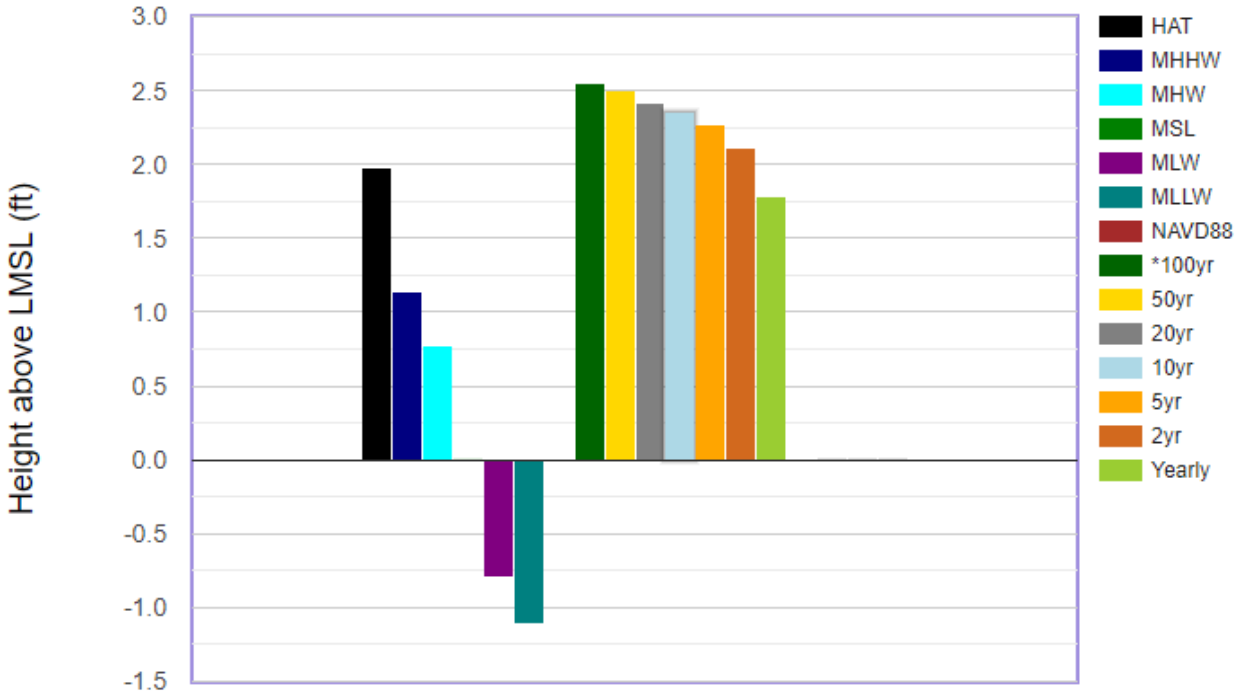


Figure 7-6: Tidal Datums and Extreme Water Levels

The highest tide level occurred in August 2017 and was 3.59 MLLW (2.47 MSL). Under *high* sea level rise conditions, this max tide level would be 8.37 MLLW (7.25 MSL) in 2100. The relative change in sea level from 2015 to 2100 is 4.78 feet. With regards to the streams in West Maui, this elevation is still very near to the ocean outlet with negligible impacts to existing or proposed project features.

The State of Hawai'i's Sea Level Rise Viewer provides a visual of the exposure area should sea level rise 3.2 ft above mean sea level (Figure 7-7). The projected extent of chronic flooding due to sea level rise is based on modeling results for three chronic flooding hazards: passive flooding, annual high wave flooding, and coastal erosion. Under this scenario (3.2 ft above MSL), flooded areas within the study area remain along the coast (PacIOOS, 2021). For reference, 3.2 ft above mean sea level (MSL) corresponds to approximately years 2415, 2145, and 2080 under *low*, *intermediate*, and *high* conditions as projected by the USACE Sea Level Change Calculator (Figure 7-5).

The difference between MLLW and MHHW is 2.25 feet; and the difference between MSL and MHHW is 1.13 feet. This shift in sea surface elevation would not cause impacts to extend beyond the currently displayed inundation areas and thus won't impact

proposed project features which would all be further inland. Neither would compounding MHHW conditions with the maximum interannual variation. Interannual variation for many Pacific stations are closely related to the ENSO. For this station, the interannual variation is near 0.15 meters (0.50 feet), as shown in Figure 7-8.

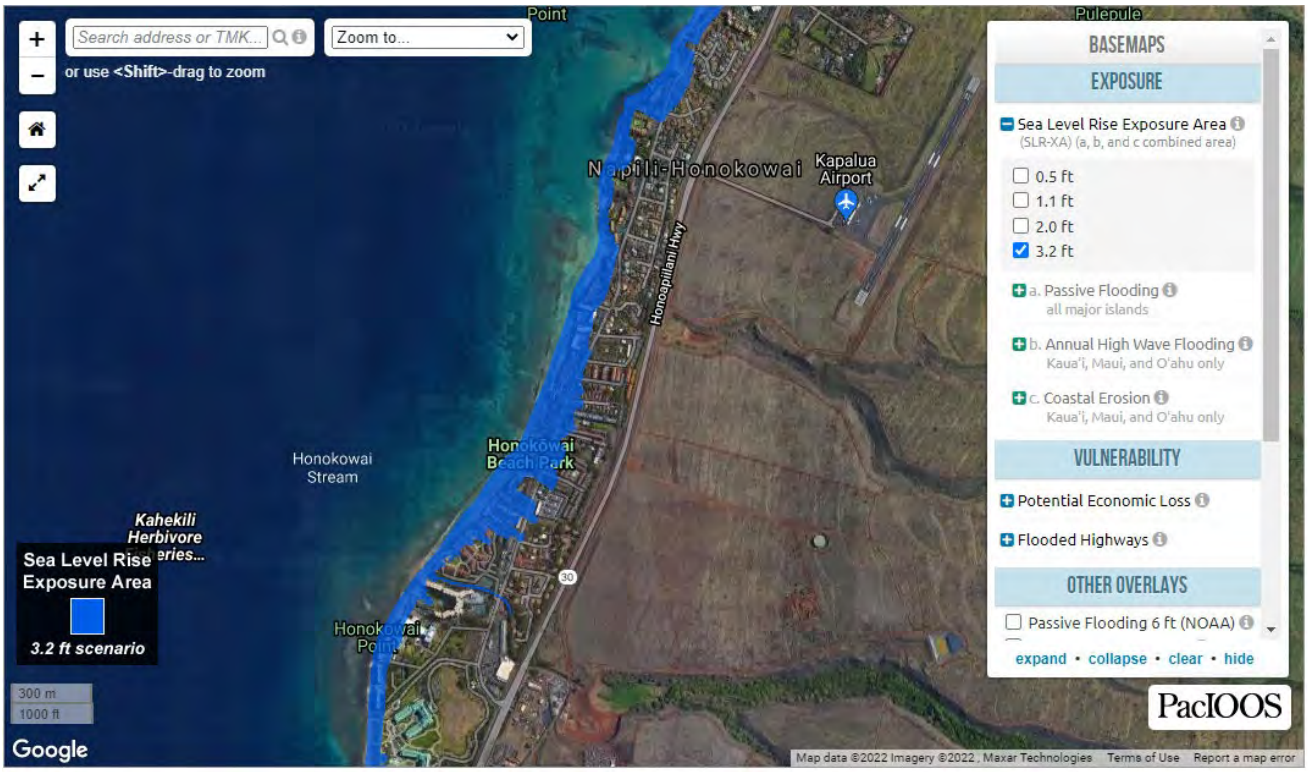


Figure 7-7: State of Hawai'i Sea Level Rise Viewer – Honokōwai, West Maui

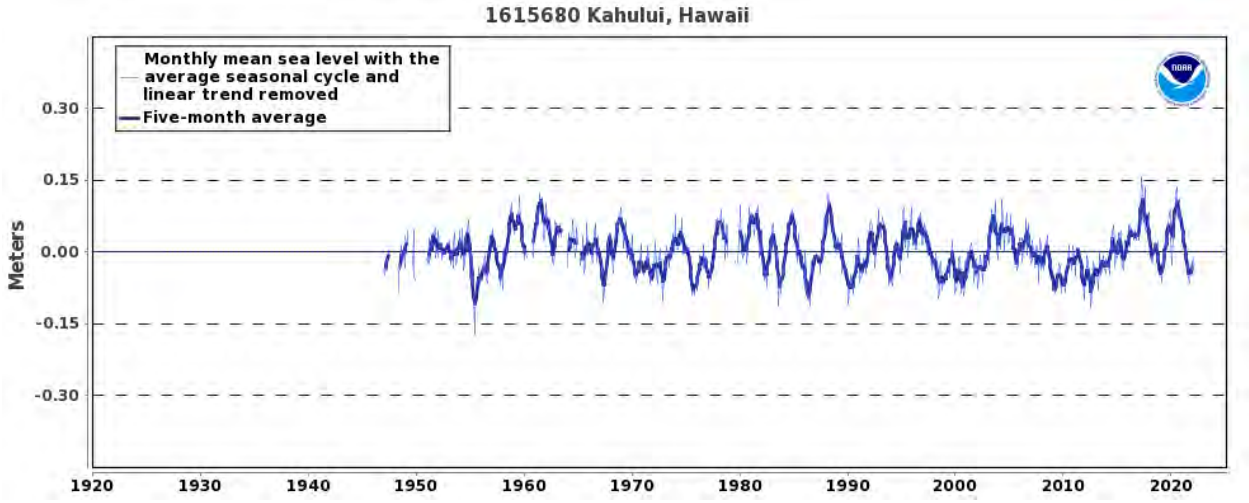


Figure 7-8: Interannual Variation, Station 1615680, Kahului, Hawaii

7.3 Summary of Impacts

Regionally and within the study area, the following climate change impacts are relevant to this project:

- Less frequent riverine sediment contributions to the nearshore environment, but with larger yields
- Greater sediment load contributions from floodplains
- Shoreline erosion
- Coral reef bleaching and loss

7.3.1 Riverine Sediment Contributions to the Nearshore Environment

It was determined from the coastal camera analysis (Section 4.3.2.2) 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. With rainfall occurring less frequently (Section 7.2.5) and base flow decreasing (Section 7.2.7), there will likely be less occurrences of flow in West Maui streams and corresponding contributions of residual sediment to the nearshore environment in the future.

However, with increasing intensity of rainfall also predicted (Section 7.2.5), there is greater likelihood that when rainfall events do occur, they are more likely to erode the in-stream historic fill terraces or result in greater hydrologic connectivity with the upper agricultural terraces (floodplain). Both occurrences would result in larger peak flows and higher sediment loads in the river systems. It is possible the peak flow estimates presented in Section 5.3.6 and magnitude-frequency estimates of suspended sediment loads presented in Section 6.4 are slightly underestimated for future conditions.

7.3.2 Greater Sediment Load Contributions from Floodplains

Typically, a warming climate results in greater evaporation and drier conditions across the region. This can increase the risk of droughts, wildfires, and flooding (EPA). The occurrence of wildfires is likely to increase due to the combined effects from rising temperatures, a growing human population, and expanding invasive grass cover (NCEI, 2022). Wildfires burn ground cover, leaving soils either 1) exposed and highly erodible, increasing the risk of sediment entering the nearshore environment, or 2) charred, barren,

and unable to absorb water, creating conditions ripe for flash flooding and mudflow. Either scenario would result in greater sediment loads entering the riverine systems (and eventually the marine environment) during significant storm events (10% AEP event or greater).

A sensitivity analysis on various hydrologic parameters used in the HMS model determined that *lag time* had a moderate effect on peak flow estimates (Section 5.3.7). Loss of vegetation due to drought conditions or wildfire would likely reduce *lag time* and result in higher peak flow estimates than initially predicted.

According to SIR 2020-5133 (Section 1.5), the storms capable of generating widespread runoff from agricultural fields are decadal events. As rainfall intensity increases due to climate change (Section 7.2.5), rainfall events are more likely to establish hydrologic connectivity between the floodplains and the adjacent streams. This would significantly increase the sediment load estimated for smaller frequency events (annual to decadal).

7.3.3 **Shoreline Erosion**

Existing properties near the shoreline are already feeling effects from rising sea levels and higher than usual tides. Annual Erosion Hazard Rates for the West Maui shoreline were previously estimated by the University of Hawai‘i at Mānoa’s Coastal Geology Group based on analyzing historical shoreline positions from 1912 to 1997 combined with projected rates of sea level rise. Light to moderate erosion is expected (averages of -0.3 ft/yr to -1.0 ft/yr). Generally, shoreline erosion is limited to areas downstream of Honoapi‘ilani Highway, except in Wahikuli and near Honolua where the highway is at risk of negative impacts (Figure 7-9).

In some areas, resorts and large condominiums are being visibly threatened by the loss of sand and sea-level rise and thereby is in the forefront of the community’s minds when thinking of potential sources of sediment to the marine environment. However, its impacts to coral reefs are not clear. Generally, the primary concern (with consideration to coral reef health) would not be erosion of sandy sources but clay and silt.



Figure 7-9: Hawai'i Shoreline Study Web Map – Wahikuli, West Maui



Figure 7-10: Hawai'i Shoreline Study Web Map – Honolua, West Maui

7.3.4 Coral Reef Bleaching and Loss

Widespread coral reef bleaching and mortality have been occurring more frequently, and by mid-century these events are projected to occur annually, especially if

current trends in emissions continue. The health of Maui's coral reefs are affected by many climate indicators, including rising sea surface temperatures, increasing frequency of ENSO occurrences, increasing frequency and intensity of tropical storms, ocean acidification, and rising sea levels.

Continued warming of Hawaiian surface waters potentially expose coral reefs and other marine ecosystems to negative impacts related to temperature increases. (Fletcher, 2010). Warmer waters mean less oxygen in the water, making it hard for corals and beneficial algae to survive (Hawai'i Climate Change Mitigation and Adaptation Commission, 2021). The first statewide coral bleaching event occurred in 2015 (a strong ENSO period) because of higher than usual ocean water temperatures. Hawai'i lost 30 percent of its living coral reefs statewide (The Nature Conservancy, 2021). The influence of hurricanes on coral reefs can be either beneficial or detrimental. Small hurricanes can provide fast relief during periods of thermal stress, whereas waves from large hurricanes can reduce a reef to rubble (Heron, Morgan, Eakin, & Skirving, 2008). Ocean acidification reduces the ability of corals to build and maintain reefs. Nutrient input can substantially exacerbate acidification of reef erosion. Reefs can generally adapt to rising sea levels that are gradual, but a rapid sea level rise would result in the reef not receiving enough sunlight to support the colonies of photosynthetic algae that it relies on for growth and becoming overgrown by deep-water coralline algae (MBARI, 2004).

Coral reefs provide habitat for nearshore fisheries, protect coasts from waves and storms, and support tourism and fishing industries worth billions of dollars. They are also fundamental to the fabric of local communities, providing a source of food, materials, and traditional activities. Loss of reef structure would reduce fish biodiversity, lower fisheries yield, result in greater damages by coastal storms, and impact the local economy.

7.4 Adaptation and Resilience

The intent of the West Maui Watershed Study is to contribute to the restoration, enhancement and resiliency of West Maui coral reefs and nearshore waters through the reduction of land-based pollution threats. Reducing chronic stress through local coral reef management efforts may increase coral resilience to global climate change and larger climate events, such as bleaching. Proposed measures to address terrestrial sediment

would reduce a local stressor on the West Maui coral reefs and contribute to their restoration. However, greater peak flows and larger sediment loads predicted for future rainfall events may indicate that any proposed measures may be undersized or only partially effective. These measures should also not be sited where they would be at risk of shoreline erosion or rising sea levels. Long-term community planning and development should evaluate the benefits of beach renourishment to the consequence of potentially increasing the amount of sediment being added to the marine environment, thereby affecting the coral reefs. Consideration of climate change effects to the proposed alternatives are discussed in Appendix C, Section 4.

8 Development of the Hydraulic Model

Two types of hydraulic models were created using the Hydrologic Engineering Center's River Analysis System (HEC-RAS) software (version 6.1.0, HEC, September 2021) with the ultimate objective of developing flow and sediment load time series data at five different watershed outlets for various frequency events. The five watersheds selected for detailed modeling are: Honolua, Ka'ōpala, Kahana, Honokōwai, and Wahikuli. These watersheds were selected based on their ability to provide a broad perspective of the varying site conditions across the entire study area (from the northern, wet Honolua watershed to the southern, dry Wahikuli watershed), the availability of corresponding historical stream flow data (Honolua and Honokōwai), their estimated annual sediment load (Kahana has the greatest annual sediment load at 285 metric tons per year), and the perceived opportunity for implementation of a proposed management measure.

The first model – a one-dimensional (1D), steady flow hydraulic model – was created to establish an elevation versus discharge rating curve at two sites where stream gages were recently installed in Honolua and Honokōwai: CWRM 6-158 and CWRM 6-124, respectively (Section 4.2). A rating curve allows for the stage data collected by the gages to be converted into flow data.

The second model – a two-dimensional (2D), unsteady flow hydraulic model – was initially created to estimate the amount of sediment eroded from the banks (mass load) over time for various frequency events, specifically along reaches near agricultural fields with historic fill terraces. It does not include considerations of deposition or the effects of any existing or proposed management measures, which were calculated separately. However, this method of estimating the sediment load over time became obsolete when sediment analysis became available in HEC-HMS. The hydraulic models are still useful for flow analysis.

8.1 Development of the 1D, Steady Flow Model

A simple, steady flow hydraulic model was created to establish a rating curve at two sites where stream gages were recently installed. The rating curve allows for the stage data collected by the gages to be converted into flow data.

Four to five cross sections were surveyed in the field at each site during the time of gage installation (Section 4.2). This data was used to create the geometry for the hydraulic model (Figure 8-1). The model was run using the *mixed* flow regime for Honolua and *supercritical* flow regime for Honokōwai under twenty five (25) different flow profiles (0.1 to 20,000 ft^3/s). *Normal depth* was used for the upstream and downstream boundary conditions, which was assumed to be equivalent to the average slope of the channel bed upstream and downstream, respectively. A Manning's roughness coefficient of 0.045 was used for Honolua and 0.050 for Honokōwai, reflective of site conditions observed in the field (Photo 8-1 and Photo 8-2).

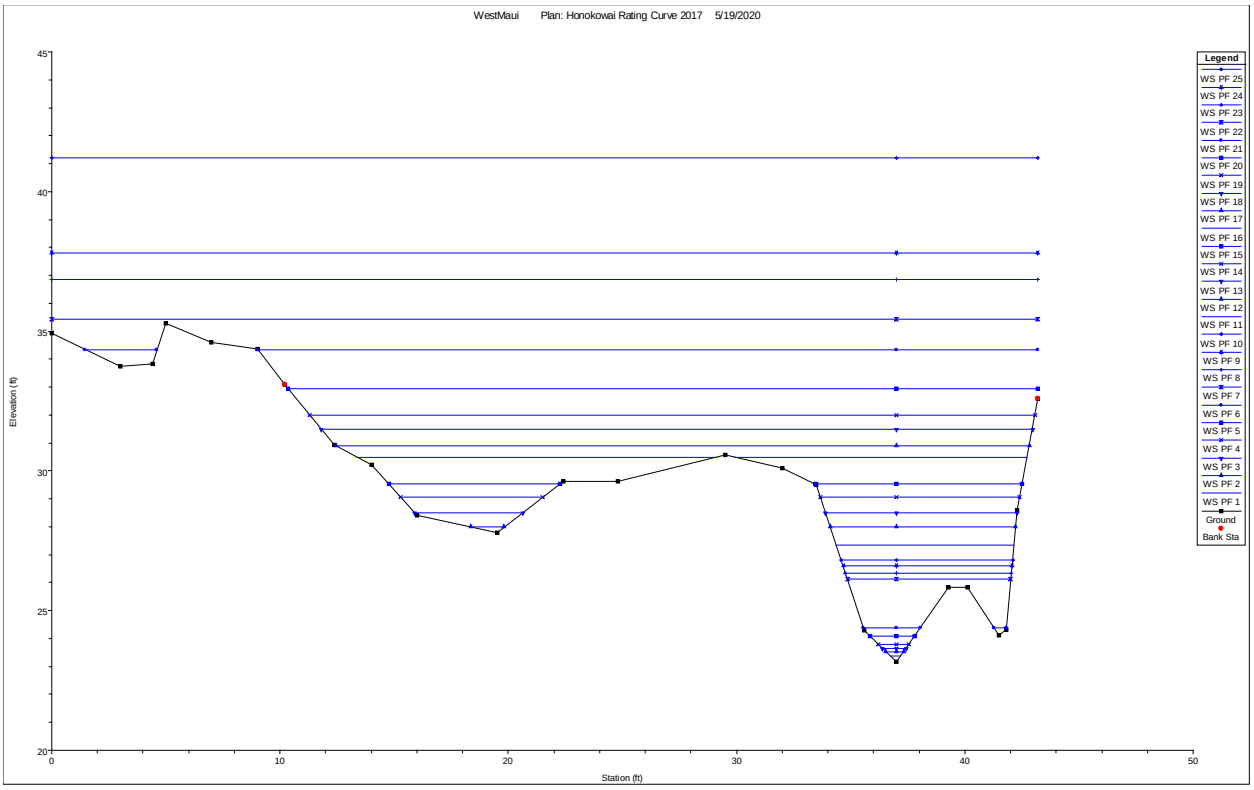


Figure 8-1: HEC-RAS Cross-Section Profile for Honokōwai (XS 3)



Photo 8-1: Typical Channel Bed Conditions for Honolua (*n* = 0.045)



Photo 8-2: Typical Channel Bed Conditions for Honokōwai (*n* = 0.050)

A rating curve was developed for each site using those flow profiles which provided a positive stage (with reference to the gage datum) and did not exceed the surveyed cross-section profile. The established rating curve for Honolua, which is applicable for recorded stages from 1 – 8 ft and has an R^2 value of 0.9951, is:

$$Q = 61.669H^2 - 116.45H + 66.975$$

where,

Q = flow rate (ft^3/s); and

H = stage (ft)

The established rating curve for Honokōwai, which is applicable for recorded stages from 1 – 8 ft, is:

$$Q = 108.77H^2 - 628.32H + 924.63$$

As an example of the application of these equations, the peak flow for two historical events at these sites were estimated and are presented in Table 8-1.

Table 8-1: Peak Flow Estimates for Historical Storm Events

Event	CWRM 6-158 (Honolua)	CWRM 6-124 (Honokōwai)
October 24, 2017	1,410 ft^3/s	1,080 ft^3/s
September 12, 2018	3,040 ft^3/s	910 ft^3/s

8.2 Development of the 2D, Unsteady Flow Model

A 2D, unsteady flow hydraulic model was created for the five watersheds previously identified with the objective of acquiring typical flow and shear stress values over time for various frequency events. This data would then be used to estimate sediment flux (mass over time) at critical points in the river system (i.e. the outlet, sited management measures). However, that method of analysis became obsolete when sediment functions were added to the HEC-HMS software. The hydraulic models that were originally created are still functional and useful for flow analysis. This section describes how they were developed.

8.2.1 **Flow Data**

Peak flow rates determined previously (Section 5.3.6) were used to represent the amount of water in the system.

8.2.1.1 Boundary Conditions

Boundary conditions are necessary to establish the starting water surface at the upstream and downstream ends of the channel system. A flow hydrograph was used to represent the amount of flow entering at the upstream ends of the hydraulic model. At some locations, it was necessary to further divide the hydrograph developed for each subbasin to represent flow entering from an additional location (typically, a smaller tributary). In this instance, the hydrograph was divided based on the corresponding drainage area for each individual reach segment.

The downstream boundary condition was set to a water surface elevation of 1.13 ft, representing the mean higher high water (MHHW) elevation (in reference to mean sea level) of the ocean. This was determined based on the MHHW elevation at NOAA tidal station at Kahului Harbor, HI – Station ID: 1615680 (NOAA).

A lateral boundary condition was set to normal depth at locations where flow may continue landward (likely north or south) beyond the limits of the model. The normal depth was set to the land slope.

8.2.2 **Geometry Data**

RAS Mapper, a geospatial interface in the HEC-RAS software, was used to fully develop the geometric data required for the river hydraulics model. The projection was set to State Plane Zone 2 (US Survey Feet) with reference to the NAD83 (PA11) coordinate system. Elevation data presented in Section 3.2 were imported to create the terrain model. Several geometric layers required for the hydraulic model were digitized, some of which are described in Table 8-2.

Table 8-2: GIS layers created for 2D hydraulic models

GIS layer	Description
2D Flow Areas	2D Flow Areas are created by constructing polygon areas representing the regions to be modelled.
Boundary Condition	A Boundary Condition (BC) line was added to identify the location for a specific flow condition on the boundary of a 2D Flow Area.
Breakline	Breaklines were sometimes used in 2D Flow Areas to align the computation cell faces along high ground and natural barriers that affect flow and direction (such as riverbanks).
SA/2D Area Connection	This internal connection feature can be used to represent embankment crests and major roads.

8.2.3 **Manning's Roughness Coefficient, *n***

Manning's roughness coefficient, *n*, is an empirically derived coefficient that is dependent on several variables, such as vegetation, obstructions, and meandering when applied to open channels. This value was selected based on site characteristics observed in the field, aerial imagery, and geospatial data as provided by the PAC-RISA program (Section 3.5). Typical *n* values selected for this study are provided in Table 8-3 for 2D Flow Areas.

These values and the geospatial data provided by PAC-RISA were used to create a Manning's n layer in RAS Mapper. 2D Flow Areas in the hydraulic model refer to this layer. At some locations, it was necessary to override the default values provided by this layer by identifying a specific area and roughness coefficient. For example, a Manning's n value of 0.045 was assigned to the footprint of the Honolua Stream, overriding default values for forest and shrub areas.

Table 8-3: Manning's n values

Land Cover Type	Manning's *n*
Alien forest, fog	0.16
Alien forest, no fog	0.16
Coffee	0.035
Developed, high-intensity	0.15
Developed, low-intensity	0.1
Developed, medium-intensity	0.08
Developed, open space	0.04
Diversified agriculture	0.035
Fallow/grassland	0.03
Golf course	0.03
Grassland	0.035
Native forest, fog	0.16
Native forest, no fog	0.16
Reservoir, not Iao	0.035
Shrubland	0.1
Sparsely vegetated	0.03
Taro	0.07
Tree plantation, no fog	0.1
Water body	0.035
Wetland	0.07

8.2.4 **Bridges**

Bridges and major culverts were represented in the model as an *SA/2D Area Connection*. Bridge data (e.g. deck width, horizontal span) required for this modeling feature was based on as-built drawings, field measurements, and as provided by *BridgeReports.com*, a searchable version of the National Bridge Inventory (Baughn, 2019). A weir coefficient of 2.6 was selected, representative of flow over a typical bridge deck. At locations where bridge data was not available, the terrain raster was modified to remove these obstacles from the raster completely, allowing for channel flows to pass through unimpeded. Considering the design flood for this study is relatively small (0.5

AEP), bridges are generally not expected to have a significant impact on flows in the channel system.

8.2.5 **Sediment Transport Analysis**

To evaluate terrestrial sediment dynamics in the nearshore environment (Appendix D), flow and sediment load time series data representative of a specific event (i.e. the 50% AEP flood) were needed as input for the hydrodynamic-sediment transport model. This data was provided to USGS in September 2020. The initial estimation of this data was determined by using flow and shear stress time series data outputs from the two dimensional (2D) hydraulic model for the 50% AEP event, and then applying the excess shear equation in Microsoft Excel to calculate the total sediment time series data (Section 8.2.5, Sediment Transport Analysis). This method assumed that the total sediment load for the 50% AEP event would be approximately equal to the total annual sediment load divided by 4.5 (the estimated number of plume-triggering events occurring over a one-year period). There is less confidence in this assumption now, after reviewing the frequency of plumes created at each outlet and finding that they occur much more frequently (Section 4.3.2.2, Coastal Camera Analysis). This assumption also assumes that each plume-triggering event had relatively the same amount of sediment in the system when the total sediment load for each event likely varies quite a bit. Finally, the flow and shear stress time-series data taken from the 2D hydraulic model is also based on a limited number of sites along the reach, and not necessarily representative of the downstream boundary conditions (at a basin or outlet).

Since that time, the methodology has been updated following the release of the Hydrologic Engineering Center's Hydrologic Modeling Software (HEC-HMS), version 4.9. The current methodology, as described in Section 6.2, relies upon the rainfall-runoff model to distribute the total annual sediment load over a one-year continuous flow simulation. A comparison of the original flow and sediment load estimates, as provided to USGS in September 2020, and the current estimates is presented in Table 8-4.

Table 8-4: Original and Current Estimates of Peak Flow and Sediment Load During the 50% AEP for Various Watersheds in West Maui

Wahikuli	Original	Current
Peak Streamflow (ft^3/s)	1,270	1,270
Sediment – Total (tons)	9.33	11.3
Sediment – Clay (tons)	0.69	1.95
Sediment – Silt (tons)	4.29	4.97
Sediment – Sand (tons)	4.02	4.01
Sediment – Gravel (tons)	0.33	0.39
Honokōwai	**Original**	**Current**
Peak Streamflow (ft^3/s)	925	646
Sediment – Total (tons)	13.80	7.49
Sediment – Clay (tons)	1.24	5.45
Sediment – Silt (tons)	7.18	7.82
Sediment – Sand (tons)	4.96	0.00
Sediment – Gravel (tons)	0.42	0.00
Kahana	**Original**	**Current**
Peak Streamflow (ft^3/s)	496	252
Sediment – Total (tons)	63.33	44.42
Sediment – Clay (tons)	4.20	16.32
Sediment – Silt (tons)	26.59	5.33
Sediment – Sand (tons)	32.34	0.00
Sediment – Gravel (tons)	0.21	0.00
Ka'ōpala	**Original**	**Current**
Peak Streamflow (ft^3/s)	182	182
Sediment – Total (tons)	13.78	12.02
Sediment – Clay (tons)	0.91	4.41
Sediment – Silt (tons)	5.78	1.44
Sediment – Sand (tons)	7.03	0.00
Sediment – Gravel (tons)	0.05	0.00
Honolua	**Original**	**Current**
Peak Streamflow (ft^3/s)	336	128
Sediment – Total (tons)	20.20	30.20
Sediment – Clay (tons)	1.44	4.92
Sediment – Silt (tons)	8.64	12.1
Sediment – Sand (tons)	8.73	11.1
Sediment – Gravel (tons)	1.40	2.09

9 Sediment Transport Analysis

This section describes the three different methods used to evaluate trap efficiency in this study.

9.1 Hydraulic Model and Excess Shear

To evaluate terrestrial sediment dynamics in the nearshore environment (Appendix D), flow and sediment load time series data representative of a specific event (i.e., the 50% AEP flood) were needed as input for the hydrodynamic-sediment transport model. This data was provided to USGS in September 2020. The initial estimation of this data was determined by using flow and shear stress time series data outputs from the two dimensional (2D) hydraulic model for the 50% AEP event, and then applying the excess shear equation in Microsoft Excel to calculate the total sediment time series data. This method assumed that the total sediment load for the 50% AEP event would be approximately equal to the total annual sediment load divided by 4.5 (the estimated number of plume-triggering events occurring over a one-year period). There is less confidence in this assumption now, after reviewing the frequency of plumes created at each outlet and finding that they occur much more frequently (Section 4.3.2.2, Coastal Camera Analysis). This assumption also assumes that each plume-triggering event had relatively the same amount of sediment in the system when the total sediment load for each event likely varies quite a bit. Finally, the flow and shear stress time-series data taken from the 2D hydraulic model is also based on a limited number of sites along the reach, and not necessarily representative of the downstream boundary conditions (at a basin or outlet). Additional information on this methodology is presented in Section 8.2.5, Sediment Transport Analysis

9.2 Rainfall-Runoff Model and Chen's Sediment Trap

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 (Table 6-1). The period 1 November 2014 to 1 November 2015 was selected because it did not include any significant flow events and seemed to be the best representation of typical flows and sediment loads experienced in any given year. The

complete record (hyetograph) for all rainfall gages relevant to Honokōwai is provided as Figure 6-1. The *Upper Honokōwai* rainfall gage was a critical record to include that began on 31 October 2014. However, the record in 2016 seemed unusually high. There was no corresponding flood event or news of intense rainfall found; it was determined to not be a reliable period of the record and possibly an error as other nearby gages did not record a similar intensity. There were significant flood events in 2017 and 2018 (see Section 4.2.1, Significant Past Flow Events) that excluded these years from the usable record for a representation of typical, low flow events. 2019 was a particularly hot year in Hawaii, with the rainfall record representing atypical drought-like conditions. These exclusions left the 1 November 2014 to 1 November 2015 period for use in the continuous flow simulation. Additional information on this methodology is presented in Section 6, Continuous Flow Simulations

9.3 Camp's Settling Velocity Equations

The trap efficiency of each basin to retain sediment during a specific type of flood event (e.g. .the 0.50 AEP flood) can also be estimated using Camp's [1946] settling velocity equations, which are as follows:

$$TE = \frac{vA}{Q}$$

where TE = trap efficiency

V = settling velocity (ft/s)

A = wetted surface area (ft^2)

Q = discharge rate (ft^3/s)

The settling velocity of clay, silt, and fine sand in stormwater can be estimated using Stoke's Law, given in the equation below:

$$V_s = \frac{g\left(\frac{p_1}{p} - 1\right) d^2}{18\upsilon}$$

where:

V_s = settling velocity of the solid

g = acceleration of gravity

$p1$ = mass density of the solid

p = mass density of the fluid

d = diameter of the solid (assuming spherical)

υ = kinematic viscosity of the fluid

For particles larger than fine sand, such as coarse gravel, the equation by Ferguson and Church is used:

$$V_s = \frac{gRd^2}{18\upsilon + (0.75CgRd^3)^{1/2}}$$

where:

V_s = settling velocity of the solid

g = acceleration of gravity

d = diameter of the solid (assuming spherical)

R = specific gravity of the particle in water

C = a constant equal to 0.4 for spheres and 1 for typical sand grains

The assumed values for each parameter needed for either equation are listed in Table 9-1. Based on average diameter limits for various soil types, typical settling velocities are provided in Table 9-2.

Table 9-1: Assumed Parameter Values for Settling Velocity Equations

Parameter	Value[1]
g	9.81 m/s^2
p1	2650 kg/m^3
p	998 kg/m^3
u	1.004E-6 m^2/s
R	2.66
C	0.4

[1]: assuming water temperatures of 20 ºC (68 ºF)

Table 9-2: Typical Settling Velocities Based on Soil Type

Name of soil separate	Diameter limits (mm)	Equation	Settling velocity, V_s (m/s)	Settling velocity, V_s (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

Using the estimated peak flow values and settling velocities previously presented in the Hydrology and Hydraulics Appendix, the recommended treatment surface area of the sediment basin can be estimated using the standard equation:

$$S_a = 1.2 * (\frac{Q_{out}}{v_s})$$

where:

S_a = treatment surface area measured at the invert of the lowest outlet of sediment basin (ft^2)

Q_{out} = Peak flow of the detention basin outlet (ft^3/s)

V_s = settling velocity of the solid (ft/s)

1.2 = EPA recommended safety factor

This equation is recommended by the Natural Resources Conservation Service as a Conservation Practice Standard for sediment basins (NRCS, 2008). This methodology was primarily used to evaluate the various proposed measures presented in Appendix C.

10 Conclusion

The final event-based sediment load and distribution time series data at the outlet of eleven watersheds within the study area were determined by flood frequency analysis, use of rainfall-runoff modeling, calibration of event-based sediment loads to previous investigations, and analysis of the trap efficiency of existing detention basins. The eleven watersheds are: Wahikuli, Hanakaʻōʻō, Honokōwai, Māhinahina, Kahana, Kaʻōpala, Honokeana, Nāpili 4-5, Nāpili 2-3, Honokahua, and Honolua.

The flood frequency analysis included stream gage analysis, application of regional regression equations, and development of a rainfall-runoff model using HEC-HMS software. The rainfall-runoff model was initially calibrated to replicate specific historical storms; however, the limited number of sites and storm events that could be used for calibration proved this method to be ineffectual. However, a Bulletin 17C stream gage analysis on two sites in the Honokōhau and Honokōwai watershed provided a strong level of confidence based on long periods of record and the rainfall-runoff model was calibrated to match these results. The final peak flow estimates adopted by this study are presented in Section 5.3.6.

The annual sediment load previously estimated by USGS was used as input for the rainfall-runoff model, paired with historical rainfall data from 1 November 2014 to 1 November 2015, to provide a reasonable estimate of typical flows and sediment loads produced by the various low flow events throughout the year. Reservoir elements in the rainfall-runoff model helped determine approximate trap efficiencies of existing detention basins within the watershed, based on Chen's sediment trap method of analysis. These results are presented in Section 6.3. The level of accuracy of these results is commensurate with the level of data that was available during this study

The output of the calibrated rainfall-runoff model was used as input for the two-dimensional, unsteady flow hydraulic model that was developed using HEC-RAS software. Models were created that are representative of the lower reaches within the Wahikuli, Honokōwai, Kahana, Kaʻōpala, and Honolua watersheds. These hydraulic models are later used to predict site conditions for existing conditions and the sited management measures proposed in the Design Appendix.

With rainfall occurring less frequently and base flow decreasing, there will likely be less occurrences of flow in West Maui streams and corresponding contributions of residual sediment to the nearshore environment in the future. However, with increasing intensity of rainfall also predicted, there is greater likelihood that when rainfall events do occur, they are more likely to result in larger peak flows and higher sediment loads in the river systems. The occurrence of wildfires is likely to increase due to the combined effects from rising temperatures, a growing human population, and expanding invasive grass cover. This would also result in greater sediment loads entering the riverine systems. In some areas, resorts and large condominiums are being visibly threatened by the loss of sand and sea-level rise and thereby is in the forefront of the community's minds when thinking of potential sources of sediment to the marine environment. However, its impacts to coral reefs are not clear. The health of Maui's coral reefs are affected by many climate indicators, including rising sea surface temperatures, increasing frequency of ENSO occurrences, increasing frequency and intensity of tropical storms, ocean acidification, and rising sea levels. Widespread coral reef bleaching and mortality have been occurring more frequently, and by mid-century these events are projected to occur annually, especially if current trends in emissions continue. Coral reefs have a greater chance of surviving a larger climate event, such as bleaching, if local threats – such as terrestrial sediment – are reduced.

10.1 Recommendations for Future Studies and Field Work

The field work and analysis provided by USGS in establishing a sediment budget for each watershed in the study area was incredibly valuable to this study. The data provided by the climate stations managed by West Maui R2R were also significant in calibrating the rainfall-runoff model. However, additional data is still needed to effectively calibrate the models to real conditions and increase confidence in the results.

1) Suspended Sediment Concentration Time Series Data.

Additional information is needed on the suspended-sediment particle-size distribution and concentration data from one or multiple reaches in the study area. Currently, the rainfall-runoff model is automatically distributing the total annual sediment load previously estimated by USGS over a one-year period in

a continuous flow simulation. Calibrating the model to an observed record of suspended sediment concentration over time would better define the flow-sediment relationship and improve confidence in related estimates (total sediment load and suspended sediment concentration). Turbidity and suspended sediment concentration (SSC) data are not the same thing.

2) Rating Curve

The stream gages installed at Honokōwai (CWRM 6-124) and Honolua (CWRM 6-158) measure stage (the height of the water surface above the gage datum). To convert stage to flow (discharge), a stage-discharge rating curve must be defined by measuring discharge at a wide range of river stages at each gage site. CWRM has already begun this process by measuring the corresponding flow for several smaller stages (baseflow or low flow events). However, the resulting rating curve does not provide reasonable estimates for larger flood events (where stage and flow are much higher). To improve the rating curve, additional flow measurements must be taken when the stage is higher. This data could then be used to improve the calibration of the rainfall-runoff model (Section 5.3).

3) A continuous stream flow gage sited just upstream of Honokōwai Basin.

Stream gages were installed in upper Honokōwai (CWRM 6-124) and below the dam (CWMR 6-156). These gages were strategically placed to analyze and monitor typical low flow conditions throughout the entire reach. For analyzing flow frequency, however, it would have been better sited at the former USGS gage site (USGS 16630200), located just upstream of Honokōwai Basin. Data from a stream gage at this site would have moderately improved calibration of the rainfall-runoff model, depending on the range of events recorded.

4) A climate station within or near the Honolua watershed.

The rainfall data provided by the various climate stations in the Honokōwai watershed (operated by West Maui R2R) proved to be incredibly valuable to this study. It was used for the continuous flow simulation (Section 6) and can also be used in improving the calibration of the rainfall-runoff model in the future once the stage-discharge relationship at Honokōwai (CWRM 6-124) is better

defined. However, these climate stations are a reasonable distance away from the northernmost watershed in the study area, Honolua. An additional climate station in the middle of the Honolua watershed would provide valuable data on the different hydrology the northern watersheds in the study area may be experiencing.

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Appendix C

Proposed Management Measures for Addressing Terrestrial Sediment in Riverine Systems

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EXECUTIVE SUMMARY

A critical nonpoint source pollutant affecting West Maui coral reefs is terrestrial sediment. A major source of terrestrial sediment is bank erosion of historic fill terraces in riverine systems. Several management measures were initially proposed for reducing the amount of terrestrial sediment being discharged by West Maui streams (Section 2, Management Measures). A management measure is a feature or activity that can be implemented to address one or more planning objectives (e.g. reduction of in-stream erosion). The Project Delivery Team (PDT)'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. Some of these measures were *not recommended* to be carried forward as an alternative after an initial assessment of various 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. These measures include use of loʻi terraces, construction of new micro basins, and modifying existing detention basins.

The management measures selected to be carried forward in the study were then sited across the study area (Section 3, Sited Measures). These sites were selected with consideration towards other management measures already existing in the watershed, stakeholder support, and the unique flow and load characteristics for each watershed. Loʻi terraces were sited at Honolua and Honokōwai. Micro basins were sited in Pāpua Gulch and at three sites in Wahikuli. A variant of the micro basin measure, rock weirs, was proposed for Kaʻōpala. Modifications to the outflow structures at Kaʻōpala and Honokōwai Basin were evaluated, along with the effectiveness of excavating Kahana Basin more frequently.

The trap efficiency of each sited measure is presented in Table E-1. The estimated amount of sediment removed from the riverine system is presented in Table E-2. The sited measures that had a meaningful impact, based on engineering judgment, were highlighted in these tables. The impact on these sited measures by climate change are discussed in Section 4, Climate Risk Assessment.

Table E-1: Trap Efficiency of Sited Measures, 50% AEP Event

Watershed	Measure	Trap Efficiency (%)				
		Total	Clay	Silt	Sand	Gravel
Honolua	Loʻi	0.12	0.06	0.13	0.13	0.13
Honolua	10 Micro Basins	83	0.15	100	100	100
Kaʻōpala	Outlet Modification[1]	-5	22	-22	100	100
Kaʻōpala	Rock Weirs	0	0.01	10	100	100
Kahana	Excavation	13	0.01	32	--	--
Honokōwai	Loʻi	0.08	0.04	0.09	0.09	0.09
Honokōwai	Outlet Modification	3	1	8	--	--
Wahikuli	Upper Micro Basin	80	0.06	43	100	100
Wahikuli	Middle Micro Basin					
Wahikuli	Lower Micro Basin	43	0.02	14	100	100

Table E-2: Sediment Load Reduction by Sited Measures, 50% AEP Event

Watershed	Measure	Sediment Removed (metric tons)				
		Total	Clay	Silt	Sand	Gravel
Honolua	Loʻi	0.00	0.00	0.02	0.01	0.00
Honolua	10 Micro Basins	9.34	0.00	4.44	3.06	0.76
Kaʻōpala	Outlet Modification	-3.21	2.23	-4.82	--	--
Kaʻōpala	Rock Weirs	0.01	0.01	--	--	--
Kahana	Excavation	20.6	0.20	20.4	--	--
Honokōwai	Loʻi	0.01	0.00	0.01	0.00	0.00
Honokōwai	Outlet Modification	0.43	0.12	0.39	--	--
Wahikuli	Upper Micro Basin	3.07	0	0.71	1.33	0.17
Wahikuli	Middle Micro Basin					
Wahikuli	Lower Micro Basin	4.86	0	0.68	3.98	0.36

[1] Earlier activation of the spillway as a result of the proposed modification results in increased silt particles being transported downstream. Sand and gravel are still completely captured by the basin during the design flow event.

One or more sited measures were then included in a conceptual alternative plan, which is presented in the main report of this study, as a means of comparing the completeness, effectiveness, acceptability, and efficiency of each alternative.

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Photos are provided by USACE, unless otherwise stated

LIST OF ACRONYMS & ABBREVIATIONS

CWRM	Commission on Water Resource Management
DAR	Division of Aquatic Resources
DLNR	Department of Land and Natural Resources
HEC	Hydrologic Engineering Center
HMS	Hydrologic Modeling Software
LMSL	Local Mean Sea Level
NOAA	National Oceanic and Atmospheric Administration
RAS	River Analysis System
ROM	Rough Order of Magnitude
State	State of Hawai‘i
USGS	U.S. Geological Survey

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1 Background Information

The intent of the West Maui Watershed Study is to contribute to the restoration, enhancement and resilience of West Maui coral reefs and nearshore waters through the reduction of land-based pollution threats – specifically, terrestrial sediment being discharged into the marine environment. This appendix explores the feasibility of various management measures to address this issue (Section 2) and identifies potential sites for implementation (Section 3). A qualitative evaluation on how climate change may affect these sited measures is included in Section 4. Some of these sited measures are combined in a comprehensive plan, herein referred to as an *alternative*, for planners to consider for implementation. Several alternatives are proposed at the end of this appendix (Section 4), with consideration to different priorities (e.g. cost, effectiveness, location).

1.1 Primary Source of Terrestrial Sediment

As documented in the 2020 Scientific Investigation Report (SIR) by USGS, *Sediment Budget for Watersheds of West Maui, Hawaii*, the primary source of terrestrial sediment is bank erosion of historic fill terraces (Stock & Cerovski-Darriau, 2020). These silt and fine-sand terraces are found only downstream of historic agricultural fields, where they were likely deposited from sidecasting excess agricultural soils into valleys. Surveys show that the fill terraces occupy approximately 40% of streambank length, making them extensive. The average sample from monitoring sites is 8% clay, 47% silt, and 45% sand by volume. An annual sediment budget from bank erosion was estimated for each watershed in the 2020 SIR. All the management measures evaluated under this study focus on reducing sediment contributions to the marine environment from this source (erosion of streambanks).

Former agricultural fields, roads, and reserve forests are not likely to measurably affect sediment pollution during smaller, more frequent storms. The relatively high rate of hydraulic conductivity (the rate at which water can pass through soil) likely requires very intense storms to generate runoff and erosion from these sites (USGS, 2019).

Contributions resulting from beach erosion was not the primary focus of the study, although it can be considered a potential source of terrestrial sediment. Annual Erosion Hazard Rates for the West Maui shoreline were previously estimated by the University of

Hawai'i at Mānoa's Coastal Geology Group based on analyzing historical shoreline positions from 1912 to 1997, with light to moderate erosion expected (averages of -0.3 ft/yr to -1.0 ft/yr). In some areas, resorts and large condominiums are being visibly threatened by the loss of sand and sea-level rise and thereby is in the forefront of the community's minds when thinking of potential sources of sediment to the marine environment. However, its impacts to coral reefs are not clear and quantifying the extent of its impact is beyond the scope of this study. Generally, the primary concern (regarding coral reef health) would not be erosion of sandy sources but clay and silt banks.

1.2 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. For some of the sited measures, references are also made to the annual peak flow event (based on the continuous flow simulation of the 1 November 2014 to 1 November 2015 period) and the decadal event. As introduced in the Hydrology and Hydraulics Appendix, historical rainfall data from 1 November 2014 to 1 November 2015 was applied to the calibrated rainfall-runoff model and paired with annual sediment loads for each watershed. This period was selected because it was determined to be a good representation of typical rainfall (no significant storms or drought periods). The decadal (10% AEP) event is referenced to compare the effectiveness of a measure under higher flow and load conditions.

2 Management Measures

This section describes the various management measures that were initially considered and evaluated during the development of conceptual alternatives. A management measure is a feature or activity that can be implemented to address one or more planning objectives (e.g. reduction of in-stream erosion). The Project Delivery Team (PDT)'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. This is in alignment with the approach taken by the USACE Committee on River Engineering. Some of these measures were *not recommended* to be carried forward as an alternative after an initial assessment of various criteria (e.g. technical feasibility, environmental impacts, cost of construction).

2.1 Upstream Alterations to the Flow Regime

Not Recommended

This approach was based on altering the flow regime (reducing the flow rate or volume) with an upstream feature to the point that either shear stresses are below the erosion threshold or the depth of water remaining in the channel remains relatively low. However, there is still likely to be some residual bed and bank erosion as even during smaller frequency events (e.g. the 50% AEP flood event), the shear stress along the channel is higher than the critical shear stress required to initiate bank erosion (0.865 Pa).

2.1.1 **Upstream Detention Basin / Dam**

Not Recommended

This measure features an upstream structure intended to maintain low flow conditions in the channel and thereby minimizing the likelihood of in-stream erosion. Such a feature would likely need to be substantial, triggering the requirement to meet federal and state dam safety criteria. It would also be challenged by high construction costs, cultural and environmental issues, limited accessibility, and increased requirements for operation and maintenance post-construction. It was not previously presented to the public but is not likely to be well-received by community members who actively promote limited development in the watershed and maintaining flow from *mauka* to *makai* (from the mountains to the ocean).

2.1.2 **Utilization of Existing Irrigation Pipe System**

Not Recommended

This measure focuses on modifying the existing irrigation system (Photo 2-1, Figure 2-1) to route most of the flow across multiple watersheds into a single stream during large storm events. The selected stream where all flows are routed to will either include a downstream sediment basin to capture the sediment or be shown through coastal modeling to have minimal impact to the reef based on its location along the shoreline. The challenges with this measure include uncertainty in the existing infrastructure conditions, limited accessibility for rehabilitation, high cost of construction, and potential environmental impacts from altering the flow and sediment regime significantly. This measure also focuses on reducing sediment contributions to the ocean during large storm events (e.g. the 1% [1/100] AEP event) rather than smaller, more frequent flows. Flow diversion has a controversial history in West Maui and this measure was not received well at the August 2018 Public Meeting when initially proposed.



Photo 2-1: Existing Irrigation Pipe in Wahikuli, West Maui

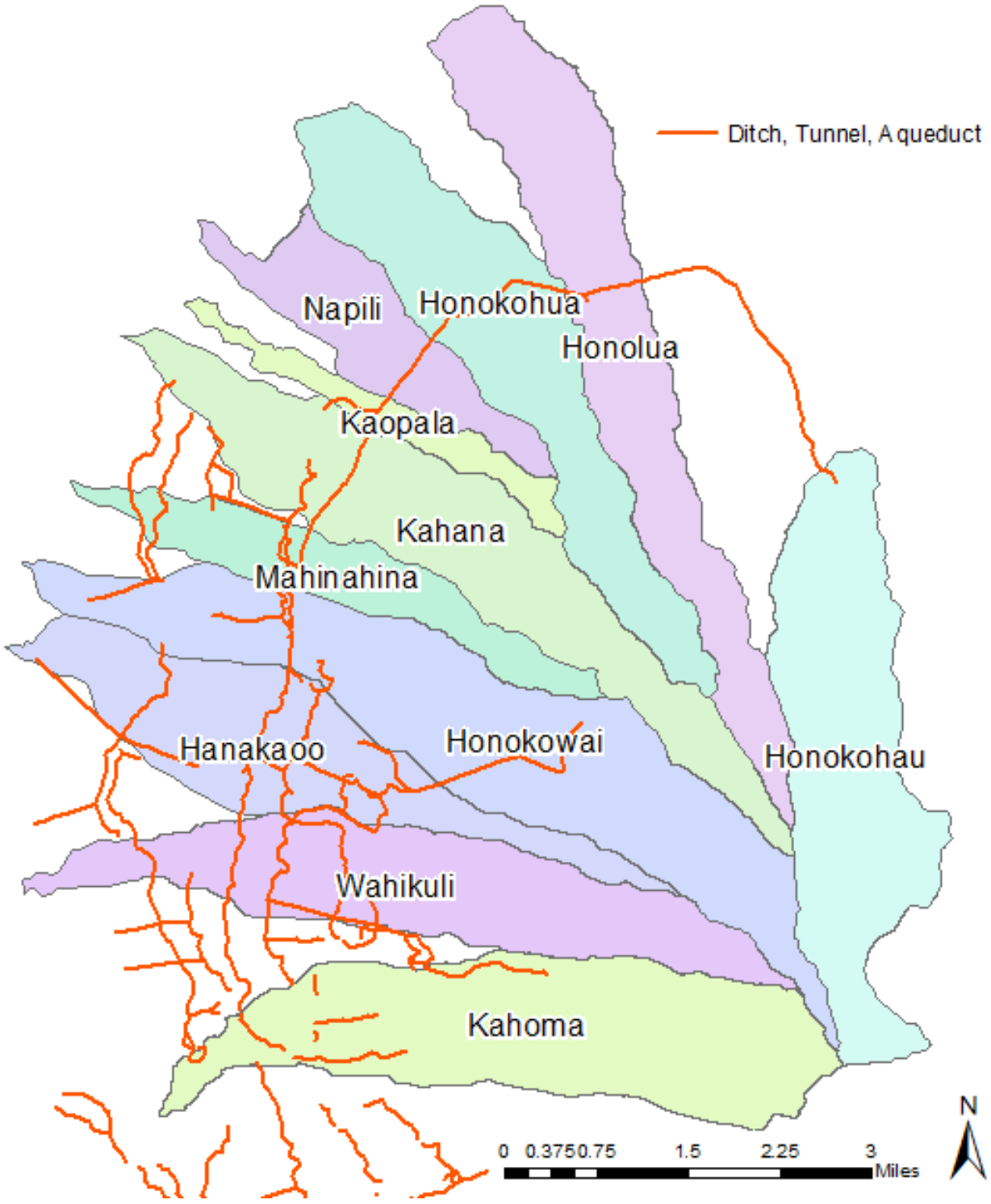


Figure 2-1: Ditches, Tunnels, and Aqueduct Systems in West Maui

2.2 Mid-Stream Structural Measures

These measures address sediment directly at the source or by implementing a measure mid-stream.

2.2.1 Manual Removal by Excavation or Dredging

Not Recommended

This measure focuses on manually removing the highly erodible, fine sediment deposits (*historic fill terraces*) directly from the source. From the 2020 SIR by USGS, "valleys adjacent to or downstream of agricultural fields have sandy silt draped over prehistoric, coarser-grained deposits. These fine-grained deposits form historic fill terraces that are the stream banks along much of the lower channel" (p. 5). Removal would be accomplished by either manually shoveling material out of the banks (excavation) or by using a vacuum (dry land dredging). The effort would be technically challenging, extensive (approximately 154 miles of total impacted stream length estimated by USGS), costly, and time-consuming. Furthermore, while this measure reduces the amount of fine-grained sediment transported to the ocean, there would still be some residual risk of erosion and sediment transport left unaddressed.

2.2.2 Loʻi Terraces

Feasible

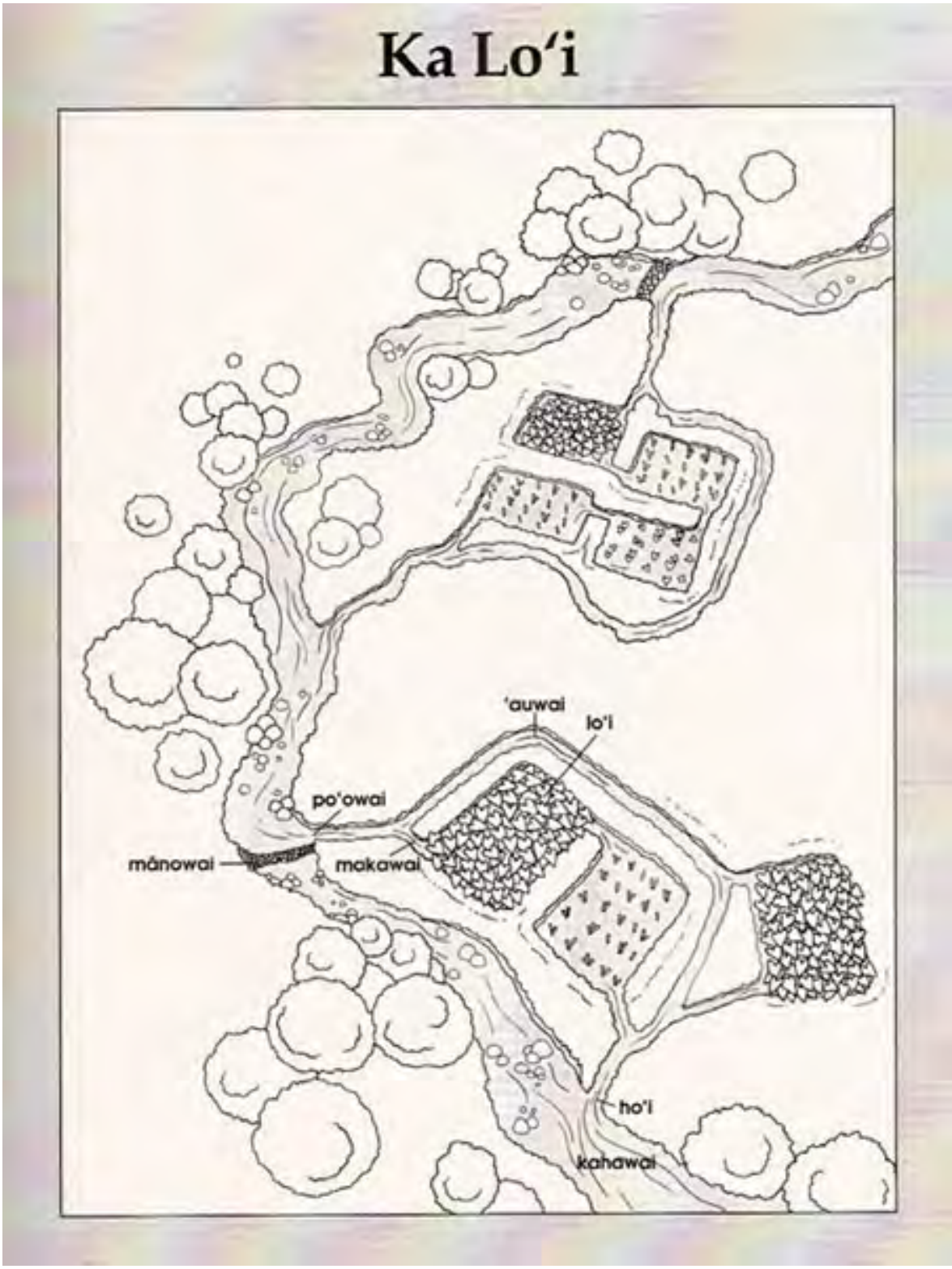
Taro patches (*loʻi*) once filled every valley in Hawaiʻi, but an influx of foreigners in the 19th century brought new crops and opportunities for trade. Several loʻi were converted to rice paddies or left dry as the streams that fed them were siphoned off to nourish pineapple and sugar cane fields (Mishan, 2019). Although taro is no longer the main staple food in Hawaiʻi, the growing and cultivation of taro is still an integral part of the Hawaiian culture. The "Hawaiian Renaissance" in the 1970s renewed interest in Hawaiian culture and taro patch restoration. The decline of the pineapple and sugar industries (and the need to siphon water from streams), along with strong community activism to maintain minimum flows in each river, has restored the opportunity to return taro to former ancestral fields. There is strong community support to restore loʻi terraces at former sites in Honokōwai and Honolua, with an opportunity to also use it to capture sediment from daily low flow conditions.

This measure focuses only on the cultivation of flooded taro, which requires continuous flow of water and heavy soil capable of impounding water without much loss

through percolation. Dry-land taro is essentially rain-fed, supplemented by irrigation, and is not intended to be flooded or to impound water. Traditionally in flooded taro, a loose wall of rocks (*manowai*) slows down waters in the main channel (*kahawai*) and creates enough headwater (*po'owai*) that some flow is diverted into a rock-lined canal (*'auwai*). 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 (Figure 2-2). The water level in each loʻi is controlled at openings in the bank (*makawai*) to keep the base of the plant submerged and maintain continuous flow.

Although primarily intended for agricultural purposes, loʻi have the added benefit of also reducing sediment in the main channel. This measure proposes either loʻi restoration at historical sites or new loʻi strategically placed within the study area. The Honokōwai and Honolua watersheds have known sites of former loʻi and community support for implementation. As documented in their 2019 Instream Flow Standard Assessment Report for Honokōwai and Honolua, the State of Hawaiʻi's Commission on Water Resource Management (CWRM) conducted a cursory assessment to identify tax map key (TMK) parcels with their associated Land Commission Awards that were likely former loʻi sites. Of particular importance was the presence of terracing and oral testimony that indicated loʻi existed in the middle reaches of Honolua (above and below the current stream diversions) and the middle reaches of Honokōwai (approximately 2.35 miles below the current stream diversions).

In 2012, a 7-months 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. 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.



Source: Gregory, 2014

Figure 2-2: Typical Taro Patch System

In 2007, the USGS completed a study to evaluate current water use for commercial wetland taro cultivation in Hawai‘i. As part of this study, flow and water temperature measurements were collected from individual taro patches (lo‘i) and groups of lo‘i (lo‘i complexes) on four islands – Kaua‘i, O‘ahu, Maui, and Hawai‘i (Gingerich, Yeung, Ibarra, & Engott, 2007). A summary of water use calculated for lo‘i and lo‘i complexes under this study is provided in Table 2-1. The median average water use for a lo‘i complex is 150,000 gallons per acre day (a typical lo‘i is about a fifth of an acre; a lo‘i complex includes several lo‘i). Converting this to flow units, water use is only 0.232 cubic feet per second (ft^3/s) per acre.

One of the implementation challenges with this measure is that building a lo‘i for flooded taro is labor intensive and requires constant maintenance and care. This measure also relies strongly upon community support in actively maintaining the lo‘i once they are constructed. Sited proposals for this measure are presented in Section 3.1.1, Honolua Lo‘i Terraces and Section 3.4.1, Honokōwai Lo‘i Terraces.

Table 2-1: Summary of water use calculated for loʻi and loʻi complexes

[gad, gallons per acre day; na, not available]

Island	Loʻi Complex				Individual Loʻi			
	Number	Average water use (gad)	Average windward water use (gad)	Average leeward water use (gad)	Number	Average water use (gad)	Average windward water use (gad)	Average leeward water use (gad)
Kauaʻi	6	120,000	97,000	260,000	2	220,000	220,000	na
Oʻahu	5	310,000	380,000	44,000	4	400,000	460,000	210,000
Maui	6	230,000	230,000	na	na	na	na	na
Hawaiʻi	2	710,000	710,000	na	na	na	na	na
Average		260,000	270,000	150,000		350,000	370,000	210,000
Median		150,000	150,000	150,000		270,000	320,000	210,000

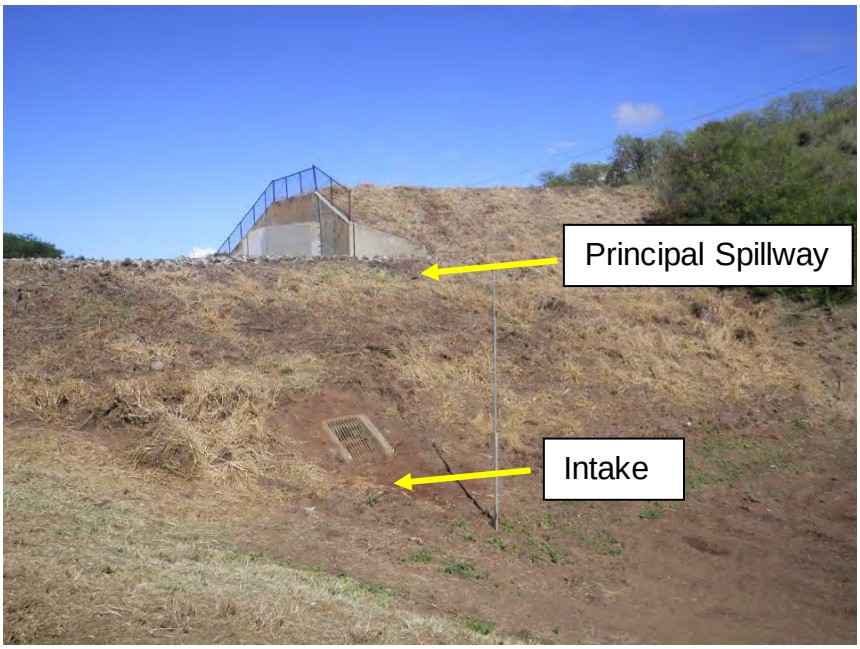
2.3 Downstream Structural Measures to Capture Sediment

This approach focuses on capturing sediment with a downstream measure before it is transported to the ocean. It allows in-stream erosion to continue as it would through natural processes before being trapped by the measure downstream. These measures would likely require occasional maintenance and periodic removal of the captured sediment.

2.3.1 **Retrofit / Redesign Existing Basins**

This measure proposes modifying existing detention basins to improve their effectiveness in capturing sediment. A brief description of the largest existing basins in the study area are provided in the Hydrology and Hydraulics Appendix. There are three existing basins worth evaluating under this study for a potential modification: Ka‘ōpala Gulch Basin, Kahana Basin, and Honokōwai Basin. The primary deficiency with the Ka’opala, Kahana, and Honokōwai Basins is the inability to control the pool elevation and sediment retention time.

The open outlet pipe at Ka’opala allows sediment-laden waters at the bottom of the reservoir pool to be released downstream immediately (Photo 2-2). Similarly, the open ports on the Honokōwai riser structure also allow sediment-laden water to be released immediately (Photo 2-3). The intake for the Kahana basin was recently uncovered. The modified intake, which was intended to have a sluice gate that opened and closed automatically, was left in the “open” position due to inoperability. Previously, the buried intake prevented the basin from properly draining. While this did significantly increase the retention time for smaller floods, the nonfederal sponsor could not effectively remove these sediments from the basin as it was nearly always saturated (Photo 2-4). Larger storms likely reactivated these particles, carrying them over the riser structure and downstream.



Source: State Dam Inventory System, State of Hawai'i

Photo 2-2: Principal Spillway and Intake, Ka'ōpala Dam



Photo 2-3: Open ports at the riser structure, Honokōwai Dam (2017)



Photo 2-4: Riser structure and saturated conditions, Kahana Dam (2017)

Providing dam owners and operators with a means to control the release of water downstream would significantly reduce the amount of sediment transported downstream also. However, controlled release of water comes with the risk of not maintaining flow continuity in the river system and may increase flood risk downstream.

Two examples of an effective detention basin regarding sediment retention are Māhinahina Basin and Nāpili 4-5 Basin. Māhinahina Basin has a small outlet pipe like Kahana Basin (Photo 2-5). However, it was designed to include a butterfly closure valve and is located halfway up the embankment rather than near the embankment toe. The concentration of sediment at this elevation is less than it would be if the outlet pipe were located at the reservoir bottom.

At Nāpili 4-5, the outlet modification installed on the embankment provides the dam operator with controlled release of flow from the top-down (Photo 2-6; Figure 2-3). The modification 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.

Site-specific proposals for Ka‘ōpala, Kahana, and Honokōwai are presented in Sections 3.2.1, 3.3.1, and 3.4.2, respectively.



Photo 2-5: Intake for the outlet pipe, Māhinahina Dam



Photo 2-6: Outlet Modification at Nāpili 4-5 (2017)

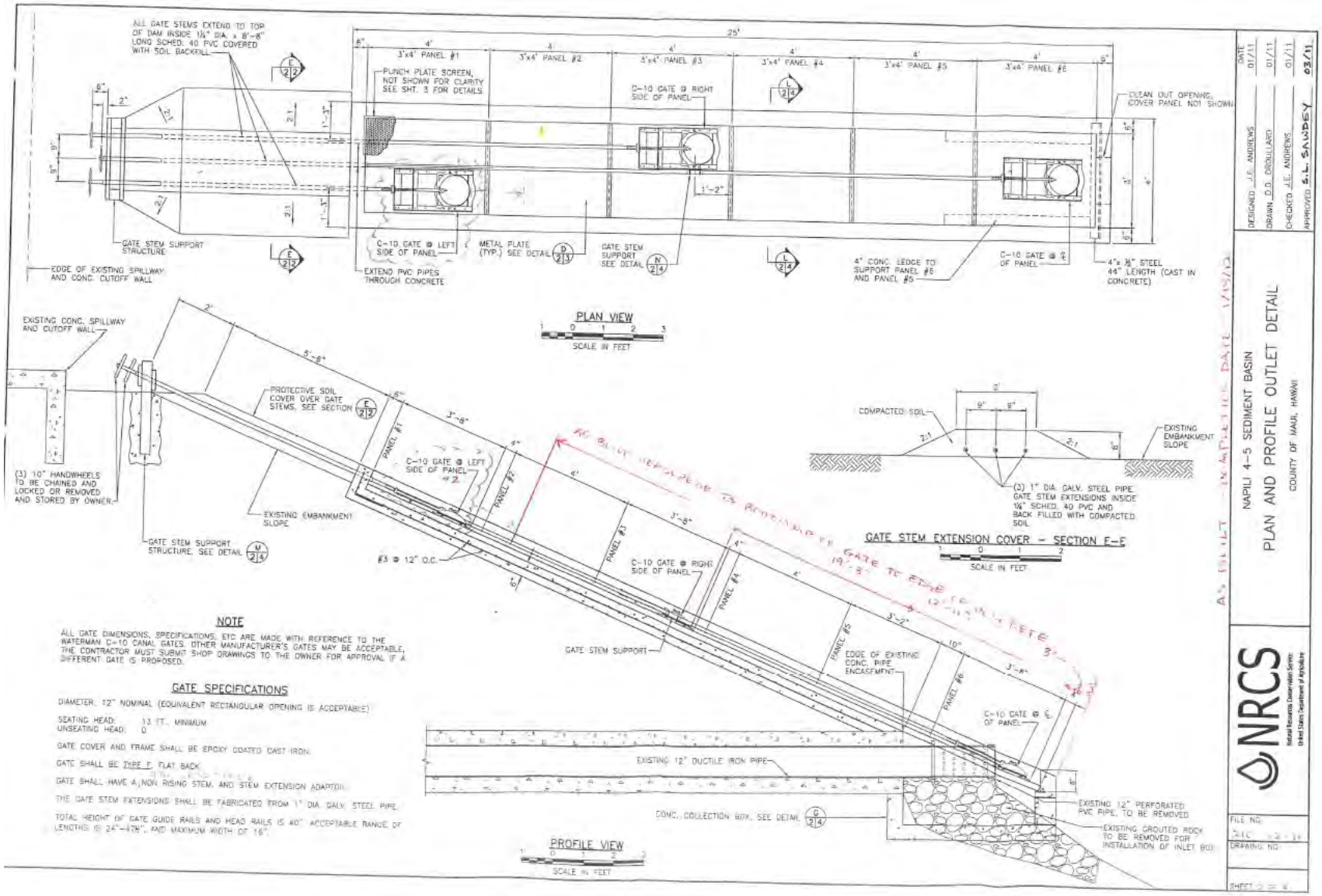


Figure 2-3: Nāpili 4-5 Outlet Modification Detail

2.3.2 **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 0.50 AEP flood) can be estimated using Camp's [1946] settling velocity equations, which are as follows:

$$TE = \frac{vA}{Q}$$

where TE = trap efficiency

V = settling velocity (ft/s)

A = wetted surface area (ft^2)

Q = discharge rate (ft^3/s)

The settling velocity of clay, silt, and fine sand in stormwater can be estimated using Stoke's Law, given in the equation below:

$$V_s = \frac{g\left(\frac{p_1}{p} - 1\right)d^2}{18\upsilon}$$

where:

V_s = settling velocity of the solid

g = acceleration of gravity

$p1$ = mass density of the solid

p = mass density of the fluid

d = diameter of the solid (assuming spherical)

υ = kinematic viscosity of the fluid

For particles larger than fine sand, such as coarse gravel, the equation by Ferguson and Church is used:

$$V_s = \frac{gRd^2}{18\upsilon + (0.75CgRd^3)^{1/2}}$$

where:

V_s = settling velocity of the solid

g = acceleration of gravity

d = diameter of the solid (assuming spherical)

R = specific gravity of the particle in water

C = a constant equal to 0.4 for spheres and 1 for typical sand grains

The assumed values for each parameter needed for either equation are listed in Table 2-2. Based on average diameter limits for various soil types, typical settling velocities are provided in Table 2-3.

Table 2-2: Assumed Parameter Values for Settling Velocity Equations

Parameter	Value[1]
g	9.81 m/s^2
$p1$	2650 kg/m^3
p	998 kg/m^3
υ	1.004E-6 m^2/s
R	2.66
C	0.4

[1]: assuming water temperatures of 20 ºC (68 ºF)

Table 2-3: Typical Settling Velocities Based on Soil Type

Name of soil separate	Diameter limits (mm)	Equation	Settling velocity, V_s (m/s)	Settling velocity, V_s (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

Using the estimated peak flow values and settling velocities previously presented in the Hydrology and Hydraulics Appendix, the recommended treatment surface area of the sediment basin can be estimated using the standard equation:

$$S_a = 1.2 * (\frac{Q_{out}}{v_s})$$

where:

S_a = treatment surface area measured at the invert of the lowest outlet of sediment basin (ft^2)

Q_{out} = Peak flow of the detention basin outlet (ft^3/s)

V_s = settling velocity of the solid (ft/s)

1.2 = EPA recommended safety factor

This equation is recommended by the Natural Resources Conservation Service as a Conservation Practice Standard for sediment basins (NRCS, 2008). Applying this equation results in the treatment surface areas requirements for addressing the various types of soil with approximately 80% effectiveness (80% reduction of the targeted soil type), which are presented in Table 2-4. These areas assume that the outflow, Q_{out}, is approximately equal to the inflow during the 50% AEP, 24-hour design storm.

As shown in Table 2-4, increasing the size (surface area) of the basin alone is not enough to effectively capture the fine sediments affecting the coral reefs (i.e. clays, silts). Using the same equations with a reduced outflow, provides the results presented in Table 2-5. Even with a baseflow as low as 1 ft^3/s, it is still not practical to capture 80% of the incoming silt.

Table 2-4: Treatment Surface Area Requirements for Various Soil Types When $Q_{in} = Q_{out}$

Subbasin ID	Location	Treatment Surface Area (sf)						
		Clay	Silt	Very fine sand	Fine sand	Medium sand	Coarse sand	Very coarse sand
		0 – 0.002 mm	*0.002 – 0.05 mm*	*0.05 – 0.1 mm*	*0.1 – 0.25 mm*	*0.25 – 0.5 mm*	*0.5 – 1.0 mm*	*1.0 – 2.0 mm*
1A	Wahikuli, near outlet	71,700,000	106,000	12,700	2,340	317	79.3	19.8
1B	Wahikuli, Hahakea Gulch	366,000,000	542,000	65,100	12,000	1,620	405.0	101.0
1C	Wahikuli, north tributary	174,000,000	257,000	30,900	5,680	769	192.0	48.1
2A	Hanakaʻōʻō, near outlet	74,100,000	110,000	13,200	2,420	328	82.0	20.5
2B	Hanakaʻōʻō	220,000,000	326,000	39,200	7,190	975	244.0	60.9
3A	Honokōwai, below dam	78,200,000	116,000	13,900	2,550	346	86.5	21.6
3B	Honokōwai, middle reach	213,000,000	315,000	37,900	6,950	942	236.0	58.9
3C	Honokōwai, middle tributary	75,700,000	112,000	13,500	2,470	335	83.8	20.9
3D	Honokōwai, upper reach	123,000,000	182,000	21,900	4,030	546	136.0	34.1
4A	Māhinahina	195,000,000	289,000	34,700	6,370	863	216.0	53.9
5A	Kahana, near outlet	23,600,000	34,900	4,200	771	104	26.1	6.5
5B	Kahana, southern tributary	99,800,000	148,000	17,700	3,260	441	110.0	27.6
5C	Kahana, middle and upper	132,000,000	195,000	23,500	4,310	584	146.0	36.5
6A	Kaʻōpala	79,400,000	117,000	14,100	2,590	351	87.8	22.0
7A	Honokeana	101,000,000	150,000	18,000	3,310	449	112.0	28.0
8A	Honokahua	83,100,000	123,000	14,800	2,710	368	91.9	23.0
8B	Honokahua, northern tributary	70,000,000	104,000	12,500	2,290	310	77.5	19.4
10A	Honolua, near outlet	77,000,000	114,000	13,700	2,510	341	85.1	21.3
10B	Honolua, middle and upper	59,000,000	87,300	10,500	1,930	261	65.3	16.3
10C	Honolua, Papua Gulch	60,300,000	89,100	10,700	1,970	267	66.7	16.7
12A	Honokōhau	725,000,000	1,070,000	129,000	23,700	3,210	802	200

Red = 1,000 sf or greater; Orange = 500 sf to 1,000 sf; and White = < 500 sf

Table 2-5: Treatment Surface Area Requirements for Various Soil Types, Various Outflow Rates

Baseflow (cfs)	Treatment Surface Area (sf)						
	Clay	Silt	Very fine sand	Fine sand	Medium sand	Coarse sand	Very coarse sand
	0 – 0.002 mm	*0.002 – 0.05 mm*	*0.05 – 0.1 mm*	*0.1 – 0.25 mm*	*0.25 – 0.5 mm*	*0.5 – 1.0 mm*	*1.0 – 2.0 mm*
1	406,780	600	71	13	2	0	0
2	813,559	1,200	141	27	4	1	0
5	2,033,898	3,000	353	67	9	2	1
10	4,067,797	6,000	706	133	18	5	1
15	6,101,695	9,000	1,059	200	27	7	2
20	8,135,593	12,000	1,412	267	36	9	2
35	14,237,288	21,000	2,471	467	63	16	4
50	20,338,983	30,000	3,529	667	90	23	6
100	40,677,966	60,000	7,059	1,333	180	45	11

As demonstrated in the above tables, maximizing the use of available land and restricting the outflow is not enough to create an effective detention or micro basin. Other methods must also be incorporated to encourage settlement of the clay and silt, such as use of a coagulant to promote flocculation (Section 2.4.1) or retaining the water for an extended period.

Using the settling velocities presented in Table 2-3, the estimated time it would take for various sediment types to settle 1-, 5-, and 10- feet are presented in Table 2-6. 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.

To effectively target clay, flocculation should be considered (Section 2.4.1).

Table 2-6: 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, Ka‘ōpala, and Wahikuli watersheds. Additional, site-specific information is provided in Sections2.3.2, 3.2.2, and 3.5, respectively.

2.3.3 **Storm Discharge Pipe**

Not Recommended

This measure proposes the construction of a large pipe to convey flow and sediments past nearshore coral reefs. It allows in-stream erosion to continue through natural processes before being captured and diverted into the deep ocean. It does not reduce the sediment load that reaches the ocean but relocates the discharge point so that the impact to nearshore coral reefs is minimized. There are several challenges associated with this measure, including its technical complexity, high cost of construction, requirements for land acquisition or easement rights, potentially significant environmental impacts, extensive permitting requirements, and increased maintenance requirements post-construction. When presented at the August 2018 public meeting, it was strongly opposed by the public.

2.4 Refinements

Refinements are features that can be incorporated into an existing or proposed management measure to improve the efficacy.

2.4.1 Coagulation and Flocculation

Fine sediment, such as clays and fine silts, require a long time to settle. Coarse to medium size silt particles can be realistically targeted for sedimentation but targeting clay and fine silts is generally not practical. However, these fine particles that are suspended in the water can be encouraged to stick together with the help of a coagulant chemical. Flocculation, a gentle mixing stage, further increases the particle size and thereby also reducing the time required for settlement. This measure compliments previously proposed measures that rely upon capturing sediment through detention.

When initially proposed at the public meeting in August 2018, there was some uncertainty regarding the impact that coagulant chemicals would have on the environmental system. Coagulation and flocculation are commonly used in water treatment facilities but has a limited performance history in Hawai‘i for addressing sedimentation issues in natural river systems. The measure was generally met with hesitancy by the public.

However, since the time of the public meeting, further research has revealed there are sources of biodegradable, natural flocculants that perform on a wide array of soil types and pH ranges; and have demonstrated no harm to aquatic organisms based on toxicity testing at recommended dosages (Dober). For example, there are chitosan-based flocculants (derived from chitin – the shells of crustaceans like shrimp, crabs, and lobsters) that could be sprayed on a static pond and clay-based bentonite flocculants that would need to be run through a flocculant belt by a pump.

Results are site-specific as each site varies in flow, load, and sediment distribution. Product distributors reference 95% reduction in turbidity. Conservatively, this study will assume only a 50% efficacy. Before implementing this refinement, jar testing can be done to find the appropriate dose and improve understanding on its effectiveness at facilitating settlement of fine sediments in West Maui streams. Furthermore, residual tests can be

done to verify and document that no residual chemistry is being released back into the environment.

An example of one type of installation is placement of a geotextile tube filled with either a gel or powder form of chitosan that dissolves as water flows over it. The design flow for this type of application is about 100 gallons per day (185 ft^3/s). Multiple socks could be placed at an existing culvert or at the outlet of a detention structure.



Source: ca.gov

Photo 2-7: Example of Flocculation Sock Installed

3 Sited Measures

The management measures carried forward from the previous section were sited across the study area, based on land area available, stakeholder support, and with consideration towards other existing measures in the watershed. This section describes the site-specific conditions, recommendations, effectiveness, and costs associated with each sited measure.

3.1 Honolua

Two management measures were sited in the Honolua watershed: loʻi terraces and micro basins.

3.1.1 **Honolua Loʻi Terraces**

At Honolua, surface water may be used for small, diversified agriculture and landscape irrigation, but no commercial agriculture is practiced.

Existing Site Conditions: Honolua Stream and its tributary in Pāpua Gulch are flowing in the upper watershed but have discontinuous flows below the Honokohau Ditch to the ocean, with most reaches losing surface water due to seepage (approximately 1.3 mgd). While the Honokohau Ditch was originally designed to remove water from the Honolua Stream to supply irrigation water for sugarcane land, the diversion has been inactive since 2003 (CWRM). It was estimated by CWRM that there was continuous stream flow from *mauka* to *makai* about 83% of the time with a mean flow of 7.6 mgd. Differences in discharges between historic and current periods are due to differences in climate from differing years of record. Honolua still has potential for this management measure to be implemented. Its impact in reducing the amount of sediment transported to the ocean, however, would be limited to addressing sediment carried by the base flow (persistent low flow in the stream) rather than the larger, flood-induced flows.

Proposed Design: The proposed design is for the construction of five new loʻi along Honolua Stream, covering a total area of approximately 1 acre. Typical design assumptions are summarized in Table 3-1. As presented in the Hydrology and Hydraulics Appendix, the 50% AEP (2-yr) peak flow for Honolua is 227 ft^3/s.

Table 3-1: Lo‘i Design Parameters and Assumptions

	Honolua
Approx. Number of Lo‘i	5
Surface Area (ac)	1
Surface Area (ft^2)	43,560
Water Depth (ft)	1.25
Capacity, C (ft^3)	54,450
Daily Inflow Rate, I (ft^3/s)	0.3
Mean velocity (ft/s)	0.001
Time of Retention, R (s)	181,500
Time of Retention, R (hr)	50.4
Sediment Index, SI (s^2/ft)	157,837,184

Trap Efficiency: Lo‘i are effective at trapping fine sediment for very low flows (< 1 ft/s). However, they are very inefficient in trapping fine sediment for flows that are likely to create plumes in Honolua Bay. They are not an effective measure for reducing terrestrial sediment impacts on West Maui coral reefs. For the design event (50% AEP, peak flow = 227 ft^3/s), it was assumed to accommodate 0.3 ft^3/s of inflow, resulting in an overall trap efficiency of 0.12%. Larger flows typical of small flood events entering the lo‘i complex are likely to destroy the measure, not improve the efficiency.

Table 3-2: Sediment Loads and Trap Efficiency for Honolua Lo‘i

Condition	Sediment (tons)				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Baseline	30.2	4.92	12.10	11.10	2.09
Lo‘i	30.2	4.92	12.08	11.09	2.09
Condition	**Trap Efficiency (%)**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Baseline	--	--	--	--	--
Lo‘i	0.12	0.06	0.13	0.13	0.13

Cost: The Rough Order of Magnitude (ROM) cost estimate to construct five loʻi totaling 1 acre area in forested land is $1,706,652. A breakdown of this estimate includes the follow:

Table 3-3: ROM Cost Estimate for Honolua Loʻi

Task	Cost
Mobilization/Demobilization/Preparation	$333k
Clear and Grub	$897k
Excavation	$112k
Boulder Weir	$0k
Disposal of Excess Excavated Material[2,3]	$298k
Care / Diversion of Water	$67k
Total:	$1.7M

The operation and maintenance of loʻi is likely heavily supported by the community and annual costs would likely be relatively low (less than $5,000 annually).

3.1.2 Pāpua Gulch Micro Basins

Pāpua Gulch was identified by West Maui R2R as a potential site for micro basins to be implemented. Pāpua Stream is an ephemeral tributary to Honolua Stream. Most of the Honolua watershed is owned by Maui Land and Pineapple, Co. There are a few residential properties in the downstream area. There are two possible sites for this measure: 1) located approximately 1,150 feet upstream from the Honolua and Pāpua Stream junction, and 2) located approximately 285 feet upstream from the junction (Figure 3-1).

Existing Site Conditions: The channel is 18 feet wide at the top, 5 feet deep, and has a bed slope of 3 - 6%. The riverbed is naturally armored with cobbles and small boulders. The overbank areas are covered with tall grasses and woody vegetation (Photo

[2] Assumes boulders can be relocated to County of Maui at baseyard for reuse at no cost, but contingency included (as design) in the event that not all boulder relocation is free.
[3] Assumes soil disposal at Central Maui Landfill for a fee. Cut trees also to be disposed of at scalehouse of Central Maui Landfill for a fee.

3-1). Remanences of past lo'i terraces can also be found along the streambank. This combination of site conditions may make clearing the site for earthwork challenging.

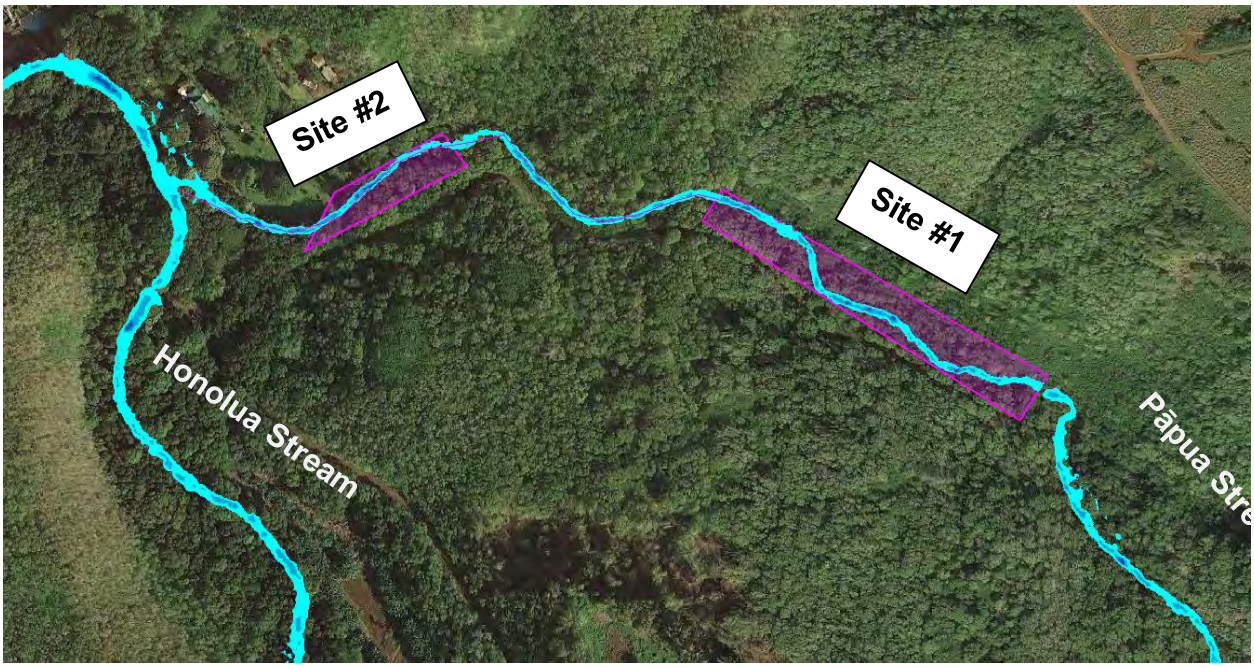


Figure 3-1: Location Map for Pāpua Gulch Micro Basin Sites #1 and #2



Photo 3-1: Typical Stream Conditions, Pāpua Gulch

The corresponding HMS element for this site is subbasin 10C. The estimated peak flow for various frequency events is provided in Table 3-20. These represent flows entering the site upstream.

Table 3-4: Peak Flow Estimates Entering this Site

Sub-basin ID	Peak flow (ft^3/s)							
	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500
10C	142	285	438	696	913	1,190	1,520	2,080

The design flow for this site is 142 ft^3/s, which represents the 50% (1/2) annual exceedance probability (AEP) flood event. The corresponding sediment load for this event is 11.2 tons of total sediment, which includes 1.78 tons of clay (16%), 4.46 tons of silt (40%), 4.06 tons of sand (36%), and 0.76 tons of gravel (6.8%).

During the continuous flow simulation, the maximum peak flow occurred on 13 February 2015 and was estimated to be 439 ft^3/s. This is approximately equivalent to the peak flow estimated for the 10% (1/10) annual exceedance probability (AEP) or the *decadal* event. However, there is less certainty in the exact frequency (AEP) of the event for this site as it is farther from the calibrating rainfall and stream gages than other watersheds. It was determined by using the best available data. This continuous flow simulation, which is based on actual rainfall that occurred during a period of no significant flow events, provides greater confidence and representation of likely conditions at the site during low flow events. The corresponding sediment load for this event was estimated to be 59.4 tons of total sediment, which includes 9.66 tons of clay (16%), 23.8 tons of silt (40%), 21.8 tons of sand (37%), and 4.10 tons of gravel (6.9%)

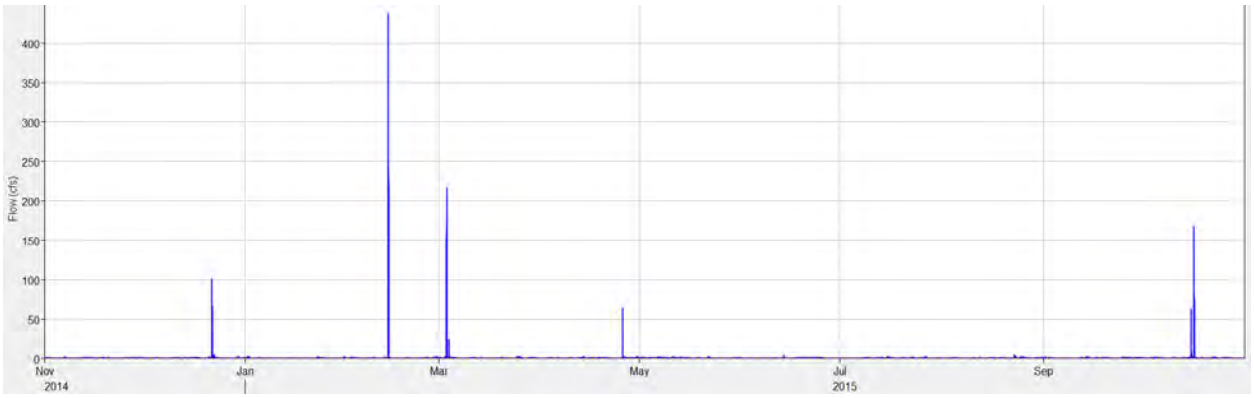


Figure 3-2: Simulated flow conditions for 1 November 2014 to 1 November 2015, Pāpua Gulch, Honolua Watershed

Proposed Design: The proposed measure is a series of in-stream detention basins, which spans a total reach length of 700 feet, widens the channel to 50 feet, and includes multiple rock weirs constructed across the channel to slow down flows during the design flow event. Each micro basin would be approximately 70 feet long, 50 feet wide and include a 4-foot-high rock weir on the downstream end (Figure 3-3, Figure 3-4). Ten micro basins are recommended for this measure to be effective at trapping fine sediments. However, fewer basins would still provide partial efficacy. An example layout of 3 micro basins at site #2 is provided as Figure 3-5.

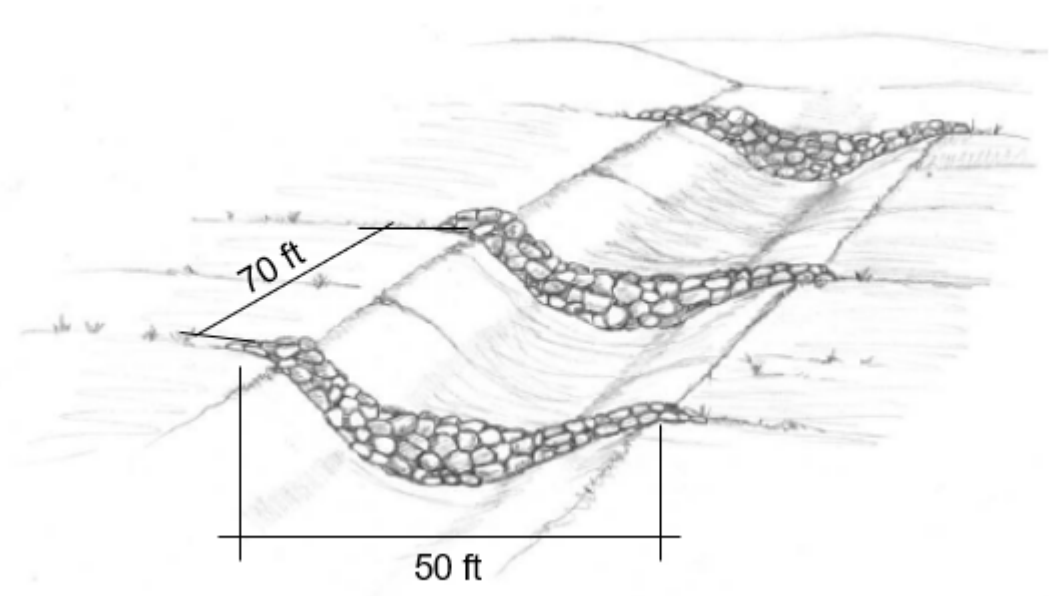
As sediment-laden water flows down Pāpua Stream, the widened channel and physical barrier of the rock weir would slow down the flow. The rock weir, constructed of loose riprap with partial grouting, would maintain flow continuity in the stream[4] as a pervious structure. As the capacity of the first micro basin is exceeded, waters would flow over the rock weir and enter the next micro basin. Each micro basin creates an opportunity for sediment to settle before continuing downstream.

Assuming a typical channel depth of 5 feet, the rock weirs would be only 4 feet high (1 foot lower than the top of bank). These weirs would be constructed of medium and large boulders, possibly sourced on site. Partial grouting would increase the structure's resilience against higher flows.

[4] Flow continuity is maintained during the flood event; streamflow in Pāpua Stream is intermittent. It does not have continuous flow throughout the year, even under existing conditions.

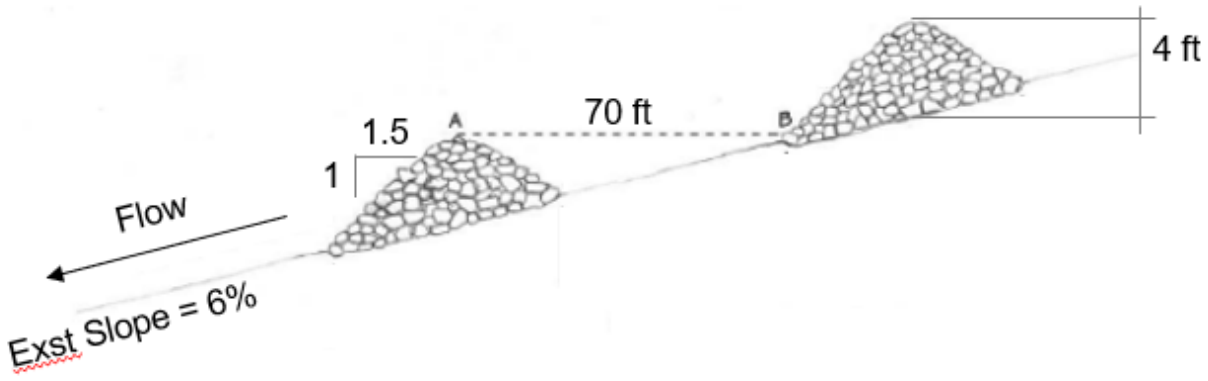
To transition the widened channel (50 feet wide) back to the existing channel (18 feet wide), a reach segment length of 5 feet is recommended based on a typical contraction ratio of 0.3. Although this is the recommended design for construction, the stream will likely adapt as needed. This ratio does not need to be maintained post-construction.

While the proposed design is relatively effective at trapping silt for the design flow event (trap efficiency is presented in Table 3-5 andTable 3-6), to effectively capture clay particles, the water must either be retained or treated with a flocculant. Water retention is not recommended for this sited measure, in favor of maintaining flow continuity and limiting the constructible features on this site. Flocculation could be incorporated into this measure by installing flocculation socks downstream of the micro basins (see Section 2.4.1, Coagulation and Flocculation).



Original figure source: USACE, ERDC/CRREL TR-14-26, 2014

Figure 3-3: Pāpua Gulch Micro Basin Design



Original figure source: USACE, ERDC/CRREL TR-14-26, 2014

Figure 3-4: Section View Along Stream Profile

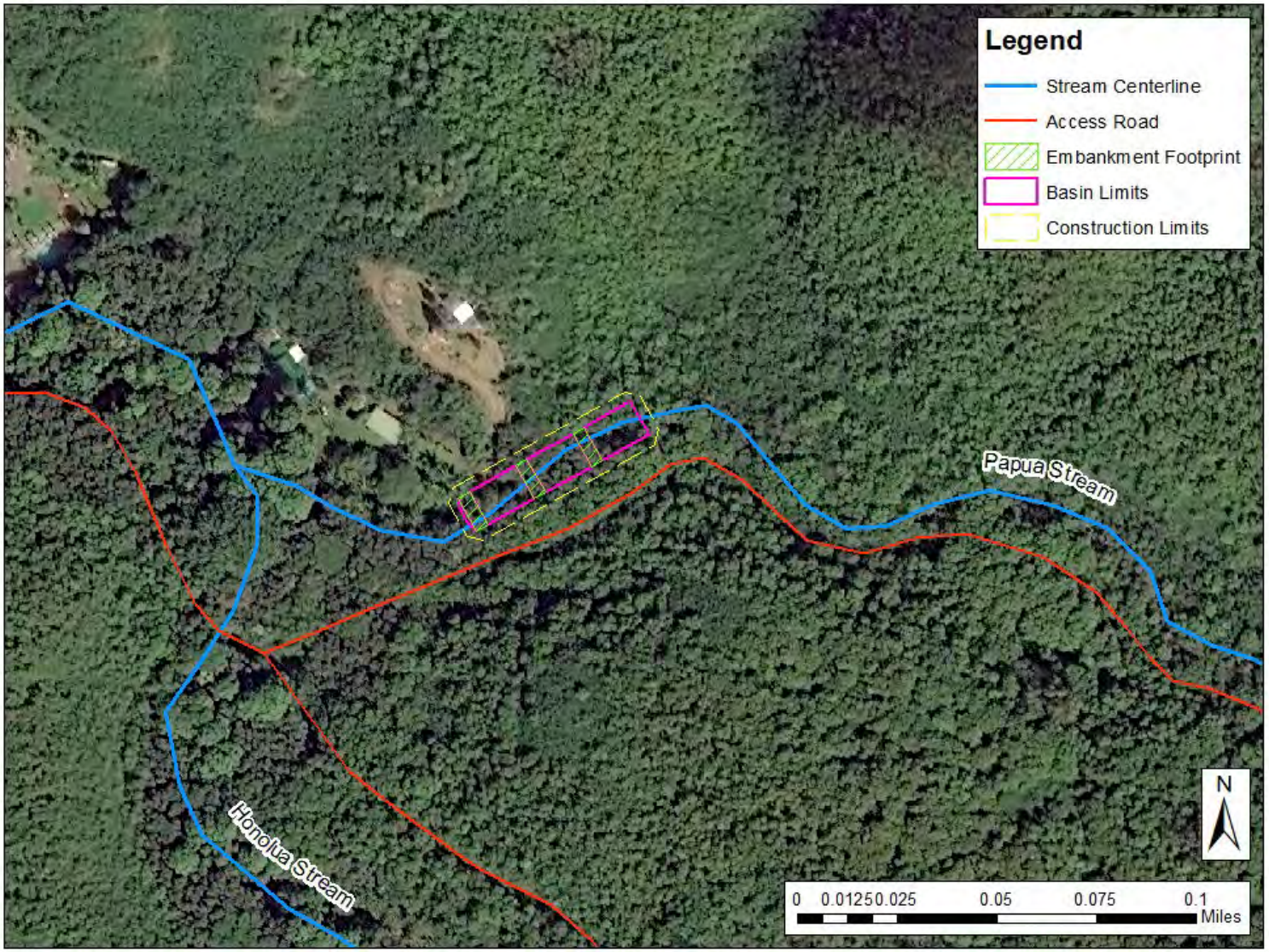


Figure 3-5: Site Map for Pāpua Gulch Micro Basins at Site #2

Trap Efficiency: Reduced sediment loads and trap efficiency estimates are presented in Table 3-5 and Table 3-6. Based on the expanded surface area created by simply widening the channel, essentially all the sand and gravel are expected to settle during the design flow event. When flow is restricted by the rock weirs, the trap efficiency of silt is improved to 10% for 1 micro basin and ~100% for 10 micro basins. However, clay is still not effectively captured (0.15% for 10 micro basins).

To effectively capture clay particles, the water must either be retained or treated with a flocculant. Although water retention was not recommended for this sited measure. Additional information is provided here for consideration. Typically, standing water is not recommended beyond 72 hours to effectively suppress mosquito production. In this time, approximately 19% of the clay particles could potentially settle. It would take about 16 days to essentially capture all clay particles for the design flow event. Water retention may be possible by incorporating either a sluice gate, outlet valve, or stop logs into each embankment. This feature would increase the maintenance required at the site. The effectiveness of flocculation on suspended sediments is site specific but has the potential to be very effective (50 – 90% trap efficiency).

Table 3-5: Sediment Load Reductions and Trap Efficiency for Pāpua Gulch Micro Basins, 50% AEP "Design" Event

Condition	Sediment (tons)				
	Total	Clay	Silt	Sand	Gravel
Baseline	11.18	1.78	4.46	4.06	0.76
1 Micro Basin	5.85	1.78	4.02	0	0
10 Micro Basins	1.84	1.78	0.02	0	0
Condition	**Trap Efficiency, %**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
1 Micro Basin	47	0.01	10	100	100
10 Micro Basins	84	0.15	100	100	100

Table 3-6: Sediment Load Reductions and Trap Efficiency for Pāpua Gulch Micro Basins, 10% AEP "Decadal" Event

Condition	Sediment (tons)				
	Total	Clay	Silt	Sand	Gravel
Baseline	59.4	9.66	23.8	21.8	4.10
1 Micro Basin	31.4	9.66	21.4	0	0
10 Micro Basins	10.1	9.65	0.10	0	0
Condition	**Trap Efficiency, %**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
1 Micro Basin	47	0.01	10	100	100
10 Micro Basins	83	0.15	100	100	100

Operation and Maintenance: During a flow event, the micro basin will operate independently. Smaller sediment traps are typically designed for a useful life of 18 – 24 months. Larger flow events have the potential to wash out the built embankment, especially if stones were sourced directly from the site (thereby already having a history of being transported by past flows) and partial grouting was not applied. To continue receiving the benefits of capturing sediment, the embankments would need to be reconstructed. One micro basin at this site has potential storage of 11,424 ft^3. While sediment will have to be removed periodically, vegetation within the widened channel is not a concern unless it begins to encroach the rock embankment. A vegetated basin (even woody vegetation) will help in slowing down flows. Woody vegetation near the rock embankment, however, can begin to break apart the structure.

Cost: The ROM cost estimate to construct 10 total microbasins at two upstream forested locations is $3,044,775. A breakdown of this estimate includes the follow:

Table 3-7: ROM Cost Estimate for 10 Pāpua Gulch Micro Basins

Task	Cost
Mobilization/Demobilization/Preparation	$342k
Clear and Grub	$844k
Excavation	$455k
Boulder Weir	$334k[5]
Disposal of Excess Excavated Material[6,7]	$334k
Care / Diversion of Water	$210k
Total:	$3M

The annual operation and maintenance costs on this measure would be moderate ($5k - $25k / year). Vegetation growth in the basin and banks post-construction is not a major concern – only if woody vegetation starts to grow in or near the constructed rock weirs (woody vegetation can potentially dislodge the stones). Small amounts of debris are permitted to build up in front of the rock weir embankment through natural processes. This can be removed with the accumulated sediment on an annual basis. Fees associated with the disposal of sediment and debris off-site will likely be the highest O&M cost associated with this feature.

[5] Assumes boulders can be relocated to County of Maui at baseyard for reuse at no cost, but contingency included (as design) in the event that not all boulder relocation is free.
[6] Assumes soil disposal at Central Maui Landfill for a fee. Cut trees also to be disposed of at scalehouse of Central Maui Landfill for a fee.
[7] Excavations assume 85% boulders and 15% soil based; contingency included (as design) for uncertainty in cross section, weir design.

3.2 Ka‘ōpala

Three management measures were sited in the Ka’opala watershed: modifying the outlet at Ka’opala Basin, rock weirs (a variant of the micro basin measure), and flocculation.

3.2.1 **Outlet Modification at Ka‘ōpala Basin**

Ka’opala Basin is seemingly effective at capturing sediment, including silt particles. However, it still releases about 8.5 tons of clay annually according to the rainfall-runoff model introduced in the Hydrology and Hydraulic Appendix. Modifying the outlet works so that Ka‘ōpala Basin operates similarly to the Nāpili 4-5 Basin, where sluice gates allow for controlled release of flow from the reservoir from the top-down, results in an increased trap efficiency of clay particles (24% to 46%). However, the trap efficiency of silt is reduced (100% to 78%) as the principal spillway is activated earlier to do the higher pool elevation created from storing more water in the reservoir.

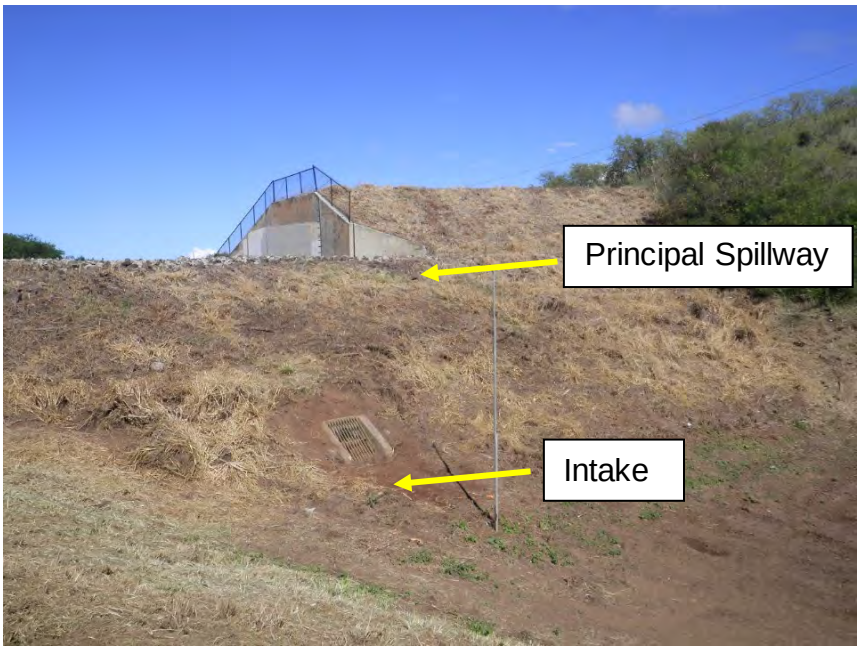
Existing Site Conditions: The reservoir bottom is at an approximate elevation of 34 – 35 ft MSL, according to LiDAR data (Photo 3-2). This elevation is also similar to the approximate limit of excavation identified on the original as-built drawings (35 ft MSL). The drain inlet invert is at elevation 41.0 ft MSL (about 6-7 feet higher; Photo 3-3). This leaves a reasonable amount of water that is unable to leave the basin except by infiltration (100% sediment captured for that volume of water).

The design flow for this site is 182 ft^3/s, which represents the 50% (1/2) annual exceedance probability (AEP) flood event. The corresponding sediment load for this event is 64.9 tons of total sediment, which includes 10.1 tons of clay (16%), 21.9 tons of silt (40%), 24.5 tons of sand (44%), and 0.17 tons of gravel (0.3%). Of the 64.9 tons of total sediment, essentially all silt, sand, and gravel are captured by the existing basin. 24% of the clay is also captured (Table 3-8).

To effectively capture clay particles, the water must either be retained or treated with a flocculant. Although some water is already being retained by the basin, which has contributed to its success in capturing fine particles, the amount of water that is retained (and the trap efficiency of clay particles) can be increased by modifying the intake for the outlet works.



Photo 3-2: Looking upstream at Ka‘ōpala Basin



Source: State Dam Inventory System, State of Hawai‘i

Photo 3-3: Principal Spillway and Intake, Ka‘ōpala Basin

Proposed Design: The proposed modification at Ka‘ōpala Basin is a replication of the outlet modification that was done at Nāpili 4-5 (Figure 3-6). Both basins are similar in size. The flow and runoff volume entering both basins are also similar. This would allow the sponsor to perform a controlled release of stored water. It also allows water to first be released from the top – where the sediment concentration is the lowest and provide additional time for the fine particles in the sediment-laden waters below to settle. Increasing the amount of water being stored in the reservoir may require a more detailed flood risk analysis that is beyond the scope of this study.

Flocculation could also be incorporated into this measure by installing 1-2 flocculation socks at the downstream end of the outlet pipe (see Section 2.4.1, Coagulation and Flocculation).

Trap Efficiency: As shown in the Table 3-8 below, 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 3-8: Evaluating Sediment Load and Trap Efficiency, 50% AEP Event

	Inflow	Existing		Modified[1]	
		Outflow	Trap Efficiency	Outflow	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%

[1]: does not include flocculation impacts

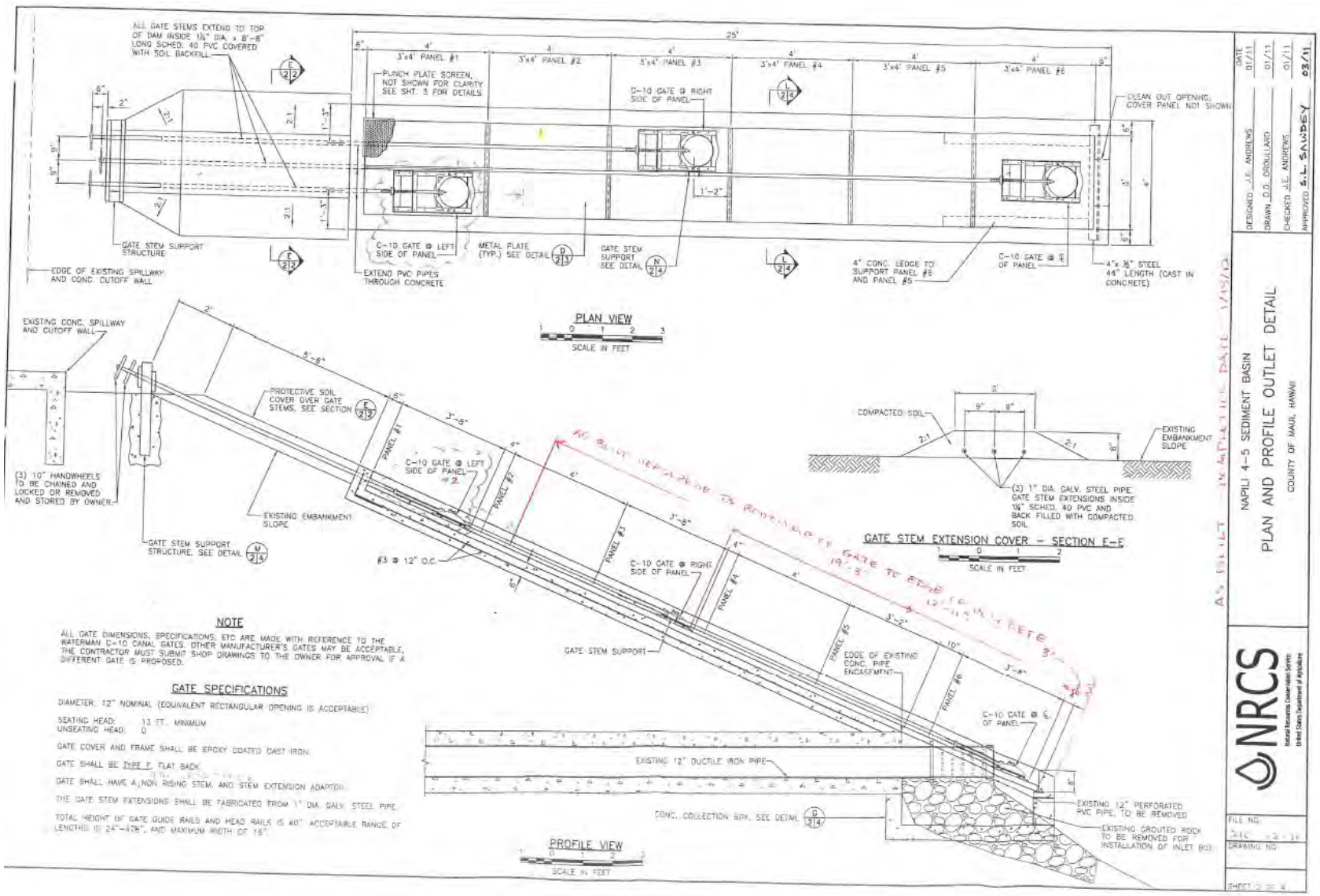


Figure 3-6: Nāpili 4-5 Outlet Modification Detail

Operation and Maintenance: The dam is currently operated and maintained by the County of Maui. As a result of this modification, additional sediment might be captured and the basin may be required to be excavated more frequently. The sluice gates will also need to be opened, as appropriate, to release flow, or in anticipation of a significant event that may cause flooding concerns. The tracks of the sluice gates will also need to be cleaned and greased occasionally to ensure they can open and close easily.

Cost: The Rough Order of Magnitude (ROM) cost estimate to modify the existing Ka‘ōpala outlet structure to become similar to the outlet structure of Nāpili 4-5 is $144,160. A breakdown of this estimate includes the follow:

Table 3-9: ROM Cost Estimate for Ka‘ōpala Basin Outlet Modification

Task	Cost
Mobilization/Demobilization/Preparation	$28k
Modify Structure	$116k
Total:	$144k

The annual operation and maintenance costs on this measure would be moderate ($5k - $25k / year). Vegetation growth in the basin and banks post-construction is not a major concern – only if woody vegetation starts to grow in or near the constructed rock weirs (woody vegetation can potentially dislodge the stones). Small amounts of debris are permitted to build up in front of the rock weir embankment through natural processes. This can be removed with the accumulated sediment on an annual basis. Fees associated with the disposal of sediment and debris off-site will likely be the highest O&M cost associated with this feature.

3.2.2 **Ka‘ōpala Rock Weirs**

Downstream of Ka‘ōpala Basin and Honoapiilani Highway, there is a site that has potential to capture residual sediments that were not captured by the basin. The existing basin upstream of the highway is effective at reducing the peak flow for low flow events, as shown in Table 3-8. However, there is still opportunity to capture additional sediment.



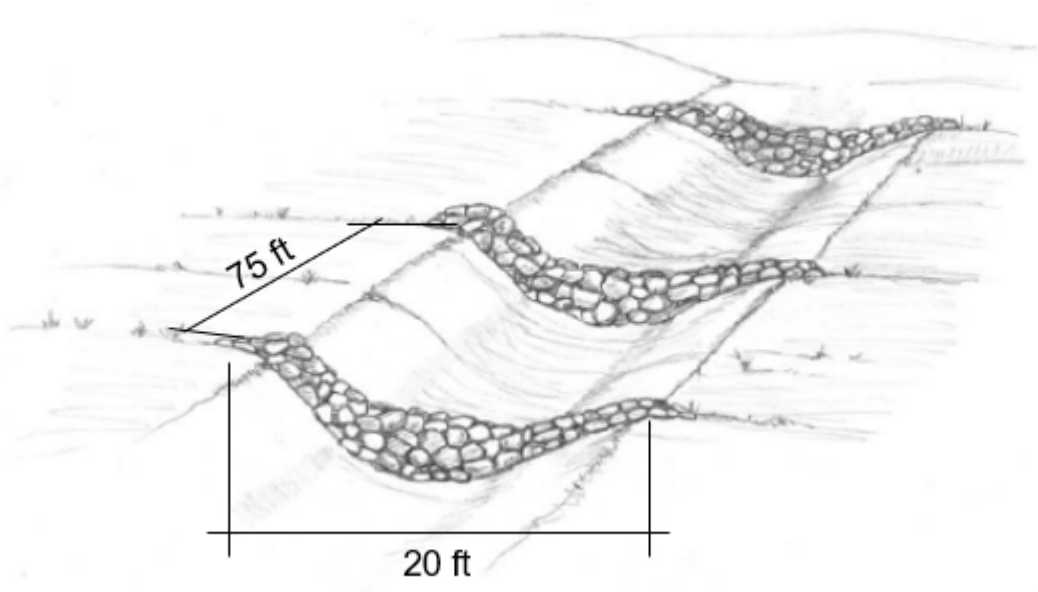
Figure 3-7: Potential Site for Ka‘ōpala Micro Basin

Existing Site Conditions: Between Honoapiilani Hwy and Lower Honoapiilani Road, there is an undeveloped area that has potential for a management measure to be implemented. The stream is not well defined. The reach length available is about 350 ft. The top of bank is about 15-20 ft, and the channel depth is about 4 feet. The channel bed slope is 3%. The property owner is Pineapple Ridge, LLC.

Due to the site’s proximity to the ocean, there is likely a shallow depth to the water table and risk of negative impacts from sea level rise in the future. The proposed measure should not be too deep or considered a permanent structure that is unable to adapt to climate change.

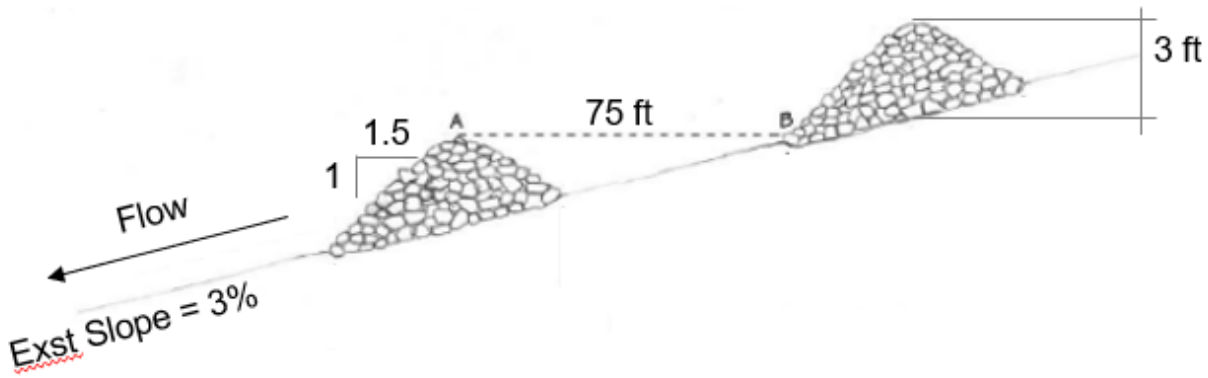
Proposed Design: The proposed design at this site is to construct short (3-ft high) rock weirs every 75 feet (Figure 3-8, Figure 3-9) along the existing channel (4 total). This type of design can also be known as a "check dam," but that name could be misinterpreted as a large, permanent, concrete structure, which is not what is being proposed here.

Attempts at constructing a traditional sediment basin at this site is not recommended. The site's proximity to the ocean discourages a permanent (concrete) structure from being installed. The high water table also restricts how deep the basin could be, limiting the amount of volume that can be stored. Clearing the area for a more intentional design, even a natural one, would remove all of the vegetation that likely aids in slowing down flows (and trapping sediment). It could also potentially remove the natural armor layer that has established (larger cobbles on the surface of the channel and floodplain), leaving the finer sediment underneath exposed.



Original figure source: USACE, ERDC/CRREL TR-14-26, 2014

Figure 3-8: Ka'ōpala Rock Weirs



Original figure source: USACE, ERDC/CRREL TR-14-26, 2014

Figure 3-9: Section View Along Stream Profile

Trap Efficiency: As mentioned in previous sections, the existing Ka'opala Basin is already reasonably effective at capturing most of the other sediment types (silt, sand, and gravel) for low flow events and lowering the peak flow. This proposed measure of rock weirs was not very effective in trapping clay (Table 3-10), which is very hard to do without storing most of the flow in a large reservoir or treating it with a coagulant.

Table 3-10: Sediment Loads and Trap Efficiency for Ka'ōpala Rock Weirs, 50% AEP Event

Condition	Sediment (tons)				
	Total	Clay	Silt	Sand	Gravel
Baseline	7.79	7.68	0	0	0
Rock Weirs	7.79	7.67	0	0	0
Condition	**Trap Efficiency (%)**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Rock Weirs	0	0.01	0	100	100

Cost: The ROM cost estimate to construct four rock weir structures on Ka'opala Stream is $495,183. A breakdown of this estimate includes the follow:

Table 3-11: ROM Cost Estimate for 4 Rock Weirs at Ka'ōpala Stream

Task	Cost
Mobilization/Demobilization/Preparation	$273k
Clear and Grub	$35k
Excavation	$43k
Boulder Weir	$44k[8]
Disposal of Excess Excavated Material[9,10]	$5k
Care / Diversion of Water	$95k
Total:	$495k

The annual operation and maintenance costs on this measure would be moderate ($5k - $25k / year). Vegetation growth in the channel post-construction is not a major concern – only if woody vegetation starts to grow in or near the constructed rock weirs (woody vegetation can potentially dislodge the stones). Small amounts of debris are permitted to build up in front of the rock weir embankment through natural processes. This can be removed with the accumulated sediment on an annual basis. Fees associated with the disposal of sediment and debris off-site will likely be the highest O&M cost associated with this feature.

3.2.3 Ka'ōpala Flocculation

Although the effectiveness of flocculation cannot yet be quantified, it is likely to be reasonably effective at improving the trap efficiency of the existing basin. The recommended site where the coagulant should be added is on the upstream end of the basin where flows pass through a culvert, under a road embankment (approximate

[8] Assumes boulders can be relocated to County of Maui at baseyard for reuse at no cost, but contingency included (as design) in the event that not all boulder relocation is free.
[9] Assumes soil disposal at Central Maui Landfill for a fee. Cut trees also to be disposed of at scalehouse of Central Maui Landfill for a fee.
[10] Excavations assume 85% boulders and 15% soil based; contingency included (as design) for uncertainty in cross section, weir design.

coordinates: 20°58'54.90"N, 156°40'11.05"W). Refer to Section 2.4.1, for more information on flocculation.

3.3 Kahana

The focus for the Kahana watershed was to improve the efficiency of the existing detention basin. One management measure is proposed within this watershed.

3.3.1 **Excavate Kahana Basin**

This measure proposes more frequent excavation of Kahana Basin and describes the benefits from having a cleared basin with regards to improved trap efficiency.

Existing Site Conditions: Kahana Basin is reasonably effective at trapping sediment, however the total sediment load contributed by this watershed is significant. Plumes still occur frequently at the outlet. This basin, which is operated and maintained by the County of Maui, has a history of challenges regarding the County's ability to remove sediment due to continuously saturated conditions in the basin. In 1997, the outlet works was modified to add a gated drain inlet, 4-inch hydraulic lines, and control housing. However, the hydraulically operated sluice gate currently does not function and remains open (uncontrolled). The County of Maui is currently in the process of having Oceanit re-design a manually operated valve system.

The basin was also excavated significantly in 2018. Figure 3-10 shows the recommended excavation limits, as prepared for the County of Maui by Fukumoto Engineering, Inc. An elevation-area curve was estimated in ArcGIS based on these contours. This has an elevation of about 40 ft MSL for the basin invert. An elevation-area curve was also estimated by Oceanit for the County of Maui using a topographic survey of the basin in 2020, which has an elevation of about 48 ft MSL for the basin invert (8 ft higher).

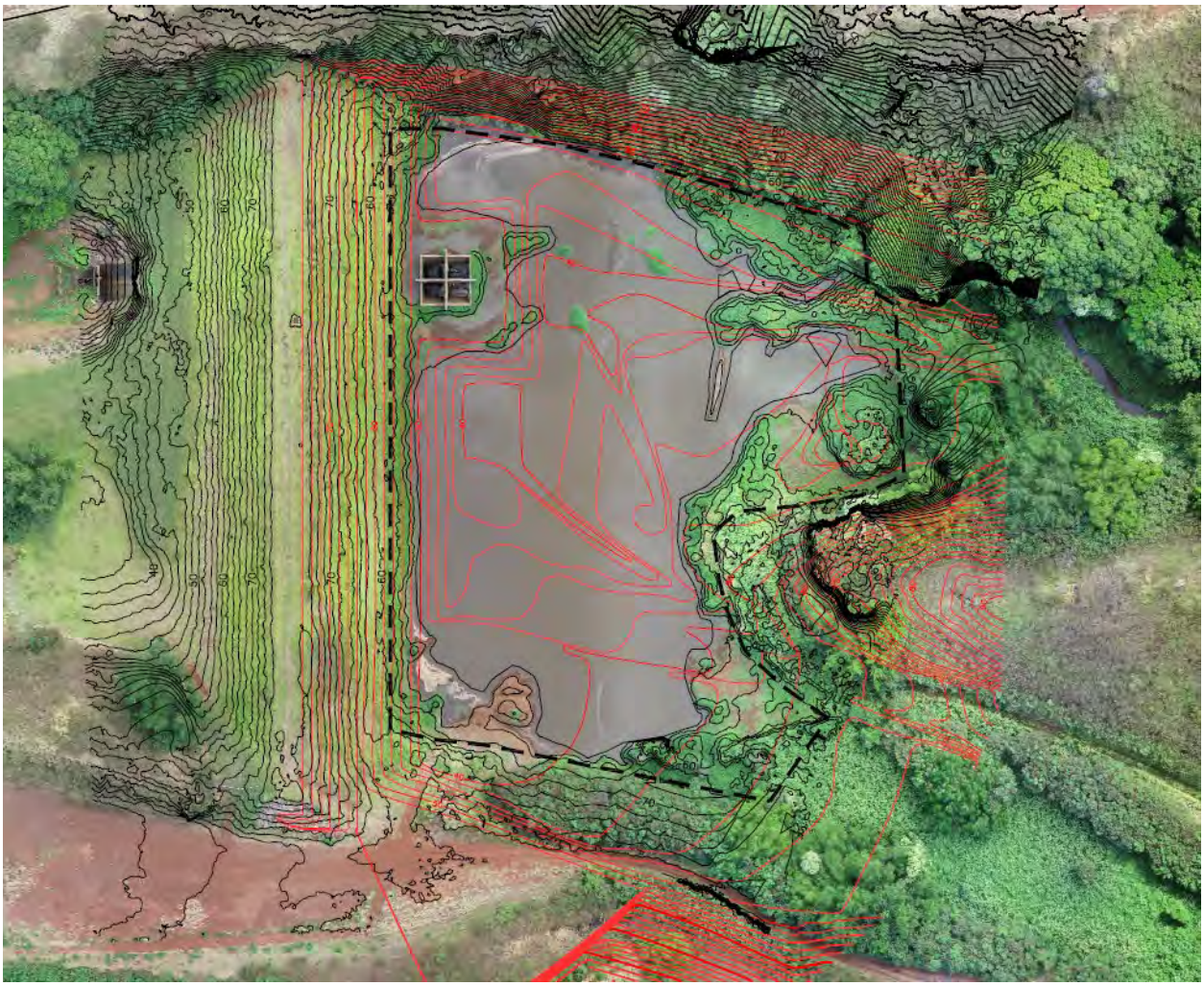


Figure 3-10: Excavation Limits Proposed in 2018

Proposed Design: The excavation limits previously proposed by Fukumoto Engineering, Inc. are re-proposed here. It is recommended the basin be excavated to this extent at least once a year.

Trap Efficiency: Excavating the basin to the recommended limits improves the trap efficiency of silt from 47% to 79% but was not very effective for clay particles (Table 3-5).

Operation and Maintenance: This modification, however, would likely increase the frequency the basin is saturated. The nonfederal sponsor responsible for maintenance has expressed frustration with frequently saturated conditions as it inhibits their ability to perform maintenance (i.e. excavate captured fine sediments before they are re-activated by a larger storm event).

Table 3-12: Sediment Loads and Trap Efficiency for Kahana Basin Excavation, 50% AEP Event

Condition	Flow (ft^3/s)	Sediment (tons)				
		Total	Clay	Silt	Sand	Gravel
Inflow	496	162	25.4	64.2	71.9	0.53
Existing (2020) Outflow	464	57.8	23.9	33.9	0	0
Excavated (2018) Outflow	392	37.2	23.7	13.5	0	0
Condition	**Flow (ft^3/s)**	**Trap Efficiency (%)**				
		Total	**Clay**	**Silt**	**Sand**	**Gravel**
Existing (2020) Outflow	464	64	6	47	100	100
Excavated (2018) Outflow	392	77	7	79	100	100

Cost: The ROM cost estimate to excavate Kahana Basin is $70,630. A breakdown of this estimate includes the follow:

Table 3-13: ROM Cost Estimate for Kahana Basin Excavation

Task	Cost
Mobilization/Demobilization/Preparation	$31k
Clear and Grub	$0k
Excavation	$0.8k
Disposal of Excess Excavated Material[11]	$42k
Care / Diversion of Water[12]	$0k
Total:	$73k

Since the initial cost is reflective of an activity that is recommended to occur annually, the annual O&M cost would be the same: $70,630.

[11] Costs are likely higher than what the County of Maui estimate may be due to offsite disposal fees.
[12] Estimate assumes that the work is not impaired by the basin being flooded.

3.4 Honokōwai

3.4.1 Honokōwai Loʻi Terraces

Existing Site Conditions: From the 2019 Instream Flow Standard Assessment Report on Honokōwai by CWRM, the reach segment below the Honokōwai diversions (where historical loʻi were previously sited) the stream is dry for more than 50% of the year. While some flow is diverted to the Kāʻanapali Coffee Farm and to meet the landscaping demands for the agricultural subdivision (approximately 9 mgd), some flow is also lost through seepage (approximately 1.1 mgd). For this reason, Honokōwai is only recommended as a potential site for this management measure if minimum flow standards are established by the State and continuous flow is maintained from *mauka* to *makai*.

Proposed Design: The proposed design is for the construction of ten new loʻi along Honokōwai Stream, covering a total area of approximately 2 acres. Typical design assumptions are summarized in Table 3-14. As presented in the Hydrology and Hydraulics Appendix, the 50% AEP (2-yr) peak flow for Honokōwai is 646 ft^3/s.

Table 3-14: Honokōwai Loʻi Design Parameters and Assumptions

	Honokōwai
Approx. Number of Loʻi	10
Surface Area (ac)	2
Surface Area (ft^2)	87,120
Water Depth (ft)	1.25
Capacity, C (ft^3)	108,900
Daily Inflow Rate, I (ft^3/s)	0.6
Mean velocity (ft/s)	0.0008
Time of Retention, R (s)	181,500
Time of Retention, R (hr)	50.4
Sediment Index, SI (s^2/ft)	157,837,184

Trap Efficiency: Loʻi are effective at trapping fine sediment for very low flows (< 1 ft/s). However, they are very inefficient in trapping fine sediment for flows that are likely to create plumes in the nearshore environment. They are not an effective measure for

reducing terrestrial sediment impacts on West Maui coral reefs. For the design event (50% AEP, peak flow = 646 ft^3/s), it was assumed to accommodate 0.6 ft^3/s of inflow, resulting in an overall trap efficiency of 0.08%. Larger flows typical of small flood events entering the loʻi complex are likely to destroy the measure, not improve the efficiency.

Table 3-15: Sediment Loads and Trap Efficiency for Honokōwai Loʻi, 50% AEP Event

Condition	Sediment (tons)				
	Total	Clay	Silt	Sand	Gravel
Baseline	6.87	1.35	3.18	2.05	0.19
Loʻi	6.86	1.35	3.17	2.05	0.19
Condition	**Trap Efficiency (%)**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Baseline	--	--	--	--	--
Loʻi	0.08	0.04	0.09	0.09	0.09

Cost: The Rough Order of Magnitude (ROM) cost estimate to construct ten loʻi totaling a 2-acre area in forested land is $3,413,304. A breakdown of this estimate includes the follow:

Table 3-16: ROM Cost Estimate for Honokōwai Loʻi

Task	Cost
Mobilization/Demobilization/Preparation	$666k
Clear and Grub	$1.79M
Excavation	$224k
Boulder Weir	$0k
Disposal of Excess Excavated Material	$596k
Care / Diversion of Water	$134k
Total:	$3.41M

The operation and maintenance of loʻi is likely heavily supported by the community, but given the remoteness of the site, annual costs would likely be moderate ($5k to $25k annually).

3.4.2 Honokōwai Riser Structure with StopLog Panels

The existing Honokōwai concrete riser could be modified to allow for controlled release of flow from the top-down via stoplog panels (Figure 3-11). 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.

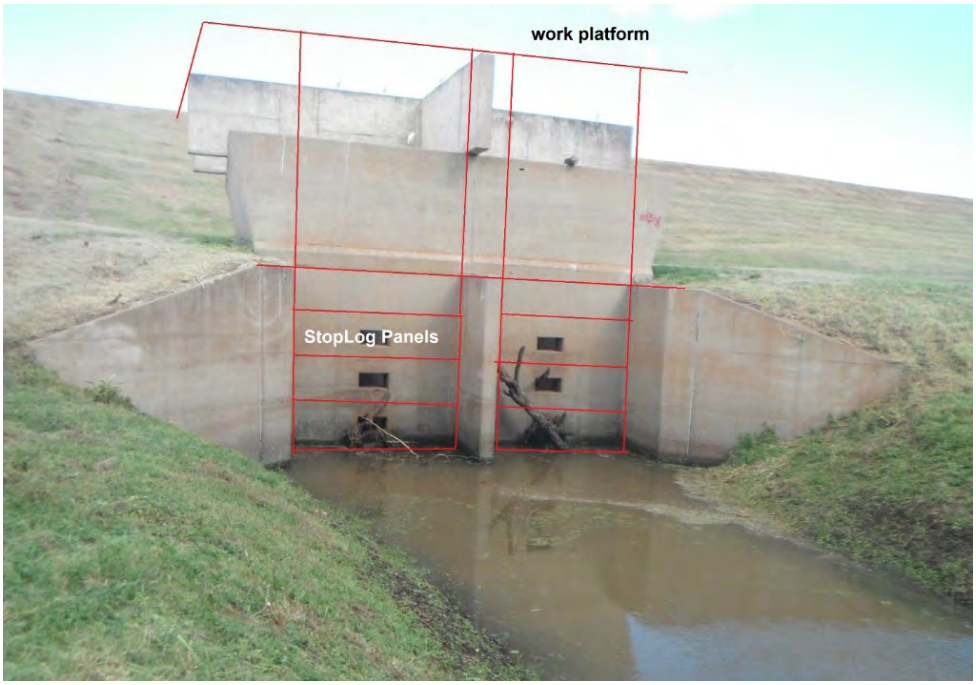


Figure 3-11: StopLog Panels and Work Platform at Honokōwai Riser

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

The corresponding HMS element for this site is Junction-3. The estimated peak flow for various frequency events is provided in Table 3-20. These represent flows entering the site upstream.

Table 3-17: Peak Flow Estimates Entering this Site

Sub-basin ID	Peak flow (ft^3/s)							
	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500
Junction-3	845	1,580	2,280	3,450	5,620	5,620	6,970	9,150

The design flow for this site is 845 ft^3/s, which represents the 50% (1/2) annual exceedance probability (AEP) flood event. The corresponding sediment load for this event is 12.3 tons of total sediment, which includes 2.42 tons of clay (20%), 5.69 tons of silt (46%), 3.68 tons of sand (30%), and 0.33 tons of gravel (2.7%).

The original rate of discharge (flow passing through the open ports of the riser structure) is about 215 ft^3/s. This was based on computed outputs in the hydraulic model simulation. When the lower 6 gates are closed by a theoretical stoplog panel, the simulated outflow is 95.7 ft^3/s. The wetted surface area during this type of event is approximately 235,300 ft^2.

Trap Efficiency:

Table 3-18: Sediment Loads and Trap Efficiency for 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

Cost: The ROM cost estimate to construct stoplog panels as a retrofit to the existing riser structure at Honokōwai Basin is $1,839,118. A breakdown of this estimate includes the follow:

Table 3-19: ROM Cost Estimate to Modify the Honokōwai Riser Structure

Task	Cost
Mobilization/Demobilization/Preparation	$188k
Deck	$1.2M
Excavation	$55k
Stop Log System	$427k
Total:	$1.8M

This activity would require personnel to operate (open and close) the stoplogs feature occasionally and very little maintenance (e.g. applying grease to the moving parts, occasionally clearing debris). The annual O&M costs are likely very low (<$5k).

3.5 Wahikuli

In Wahikuli, there are three potential sites for implementing the micro basin measure (Section 2.3.2). They can be implemented either individually or together.

3.5.1 Upper Wahikuli Micro Basins

The Coral Reef Alliance previously identified a site along Hahakea Stream, near the location of the Honokohau diversion pipeline crossing, that had the space available for various measures to be considered for implementation. The property owner is the State of Hawai‘i. This site has ample space available and is reasonably accessible by agricultural roads and existing pathways. The site has some woody vegetation in the overbank areas (Photo 3-4) and the riverbed is naturally armored with large cobbles and boulders (Photo 3-5). This may make clearing the site for earthwork challenging. It should also be noted that this measure does not address sediment contributed by Hahakea Stream downstream from the site, or the north fork of Wahikuli Stream, but can still be part of a comprehensive plan to reduce sediment contributed by the Wahikuli watershed overall.



Photo taken on 2017 April 7 by USACE

Photo 3-4: Dry grass and woody vegetation in the overbank, Hahakea Gulch



Photo taken on 2017 April 7 by USACE

Photo 3-5: Large boulders in the riverbed of Hahakea Stream

The corresponding HMS element for this site is subbasin 1B. The estimated peak flow for various frequency events is provided in Table 3-20. These represent flows entering the site upstream.

Table 3-20: Peak Flow Estimates Entering this Site

Sub-basin ID	Peak flow (ft^3/s)							
	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500
1B	855	1,530	2,100	3,050	3,860	4,680	5,620	7,060

The design flow for this site is 855 ft^3/s, which represents the 50% (1/2) annual exceedance probability (AEP) flood event. The corresponding sediment load for this event is 3.82 tons of total sediment, which includes 0.65 tons of clay (17%), 1.66 tons of silt 43%), 1.33 tons of sand (3%), and 0.17 tons of gravel (4%). The decadal (10% AEP) event has a peak flow of 2,100 ft3/s and total sediment load of 45.7 tons.

Proposed Design: The proposed measure for this site is to divert moderate to low flows through an offset micro basin to facilitate settlement of fine particles before returning flow to the main channel. By spreading the flow across a wide area, the depth is reduced significantly and sediments will only have to travel a short vertical distance before settling to the bottom.

In-stream micro basins like what was proposed for Pāpua Gulch (Section 3.1.2) were initially considered, however, they would not be very effective for this site and likely to be washed out frequently.

Diversion Weir

A short (4-foot-high), diversion weir embankment will be constructed across Hahakea Stream about 80 ft downstream of the existing road crossing and at about a 45° angle (Table 3-21). This purpose of this rock weir is to divert moderate to low flows into the adjacent micro basin. It can be constructed of rock and fill material sourced on site. It should be able to withstand moderate to low flow events (at least up to the 10-year flow event), but intentionally be washed out during higher flow events (which is why it is not armored with grout or concrete). It is better for the rock embankment to be washed out than to divert high flows into the micro basin and causing extensive damages there.

Table 3-21: Dimensions for Diversion Weir

Existing Site Characteristics	
Channel Top Width	30 ft
Channel Depth	8 ft
Channel Slope	6%
Design Features	
Weir Length	50 ft
Weir Height	4 ft
Weir Bottom Width	13 ft

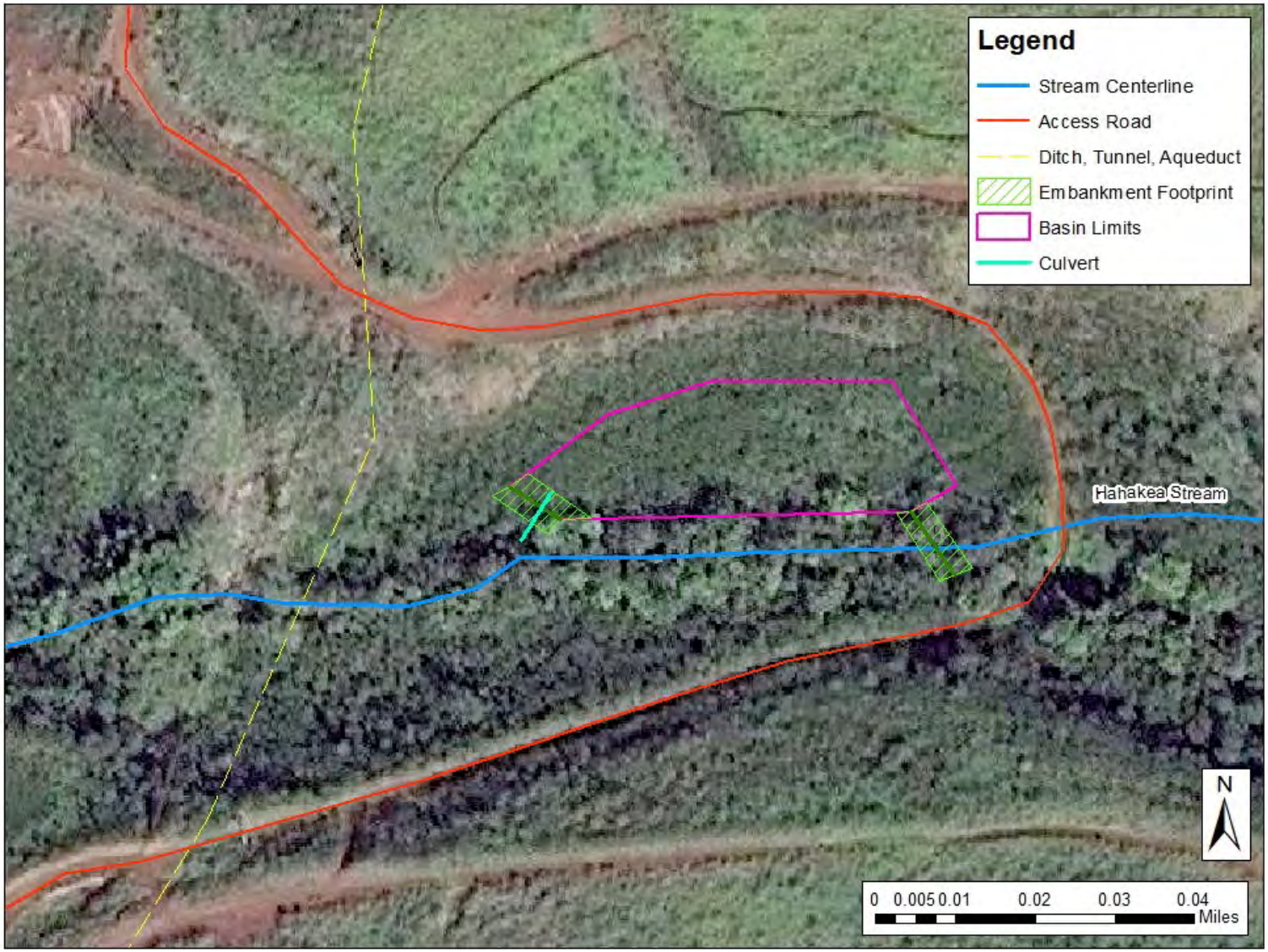


Figure 3-12: Site Map for Proposed Micro Basin at Upper Wahikuli

Micro Basin

The proposed micro basin is located on the right bank of Hahakea Stream. The footprint is approximately 20,000 ft^2. The recommended depth is 3 feet. Grassy vegetation in the basin will aid in slowing down flows, but woody vegetation would make it difficult to remove the captured sediment. The shape of the micro basin was determined based on the land available. Additional information is provided in Table 3-22.

Table 3-22: Dimensions for Micro Basin

Existing Site Characteristics	
Floodplain Slope	4%
Design Features	
Basin Length	400 ft
Basin Width	100 ft
Basin Slope	4%
Basin Depth	3 ft
Bank Slopes	2H:1V

Outflow Structure

A second rock weir embankment is proposed at the downstream end of the micro basin to restrict the rate of flow leaving to 75 ft^3/s. The height of the embankment is flush with the surrounding floodplain (about 3 ft). A 32-inch culvert should also be installed at the basin invert and sloped to return flows to the main channel (2% slope minimum, 45° angle). A sluice gate could also be installed on the outflow structure to retain water within the basin for a longer period. However, it was not included or recommended given the remote nature of the site.

Trap Efficiency: The trap efficiency from this measure is summarized in Table 3-23 and Table 3-24. This measure is 43% effective at reducing silt and 0.06% at reducing clay along Hahakea Stream for the design flow (50% AEP) event. Retaining water (such as including a sluice gate on the outflow structure) or flocculation would improve these numbers significantly.

Table 3-23: Sediment Load Reductions and Trap Efficiency for Hahakea Gulch Micro Basins, 50% AEP "Design" Event

Condition	Sediment (tons)				
	Total	Clay	Silt	Sand	Gravel
Baseline	3.82	0.65	1.66	1.33	0.17
Micro Basin	0.75	0.65	0.95	0	0
Condition	**Trap Efficiency, %**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Micro Basin	80	0.06	43	100	100

Table 3-24: Sediment Load Reductions and Trap Efficiency for Hahakea Gulch Micro Basins, 10% AEP "Decadal" Event

Condition	Sediment (tons)				
	Total	Clay	Silt	Sand	Gravel
Baseline	45.7	7.79	19.9	16.0	2.01
Micro Basin	8.94	7.79	11.4	0	0
Condition	**Trap Efficiency, %**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Micro Basin	80	0.06	43	100	100

Operation and Maintenance: The diversion weir is likely to get washed out during higher flow events and will need to be reconstructed periodically (about once a year). Woody vegetation should be removed from the micro basin, as needed, to preserve accessibility for maintenance vehicles. Otherwise, deposited sediments would need to be removed manually.

Cost: The ROM cost estimate to construct 3' deep diversion micro basins in the dry, woody vegetated overbank is $1,045,806. A breakdown of this estimate includes the follow:

Table 3-25: ROM Cost Estimate for Upper Wahikuli Micro Basin

Task	Cost
Mobilization/Demobilization/Preparation	$295k
Clear and Grub	$145k
Excavation	$157k
Boulder Weir	$12k
Disposal of Excess Excavated Material[13,14]	$345k
Install 32" HDPE Culvert	$41k
Care / Diversion of Water	$52k
Total:	$1M

The annual operation and maintenance costs on this remote measure could potentially be high (>$25k / year). Vegetation growth in the basin and banks post-construction is not a major concern – only if woody vegetation starts to grow in or near the constructed rock weirs (woody vegetation can potentially dislodge the stones). Small amounts of debris are permitted to build up in front of the rock weir embankment through natural processes. This can be removed with the accumulated sediment on an annual basis. Fees associated with the disposal of sediment and debris off-site will likely be the highest O&M cost associated with this feature.

[13] Assumes soil disposal at Central Maui Landfill for a fee. Cut trees also to be disposed of at scalehouse of Central Maui Landfill for a fee.
[14] Excavations assume 85% boulders and 15% soil based; contingency included (as design) for uncertainty in cross section, weir design.

3.5.2 Lower Wahikuli Micro Basins

In lower Wahikuli Stream, just upstream of Honoapiilani Highway (Hwy) and adjacent to the Kā'anapali Golf Course, there is a small site (approximately 4 acres) available for a potential measure to be implemented. The current property owner of this site is HHR Maui Golf LLC, who also owns the Kā'anapali Golf Course. The recommended measure for this site is based on earlier proposals by the Coral Reef Alliance for offset micro basins that could also be used for groundwater recharge, habitat, and recreation.

Existing Site Characteristics: The corresponding HMS element for this site is Junction-1. The estimated peak flow for various frequency events is provided in Table 3-20. These represent flows entering the site upstream.

Table 3-26: Peak Flow Estimates Entering this Site

Sub-basin ID	Peak flow (ft^3/s)							
	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500
Junction-1	1,270	2,330	3,220	4,750	6,080	7,460	9,010	11,400

The design flow for this site is 1,270 ft^3/s, which represents the 50% (1/2) annual exceedance probability (AEP) flood event. The corresponding sediment load for this event is 11.3 tons of total sediment, which includes 1.93 tons of clay (17%), 4.89 tons of silt (43%), 3.98 tons of sand (35%), and 0.36 tons of gravel (3.2%).



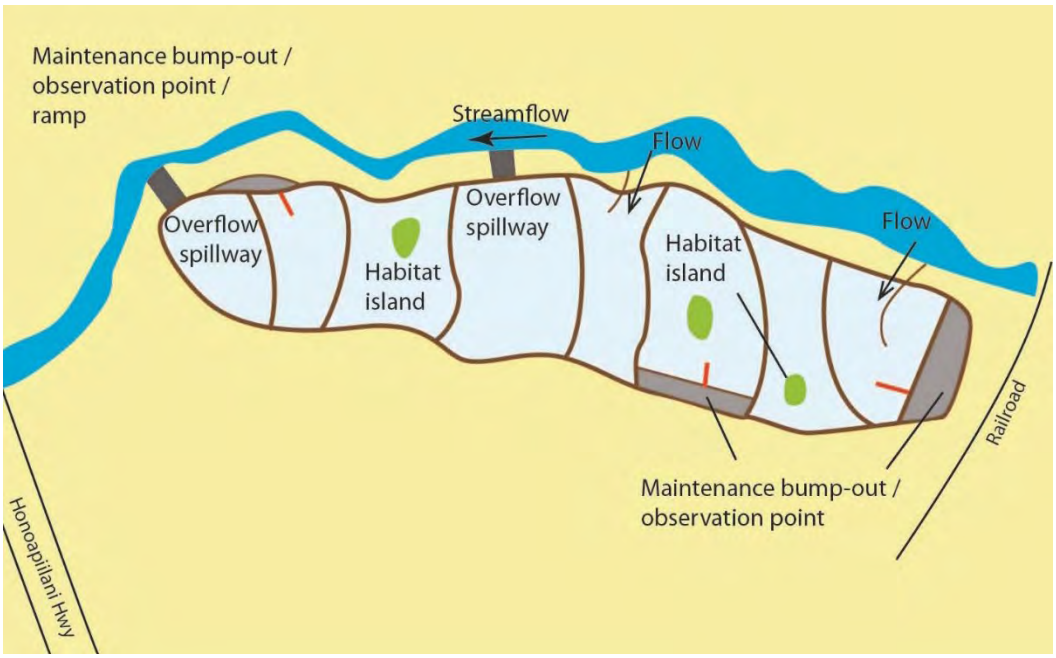
Figure 3-13: Approximate Location of Site



Photo taken on 2018 November 14 by USACE

Photo 3-6: Typical Stream Conditions, Lower Wahikuli Stream

Proposed Design: The concept sketch and rendering for this measure, originally included in the 2017 technical solutions report prepared by Christy Chung, are included as Figure 3-14 and Figure 3-15. The proposed design is series of small detention basins that cover an area approximately 820 feet long and 160 feet wide on the south overbank of Wahikuli Stream.



Source: West Maui R2R, Coral Reef Alliance, and U.C. Berkeley (2017)

Figure 3-14: Concept Sketch for Lower Wahikuli Micro Basins



Source: West Maui R2R, Coral Reef Alliance, and U.C. Berkeley (2017)

Figure 3-15: Bird's Eye View Rendering of Lower Wahikuli Micro Basins

Trap Efficiency: The trap efficiency of the proposed measure is 0.02% for clay, 14% for silt, and essentially all sand and gravel ("100%"). A summary is provided in Table 3-27.

Table 3-27: Sediment Load Reductions and Trap Efficiency for the Lower Wahikuli Gulch Micro Basins

Condition	Sediment (tons)				
	Total	Clay	Silt	Sand	Gravel
Existing	11.3	1.93	4.89	3.98	0.36
Proposed	6.44	1.93	4.21	0	0
Condition	**Trap Efficiency, %**				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Proposed	43	0.02	14	100	100

Cost: The ROM cost estimate to construct 8 micro basins in lower Wahikuli is $3,566,388. A breakdown of this estimate includes the follow:

Table 3-28: ROM Cost Estimate for Middle Wahikuli Micro Basin

Task	Cost
Mobilization/Demobilization/Preparation	$355k
Clear and Grub	$163k
Excavation	$408k
Boulder Weir	$2.3M
Disposal of Excess Excavated Material[15,16]	$104k
Care / Diversion of Water	$213k
Total:	$3.6M

The annual operation and maintenance costs on this complex measure could potentially be high (>$25k / year).

[15] Assumes soil disposal at Central Maui Landfill for a fee. Cut trees also to be disposed of at scalehouse of Central Maui Landfill for a fee.
[16] Excavations assume 85% boulders and 15% soil based; contingency included (as design) for uncertainty in cross section, weir design.

3.5.3 Middle Wahikuli Micro Basins

The proposed design for Lower Wahikuli can also be implemented upstream at a site located above Old Stuart Road. The flow, load, and trap efficiency would essentially be the same (14% trap efficiency for silt). If both sites implemented this measure (a 180-ft long, 160-ft wide area of micro basins), the trap efficiency would be doubled (28% trap efficiency for silt).



Figure 3-16: Approximate Location of Alternate Site for Wahikuli Stream Micro Basin

Cost: The ROM cost estimate to construct 1 micro basins in middle Wahikuli is $445,799 – 1/8 the ROM cost estimate of the lower Wahikuli micro basins corresponding with the reduced size (1/8). The annual operation and maintenance costs on this measure would be moderate ($5k – $25k / year).

4 Climate Risk Assessment

Engineering Construction Bulletin (ECB) 2018-14, *Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Work Studies, Designs and Projects* requires the evaluation of the risk climate change poses to the project features. A qualitative analysis on climate and hydrology was conducted in accordance with ECB 2018-14 and introduced in the Hydrology and Hydraulics Appendix, Section 7. Regionally and within the study area, the following climate change indicators are relevant to this project:

- Rising surface air temperatures
- Rising sea surface temperatures
- Winds changing
- More frequent El Niño-Southern Oscillation occurrences
- Less frequent, but more intense rainfall;
- More frequent and more intense tropical cyclones;
- Declining base flow in streams;
- Ocean acidification
- Rising sea levels

Corresponding regional impacts from these climate change indicators that are relevant to the study and proposed alternatives include:

- Less frequent riverine sediment contributions to the nearshore environment, but with larger yields
- Greater sediment load contributions from floodplains
- Shoreline erosion
- Coral reef bleaching and loss

In following Engineer Regulation 1100-2-8162, *Incorporating Sea Level Change in Civil Works Programs* and ETL 1100-2-1, *Procedures to Evaluate Sea Level Change: Impacts, Responses, and Adaptation*, three scenarios of sea level change were projected, as presented previously in Appendix B, Section 7. The proposed alternative plans and designs were evaluated against SLC to determine their sensitivity to these projections.

All sited measures, as presented in Section 3, were also evaluated against other climate change indicators, as presented in Table 4-1. Rising sea levels were not included as a trigger for measures that were well beyond the shoreline and were very unlikely to be impacted by any sea level changes. All of the measures are at risk of becoming less effective in trapping sediment as climate change is likely to increase the amount of sediment entering the river systems in the future. To mitigate these effects, the nonfederal sponsor may choose a more conservative measure with a greater trap efficiency.

Table 4-1: Climate Change Risk

Feature or Measure	Trigger	Hazard	Harm	Qualitative Likelihood
All measures	Rising surface air temperatures	Increased evapotranspiration; increased wildfire frequency; increases in invasive species; more abandoned agricultural land	Land surface is more susceptible to erosion during storm events; More erosion results in additional sediment load; the proposed measure is less effective	Likely
All measures	Decreasing annual average precipitation	Increased evapotranspiration; increased wildfire frequency; increases in invasive species; more abandoned agricultural land	Declining groundwater and surface water supplies will likely result in decreased maintenance of current agricultural land and higher sediment loads; land surface is more susceptible to erosion during storm events; more erosion results in additional sediment load; the proposed measure is less effective	Possible
Honolua Loʻi; Honokōwai Loʻi	Decreasing annual average precipitation	Declining baseflow in streams	Loʻi requires nearly constant streamflow to support the cultivation of taro; the proposed measure is less effective	Likely
All measures	Increasing frequency of heavy rainfall events / tropical cyclones	Increased stream bank erosion; increased overland flooding	Increased erosion of in-stream fill terraces; the proposed measure is less effective; Increased possibility of the constructed measure being washed out (destroyed); the proposed measure is less effective	Possible
Papua Gulch Micro Basins; Lower Wahikuli Micro Basins	Rising sea levels	Coastal flooding; shoreline erosion; increased frequency of wave run up events	Measures sited along the coast are at a higher risk of failure and inundation.	Possible

5 Conclusion

The management measures considered to be practical were explored in greater detail, before being sited and further evaluated. These measures include use of loʻi terraces, construction of new micro basins, and modifying existing detention basins. The trap efficiency of each sited measure is presented in Table 5-1. The estimated amount of sediment removed from the riverine system is presented in Table 5-2. The sited measures that had a meaningful impact, based on engineering judgment, were highlighted in these tables.

Table 5-1: Trap Efficiency of Sited Measures, 50% AEP Event

Watershed	Measure	Trap Efficiency (%)				
		Total	Clay	Silt	Sand	Gravel
Honolua	Loʻi	0.12	0.06	0.13	0.13	0.13
Honolua	10 Micro Basins	83	0.15	100	100	100
Kaʻōpala	Outlet Modification[17]	-5	22	-22	100	100
Kaʻōpala	Rock Weirs	0	0.01	10	100	100
Kahana	Excavation	13	0.01	32	--	--
Honokōwai	Loʻi	0.08	0.04	0.09	0.09	0.09
Honokōwai	Outlet Modification	3	1	8	--	--
Wahikuli	Upper Micro Basin	80	0.06	43	100	100
Wahikuli	Middle Micro Basin					
Wahikuli	Lower Micro Basin	43	0.02	14	100	100

[17] Earlier activation of the spillway as a result of the proposed modification results in increased silt particles being transported downstream. Sand and gravel are still completely captured by the basin during the design flow event.

Table 5-2: Sediment Load Reduction by Sited Measures, 50% AEP Event

Watershed	Measure	Sediment Removed (metric tons)				
		Total	Clay	Silt	Sand	Gravel
Honolua	Loʻi	0.00	0.00	0.02	0.01	0.00
Honolua	10 Micro Basins	9.34	0.00	4.44	3.06	0.76
Kaʻōpala	Outlet Modification	-3.21	2.23	-4.82	--	--
Kaʻōpala	Rock Weirs	0.01	0.01	--	--	--
Kahana	Excavation	20.6	0.20	20.4	--	--
Honokōwai	Loʻi	0.01	0.00	0.01	0.00	0.00
Honokōwai	Outlet Modification	0.43	0.12	0.39	--	--
Wahikuli	Upper Micro Basin	3.07	0	0.71	1.33	0.17
Wahikuli	Middle Micro Basin					
Wahikuli	Lower Micro Basin	4.86	0	0.68	3.98	0.36

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Appendix D

Terrestrial Sediment Dynamics in the Nearshore Environment

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1 Introduction

This appendix includes information on how terrestrial sediment from the West Maui watersheds is dispersed into the marine environment and the associated residence time over nearshore coral reefs. Terrestrial sediment data was calculated by the U.S. Army Corps of Engineers (USACE) for existing site conditions and two potential watershed restoration scenarios, as described in Section 2. This data was provided to the U.S. Geological Survey (USGS), who partnered with Deltares to set up a physics-based, hydrodynamic-sediment transport coupled numerical model. A summary of the modeling results is provided in Section 3.

1.1 Sediment Impacts to Coral Reefs

From a 2011 publication, *Impacts of Sediment on Coral Reefs*, there are essentially three ways in which sediments stress corals: 1) decreasing the available light and thereby also reducing the amount of energy supplied by the zooxanthellae to the coral host; 2) draining their metabolic system as the corals try to rid themselves of the sediment by ciliary action, tentacle waving, or mucus sheet secretion; and 3) increasing bacterial activity and the virulence of disease (Risk & Edinger, pp. 578 - 579). Different sediments exert greatly contrasting levels of stress on the corals, depending on the grain size, organic content, and geochemistry. Clay- and silt-sized sediments have a greater negative impact to corals as they settle more slowly and are more susceptible to resuspension thereby reducing light transmission for a longer period (Storlazzi, Norris, & Rosenberger, 2015). Tissue damage under a layer of sediment increases with decreasing grain size (Risk & Edinger, 2011, p. 579). Additionally, finer-grained sediments can be more difficult for coral to remove. Fine-grained sediments, such as clays and silts, should be targeted for removal for the greatest impact to improving coral health.

1.2 Scope of Work

The agreement between USACE and USGS was for USGS (in partnership with Deltares) to model terrestrial sediment dispersal from five point-sources along the West Maui shoreline for three scenarios. After consulting with the West Maui Watershed and Coastal Management Coordinator, USACE determined the five point-sources should be representative of the sediment output from the following watersheds: Wahikuli,

Honokōwai, Kahana, Ka‘ōpala, and Honolua. These five watersheds were selected based on their ability to provide coverage across the entire study area (from Wahikuli to Honolua), their estimated annual sediment load (Kahana has the greatest annual sediment load at 285 metric tons per year), and the perceived opportunity for implementation of a proposed management measure. The three scenarios would represent sediment loads expected during a 50% annual exceedance probability flood event for existing site conditions and two potential watershed restoration scenarios (USGS, 2023).

2 Terrestrial Sediment Data

At the time when data needed to be provided to USGS (September 2020), the methodology for estimating flow and sediment load contributions from each watershed was different from what is presented in the Hydrology and Hydraulics Appendix B. The original methodology relied upon the outputs from two-dimensional, unsteady flow hydraulic models created for each watershed and spreadsheet calculations based on the excess shear equation. It assumed that the total sediment load during a 50% annual exceedance probability (AEP) event would be approximately equal to 22% of the total annual load, based on the assumption that "plume-triggering events" occur approximately 4 to 5 times a year.

Since that time, the methodology has been updated following the release of the Hydrologic Engineering Center's Hydrologic Modeling Software (HEC-HMS), version 4.9. Prior to 2021, sediment transport features were not included in the publicly available HMS software. The current methodology, as described in the Hydrology and Hydraulics Appendix B, relies upon the rainfall-runoff model to distribute the total annual sediment load over a one-year continuous flow simulation. The increased accuracy in the HEC-HMS methodology improved our understanding of the flow-load relationship to yield more accurate total sediment load and particle size distribution. A comparison of the original flow and sediment load estimates, as provided to USGS in September 2020, and the current estimates is presented in Table 2-1.

Table 2-1: Original and Current Estimates of Peak Flow and Sediment Load During the 50% AEP for Various Watersheds in West Maui

Wahikuli	Original	Current
Peak Streamflow (ft^3/s)	1,270	1,270
Sediment – Total (tons)	9.33	11.3
Sediment – Clay (tons)	0.69	1.95
Sediment – Silt (tons)	4.29	4.97
Sediment – Sand (tons)	4.02	4.01
Sediment – Gravel (tons)	0.33	0.39

Honokōwai	Original	Current
Peak Streamflow (ft^3/s)	925	646
Sediment – Total (tons)	13.80	6.87
Sediment – Clay (tons)	1.24	5.00
Sediment – Silt (tons)	7.18	7.17
Sediment – Sand (tons)	4.96	0.00
Sediment – Gravel (tons)	0.42	0.00
Kahana	**Original**	**Current**
Peak Streamflow (ft^3/s)	496	496.3
Sediment – Total (tons)	63.33	44.42
Sediment – Clay (tons)	4.20	16.32
Sediment – Silt (tons)	26.59	5.33
Sediment – Sand (tons)	32.34	0.00
Sediment – Gravel (tons)	0.21	0.00
Ka‘ōpala	**Original**	**Current**
Peak Streamflow (ft^3/s)	182	182
Sediment – Total (tons)	13.78	12.02
Sediment – Clay (tons)	0.91	4.41
Sediment – Silt (tons)	5.78	1.44
Sediment – Sand (tons)	7.03	0.00
Sediment – Gravel (tons)	0.05	0.00
Honolua	**Original**	**Current**
Peak Streamflow (ft^3/s)	336	227
Sediment – Total (tons)	20.20	30.20
Sediment – Clay (tons)	1.44	4.92
Sediment – Silt (tons)	8.64	12.1
Sediment – Sand (tons)	8.73	11.1
Sediment – Gravel (tons)	1.40	2.09

2.1 Watershed Restoration Scenarios

In addition to simulating the existing conditions during the 50% AEP flood event, hereby referred to as “Alternative 1”, two additional scenarios could be simulated. It was decided that Alternative 2 would represent future conditions with smaller management measures implemented across the study area and Alternative 3 would represent future conditions with both small and large management measures implemented.

2.1.1 **Alternative 2**

The smaller management measures being proposed under Alternative 2 were lo’i restoration in Honolua and Honokōwai; and micro basins in Ka‘ōpala and Wahikuli. There were no small measures proposed for Kahana at the time. The percent that sediment was reduced within each watershed is presented in Table 2-2. As the marine sediment transport model would only include fine-grained sediment particles, reduced sediment loads for the coarser particles (sand and gravel) were not calculated during this phase of the study. These were also not the primary sediment types affecting coral reef health, as mentioned earlier in Section 1.1.

Table 2-2: Percent Sediment Reduction Under Alternative 2

	Sediment Reduction, %				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Wahikuli	4%	8%	8%	0%	0%
Honokōwai	0.2%	0.2%	0.4%	0%	0%
Kahana	0%	0%	0%	0%	0%
Ka‘ōpala	41%	85%	85%	0%	0%
Honolua	0%	1%	1%	0%	0%

2.1.2 **Alternative 3**

In addition to the smaller measures proposed under Alternative 2 (Section 2.1.1), Alternative 3 includes larger management measures – specifically, improvements made to the existing Honokōwai, Kahana, and Ka‘ōpala detention basins. The percent that sediment was reduced within each watershed under this alternative is presented in Table 2-3. The corresponding sediment loads are included in Table 2-4.

Table 2-3: Percent Sediment Reduction Under Alternative 3

	Sediment Reduction, %				
	Total	**Clay**	**Silt**	**Sand**	**Gravel**
Wahikuli	4%	8%	8%	0%	0%
Honokōwai	18%	30%	30%	0%	0%
Kahana	32%	65%	65%	0%	0%
Ka‘ōpala	42%	86%	86%	0%	0%
Honolua	0%	1%	1%	0%	0%

Table 2-4: Peak Flow and Sediment Load Estimates for Existing and Watershed Restoration Scenarios During the 50% AEP for Various Watersheds in West Maui

Wahikuli	Alternative 1	Alternative 2	Alternative 3
Peak Streamflow (ft^3/s)	1,270	1,270	1,270
Sediment – Total (tons)	9.33	8.93	8.93
Sediment – Clay (tons)	0.69	0.63	0.63
Sediment – Silt (tons)	4.29	3.95	3.95
Sediment – Sand (tons)	4.02	4.02	4.02
Sediment – Gravel (tons)	0.33	0.33	0.33
Honokōwai	**Alternative 1**	**Alternative 2**	**Alternative 3**
Peak Streamflow (ft^3/s)	926	926	1,038
Sediment – Total (tons)	13.8	13.8	11.3
Sediment – Clay (tons)	1.24	1.24	0.87
Sediment – Silt (tons)	7.18	7.15	5.00
Sediment – Sand (tons)	4.96	4.96	4.96
Sediment – Gravel (tons)	0.42	0.42	0.42
Kahana	**Alternative 1**	**Alternative 2**	**Alternative 3**
Peak Streamflow (ft^3/s)	496	496	496
Sediment – Total (tons)	63.33	63.33	43.33
Sediment – Clay (tons)	4.20	4.20	1.47
Sediment – Silt (tons)	26.59	26.59	9.31

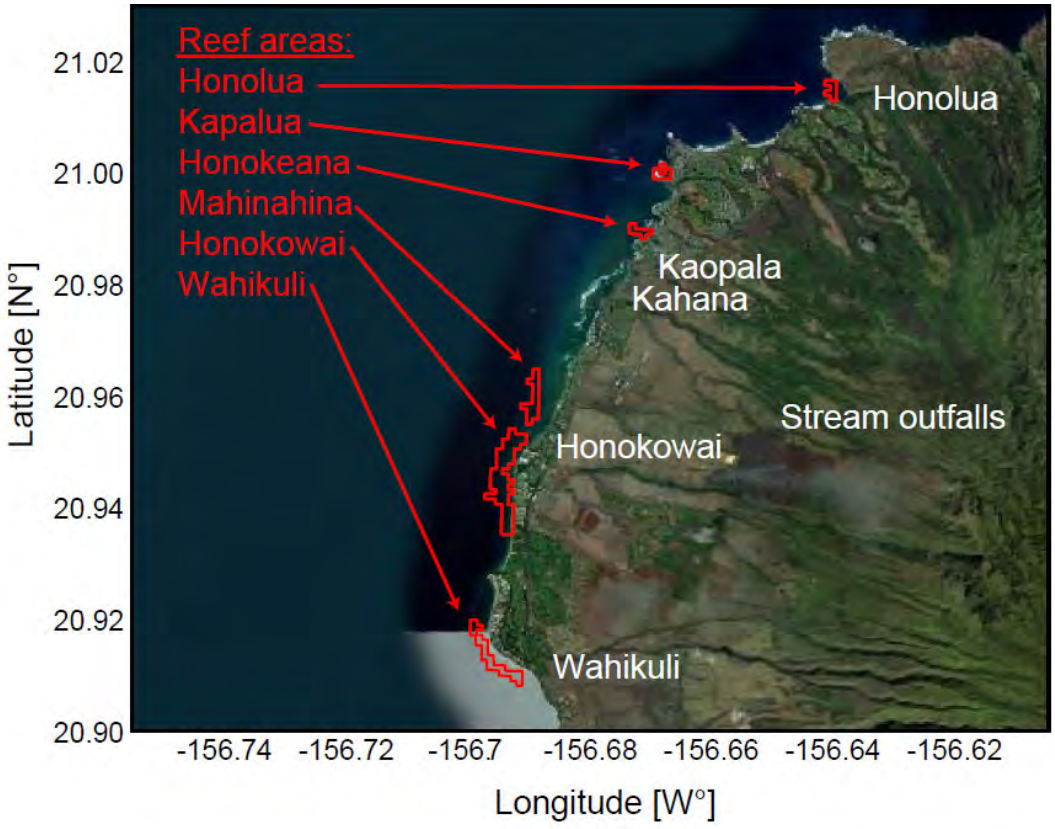
Sediment – Sand (tons)	32.34	32.34	32.34
Sediment – Gravel (tons)	0.21	0.21	0.21
Ka‘ōpala	**Alternative 1**	**Alternative 2**	**Alternative 3**
Peak Streamflow (ft^3/s)	182	182	182
Sediment – Total (tons)	13.78	8.09	8.0348
Sediment – Clay (tons)	0.91	0.14	0.13
Sediment – Silt (tons)	5.78	0.87	0.82
Sediment – Sand (tons)	7.03	7.03	7.03
Sediment – Gravel (tons)	0.05	0.05	0.05
Honolua	**Alternative 1**	**Alternative 2**	**Alternative 3**
Peak Streamflow (ft^3/s)	336	336	336
Sediment – Total (tons)	20.20	20.14	20.14
Sediment – Clay (tons)	1.44	1.43	1.43
Sediment – Silt (tons)	8.64	8.58	8.58
Sediment – Sand (tons)	8.73	8.73	8.73
Sediment – Gravel (tons)	1.40	1.40	1.40

3 Marine Sediment Transport Modeling

This section provides a summary on the numerical modeling results completed by USGS and Deltares to evaluate the varying impacts that individual and combined stream plumes have on the different reef areas along the West Maui coastline. Additional details, such as how the model was set up and calibrated, can be found in their official publication, *Observations of Coastal Circulation, Waves and Sediment Transport along West Maui, Hawaii (November 2017–March 2018) and Modeling Effects of Potential Watershed Restoration on Reducing Sediment Loads to Adjacent Coral Reefs* (2022).

3.1 Study Area

The sediment discharge from five West Maui streams was modeled: Honolua, Kaʻōpala, Kahana, Honokōwai, and Wahikuli, along with six primary nearshore coral reef areas: Honolua, Kapalua, Honokeana, Māhinahina, Honokōwai, and Wahikuli. These stream outfalls and reef areas are identified in **Error! Reference source not found.**



Source: Deltares, 2020

Figure 3-1: West Maui Stream Outfalls and Reef Areas

3.2 Terrestrial Sediment Impacts

This study investigated two major impacts to corals from terrestrial-derived sediment: 1) sediment settling on the corals, and 2) the light attenuation from increased turbidity. The impact of terrestrial sediment settling on the corals was addressed by examining the total amount (as net sediment deposited mass per unit area). A threshold was set at 10 milligrams per square meter (mg/m^2) to frame how exposed the reefs were to higher rates of sedimentation.

The impact of the light attenuation from increased turbidity was addressed by examining both the concentration of suspended sediment present in the water column (as depth-averaged concentrations per unit area) and the fraction of sunlight that reaches the seabed (as percent of surface irradiance). A threshold was also set for suspended sediment concentrations at 10 milligrams per liter per square meter ($10\ mg/L/m^2$) to frame how exposed the reefs were to higher turbidity.

3.3 Flood Scenarios

Two different flood scenarios were simulated, referred to in this study as “Flood Only” and “Flood + Waves.” Both scenarios involved 10-day model runs with the same initial conditions for the first 3 days: trade winds at 10 meters per second (m/s) out of the northeast, 0.5 meter (m) significant wave height, and 15-second (s) peak period waves direct out of the north-northeast. After the first 3 days, a 24-hour flood occurred, with the sediment load from the stream discharge entering the coastal waters. Additionally, the winds rotated 180 degrees (°). In the “Flood Only” scenario, the waves and wind speed remained unchanged (except for the 180° rotation). In the “Flood + Waves” scenario, the wave heights increased to 1.5 m over 8 hours, and the winds decreased to 5 m/s.

3.4 Watershed Scenarios

Initially three watershed scenarios were considered, representative of existing conditions (Alternative 1), future conditions with smaller management measures implemented (Alternative 2), and future conditions with larger management measures implemented (Alternative 3). However, the smaller management measures proposed under Alternative 2 (loʻi and micro basins) were found not to be very effective, except at Kaʻōpala (Table 2-2). As a result, only Alternative 1 and Alternative 3 were included in the

marine sediment transport analysis. USGS refers to Alternative 1 as the “Baseline” scenario and Alternative 3 as the “Restoration” scenario in their publication.

3.5 Results

Modeling results are presented in three temporal “snap-shots”: “Day 0” – the day of the flood, “Day 1” – one day after the flood event, and “Day 7” – one week after the flood event. The following sections describe the impact that each stream has on the nearshore reef areas during the simulated event (~50% AEP flood). Related figures from the original USGS publication on how terrestrial sediment from the five streams affect the six reef areas are included as Figure 3-2 and Figure 3-3.

3.5.1 **Honolua Stream**

For all scenarios, Honolua Stream only affected Honolua Reef. The impact was immediate, with a large amount of sediment (>0.4 g/m^2) being deposited on the reefs on the day of the flood event (Day 0). This is likely due to the proximity of the stream outfall to the reef. Despite this high amount of sediment deposited on Day 0, exposure above the deposition threshold (10 mg/m^2) was limited to just 7-9% of the time.

With regards to turbidity, there was a very high concentration of suspended sediment in the water column (>6 mg/L/m^2) on Day 0, but a much lower concentration by Day 1. Suspended sediment was above the established threshold for this study (>10 mg/L/m^2) about 20-30% of the time on Day 0 and Day 1. By Day 7, essentially all of the suspended sediment generated in the simulation had dispersed.

3.5.2 **Ka‘ōpala and Kahana Streams**

The terrestrial sediment contributed by Ka‘ōpala and Kahana Streams behaved similarly in the nearshore environment. This is likely due to the proximity of the outfalls to each other. The impact was more significant from Kahana given the larger sediment load that it discharges. The reefs affected by both streams include Honokeana, Māhinahina, and Honokōwai. However, during the “Flood + Waves” scenario, there was little to no impact to Honokeana Reef in the north, and a greater impact to the southern reefs, Māhinahina and Honokōwai.

During the “Flood Only” scenario, a small amount (<0.2 g/m^2) of sediment sourced by these two streams is deposited onto Honokeana Reef on Day 1 and Day 7. Honokeana

Reef is exposed to greater than 10 mg/m^2 of sediment approximately 3-8% of the time (small exposure). There is also a small amount of sediment that is suspended over Honokeana Reef (< 1 mg/L/m^2), with moderate exposure (12-18% of the time) when the suspended sediment concentration is above the 10 mg/m^2 threshold. During the "Flood + Waves" scenario, there is a near total reduction in the amount of sediment deposited onto and suspended over Honokeana Reef (~0 g/m^2 and ~0 mg/L/m^2).

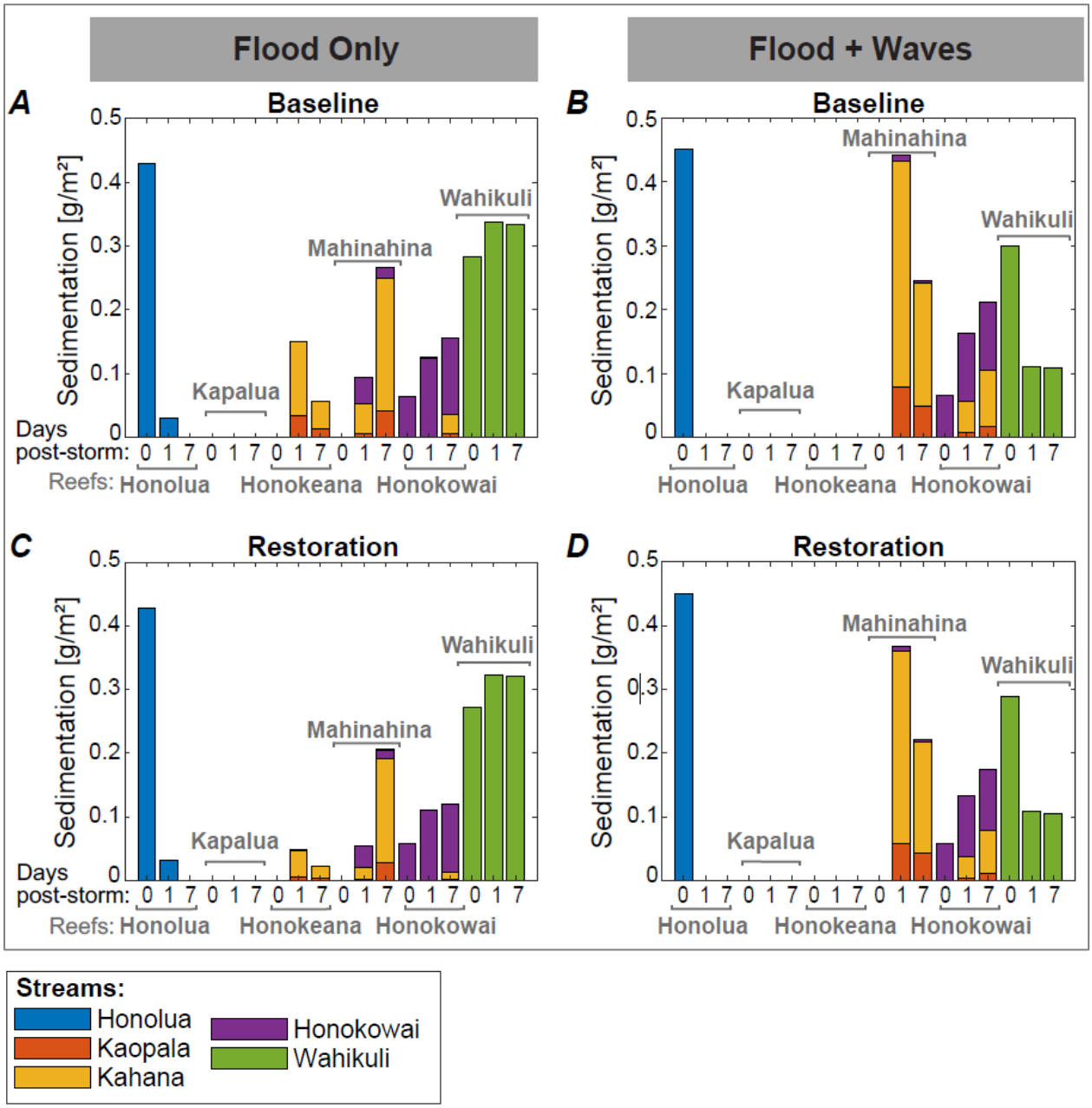
During the "Flood Only" scenario, a small amount (<0.1 g/m^2) of sediment sourced from the Ka'ōpala and Kahana Streams is deposited onto Māhinahina Reef on Day 1, and a moderate amount (<0.3 g/m^2) on Day 7. Exposure to the reefs above the threshold was limited (7% of the time). During the "Flood + Waves" scenario, a large amount (>0.4 g/m^2) of sediment is deposited on to Māhinahina Reef on Day 1, and a moderate amount (<0.3 g/m^2) on Day 7. Exposure was greater under this scenario (13-15% of the time). In both scenarios, Kahana Stream is the major contributor of terrestrial sediment being deposited onto Māhinahina Reef (~80%). The suspended sediment concentration and associated exposure over Māhinahina Reef was small in both scenarios.

There is also small impact to Honokōwai Reef by these streams, which is more noticeable during the "Flood + Waves" scenario. However, the amount of sediment deposited onto this reef is still small (<0.15 g/m^2). Exposure above threshold limits (10 mg/m^2) is limited (<7% of the time). The suspended sediment concentration (SSC) over Honokōwai Reef is also small (<1 mg/L/m^2) with limited exposure above the threshold (<2% of the time).

3.5.3 **Honokōwai Stream**

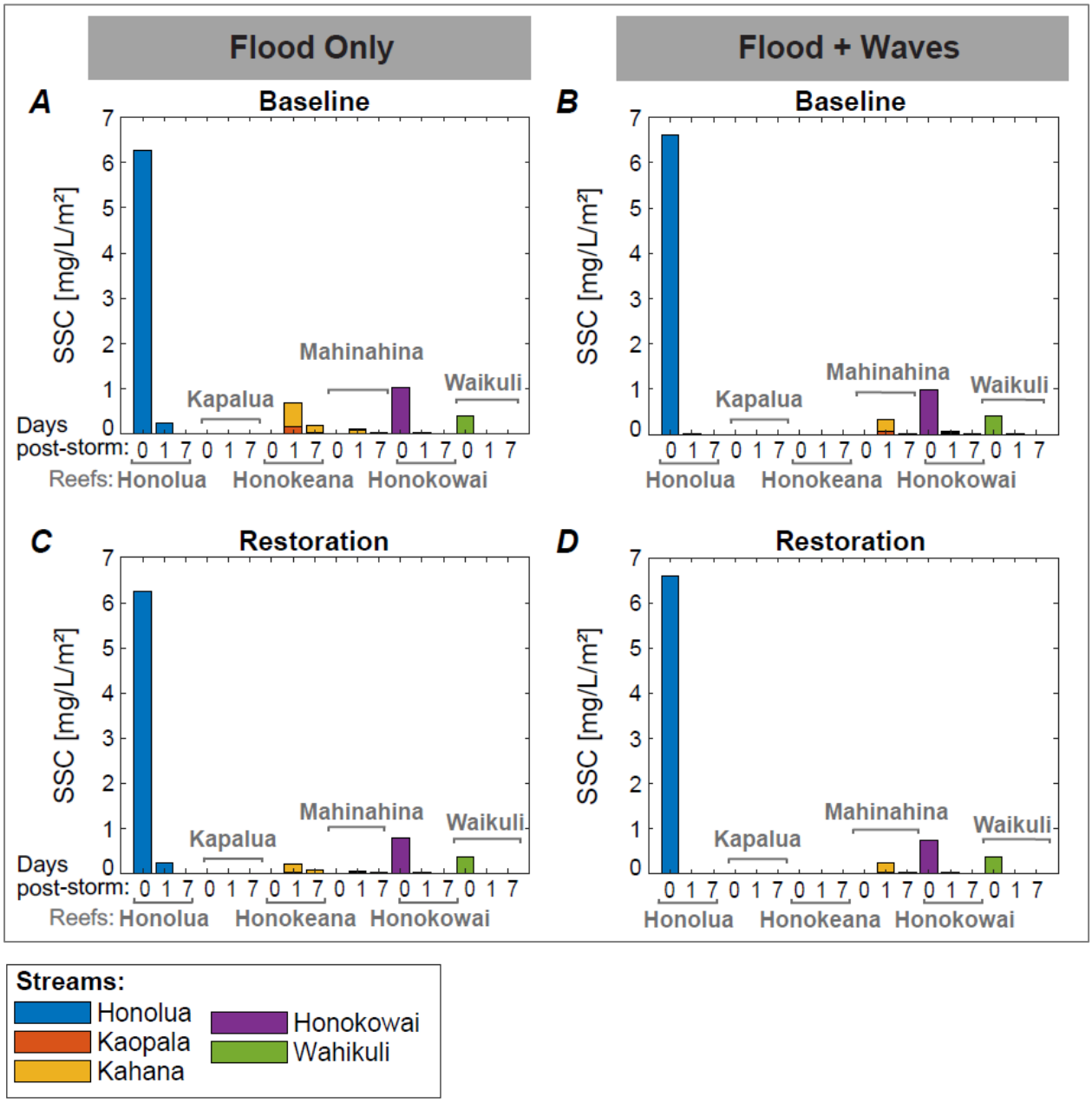
Terrestrial sediment discharged from Honokōwai Stream primarily affected Honokōwai Reef, with limited impacts to Māhinahina Reef in the north. The impact to Honokōwai Reef was immediate due to the proximity of the stream outfall to the reef area. Small amounts of sediment (<0.15 g/m^2) were deposited on Day 0, Day 1, and Day 7. Exposure was limited, with sedimentation greater than 10 mg/m^2 occurring between 1% and 7% of the time on Day 0 and Day 7, respectively. SSC over Honokōwai Reef was also limited (<1 mg/L/m^2), with very limited exposure above the threshold limit (<2% of the time).

Figure 3-2: Sedimentation Per Reef Area



Source: USGS and Deltares, 2021

Figure 3-3: Depth-Averaged Suspended Sediment Concentrations (SSC) Per Reef Area



Source: USGS and Deltares, 2021

3.5.4 **Wahikuli Stream**

For all scenarios, Wahikuli Stream only affected Wahikuli Reef. The impact was immediate, with a large amount of sediment (>0.3 g/m^2) being deposited on the corals and a small concentration of suspended sediments (<0.5 mg/L/m^2) in the water column on the day of the flood event (Day 0). This is likely due to the proximity of the stream outfall to the reef. Large amounts of sediment (>0.3 g/m^2) continued to be deposited onto Wahikuli Reef throughout the simulation (Day 1 – Day 7) but were moderately reduced during the "Flood + Waves" scenario. Exposure to sedimentation levels above 10 mg/m^2 was limited (3% on Day 1, 7% on Day 7). Exposure to suspended sediment concentrations above 10 mg/L/m^2 was minimal (<3% of the time).

3.5.5 **Restoration Effects**

The proposed measures under the restoration scenario reduced the sediment contributed by the Honolua and Wahikuli Streams by a marginal amount. This was reflective of conditions under Alternative 3, as presented earlier in Section 2.1.2. As expected, the corresponding reduced impacts to the Honolua and Wahikuli Reefs were negligible.

However, there were significant reductions to the sediment loads being discharged by Ka‘ōpala Stream (86% reduction of fine sediments) and Kahana Stream (65% reduction of fine sediments), which resulted in a large (50-70%) reduction in the amount of sediment deposited onto Honokeana Reef, and a moderate (10-20%) reduction in the amount of sediment deposited onto Māhinahina Reef. These effects were primarily driven by reducing the larger contributor of terrestrial sediment – Kahana Stream. The reefs were also exposed to much lower concentrations of suspended sediment as a result of the reduced sediment loads.

30% of the fine sediments were also removed from Honokōwai Stream under the restoration (Alternative 3) scenario. There was a moderate (20%) reduction in the amount of sediment deposited onto Honokōwai Reef and a moderate (20%) reduction in the time that the reef was exposed to sedimentation above 10 mg/m^2. With regards to suspended sediment concentrations, there was a moderate (25%) reduction in the total amount and moderate reduction (25-50%) in the time that the reef was exposed to suspended sediments above the established threshold (10 mg/L/m^2).

4 Discussion

This section frames the marine sediment transport modeling results in context with the overall goal of the West Maui Watershed Study – to contribute to the restoration, enhancement and resiliency of West Maui coral reefs and nearshore waters through the reduction of land-based pollution threats. Several alternatives are proposed under this study to reduce what is considered a major land-based pollution threat – terrestrial sediment. How terrestrial sediment impacts the nearshore reef area is critical piece in understanding how the proposed measures could improve conditions for West Maui coral reefs and in understanding which watershed or measures should be prioritized.

4.1 Commentary on the Terrestrial Sediment Data Update

The original terrestrial sediment data provided to USGS in September 2020 was used in the marine sediment transport model to determine the likely effects caused by sediment discharge from five watersheds during the 50% AEP flood event. However, current estimates (see comparison at Table 2-1) indicate the sediment load and fine sediment distribution is likely higher than originally presumed and a greater amount of sediment is deposited onto the reefs, increasing turbidity in the nearshore environment. Likewise, impacts to coral reefs are likely underestimated. It should be noted that there is natural variability in flow and load during real-world events also.

To improve confidence in the terrestrial sediment data, additional information is needed on the suspended-sediment particle-size distribution and concentration data from one or multiple reaches in the study area. The results of the marine sediment transport analysis are still valid in providing insight into the likely impacts during a smaller frequency flood event, similar to the 50% AEP flood.

4.2 Watershed Prioritization

A qualitative summary on the impacts that each stream has on the nearshore reef areas is provided in the table below. Using the baseline sediment and flow data, we can identify which streams generate the greatest sediment outputs and couple that information with the USGS data to determine which reef(s) is impacted to determine which streams impact the marine environment and to what degree. Based on this amalgamation of data, we can recommend prioritization of certain streams to address the study objective of managing land-based pollution to improve coral

reef health. As represented in Table 4-1, Kahana Stream and Honolua Stream have the greatest baseline negative impact to West Maui coral reefs during a low frequency flood event (~50% AEP) and accordingly management measures proposed in these watersheds should be prioritized for implementation. Table 4-1: Summary of Impacts to West Maui Coral Reefs by Stream

	Honolua Stream	**Ka‘ōpala Stream**	**Kahana Stream**	**Honokōwai Stream**	**Wahikuli Stream**
Affected Reefs	1	3	3	2	1
Sedimentation	Large	Small	Large	Moderate	Large
Exposure (>10 mg/m^2)	Limited	Limited	Small	Limited	Limited
Suspended Sediment Concentration	Large	Limited	Small	Small	Small
Exposure (>10 mg/L/m^2)	Moderate	Limited	Moderate	Limited	Limited
Overall Potential for Impact:	**High**	**Low**	**High**	**Medium**	**Medium**

4.3 Restoration Effects

As demonstrated by the reduced sedimentation and suspended sediment concentrations over the affected reefs during the restoration scenario, management measures do have the potential to contribute to the restoration, enhancement, and resiliency of West Maui coral reefs in a significant way.

4.4 Additional Analysis

In addition to validating the terrestrial stream data with additional information on the suspended-sediment particle-size distribution and concentration data from one or multiple reaches in the study area (recommended in Section 4.1), additional marine sediment transport simulations could provide additional information on how terrestrial sediment impacts reefs during smaller or larger flood events, or under different restoration scenarios. How sediment moves in the nearshore environment during the decadal event is still unknown. The effects on Honolua Reef and Wahikuli Reef under a more effective

restoration scenario are also unknown. Additional analysis on these scenarios is recommended for a future study.

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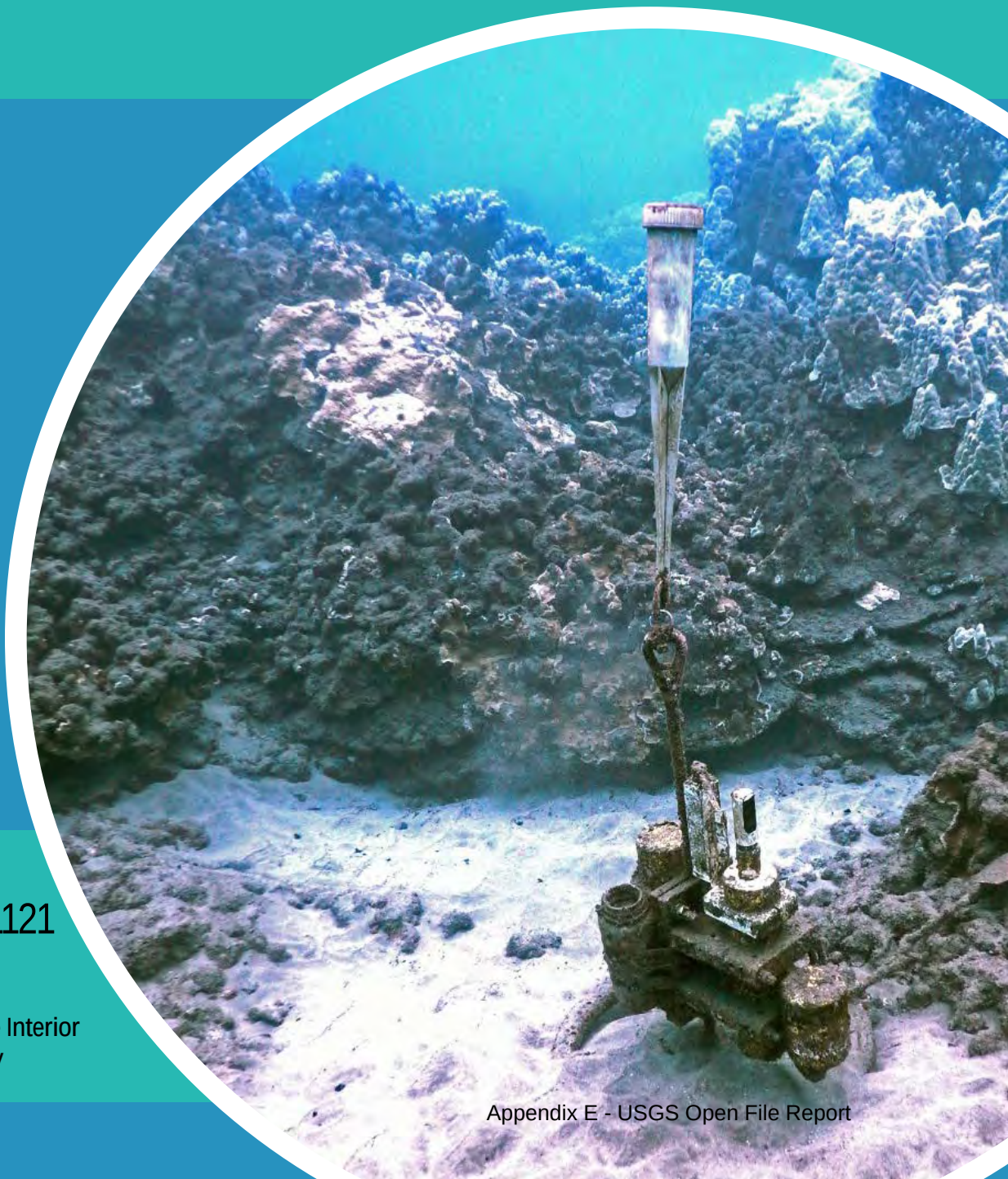
Appendix E

USGS Open File Report 2022-1121

USGS
science for a changing world

Prepared in cooperation with the USGS Coastal and Marine Hazards and Resources Program and the Deltares Impacts of Extreme Weather Strategic Research Program

Observations of Coastal Circulation, Waves, and Sediment Transport along West Maui, Hawai‘i (November 2017–March 2018), and Modeling Effects of Potential Watershed Restoration on Decreasing Sediment Loads to Adjacent Coral Reefs



Open-File Report 2022–1121

U.S. Department of the Interior
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Appendix E - USGS Open File Report

Cover: Underwater photograph in April 2018 of the oceanographic instrument package at the Wahikuli shallow site, showing the surrounding coral reef and seafloor covered with dark, volcanic sediment from the adjacent impaired watershed. U.S. Geological Survey photograph by Curt D. Storlazzi.

Observations of Coastal Circulation, Waves, and Sediment Transport along West Maui, Hawai‘i (November 2017–March 2018), and Modeling Effects of Potential Watershed Restoration on Decreasing Sediment Loads to Adjacent Coral Reefs

By Curt D. Storlazzi, Olivia M. Cheriton, Katherine M. Cronin, Luuk H. van der Heijden, Gundula Winter, Kurt J. Rosenberger, Joshua B. Logan, and Robert T. McCall

Prepared in cooperation with the USGS Coastal and Marine Hazards and Resources Program and the Deltares Impacts of Extreme Weather Strategic Research Program

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
meter per second (m/s)	3.281	foot per second (ft/s)
millimeter per second (mm/s)	0.0394	inch per second (in/s)
millimeter per hour (mm/h)	0.0394	inch per hour (in/h)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Datum

Vertical coordinate information is referenced to the World Geodetic System 1984 (WGS 84).

Horizontal coordinate information is referenced to the World Geodetic System 1984 (WGS 84) or to the Universal Transverse Mercator coordinate system, zone 4N.

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

AWAC	acoustic wave and current profiler
BSR	benthic substrate ratio
ENSO	El Niño-Southern Oscillation
MHW	mean high water
MSL	mean sea level
NOAA	National Oceanic and Atmospheric Administration
NTU	Nephelometric Turbidity Unit
NWS	National Weather Service
OBS	optical backscatter sensor
RMSE	root mean square error
R/V	research vessel
SSC	suspended-sediment concentration
SWAN	Simulating WAves Nearshore
USCRTF	U.S. Coral Reef Task Force
USGS	U.S. Geological Survey
WPI	Watershed Priority Initiative
YD	year day

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Observations of Coastal Circulation, Waves, and Sediment Transport along West Maui, Hawai‘i (November 2017–March 2018), and Modeling Effects of Potential Watershed Restoration on Decreasing Sediment Loads to Adjacent Coral Reefs

By Curt D. Storlazzi,[1] Olivia M. Cheriton,[1] Katherine M. Cronin,[2] Luuk H. van der Heijden,[2] Gundula Winter,[2] Kurt J. Rosenberger,[1] Joshua B. Logan,[1] and Robert T. McCall[2]

Abstract

Terrestrial sediment discharging from watersheds off West Maui, Hawai‘i, has been documented as a primary stressor to local coral reefs, causing coral reef health to decline. The U.S. Geological Survey acquired and analyzed physical oceanographic and sedimentologic field data off the coast of West Maui to calibrate and validate physics-based, numerical hydrodynamic and sediment transport models of the study area developed by Deltares. These models simulated terrestrial sediment transport and dispersal from West Maui watersheds into coastal waters and how terrestrial sediment affects nearby coral reefs under different oceanographic forcing and watershed restoration scenarios.

Wave energy and near-bed turbidity are positively correlated in the field observations, illustrating a process not captured by the model simulations in which sediment already deposited on the seabed is resuspended by wave action and subsequently transported by prevailing currents. In the model simulations, large waves during flood events led to a decrease in suspended-sediment concentrations. Notably, however, the model results only consider sediment entering coastal waters from five stream sources and do not simulate sediment already present on the seabed.

The model simulations project that the Honokeana and Māhinahina coral reefs would experience the greatest reduction in sediment impacts from theoretical watershed restoration. Additionally, when large waves coincide with flood events, post-storm sedimentation generally decreases in the nearshore region, but increases in the region offshore of the reefs. The measured and modeled sediment dynamics demonstrate a demarcation between the coral reefs sheltered within embayments (Honolua reef) or behind points (Wahikuli reef) and those along the relatively open coastline between Kapalua and Kā‘anapali (Kapalua, Honokeana, Māhinahina, and Honokōwai reefs). The sheltered sites are affected by terrestrial sediment from single stream mouths, where most sediment is delivered within hours of a flood (rain) event. Once this sediment enters the nearshore, it settles out and remains within the reef area for a prolonged period owing to a lack of wave or current-driven bed shear stress. Thus, the primary effect of sediment on the reefs within these sheltered areas is sedimentation. In contrast, coral reefs along the unsheltered (or “open”) section of coastline (between Kapalua and Kā‘anapali) are more exposed to waves and terrestrial sediment from multiple stream sources. At these reefs, fine-grained terrestrial sediment can rarely settle but instead remains in suspension. Thus, even long after a flood event has occurred, these sites chronically experience light attenuation from suspended sediment.

These analyses underscore the importance of understanding how coastal ocean waves and circulation can lead to different sediment dynamics and stressors for coral reefs along the same region of the West Maui coastline. These differing factors indicate that the most effective watershed restoration and mitigation strategies may vary among the different coral reefs and streams. An important next step is to determine how the science of this study can support management goals for these coral reefs: what are target reductions of sedimentation, suspended-sediment concentrations, or the resulting light attenuation? Then, using the coupled hydrodynamic-sediment model, we can examine which watershed restoration scenarios in each stream will best achieve those targets.

Introduction

Terrestrial sediment discharging from watersheds off West Maui, Hawai‘i, has been documented by Federal, State of Hawai‘i, local, and academic partners as a primary stressor to local coral reefs, causing coral reef health to decline. This area has been designated a U.S. Coral Reef Task Force (USCRTF) West Maui Watershed Partnership Initiative (WPI) priority study area in an effort to bring together research

[1]U.S. Geological Survey.

[2]Deltares.

and restoration science and management to better protect and preserve the U.S. coral reefs in the area. In order to address terrestrial sediment dispersal from watersheds and its subsequent effect on coral reefs, we must first understand how coastal ocean hydrodynamics (waves and currents) control the transport to, settling on, and removal of sediment from coral reef areas. Furthermore, by understanding such processes, it becomes possible to identify the primary watersheds affecting each coral reef, which will enable Federal, State of Hawai‘i, and local resource managers to more effectively direct watershed restoration efforts and better protect and manage their coral reef resources.

The U.S. Geological Survey (USGS) acquired and analyzed physical oceanographic and sedimentologic data in the USCRTF West Maui WPI priority study area (fig. 1). These data were used to calibrate and validate physics-based,

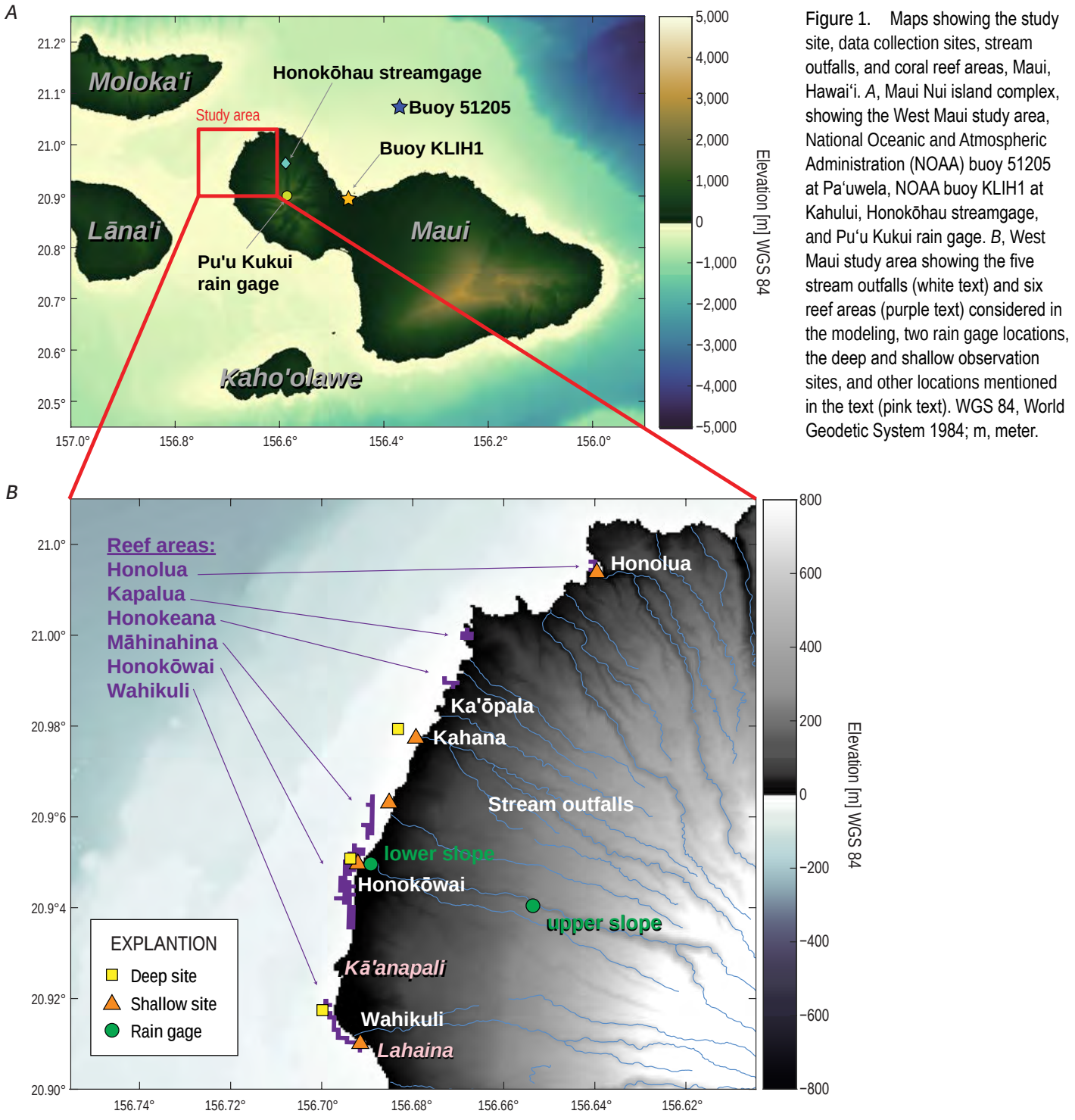


Figure 1. Maps showing the study site, data collection sites, stream outfalls, and coral reef areas, Maui, Hawai‘i. *A*, Maui Nui island complex, showing the West Maui study area, National Oceanic and Atmospheric Administration (NOAA) buoy 51205 at Pa‘uwela, NOAA buoy KLIH1 at Kahului, Honokōhau streamgage, and Pu‘u Kukui rain gage. *B*, West Maui study area showing the five stream outfalls (white text) and six reef areas (purple text) considered in the modeling, two rain gage locations, the deep and shallow observation sites, and other locations mentioned in the text (pink text). WGS 84, World Geodetic System 1984; m, meter.

numerical hydrodynamic and sediment transport models of the study area (models were developed by Deltares[3]). The oceanographic data include information on tides, waves, currents, and turbidity for a 4-month period extending from late autumn 2017 into early spring 2018. These in-situ data provide insight into the meteorologic and oceanographic controls on circulation and sediment dynamics over the area's coral reefs.

These models simulated terrestrial sediment transport and dispersal from USCRTF West Maui WPI watersheds into coastal waters, and how this terrestrial sediment affects the nearby coral reefs under different oceanographic and watershed restoration scenarios. This report presents the field observations and numerical modeling results to provide information to help guide possible watershed restoration efforts to meet the USCRTF's goals to protect and preserve U.S. coral reefs.

Project Objectives

The project goals were to (1) resolve and simulate the hydrodynamics and terrestrial sediment dynamics off the coast of the USCRTF WPI priority study area and (2) provide information on terrestrial sediment dispersal and residence times over nearshore coral reefs for present conditions as well as potential watershed restoration scenarios.

To achieve these goals, the USGS and Deltares collaborated on a two-part effort involving a field campaign and a physics-based, coupled circulation and sediment dynamics model for the West Maui region. During the 4-month field campaign, the USGS collected time series data of tides, waves, currents, and turbidity off the coast of West Maui. These data were then used to calibrate and validate the model, which simulated rain-driven flood events during different wave conditions and watershed restoration scenarios. With these model simulations, we examine how sediment that discharged from West Maui streams affects coral reefs habitats in the adjacent coastal waters, and we assess how the patterns and magnitude of these effects change under different wave conditions and watershed restoration scenarios.

Description of Study Area

Geology and Ecology

This study was conducted along the northwest coast of the island of Maui, Hawai‘i, from 20.9° N. to 21.0° N. and from 156.6° W. to 156.7° W., encompassing approximately 14.5 kilometers (km) of coastline stretching from the Wahikuli Gulch outlet (southern extent) to Honolua Bay (northern extent) (fig. 1). This coastline flanks a large basaltic shield volcano (informally known as Mauna Kahalawai) and is characterized by low basaltic sea cliffs and carbonate sand beaches (Clague and others, 1989). Historically, the land adjacent to this coastline has been used for pineapple and sugarcane cultivation, but more recently, urbanization and development in the area have increased substantially. This land-use change has led to the increased export of terrestrial sediment and land-based pollutants to nearshore waters through ephemeral stream dishcharge, surface runoff, and submarine groundwater discharge (Dailer and others, 2010; Stock and others, 2015; Prouty and others, 2017; Stock and Cerovski-Darriau, 2021). The resulting increase in turbidity and decline in nearshore ocean water quality has adversely affected the West Maui coastal marine ecosystem, with a mean decline of 25 percent of live coral coverage from 1994 to 2006, particularly in the northern part of this coastline (Hawaii Department of Aquatic Resources, 2007; Sparks and others, 2015). Multiple entities, including Federal, State, local, and academic partners, have identified terrestrial sediment as the primary stressor to coral reefs in this region. In 2011, this area was designated a USCRTF priority study area, and the WPI was established with the goal of leveraging research and conservation efforts to counteract the decline in coral reef health.

There are five primary streams in the study area (from north to south)—Honolua, Ka‘ōpala, Kahana, Honokōwai, and Wahikuli (fig. 1*B*). The lower reaches of these streams are ephemeral and can be dry for long periods of time, whereas the upper reaches have more consistent flow owing to groundwater discharge into the streams. There are six primary nearshore coral reef areas in the study area (listed from north to south)—Honolua, Kapalua, Honokeana, Māhinahina, Honokōwai, and Wahikuli reefs (fig. 1*B*). These reef areas were identified based on their benthic substrate ratio (BSR), which is a function of the relative percentage of benthic cover by calcifiers and algae, where BSR = (coral + crustose coralline algae) ÷ (macroalgae + turf algae), per Vargas-Angel and others (2017). The reefs were defined as groups of adjacent 50 × 50 meter (m) pixels with BSR > 0.5, or those with a relatively high percentage of coral and coralline algae. A more in-depth description of the ecological status of the coral reefs in the study area is provided by Vargas-Angel and others (2017).

Oceanography and Meteorology

For the Hawaiian Islands, the wet season runs from November through April, with May through October constituting the dry season, and annual air and water temperature varies little. Typically, four to five tropical cyclones occur in the Central Pacific Ocean each year between June and November, but these storms rarely affect the Hawaiian Islands directly (Murakami and others, 2013). On longer time scales, the El Niño-Southern Oscillation (ENSO) drives meteorological and oceanographic variability, with El Niños generally driving drier than average conditions (Chu and Chen, 2005), warmer ocean waters, higher runup from increased wave forcing, and a northward shift in tropical cyclone tracks, resulting in greater threats to the Hawaiian Islands from these storms (Jin and others, 2014).

[3]Deltares is an independent knowledge institute for applied research in the field of water and the subsurface (https://www.deltares.nl/en/about-us).

Northeasterly trade winds buffet the Hawaiian Islands throughout the year but are strongest and most consistent (10–20 meters per second [m/s]) during the summer (April–October). During autumn and winter (October–March), winds can lessen or reverse; these southerly or southwesterly winds—often called “Kona winds”—are associated with storms and increased precipitation. On Maui, the West Maui mountains create a wind and rain shadow on the leeward (west) side of Maui, where the study site was located (fig. 1*A*). Along the northwestern coastline, there is an along-shore gradient in precipitation whereby areas farther north (for example, Kahana and Honolua) receive more rainfall than those to the south (for example, Kā‘anapali), resulting in a general north-to-south gradient in frequency of precipitation in the watersheds.

The wave climate off West Maui is characterized by three primary wave sources—North Pacific swell, northeast trade-wind waves, and Southern Ocean swell (Moberly and Chamberlain, 1964). During winter (November–March), storms tracking across the North Pacific generate North Pacific swell with significant wave heights (H_s) from 3 to 8 meters (m) and peak periods (T_p) of 10–20 seconds (Storlazzi and others, 2006). Waves generated by northeast trade winds occur throughout the year but are largest during the summer, when the trade winds are the strongest. These wind waves typically are smaller and have shorter periods than the North Pacific swell ($1 < H_s < 4$ m; $5 < T_p < 8$ seconds). Swells from storms in the Southern Ocean also approach the Hawaiian Islands during boreal summer; although these waves tend to be smaller ($1 < H_s < 2$ m), they have longer periods ($14 < T_p < 25$ seconds). Wave energy along the West Maui coastline tends to be lowest in central West Maui (for example, Lahaina), increasing toward the north (North Pacific swell influence) and the south (Southern Ocean swell influence). Tides along the West Maui coastline are mixed semidiurnal, with two unequal high and low tides per day and a maximum excursion of about 1 m (Storlazzi and others, 2006).

Field Operations

This section provides information about the personnel, equipment, and field operations used during the study. Complete listings of instrument and deployment information are shown in tables 1–2.

Equipment and Data Review

Acoustic Wave and Current Profilers.—Three upward-looking 600-kilohertz acoustic wave and current profiler (AWAC) instruments were deployed at the deep sites along the 10-m isobath offshore of Kahana, Honokōwai, and Kā‘anapali (fig. 1*B*). The AWACs measured current velocity at ten 1.0-m bins from 2.2 m above the seafloor up to the surface for 10 minutes every 20 minutes. The AWACs also recorded directional wave data, collecting 1,024 measurements at a rate of 1 hertz (Hz) (17-min burst) every hour to allow calculation of tides (in meters), significant wave height (in meters), dominant wave period (in seconds), mean wave direction (in degrees true), and directional spread (in degrees). The AWAC locations are listed in tables 1 and 2; complete AWAC and processing information is listed in appendix 1.

Single-Point Current Meters.—Five single-point current meters were installed at water depths ranging from 2.7 to 5.8 m at the shallow Honolua, Kahana, Māhinahina, Honokōwai, and Wahikuli sites (fig. 1*B*). The current meters measured speed and direction of flow at 1.1 m above the seafloor; every 20 minutes, 1,024 samples were collected at 1 Hz (17-minute [min] burst). The speed and direction were averaged over each 17-min burst. Wave direction also was computed from the current meter measurements using current orbital ellipses. These current meters also recorded water temperature, which was averaged into hourly bins. The current meter locations are listed in table 1; complete current meter and processing information is listed in appendix 2.

Table 1. Instrument package location information, offshore West Maui, Hawai‘i.

[m, meter; WGS 84; World Geodetic System 1984]

Site name (fig. 1*B*)	Water depth (m)	Latitude (WGS 84, decimal degrees)	Longitude (WGS 84, decimal degrees)
Honolua Shallow	5.8	21.01406	−156.63955
Kahana Deep	10.7	20.97933	−156.68323
Kahana Shallow	3.1	20.97761	−156.67929
Māhinahina Shallow	3.4	20.96335	−156.68518
Honokōwai Deep	10.9	20.95079	−156.69371
Honokōwai Shallow	2.7	20.94993	−156.69205
Kā‘anapali Deep	9.8	20.91741	−156.69983
Wahikuli Shallow	4.6	20.91036	−156.69151

Table 2. Instrument package sensors deployed at each study site, offshore West Maui, Hawai‘i.

[m, meter; kHz, kilohertz]

Sensor depth (m)	Sensors
	Site: Honolua Shallow
4.7	Marotte HS drag-tilt current meter
5.3	RBR Virtuoso turbidity sensor
5.7	RBR Virtuoso Dwave logger
	Site: Kahana Deep
10.2	Nortek 600-kHz acoustic wave and current profiler
10.2	Seapoint optical backscatter turbidity sensor
	Site: Kahana Shallow
2.0	Marotte HS drag-tilt current meter
2.6	RBR Virtuoso turbidity sensor
3.0	RBR Virtuoso Dwave logger
	Site: Māhinahina Shallow
2.3	Marotte HS drag-tilt current meter
2.9	RBR Virtuoso turbidity sensor
3.3	RBR Virtuoso Dwave logger
	Site: Honokōwai Deep
10.4	Nortek 600-kHz acoustic wave and current profiler
10.4	Seapoint optical backscatter turbidity sensor
	Site: Honokōwai Shallow
1.6	Marotte HS drag-tilt current meter
2.2	RBR Virtuoso turbidity sensor
2.6	RBR Virtuoso Dwave logger
	Site: Kā‘anapali Deep
9.3	Nortek 600-kHz acoustic wave and current profiler
9.3	Seapoint optical backscatter turbidity sensor
	Site: Wahikuli Shallow
3.5	Marotte HS drag-tilt current meter
4.1	RBR Virtuoso turbidity sensor
4.5	RBR Virtuoso Dwave logger

Wave and Tide Gages.—Five wave and tide gages were placed with the single-point current meters at the shallow sites (fig. 1*B*). These gages collected 1,024 measurements of pressure at 1 Hz (17-min burst) every hour. From these pressure measurements, we derived hourly water levels (in meters), significant wave height (in meters), and wave period (in seconds). The wave gage locations are listed in table 1; complete wave gage and processing information is listed in appendix 2.

Optical Backscatter Sensors.—Eight optical backscatter sensor (OBS) instruments were deployed—three were co-located with the AWACs at the deep (10-m) sites and five were deployed with the single-point current meters and wave gages at the shallow sites (fig. 1*B*). The three deep OBSs were operated off the AWACs, collecting measurements of optical backscatter in counts every 20 minutes. The counts were converted to turbidity (in Nephelometric Turbidity Units [NTU]) using instrument manufacturer calibration conversions. The OBSs at the shallow sites were self-logging and collected a 5-min burst of 20 measurements of turbidity (in NTU) every 20 minutes. All eight OBSs had a wiper that wiped the optical face of the sensor every 4 hours. Erroneous spikes (no temporal width) were removed from the data using a cutoff of two times the standard deviation. The OBS locations are listed in table 1; complete OBS and processing information is listed in appendix 2.

Miscellaneous Data Sources.—Meteorological and oceanographic data from the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service buoy KLIH1 at Kahului and buoy 51205 at Pa‘uwela were obtained from the NOAA National Data Buoy Center (NOAA, 2018a, b) (fig. 1*A*). Rainfall data were provided by the West Maui Ridge-2-Reef Initiative group from two sites: (1) “shoreline,” where the rain gage is installed on top of a tall building adjacent to the shoreline at Kā‘anapali, and (2) “lower slope,” which is approximately 4 km inland and upslope from the shoreline gage, at 210 m above sea level (fig. 1*B*). Stream discharge data were obtained from the USGS Honokōhau streamgage (location 16620000; https://waterdata.usgs.gov; USGS, 2018), located at 20.9597° N. and 156.5871° W., on the north slope of the West Maui mountains approximately 290 m above sea level (fig. 1*A*); this is the nearest operational streamgage to our study area that collected measurements during the deployment period.

Research Platform

The instrument deployments and recoveries were conducted using the 28-foot (ft)-long research vessel (R/V) *Alyce C.*, owned and operated by Alyce C. Sport Fishing. Vessel operations, including mobilization and demobilization, were based out of Lahaina Boat Harbor (fig. 1*B*). The R/V *Alyce C.* is a sport-fishing boat that was modified for instrument deployment and recovery. The port beam was used for instrument package deployment and recovery operations, which included the use of an overhead davit. The instruments were deployed using a slip line to the instrument package. Once the instruments were lowered to the seafloor, the slip line was recovered. Scuba divers then moved the instrument package into position. All instrument packages were anchored using weights.

Field Data Acquisition and Quality

Data were acquired for 144 days from 2017 year-days (YD) 314–456 (November 9, 2017, through April 1, 2018). More than 120,000 temporal (every 20 minutes) data points were recorded by the AWACs, current meters, wave gages, and OBSs. The raw data were archived, and copies of the data were post-processed for analysis (Cheriton and others, 2023; Winter et al., 2023).

All three sets of AWAC wave and water-column profiler data generally are of high quality. The Marotte current meter at the Honolua Shallow site stopped recording data on February 22, 2018 (2017 YD 418). The OBS at the Māhinahina Shallow site was recovered with a broken sensor cover, but the data were retrievable and limited only by fouling. Each of the OBS sensors fouled at different times. For the shallow sites, unfouled turbidity measurements were recorded for 105.0 days at Honolua Shallow, 13.0 days at Kahana Shallow, 25.0 days at Māhinahina Shallow, 23.0 days at Honokōwai Shallow, and 31.0 days at Wahikuli Shallow. For the deep sites, unfouled turbidity measurements were recorded for 62.0 days at Kahana Deep, 58.0 days at Honokōwai Deep, and 142.0 days at Kā‘anapali Deep.

A weather station was installed on the roof of a condominium building along the shoreline near Honokōwai, but this station failed to record any data; thus, we relied on meteorological measurements from Kahului Airport.

In order to determine the contributions of different forcing mechanisms to wave, flow, and turbidity patterns, the in-situ data were constrained to periods when different forcing mechanisms of interest were dominant. For example, to identify the influence of winds on flow patterns, a period of time was identified without concurrent large waves. To remove tidal effects, wave and current time series were low-pass filtered using a 36-hour cut-off. To identify the contribution of tides to circulation patterns, the entire record was 10–28 hour band-pass filtered, and tidal slope was used to delineate flood and ebb tide periods. For the AWAC measurements, near-surface currents are a depth average of the top two bins, and near-bed currents are a depth average of the deepest two bins. Near-bed currents at the shallow sites are the observations from the Marotte sensors that were approximately 1 m above the seabed.

Hydrodynamic Model

Background

To resolve and simulate coastal and marine water levels, waves, and currents throughout the study area, two models were coupled together—Delft3D-FLOW (Lesser and others, 2004) version 6.03.00.62794 and Simulating WAves Nearshore (SWAN) (Booij and others, 1999) version 3.07.00.62794. Delft3D-FLOW is an open source, three-dimensional hydrodynamic model that calculates non-steady flow and transport phenomena resulting from tidal and meteorological forcing, and SWAN is a state-of-the-art, third generation wave model that computes random, short-crested wind-generated waves in coastal regions and inland waters. Both Delft3D-FLOW and SWAN are maintained and continuously updated by Delft University of Technology.

The following sections detail the hydrodynamic modeling configurations and settings, as well as the validation that was performed using the collected observations.

Model Domains

The hydrodynamic model was composed of four nested models of different scales (fig. 2). The largest model (“Hawaii”) encompassed the oceanographic region around the main Hawaiian Islands with a 5-km horizontal spatial resolution and used a 5-minute time step. The intermediate nested model (“Maui”) encompassed the Maui Nui complex with a 1-km resolution grid and operated with a 2-minute time step. The Hawaii and Maui models were originally set up to simulate coral larvae dispersal and inter-island connectivity (Storlazzi and others, 2017); both have a three-dimensional rectangular grid consisting of 20 vertical layers of fixed thickness and were coupled with a SWAN wave model. Two new coupled Delft3D-FLOW and SWAN models were created to model flow and waves over the nearshore reefs off West Maui—one with 200-m horizontal spatial resolution that covered the offshore region of West Maui (“WMaui”) and one that covered the nearshore region along the West Maui coastline (“Nearshore”) with a 40-m resolution. These finer-scale models were nested within the larger Hawaii and Maui models and both had a 12-second time step. Like the two larger models, the WMaui model was composed of a rectangular grid with 20 vertical layers. The Nearshore model used a curvilinear grid set by the shoreline curvature and had 10 vertical (equidistant) sigma layers to accurately resolve the vertical profile in the coastal zone. All four three-dimensional hydrodynamic models used an implicit numerical scheme that is unconditionally stable, regardless of the chosen time step. However, because the time step does influence the accuracy of the results, for each model, we identified the longest time step that still produced reliable model results. Further details on the nesting configuration of the models are provided in appendix 3.

The bathymetry for the Nearshore model was constructed from a digital elevation model of Lahaina (Taylor and others, 2008), which has a horizontal spatial resolution of approximately 10 m and is referenced to mean high water. Additional details on the bathymetry are presented in appendix 4, and more information on the physical parameter settings of the models, including bed roughness, turbulence, and wave computations, is provided in appendix 5.

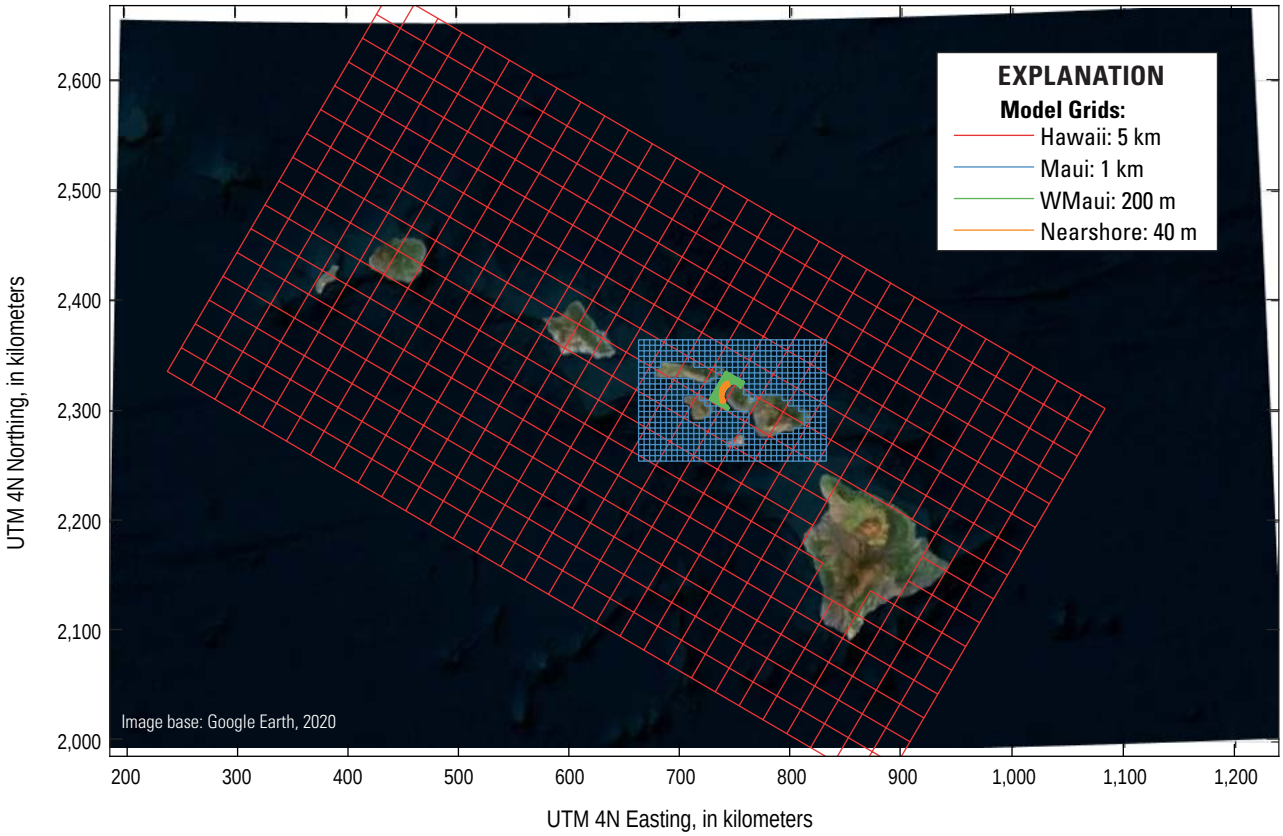


Figure 2. Map of main Hawaiian Islands showing the four nested model grids—"Hawaii" (red), "Maui" (blue), "WMaui" (green), and "Nearshore" (orange). The horizontal spatial resolution for each grid is indicated in the explanation. Abbreviations: UTM 4N, Universal Transverse Mercator zone 4N; km, kilometer; m, meter.

Model Validation

This section briefly summarizes the validation of the Nearshore model using the in-situ oceanographic time series of water levels, wave parameters, and current velocity. Details on the validation of the larger Hawaii model are provided in appendix 6. In general, the modeled hydrodynamics using the Nearshore model agree well with the measured values. The error estimates given by root mean square error (RMSE) and bias show decent values in most of the observational points for water levels, waves, and currents (tables 3–4). There were some discrepancies between the model bathymetry and the measured depths at instrument sites owing to the high relief in reef morphology that is not fully captured by the digital elevation model of the study area, which had a spatial resolution of 10 m (table 5). These depth differences are likely the primary cause of the large biases in the wave directions, as the sites with the largest wave direction biases also are those with the largest bathymetry disagreements between model bathymetry and measured depths. The Nearshore model also performed well at capturing the spatial patterns of wave transformation and currents (fig. 3).

Table 3. Root mean square error and bias between modeled and measured water levels and wave parameters.

[RMSE, root mean square error; m, meter; H_s, significant wave height; T_p, peak wave period; s, second; WDIR, mean wave direction; °T, degree from true north]

Site name	Water level [m]		H_s [m]		T_p [s]		WDIR [°T]	
	RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias
Honolua Shallow	0.13	0.11	0.54	0.39	4.5	−3.0	21	2
Kahana Deep	0.06	0.01	0.39	0.29	3.3	−2.6	51	9
Kahana Shallow	0.11	0.10	0.64	0.59	3.7	−0.8	35	32
Māhinahina Shallow	0.16	0.10	0.40	0.31	4.0	−3.0	28	24
Honokōwai Deep	0.04	0.01	0.40	0.30	3.9	−3.4	43	18
Honokōwai Shallow	0.80	0.08	0.70	0.62	4.4	−3.7	32	33
Kā‘anapali Deep	0.06	0.02	0.14	−0.01	6.5	−6.0	59	39
Wahikuli Shallow	0.12	0.11	0.22	−0.12	8.8	−8.1	51	35

Table 4. Root mean square error and bias between modeled and measured depth-averaged current velocity parameters.

[U, eastward velocity; V, northward velocity; CMAG, current magnitude; m/s, meter per second; CDIR, current direction; °T, degree from true north; RMSE, root mean square error]

Site name	U [m/s]		V [m/s]		CMAG [m/s]		CDIR [°T]	
	RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias
Honolua Shallow	0.058	0.012	0.018	−0.003	0.055	−0.024	193	−32
Kahana Deep	0.072	0.031	0.162	−0.051	0.124	−0.062	103	−43
Kahana Shallow	0.075	−0.024	0.175	−0.125	0.158	0.102	200	−146
Māhinahina Shallow	0.075	−0.012	0.072	−0.024	0.077	0.032	184	−102
Honokōwai Deep	0.043	0.017	0.086	0.033	0.073	−0.026	90	−2
Honokōwai Shallow	0.061	0.005	0.047	−0.012	0.049	0.008	178	−95
Kā‘anapali Deep	0.196	0.071	0.184	0.084	0.224	−0.169	87	−5
Wahikuli Shallow	0.041	0.014	0.018	0.003	0.037	−0.013	124	10

Table 5. Difference between measured seafloor depth at the study sites and the bathymetry used in the model.

[m, meter]

Site name	**Seafloor depth [m]**	
	Measured	Modeled
Honolua Shallow	6.4	9.3
Kahana Deep	11.2	12.5
Kahana Shallow	3.0	3.1
Māhinahina Shallow	4.7	3.3
Honokōwai Deep	11.9	14.7
Honokōwai Shallow	3.5	3.2
Kā‘anapali Deep	9.9	14.8
Wahikuli Shallow	5.5	4.9

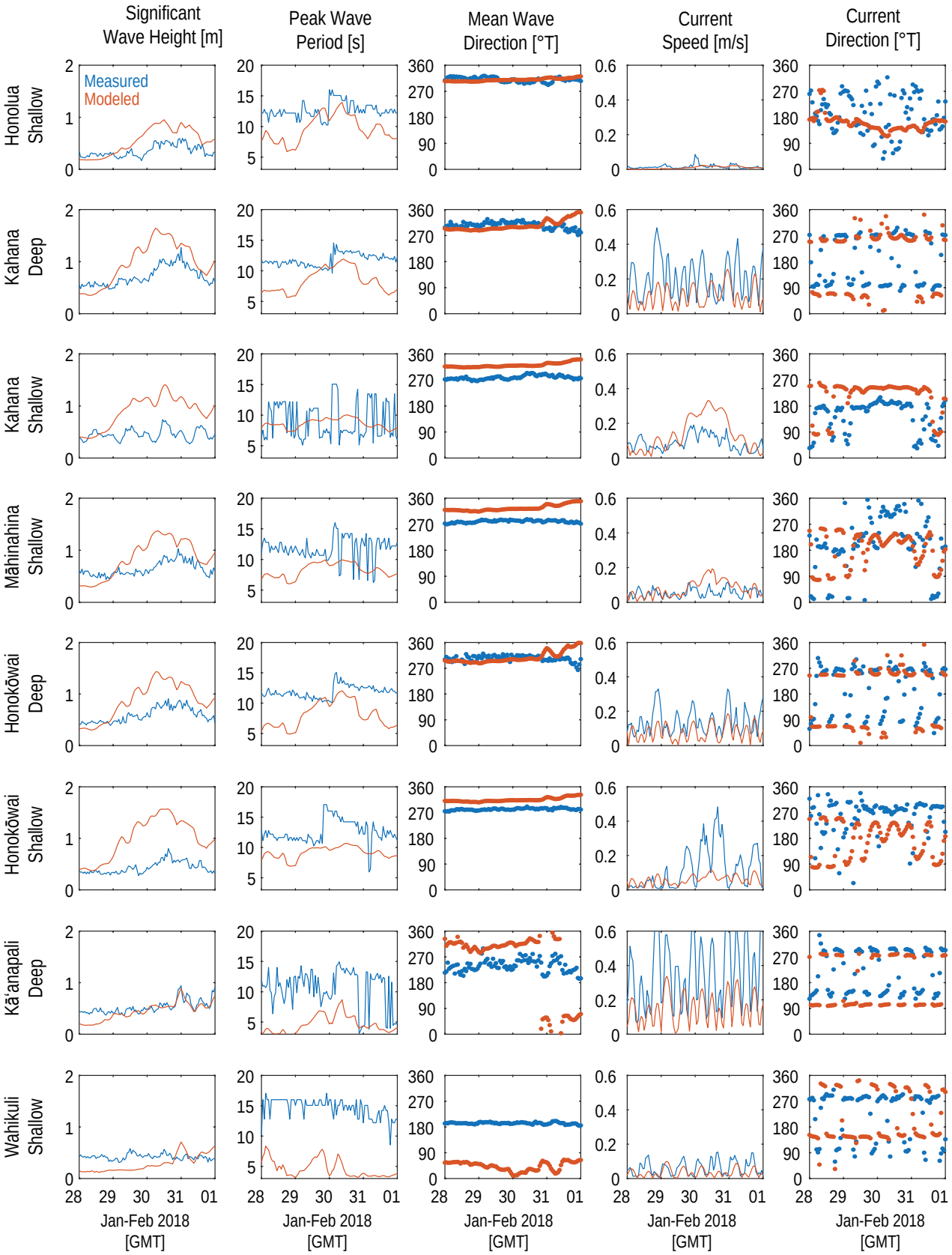


Figure 3. Time-series plots showing a 4-day-long comparison between the measured (blue) and modeled (orange) oceanographic variables for each of the eight study sites from north to south. Mean wave direction, reported in meteorological convention (direction of origin), in degrees from true north (°T); depth-averaged current speed in meters per second (m/s); and depth-averaged current direction, reported as heading (direction of flow), in degrees from true north. Other abbreviations: m, meter; s, second; Jan, January; Feb, February; GMT, Greenwich mean time.

Sediment Transport Model

Background

Delft3D-WAQ is a water-quality model framework that also is part of the Delft3D software suite. It solves the advection-diffusion reaction equation on a predefined computational grid for a wide range of model substances, including fine-grained sediments. Delft3D-WAQ uses hydrodynamic conditions (current velocities, water elevations, vertical eddy viscosity, and vertical eddy diffusivity) derived from the Delft3D-FLOW module, but sediment transport is simulated offline (non-coupled). Advection and diffusion processes are simulated in the water column and exchange between the water column and seabed layers are included. The deposition flux is calculated by multiplying the settling velocity (determined by the particle diameter) with the sediment particle concentration in the water column.

Using this water-quality model in combination with the hydrodynamic model, we can simulate the plume dispersion from each stream and the resulting effects on nearshore coral-reef habitats. These effects include both sedimentation and light attenuation owing to sediment in suspension. We first assess the affect of present-day stream discharge on six different reef areas. Next, we determine how these effects change under different wave conditions. Lastly, we evaluate the effectiveness of restoration measures in the watershed at reducing harmful effects on the reefs.

Sediment

Sediment Size Classes.—Only fine-grained sediment particles (clays to fine sands) were used in the simulations, as these are the relevant fractions for plume dispersion. The particles were delineated into three separate groups—clay (diameter [D] < 0.002 millimeter [mm]), silt (0.002 < D < 0.050 mm), and fine sand (0.050 < D < 0.250 mm). All sediment fractions were tagged individually in the model so that the turbidity and depositional patterns of each fraction from each stream could be traced separately. The settling velocities for sediment particles were determined by the particle sizes, with clay settling at 0.02 millimeter per second (mm/s), silt at 0.69 mm/s, and fine sand at 1.90 mm/s.

Light Extinction.—The light extinction coefficient (K) was determined for each size class (clay and silt: $K_{silt\text{-}clay}$ = 0.090/m; fine sand: K_{fsand} = 0.0062/m). These light extinction coefficients are from Storlazzi and others (2015a) and are described in detail in appendix 7. Within the model, the overall light extinction (K_{total}) was determined for each cell as the sum of the light extinction coefficients multiplied by the particle concentration (C) for each size class:

$$K_{total} = [K_{silt\text{-}clay} \times C_{clay}] + [K_{silt\text{-}clay} \times C_{silt}] + [K_{fsand} \times C_{fsand}].$$

The background extinction was set to zero so that any light reduction resolved in the model is due only to stream sediment discharges.

Flood Scenarios

We simulated two different 24-hour rainfall-driven flood scenarios. A flood is defined here as a heavy rain event that drives large sediment discharges into the coastal ocean. The first scenario, Flood Only, was forced with low-energy (unchanging) waves and trade winds. The second scenario, Flood+Waves, was forced with energetic waves and Kona winds. The waves for both scenarios were out of the northwest but were larger for the Flood+Waves scenario (fig. 4). Regional currents were similar between the two scenarios, with predominant flow directed alongshore toward the north; however, in the Flood+Waves scenario, the southward return flow adjacent to the shore intensified (fig. 5). Remarkably, the Nearshore model reproduced short-term recirculation around the reefs in which the wave-driven flow over the reef was directed southward, opposing the northward tidal current outside the reef (fig. 5). During each scenario, the flood was simulated by modeling stream discharges and associated sediment loads at each of the five stream outfall locations (fig. 1). Both scenarios involved 10-day model runs with the same initial conditions for the first 3 days: trade winds at 10 m/s out of the northeast and waves with a 0.5-m significant wave height and 15-second peak period directed out of the north-northwest (fig. 6). Water levels (tide) for both scenarios were taken from the time series segment used for the model validation; this was a period in which the semidiurnal (12.42-hour period) lunar component dominated, and the flow was minimally affected by surface winds. After the first 3 days, a 24-hour flood occurred, with sediment load from stream discharge entering the coastal waters and an approximate 180-degree rotation in winds from out of the northeast to out of the southeast. In the Flood+Waves scenario, wave heights increased to 1.5 m over 8 hours and winds decreased to 5 m/s, whereas in the Flood Only scenario, wave heights and wind speed remained unchanged, but winds still rotated (fig. 6).

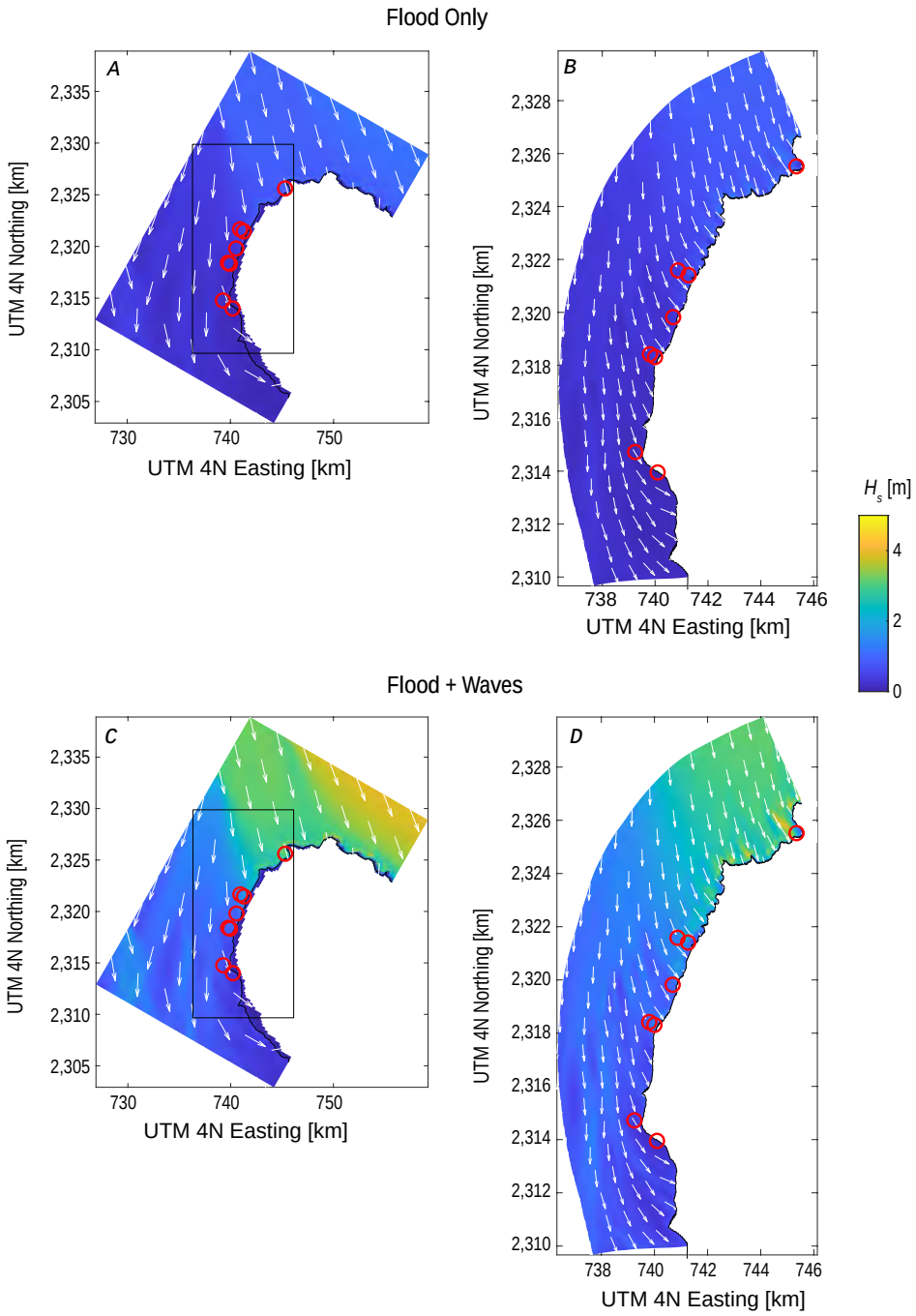


Figure 4. Map plots of the West Maui (*A* and *C*) and Nearshore (*B* and *D*) model grids showing mean modeled wave heights and direction for the Flood Only (*A* and *B*) and Flood+Waves (*C* and *D*) scenarios. For all panels, arrows indicate wave direction (uniform arrow length; in direction of flow) and color ramp indicates significant wave height (in meters [m]). Red circles show study sites. *A*, West Maui model grid for the Flood Only scenario. *B*, Nearshore model grid, indicated by box outline in *A*, for the Flood Only scenario. *C*, West Maui model grid for the Flood+Waves scenario. *D*, Nearshore model grid, indicated by box outline in *C*, for the Flood+Waves scenario. UTM 4N, Universal Transverse Mercator zone 4N, km, kilometer; H_s, significant wave height.

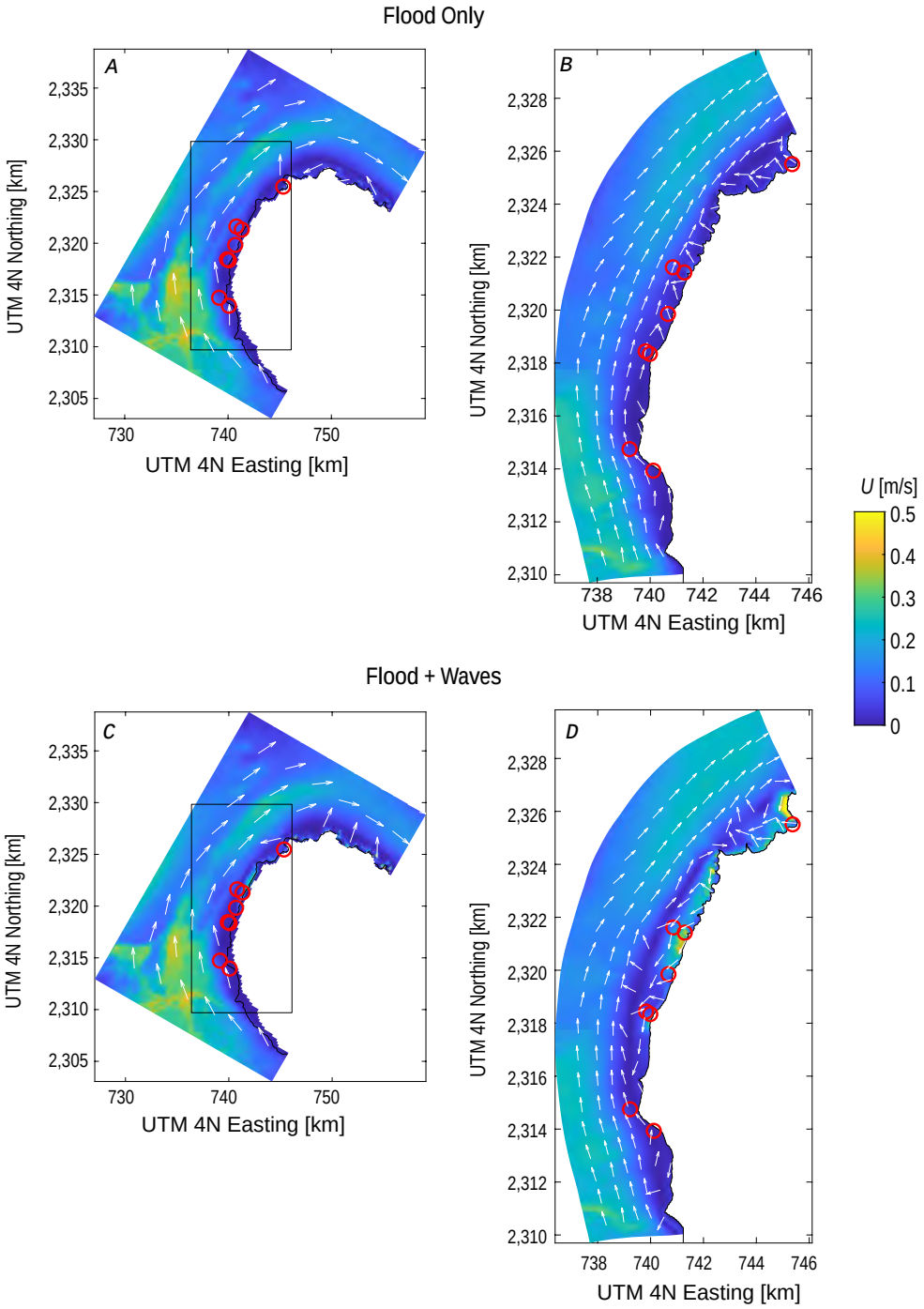


Figure 5. Map plots of the West Maui (*A* and *C*) and Nearshore (*B* and *D*) model grids showing modeled depth-averaged ocean current speed (*U*) and direction for the Flood Only (*A* and *B*) and Flood+Waves (*C* and *D*) scenarios. For all panels, arrows indicate current direction (uniform arrow length; in dicrection of flow) and the color ramp indicates current speed, in meters per second (m/s). Red circles show study sites. *A*, West Maui model grid for the Flood Only scenario. *B*, Nearshore model grid, indicated by box outline in *A*, for the Flood Only scenario. *C*, West Maui model grid for the Flood+Waves scenario. *D*, Nearshore model grid, indicated by box outline in *C*, for the Flood+Waves scenario. Map coordinates in kilometers (km). UTM 4N, Universal Transverse Mercator zone 4N.

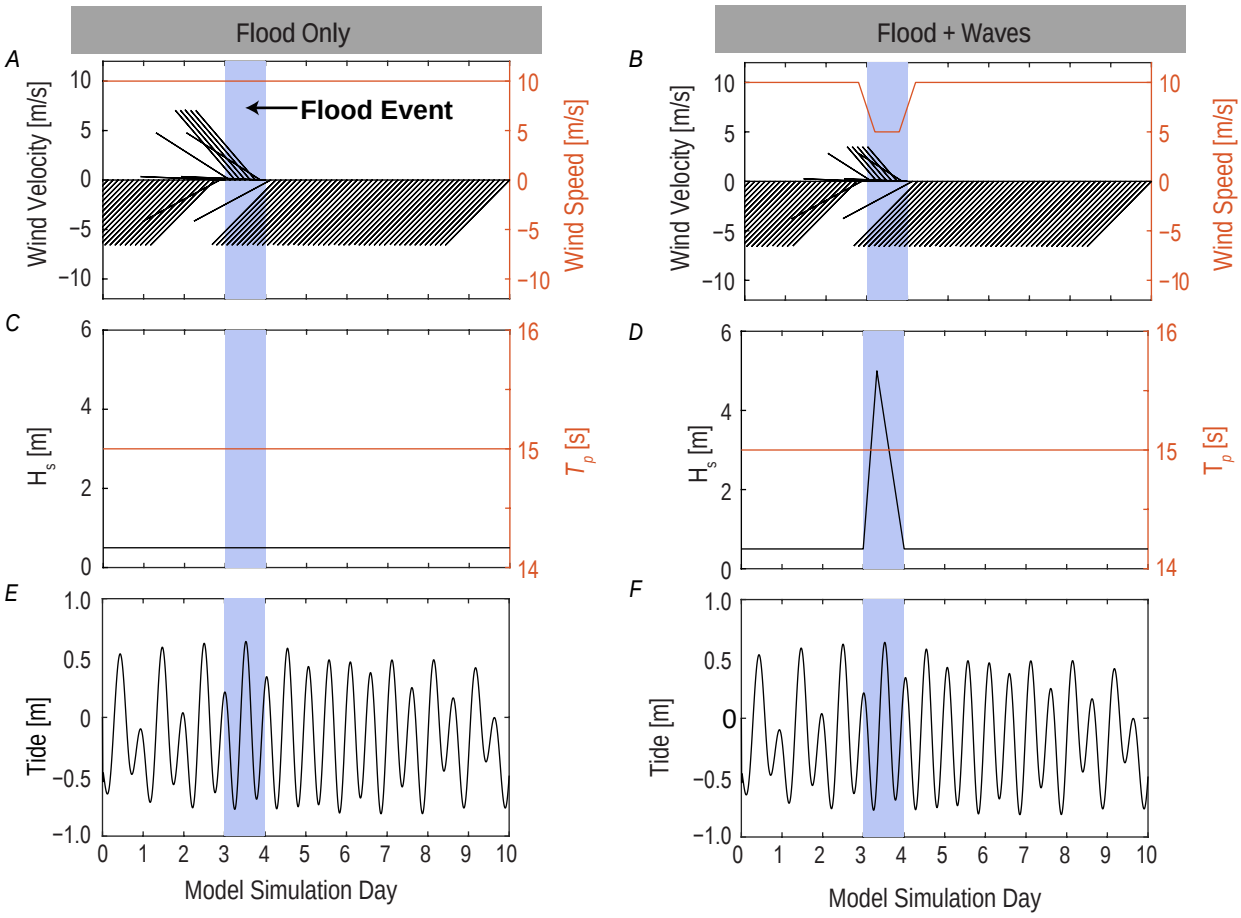


Figure 6. Time-series plots of 10-day model simulations showing meteorological and oceanographic conditions used for two simulated flood conditions—Flood Only (*A*, *C*, *E*) and Flood+Waves (*B*, *D*, *F*). *A*, *B*, Wind velocity (black), in meters per second (m/s) and degrees clockwise from true north (direction of origination; north is up; length scales with wind speed), and wind speed (orange) in meters per second. Note wind velocity was down-sampled to 3-hour intervals even though the model forcing is in 5-minute intervals. *C*, *D*, Significant wave height (H_s) (black line), in meters (m), and peak wave period, T_p (orange), in seconds (s). *E*, *F*, Tidal height from the Kahana Deep site, in meters. Blue shaded region on day 3 indicates the flood event, when stream discharge and sediment load were input to coastal waters during the model simulation.

Stream Discharge and Sediment Load Scenarios

The model considered sediment discharge from five West Maui streams (listed from north to south)—Honolua, Kaʻōpala, Kahana, Honokōwai, and Wahikuli (fig. 1*B*). Only terrestrial sediment discharged from stream outfalls was considered; no background marine sediment concentrations or existing seabed sediments were included. During a simulated rainfall-driven flood event, the sediment from each stream was discharged with a uniform sediment concentration into a single grid cell. Although terrestrial sediment discharged from each stream was allowed to interact with that from other streams, each stream's discharged sediment was numerically tagged (differentiated from the other streams) to understand the fate of sediment from each stream. Two stream discharge and sediment load scenarios were provided by the U.S. Army Corps of Engineers: (1) a base scenario ("Baseline"), representing no management measures, and (2) a decreased load scenario ("Restoration"), representing watershed management measures (fig. 7*A–B*). In the Restoration scenario, the decreases in sediment load are attributed to watershed management efforts. These management efforts, which were designed and modeled by the U.S. Army Corps of Engineers, varied by water basin but included dam modifications and the installation of microbasins and loʻi (irrigated terraces).

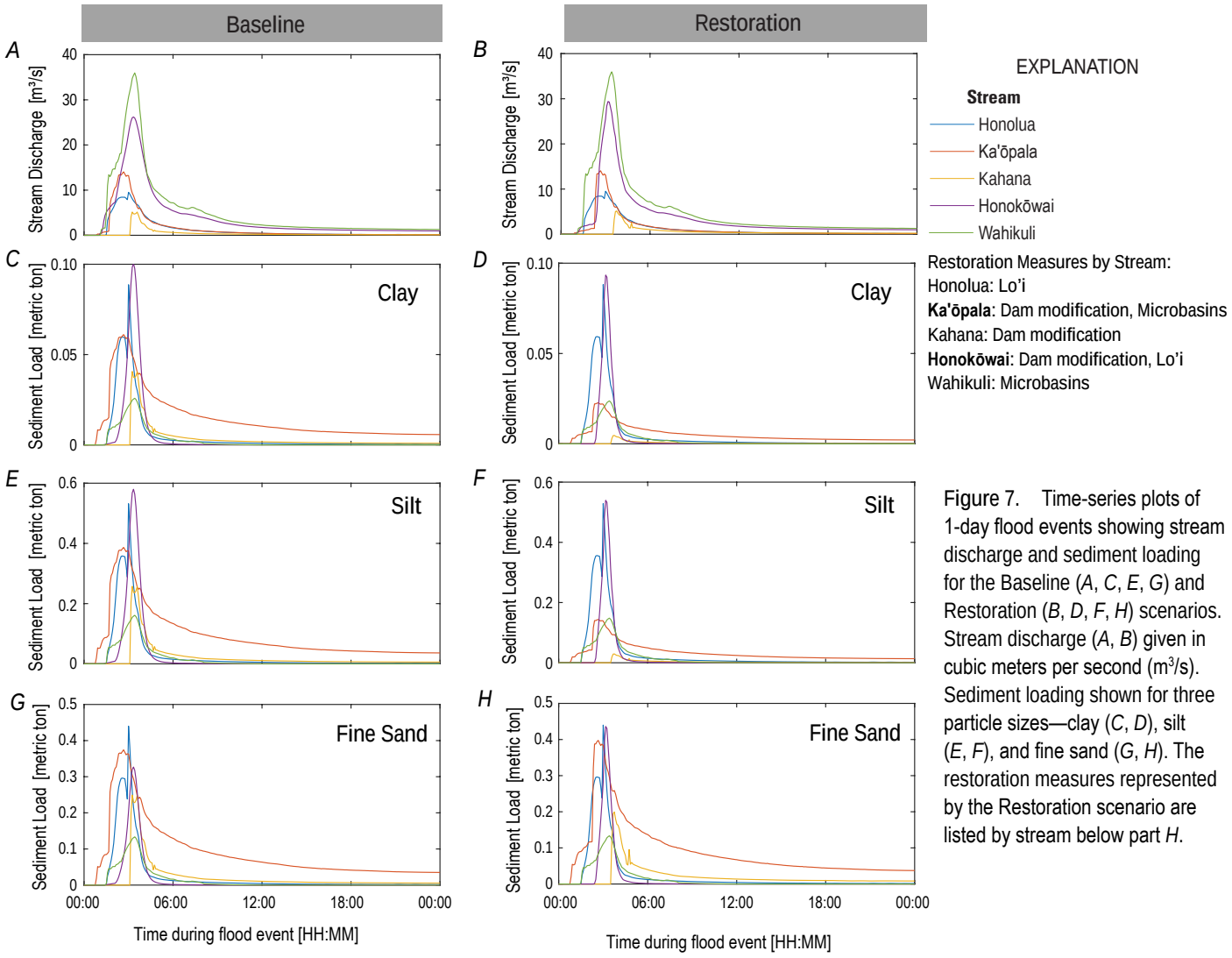


Figure 7. Time-series plots of 1-day flood events showing stream discharge and sediment loading for the Baseline (*A*, *C*, *E*, *G*) and Restoration (*B*, *D*, *F*, *H*) scenarios. Stream discharge (*A*, *B*) given in cubic meters per second (m^3/s). Sediment loading shown for three particle sizes—clay (*C*, *D*), silt (*E*, *F*), and fine sand (*G*, *H*). The restoration measures represented by the Restoration scenario are listed by stream below part *H*.

For each flood event, the streams were assigned a unique 24-hour time series of stream discharge and sediment load (per 5-minute interval) with different sediment loads for the three considered size classes (clay, silt, and fine sand; fig. 7*C–H*). The resulting sediment concentration for each size class was determined by the ratio of the load to the discharge rate (concentration = load/discharge).

Results

Climatological Context

Using the records for buoy KLIH1 (at Kahului) spanning 2005–2018, the monthly climatology for meteorological forcing was determined to place the conditions during our study period in the context of long-term records. In general, the monthly averaged air pressure, air temperature, and wind speed during the study period were within 1 standard deviation of the long-term record (fig. 8*A–C*). The rain climatology was based on records spanning 2014–2019. Compared to this 5-year record, the precipitation monthly total during the study period was above average for December and February (fig. 8*D*). The greater-than-average precipitation during the study period may have been due in part to this time period coinciding with a weak La Niña phase of the El Niño-Southern Oscillation. However, long-term records indicate that the relationship between La Niña events and excess precipitation on the Hawaiian Islands has weakened since 1983 (O'Connor and others, 2015).

Temporal and Spatial Patterns from Measurements

This section reviews the data collected by deployed instruments to better understand the oceanographic conditions in the study area during our study period. Full time series of measured waves, currents, and water temperature from the deep and shallow sites are provided in appendixes 8 and 9, respectively.

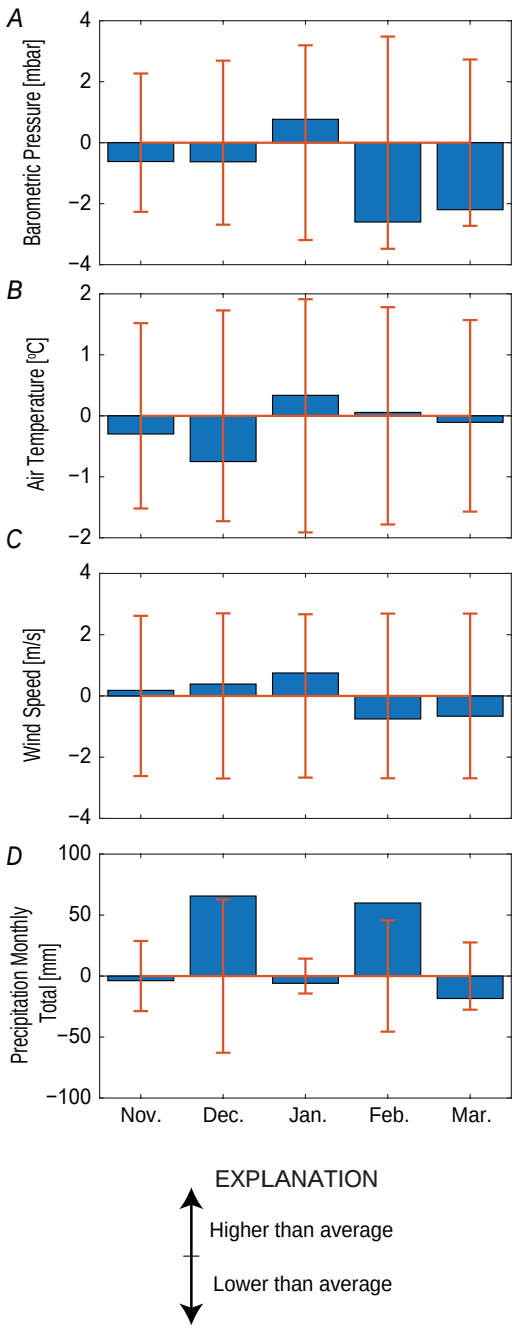


Figure 8. Plots showing the difference between monthly mean conditions during the study period to the mean 5-year climatological record (boxes); error bars show ±1 standard deviation. Values greater than zero indicate that the given metric was greater than the 5-year climatological record for that month. *A*, Barometric pressure, in millibars (mbar), from National Oceanic and Atmospheric Administration (NOAA) buoy KLIH1 in Kahului Harbor. *B*, Air temperature, in degrees Celsius (°C) from buoy KLIH1. *C*, Wind speed, in meters per second (m/s), from buoy KLIH1. *D*, Precipitation monthly total, in millimeters (mm), from the Kā‘anapali shoreline gage maintained by the West Maui Ridge-2-Reef Initiative. Nov, November; Dec, December; Jan, January; Feb, February; Mar, March.

Oceanographic and Atmospheric Forcing

The study period, from November 2017 through March 2018, was timed to coincide with the rainy season. Winds recorded at Kahului Airport indicate that the shift from the summer trade-wind-dominated season to the more variable wind season occurred around October 22, 2017, before the start of the study period, and this variable wind pattern persisted until after the end of the study period.

The meteorological conditions during the study period are shown in figure 9. The barometric pressure ranged from approximately 1,006 to 1,023 millibars (mbar), with periodic pressure decreases associated with rain events (fig. 9*A*). The long-term air temperature was relatively consistent but exhibited daily excursions of approximately 18 to 27 degrees Celsius (°C) (fig. 9*B*). During this 4-month period, there were several Kona (southerly) wind events (fig. 9*C*). However, because these winds represent the wind forcing on the northern coast of the island, we note that they do not necessarily correspond to the local wind forcing along the West Maui coastline.

Precipitation on the highest peak of the West Maui mountains, Puʻukukui, occurred at much greater rates than rain events on the lower slope and adjacent shoreline, although the timing of the events were often coincident (fig. 9*D–E*). Precipitation on the West Maui shoreline and lower slope was sporadic throughout the study period (fig. 9*E*). The strongest precipitation event occurred on YD 354, during which precipitation rates at the shoreline reached 25 millimeters per hour (mm/h) for a cumulative rainfall of 90 mm over 33 hours. This one event provided 22 percent of the total cumulative precipitation during the 142-day study. During this event, the National Weather Service (NWS) issued flash flood warnings for many locations across the West Maui region. A series of smaller rain events occurred between YD 400 and 420 (February 3–23, 2018; fig. 9*E*); NWS issued a flood watch prior to these rain events, which was then later canceled. Otherwise, rainfall at the shoreline and lower slope sites was relatively sparse, with only eight events at the shoreline wherein precipitation daily totals exceeded 20 mm (fig. 9*E*).

The mean ±1 standard deviation stream discharge at the northern upper slope site was 1.8±2.7 cubic meters per second (m^3/s) and ranged from 0.4 to 18.3 m^3/s, which occurred on YD 354 during the strong precipitation event (fig. 9*F*). The magnitude of the stream discharge at this northern location did not consistently scale with precipitation measured on the West Maui lower slope and shoreline owing to the location offsets; the streamgage site captures the wetter, higher precipitation experienced by the northern part of the West Maui mountains. For example, the rain event on YD 403, which had greater precipitation daily totals at the shoreline than higher on the slope, had no corresponding stream discharge at the northern upper slope location (fig. 9*F*).

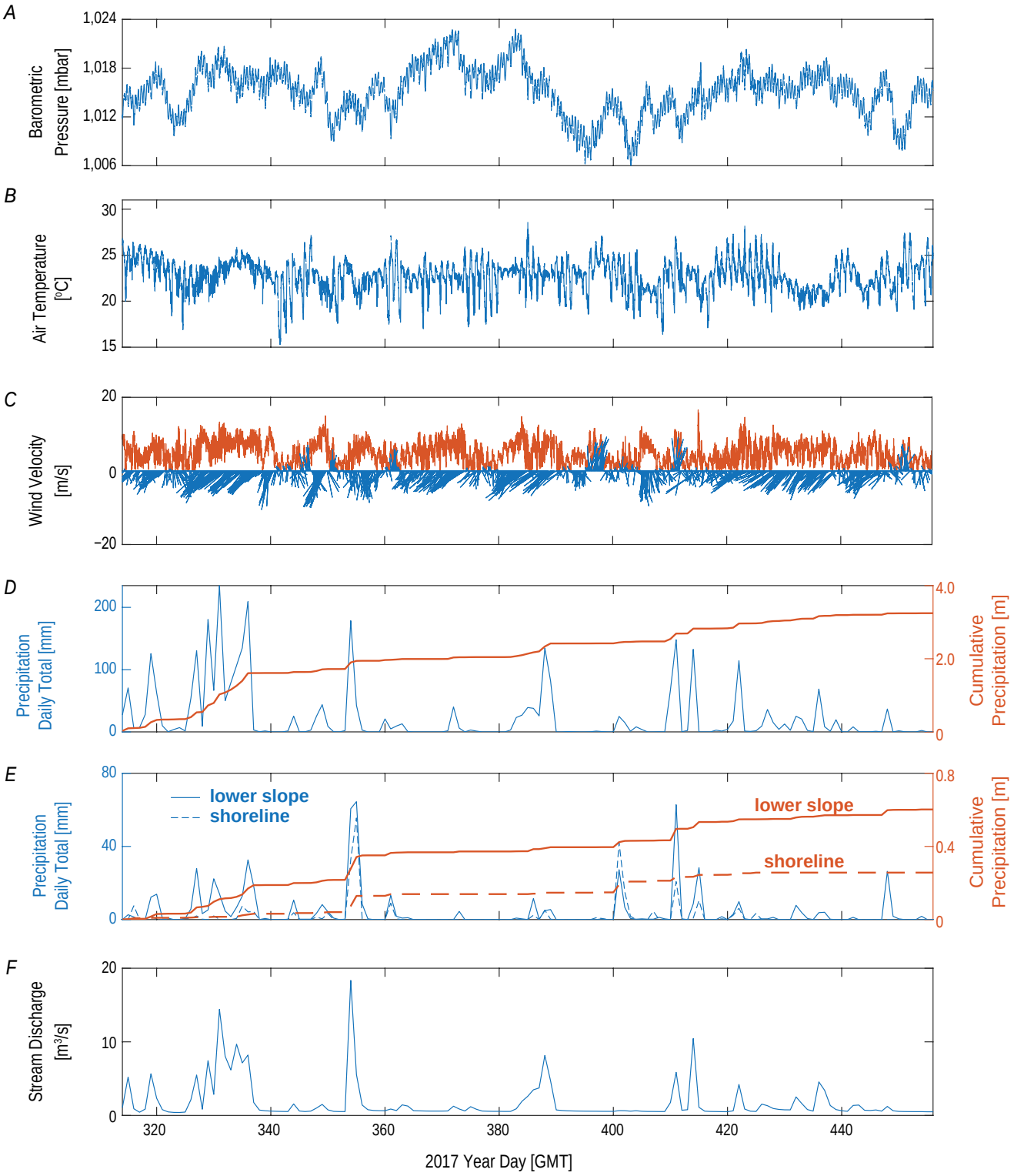


Figure 9. Time-series plots of meteorological conditions during the study period. *A*, Barometric pressure, in millibars (mbar), from National Oceanic and Atmospheric Administration (NOAA) buoy KLIH1 in Kahului Harbor. *B*, Air temperature, in degrees Celsius (°C), from buoy KLIH1. *C*, Three-hour-averaged wind speed (orange), in meters per second (m/s), and wind velocity (blue), in degrees clockwise from true north (direction is direction of origination; north is up; length scales with wind speed), from buoy KLIH1. *D*, Precipitation daily totals (blue), in millimeters (mm), and cumulative precipitation (orange), in meters (m), from the U.S. Geological Survey rain gage on Puʻukukui (summit of West Maui mountains; gage 205327156351102). *E*, Precipitation daily totals (blue), in millimeters, and cumulative precipitation (orange), in meters, from the shoreline (Kāʻanapali) and lower slope (Maui Cultural Lands) gages maintained by the West Maui Ridge-2-Reef Initiative. *F*, Daily averaged stream discharge, in cubic meters per second (m^3/s), from the U.S. Geological Survey Honokōhau streamgage (16620000). GMT, Greenwich mean time.

Tides

The study period encompassed 10 complete spring-neap tidal cycles (fig. 10*A*). The tides along West Maui are predominantly mixed, containing both diurnal and semidiurnal components of comparable amplitude. As such, the tides change approximately every 6 hours, with two uneven high and low tides per day. The mean daily tidal range was approximately 0.51 m, with a range of 0.10 to 0.94 m. The highest high tide was +0.51 m and the lowest low tide was −0.44 m.

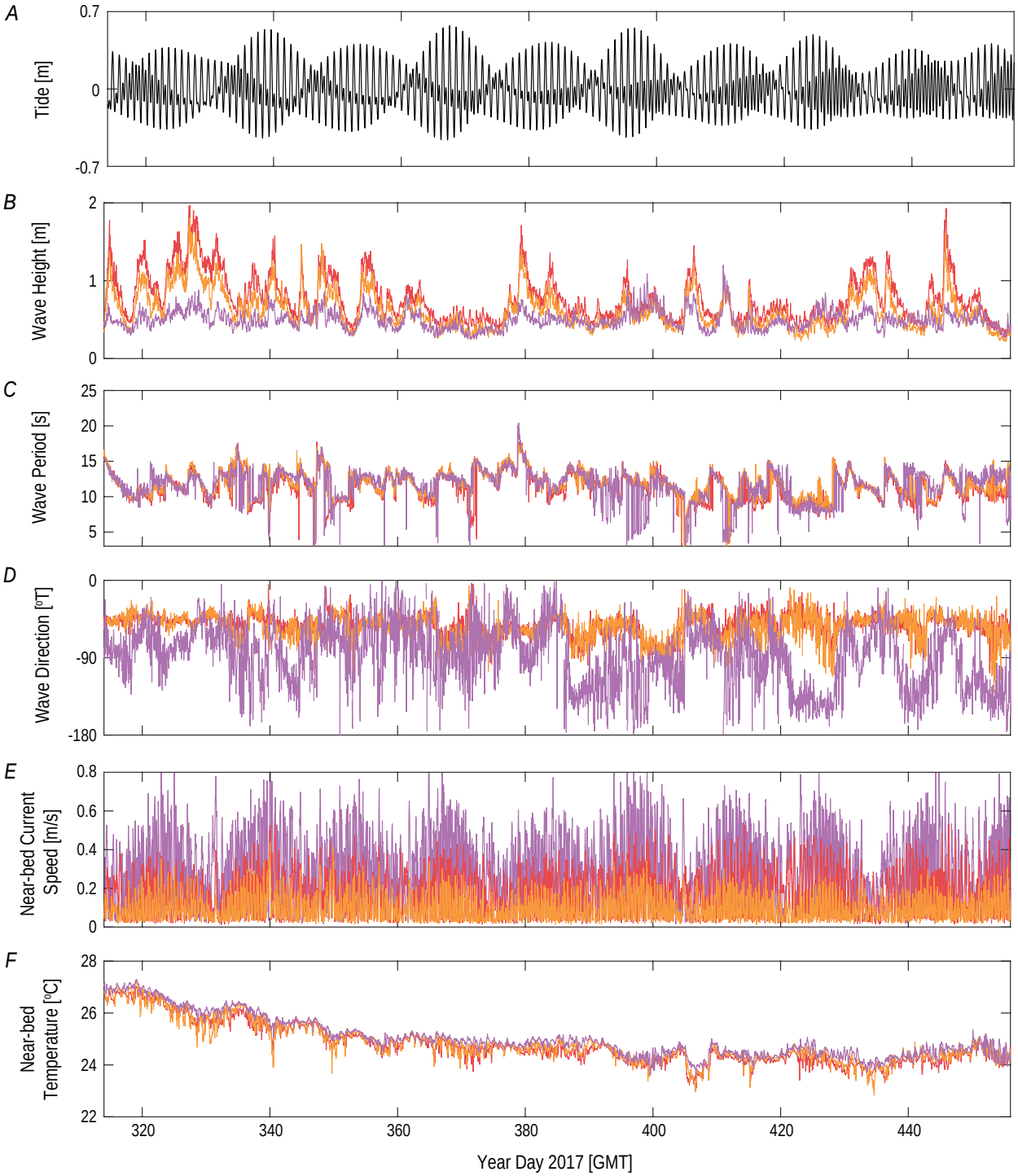


Figure 10. Time-series plots of oceanographic measurements during the study period from three deep-water study sites. *A*, Tide water levels, in meters (m), from the Kahana Deep site. *B*, Significant wave height, in meters. *C*, Peak wave period, in seconds (s). *D*, Wave direction at peak period (direction of origination), in degrees clockwise from true north (°T). *E*, Near-bed current speed, in meters per second (m/s). *F*, Near-bed water temperature, in degrees Celsius (°C). GMT, Greenwich mean time.

Winds

Hourly wind speeds at Kahului Airport ranged from 0.0 to 16.6 m/s, with a mean speed ±1 standard deviation of 4.7±2.7 m/s (fig. 9*C*, table 6). The winds at this site exhibit a diurnal pattern, with strongest daily winds in the early afternoon (local time). During the study period, winds were out of the northeast (trade winds) 65 percent of the time and out of the south 10 percent of the time.

Table 6. Meteorological statistics for offshore West Maui, Hawai‘i.

[All values calculated for 2017 days 314–456; wind direction is direction from which wind originates. Abbreviations: mb, millibar; °C, degrees Celsius; mm/h, millimeter per hour; m/s, meter per second; °, degree; σ, standard deviation; –, not determined]

Meteorological data	Mean ±1σ	Minimum	Maximum
Sea-level barometric pressure [mb]	1,015.6±2.9	1,006.5	1,022.9
Air temperature [°C]	22.7±1.7	15.3	28.6
Lower slope precipitation [mm/h]	0.2±1.0	0	26.2
Nearshore precipitation [mm/h]	0.1±0.8	0	25.2
Wind speed [m/s]	4.7±2.7	0.0	16.6
Wind direction [°]	32.1±48.5	–	–

Waves

Waves that impacted the West Maui study area during the experiment are shown in figures 10–12, and statistics for each site are shown in table 7. Significant wave heights across all study sites ranged from less than 0.1 to 2.0 m, with peak wave periods ranging from approximately 3 to 20 seconds. Across the study sites, there was a delineation in wave characteristics between the two southern sites (Kā‘anapali Deep and Wahikuli Shallow) and the rest of the sites to the north. For the sites north of Kā‘anapali, waves approached the study area out of the northwest, becoming more shore-normal (westerly) closer to shore (fig. 12). At Kā‘anapali Deep, waves approached predominantly from the west, but the wave directionality also was highly variable and included longer-period swell from the southwest (figs. 10*D*, 11*D*, 12). At Wahikuli, waves approached the shoreline from the south (approximately shore normal; fig. 12). In general, significant wave heights increased to the north, with the largest waves recorded at Kahana Deep (figs. 10*B*, 12). Of the shallow sites, waves were consistently large at Māhinahina Shallow; however, the largest recorded wave height occurred at Honolua Shallow (H_s = 1.6 m; fig. 11*B*) on YD 379.5 during a notable long-period northerly swell event, during which period the farther-offshore buoy 51205 (at Pa‘uwela) recorded significant wave heights of 5.5 m and peak wave periods greater than 22 seconds. Only at Kahana Shallow was there a strong positive correlation between wave heights and water levels (correlation coefficient [r] = 0.7; p-value [p] << 0.005; degrees of freedom [df] = 3,406), indicating that waves here are depth-limited.

Table 7. Wave statistics for study sites offshore West Maui, Hawai‘i.

[Wave direction is direction from which wave originates. Abbreviations: m, meter; s, second; °, degree; σ, standard deviation; –, not determined]

Parameter	Mean ±1σ	Minimum	Maximum
Site: Honolua Shallow			
Height [m]	0.32±0.18	0.07	1.64
Period [s]	12.9±1.6	7.8	21.3
Direction [°]	308±38	–	–
Site: Kahana Deep			
Height [m]	0.77±0.30	0.27	1.97
Period [s]	11.3±2.0	3.1	17.8
Direction [°]	308±34	–	–
Site: Kahana Shallow			
Height [m]	0.43±0.09	0.19	0.75
Period [s]	9.6±3.1	5.1	21.3
Direction [°]	283±10	–	–
Site: Māhinahina Shallow			
Height [m]	0.61±0.22	0.22	1.37
Period [s]	11.7±2.4	5.1	21.3
Direction [°]	290±16	–	–
Site: Honokōwai Deep			
Height [m]	0.62±0.25	0.22	1.81
Period [s]	11.8±1.8	3.0	17.4
Direction [°]	305±32	–	–
Site: Honokōwai Shallow			
Height [m]	0.42±0.15	0.12	1.06
Period [s]	13.0±2.3	5.1	21.3
Direction [°]	289±16	–	–
Site: Kā‘anapali Deep			
Height [m]	0.50±0.12	0.25	1.2
Period [s]	11.6±2.4	3.0	20.4
Direction [°]	271±25	–	–
Site: Wahikuli Shallow			
Height [m]	0.39±0.10	0.17	0.85
Period [s]	13.2±2.1	5.1	21.3
Direction [°]	195±66	–	–

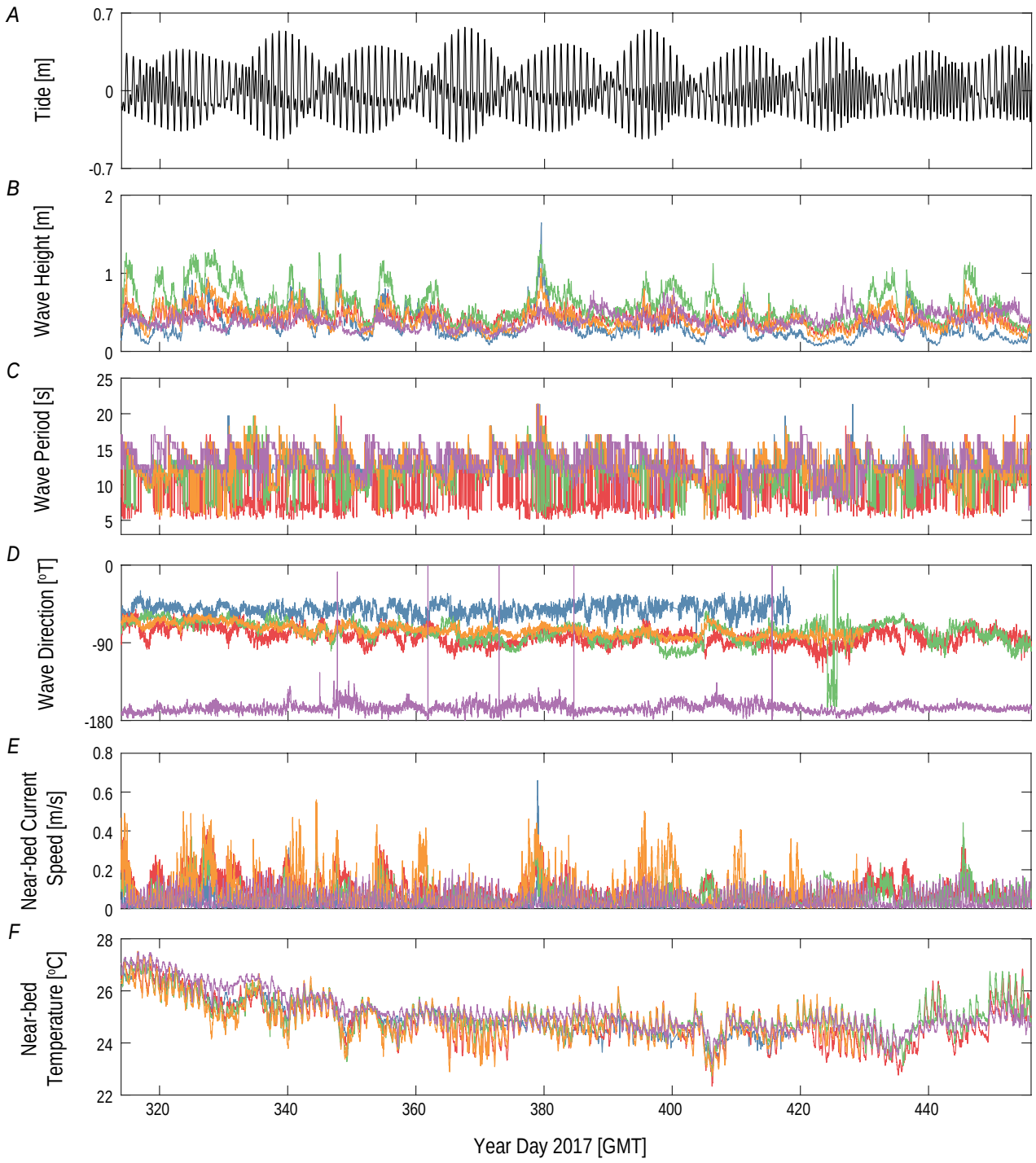


Figure 11. Time-series plots of oceanographic measurements during the study period from five shallow-water study sites. *A*, Tide water levels, in meters (m), from the Kahana Deep site. *B*, Significant wave height, in meters. *C*, Peak wave period, in seconds (s). *D*, Wave direction at peak period (direction of origination), in degrees clockwise from true north (°T). *E*, Near-bed current speed, in meters per second (m/s). *F*, Near-bed temperature, in degrees Celsius (°C). GMT, Greenwich mean time.

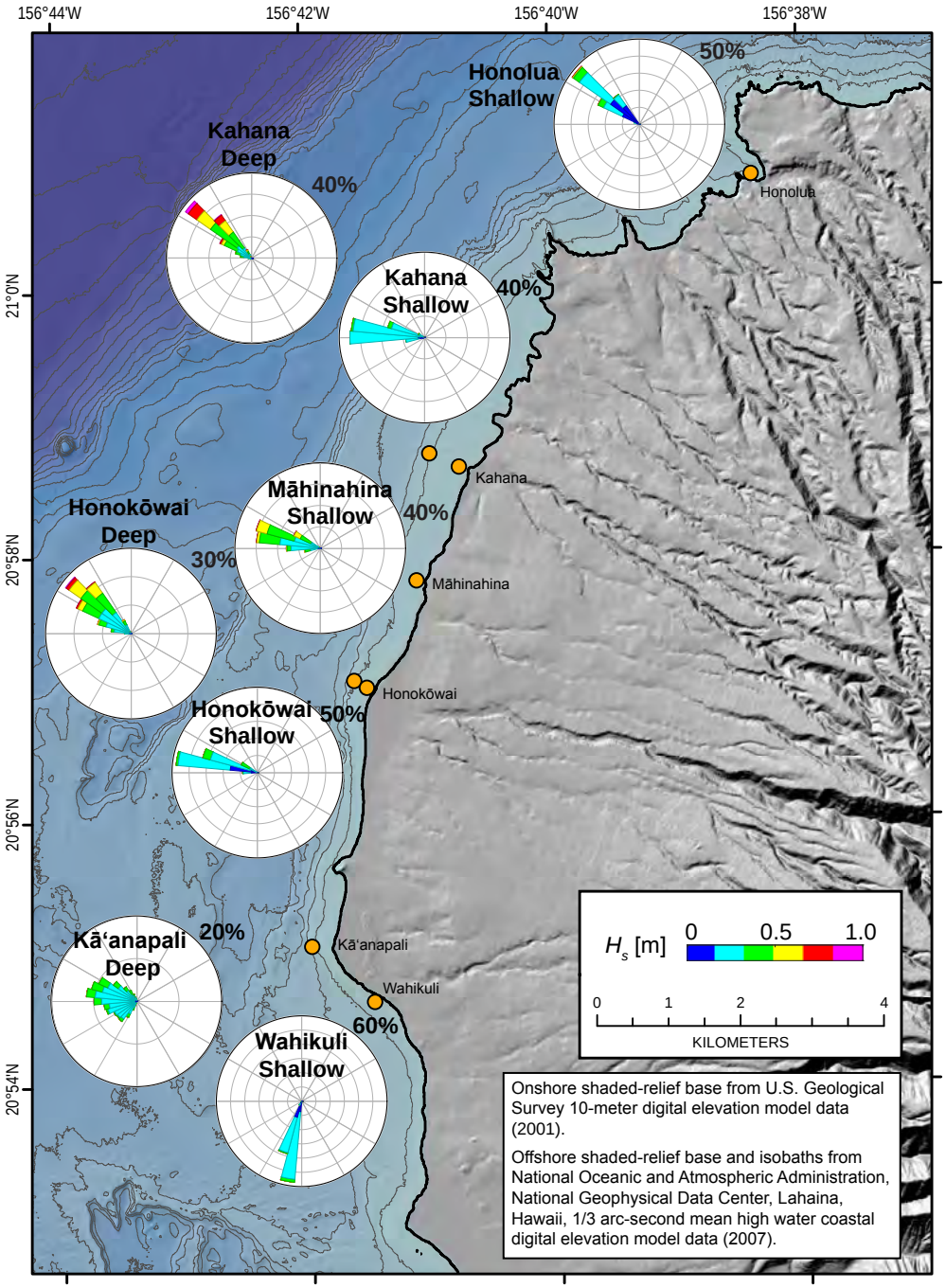


Figure 12. Map of West Maui study area and locations of study sites (orange points), showing directional wave histograms for each site (direction of origination). Rose diagram indicates percentage of total wave observations, with increments of 10 percent; percentage scale is shown for outermost ring. Colors on rose diagrams indicate measured significant wave heights (H_s), in meters (m), associated with each directional bin.

Currents

Mean current speeds and directions measured during the West Maui experiment are shown in figures 13–15, and statistics for each site are shown in table 8. Previous observations of current patterns in the study area determined that nearshore flows are controlled by prevailing northerly winds and waves, whereas currents farther offshore (fore-reef and deeper) are primarily controlled by tides and commonly occur in the opposite direction from the nearshore currents (Storlazzi and others, 2006). Our observations generally fit with this conceptual model of flow along the West Maui coastline, where deep sites are located within the transition zone between these two flow regimes (approximately from the 3- to 30-m isobaths) and shallow sites are well within the nearshore, wind-driven flow region.

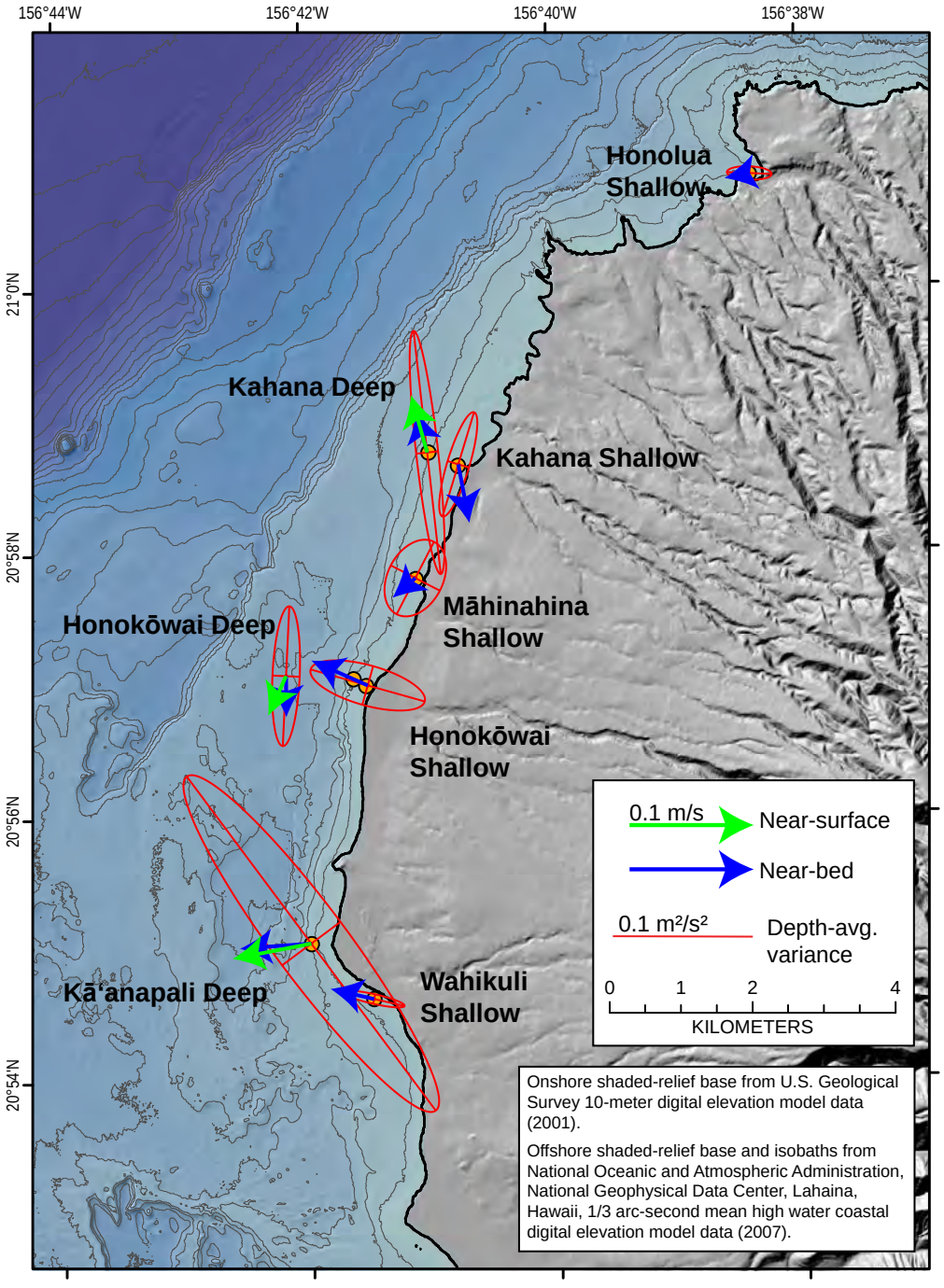


Figure 13. Map of West Maui study area showing mean near-surface and near-bed current velocities (arrows) with directions (direction of flow), in degrees from true north, and speeds, in meters per second (m/s), during the 2017–2018 experiment at the shallow and deep study sites. Also shown are the predominant axes of variance of the current velocities (red ellipses), in meters squared per second squared (m^2/s^2). Depth-avg., Depth-averaged.

The mean current direction at Kahana Deep was oppositely directed from the mean flow at the offshore site to the south, Honokōwai Deep (fig. 13). At Kahana Deep, the mean flow was 0.05 m/s toward the northwest (346 degrees from true north [°T]); at Honokōwai Deep, it was 0.03 m/s toward the south (192 °T); and at Kā‘anapali Deep, it was 0.09 m/s toward the west-southwest (246 °T) (fig. 13).

At all three deep sites, the near-surface and near-bed alongshore flows were highly correlated ($r > 0.90$, $p << 0.005$, $df = 10{,}222$), indicating minimal vertical current shear between near-surface and near-bed flows. However, compared to Kahana Deep and Kā‘anapali Deep, there was greater shear at Honokōwai Deep, where 38 percent of the record had rotation >45° from near-surface to near-bed flows, with a

Table 8. Ocean current statistics for study sites offshore West Maui, Hawai‘i.

[Direction is direction current flows toward. Minimum speed recorded at each site was 0.00 m/s. Abbreviations: m/meter; m/s, meter per second; °, degree; σ, standard deviation]

Water depth [m]	Mean speed ±1σ [m/s]	Mean direction [° true]	Maximum speed [m/s]
Site: Honolua Shallow			
4.7	0.02±0.03	259	0.53
Site: Kahana Deep			
3.2	0.20±0.12	344	0.64
8.7	0.15±0.09	345	0.47
Site: Kahana Shallow			
2.0	0.09±0.06	169	0.33
Site: Māhinahina Shallow			
2.3	0.06±0.06	228	0.42
Site: Honokōwai Deep			
3.9	0.13±0.08	204	0.52
9.4	0.08±0.05	180	0.33
Site: Honokōwai Shallow			
1.6	0.08±0.09	294	0.47
Site: Kā‘anapali Deep			
2.9	0.32±0.19	259	1.08
7.4	0.28±0.17	266	0.93
Site: Wahikuli Shallow			
3.5	0.05±0.04	283	0.19

mean change in flow direction of 50° (±46°). The correlation between the near-surface and near-bed cross-shore flows was only robust at Kā‘anapali Deep ($r = 0.90$, $p << 0.005$, $df = 10{,}222$), possibly indicating topographically controlled flow at this site, whereas the cross-shore flow at Kahana and Honokōwai may be primarily wave driven.

Current speeds at the deep sites were strongly controlled by tides, where greater speeds occurred during spring tide periods (fig. 10*E*). During ebb currents, flow was directed northward with greater speed than during flood currents, which had flow directed southward (fig. 14). The strongest offshore currents were at Kā‘anapali Deep, which was located 300 m directly offshore of Hanaka‘ō‘ō Point, likely intensifying flow there. Tidally driven flow is primarily alongshore and the depth-averaged alongshore flows were, on average, seven times greater at Kahana Deep, five times greater at Honokōwai Deep, and three times greater at Kā‘anapali Deep compared to depth-averaged cross-shore flow speeds.

Although offshore flow patterns were predominantly tidally driven, near-bed current speeds at the shallow study sites primarily were controlled by waves (fig. 11). However, the nearshore sites of Honolua, Kahana, and Honokōwai Shallows exhibit more cross-shore-directed near-bed flows (fig. 15). The energy density spectra for the predominant flow components further show robust peaks at the diurnal and semidiurnal (that is, tidal) frequencies for deep study sites, but at the shallow sites these peaks generally are weaker (fig. 16). We note that the diurnal peak also can capture energy from daily wind patterns. In the case of Honolua Shallow, there is no evidence of a periodic signal at any frequency, underscoring the sporadic nature of event-driven flows at this site (fig. 16*D*). Within Honolua Bay, the maximum near-bed flow (and the fastest flow measured at all nearshore sites) reached 0.70 m/s during the large wave event on YD 379.5 (January 13, 2018; fig. 11*E*), and this exceptional flow was directed out of the bay (276 °T). Except for this large wave event, near-bed flow at Honolua Shallow was relatively slow, with a mean ±1 standard deviation speed of 0.02±0.02 m/s and a maximum of only 0.30 m/s. We note that the Honolua Shallow site was placed on the south side of Honolua Bay and, thus, may be sensitive to wave direction into the bay.

For each shallow site, the relationship between waves and near-bed current speed was evaluated by finding the correlation coefficient between the low-pass filtered (period cut-off = 33 hours) significant wave heights and the similarly low-pass filtered near-bed flow speeds. The wave heights were low-pass filtered to remove the influence of tides on wave heights, which was most pronounced at Kahana Shallow. The correlation between wave heights and flow speeds was robust at Honolua Shallow ($r = 0.55$, $p << 0.005$, $df = 7{,}909$) and Honokōwai Shallow ($r = 0.64$, $p << 0.05$, $df = 8{,}331$), and moderate at Kahana Shallow ($r = 0.43$, $p << 0.05$, $df = 10{,}219$) and Māhinahina Shallow ($r = 0.49$, $p << 0.05$, $df = 10{,}219$), indicating that larger waves commonly coincide with stronger near-bed currents at these sites. However, there was no correlation between wave heights and flow speeds at Wahikuli Shallow, where near-bed currents appear to be primarily controlled by tides, with the greatest speeds occurring immediately after the daily highest high tide.

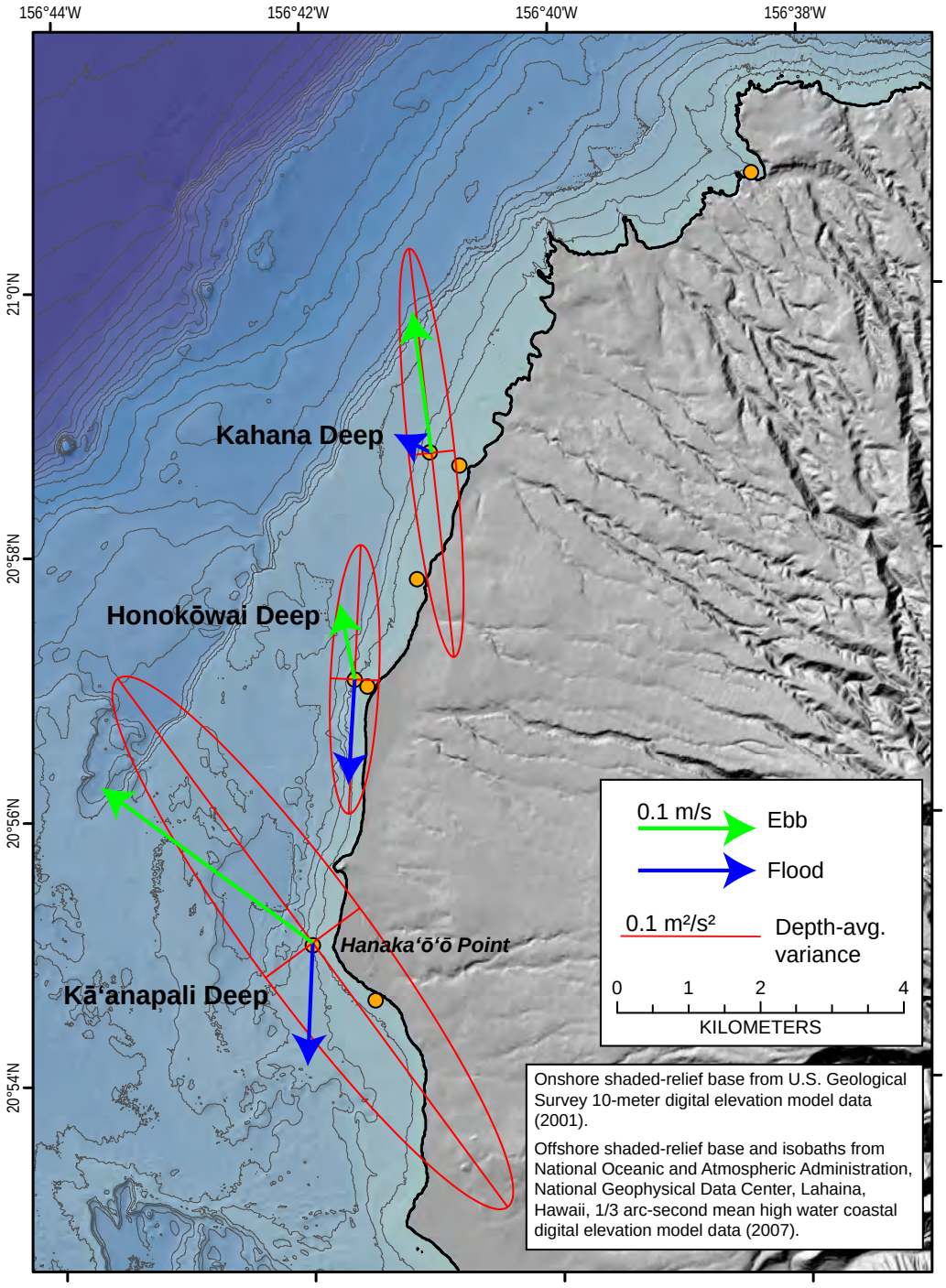


Figure 14. Map of West Maui study area showing mean near-surface current velocities (arrows) with directions (direction of flow), in degrees from true north, and speeds, in meters per second (m/s), at deep study sites during flood and ebb tides during the 2017–2018 experiment. Also shown are the predominant axes of variance of the current velocities (red ellipses), in meters squared per second squared (m^2/s^2). Near-surface velocity was not measured at the shallow study sites. Orange points show all (deep and shallow) study sites. Depth-avg., Depth-averaged.

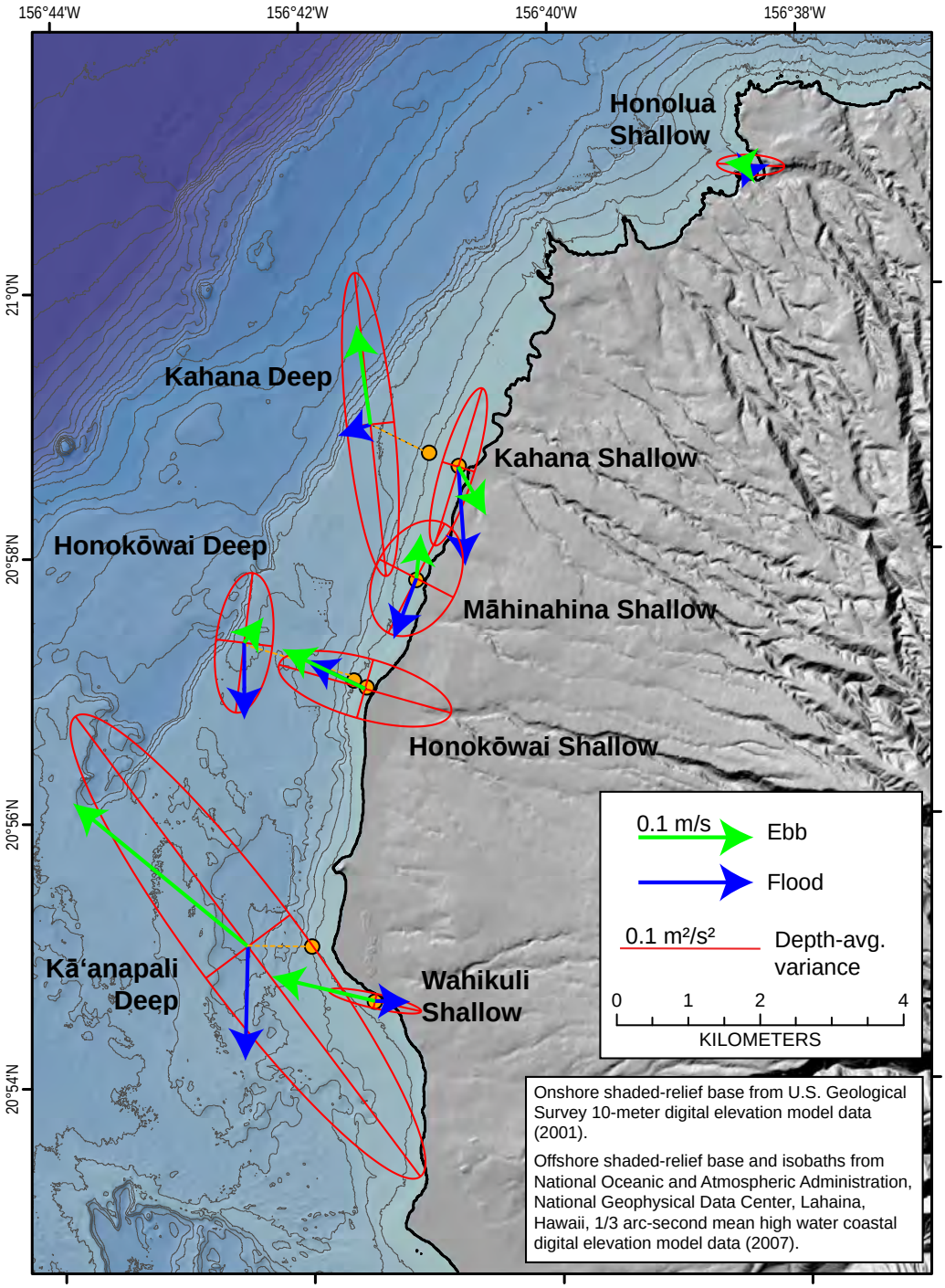


Figure 15. Map of West Maui study area showing mean (arrows) and variance (ellipses; in meters squared per second squared [m^2/s^2]) of near-bed current directions (direction of flow), in degrees from true north, and speeds, in meters per second (m/s), during flood and ebb tides during the 2017–2018 experiment at the shallow and deep study sites. Depth-avg., Depth-averaged.

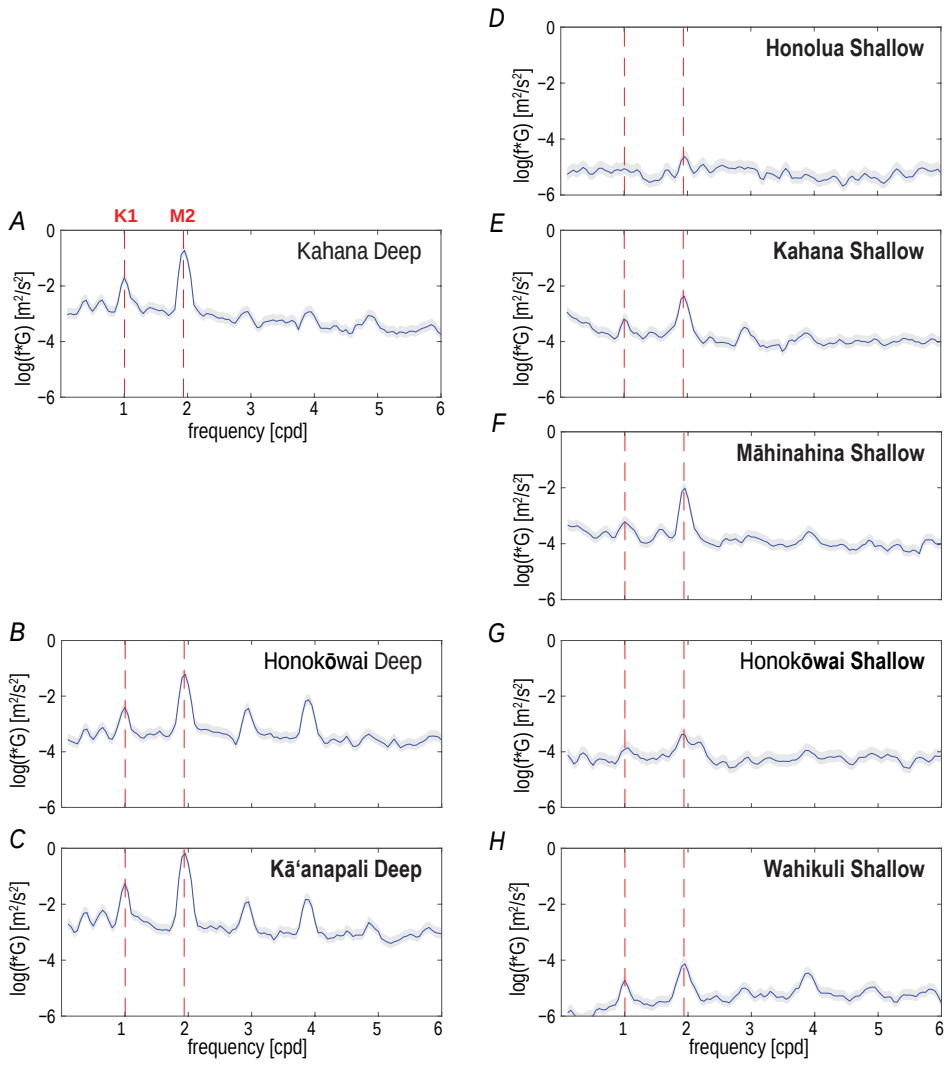


Figure 16. Energy density spectra plots of the predominant flow component from the deep (*A*, *B*, *C*) and shallow (*D*, *E*, *F*, *G*, *H*) study sites. Each graph displays variance-preserved energy density (G) of current velocity, in meters squared per second squared (m^2/s^2) on the log-scale y-axis, plotted according to frequency (f) as cycles per day (cpd) on the x-axis. The diurnal (K1) and semidiurnal (M2) tidal frequencies are indicated by dashed lines. The 95-percent confidence intervals are indicated by gray shading.

Near-Bed Temperature

Temperatures measured during the West Maui experiment are shown in figures 10*F* and 11*F*, and statistics are shown in table 9. Throughout the study period, near-bed temperatures decreased, from a maximum of 30.9 °C (at Kā‘anapali Deep on YD 319; fig. 10*F*) to a minimum of 22.3 °C (at Kahana Shallow on YD 406; fig. 11*F*). The two shallowest sites (Kahana and Honokōwai Shallows) exhibited daily decreases in temperature of up to 2.6 °C, possibly indicating the linkage between cooler, fresher water from stream discharge in the nearshore (Storlazzi and others, 2006). With the exception of Honolua Shallow, near-bed temperature fluctuated at both diurnal and semidiurnal periods at all shallow sites.

Table 9. Water temperature statistics for study sites offshore West Maui, Hawai‘i.

[m, meter; T, temperature; σ, standard deviation; °C, degree Celsius]

Site	Depth [m]	Mean T ±1σ [°C]	Minimum T [°C]	Maximum T [°C]
Honolua Shallow	4.7	25.0±0.8	23.3	27.0
Kahana Deep	10.2	24.8±0.8	23.1	27.0
Kahana Shallow	2.0	24.8±0.8	22.4	27.1
Māhinahina Shallow	2.3	25.0±0.7	22.8	27.2
Honokōwai Deep	10.4	24.9±0.8	22.8	27.2
Honokōwai Shallow	1.6	24.9±0.8	22.8	27.5
Kā‘anapali Deep	9.3	25.0±0.8	23.6	30.9
Wahikuli Shallow	3.5	25.2±0.8	23.2	27.3

Turbidity and Resuspension

To examine the conditions leading to enhanced near-bed turbidity, we binned the observations according to six different meteorological and oceanographic forcing conditions— trade winds and small waves (C1), Kona winds and small waves (C2), trade winds and large waves (C3), weak winds and large waves (C4), weak winds and small waves (C5), and a flood (that is, rain) event (C6) (fig. 17). Small waves were defined as waves with H_s < 1 m and weak winds were defined as wind speeds < 4 m/s. In order to account for the time lag of physical responses, we focused on selecting time periods for each condition that were at least one day long; an exception was made for C2 because the Kona wind events were often short-lived. The mean wind speeds and wave heights during these six forcing conditions are provided in table 10. These forcing classifications constitute 86 percent of the study period, with the other 14 percent representing forcing conditions that did not meet the classification criteria (denoted as “other” in fig. 17). The most frequent forcing condition was weak winds and small waves (C5, 40 percent), followed by trade winds and small waves (C1, 21 percent), trade winds and large waves

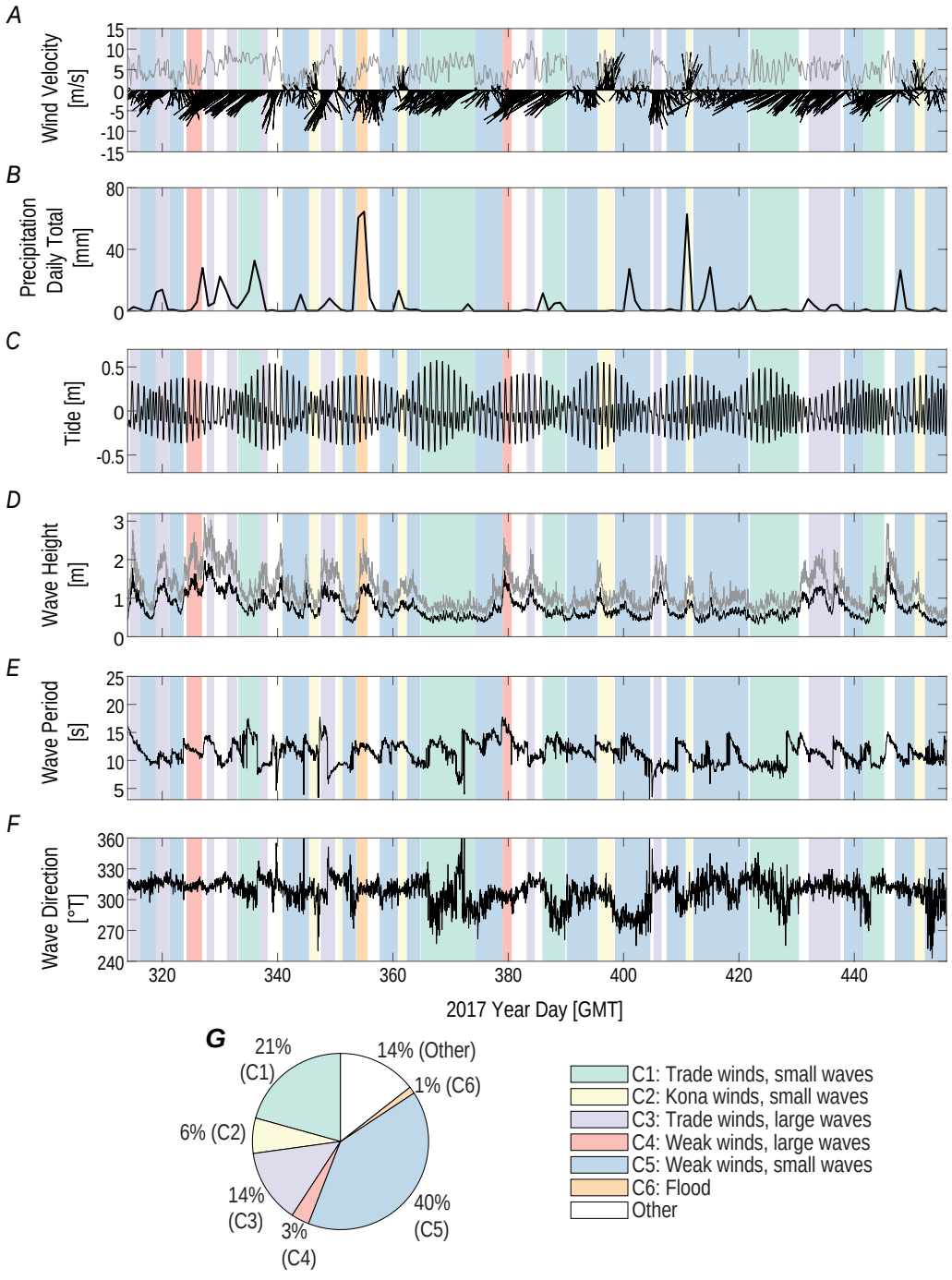


Figure 17. Time-series plots of meteorological and oceanographic conditions showing periods selected for each of the six forcing condition categories. *A*, Three-hour-averaged wind speed (gray line), in meters per second (m/s), and wind velocity (black line; direction of flow), in degrees clockwise from true north (north is up; length scales with wind speed), from National Oceanic and Atmospheric Administration (NOAA) buoy KLIH1 in Kahului Harbor. *B*, Total daily rainfall, in millimeters (mm), from the lower slope (Maui Cultural Lands) gage maintained by the West Maui Ridge-2-Reef Initiative. *C*, Tide height, in meters (m), from the Kahana Deep study site. *D*, Maximum (gray line) and significant (black line) wave heights, in meters, from the Kahana Deep study site. *E*, Peak wave period, in seconds (s), from the Kahana Deep study site. *F*, Wave direction at peak period, in degrees from true north (°T), from the Kahana Deep study site. *G*, Pie chart showing portions of the study period, in percentages, classified by different forcing conditions. GMT, Greenwich mean time.

(C3, 14 percent), Kona winds and small waves (C2, 6 percent), weak winds and large waves (C4, 3 percent), and the flood event (C6, 1 percent) (fig. 17*G*).

Statistics on turbidity for each site are given in table 11. The turbidity measurements are confined to time periods prior to the OBS sensor fouling, and the length of this period varies for each site; the last day of viable data is given in table 12. In general, turbidity was lower at deep sites and greater at shallow sites. The highest mean turbidity occurred at Māhinahina Shallow, followed by the Honokōwai and Honolua Shallow sites (fig. 18). The conditions that resulted in the greatest turbidity were conditions with large waves (C3 and C4), followed by strong trade winds (C1). Honolua Shallow showed a strong response under a flood event, but

Table 10. Meteorological and oceanographic conditions identified in measurements at study sites offshore West Maui, Hawai‘i.

[m, meter; m/s, meter per second; °T, degree from true north; H_s, significant wave height]

Condition	Total time [days]	Mean wind speed [m/s]	Mean wind direction [°T]	Mean H_s [m]	Mean wave direction [°T]
C0: Overall	142.0	4.7±2.7	32±41	0.8±0.3	308±13
C1: Trade winds, small waves	29.4	6.0±2.5	46±51	0.6±0.1	305±17
C2: Kona winds, small waves	9.2	4.9±2.5	184±27	0.7±0.1	307±10
C3: Trade winds, large waves	19.3	6.9±2.4	36±47	1.1±0.2	315±7
C4: Weak winds, large waves	4.7	2.9±1.9	347±35	1.3±0.2	309±6
C5: Weak winds, small waves	57.1	2.9±1.8	4±41	0.6±0.2	306±14
C6: Flood event	1.8	5.1±2.0	7±43	1.3±0.2	310±4

Table 11. Turbidity statistics for study sites offshore West Maui, Hawai‘i.

[m, meter; σ, standard deviation; NTU, Nephelometric Turbidity Unit]

Site	Depth [m]	Mean turbidity ±1σ [NTU]	Minimum turbidity [NTU]	Maximum turbidity [NTU]
Honolua Shallow	5.3	9.0±6.9	3.1	47.4
Kahana Deep	10.2	4.0±4.5	0.8	103.8
Kahana Shallow	2.6	16.2±10.6	4.7	46.7
Māhinahina Shallow	2.9	21.5±14.3	3.4	90.6
Honokōwai Deep	10.4	4.5±5.3	0.6	70.3
Honokōwai Shallow	2.2	17.6±10.7	3.2	76.5
Kā‘anapali Deep	9.3	0.9±1.4	0.3	30.9
Wahikuli Shallow	4.1	3.8±1.3	2.7	34.6

Table 12. Turbidity sensor operation time periods for study sites offshore West Maui, Hawai‘i.

[YD, year day; C0, overall; C1, trade winds, small waves; C2, Kona winds, small waves; C3, trade winds, large waves; C4, weak winds, large waves; C5, weak winds, small waves; C6, flood event]

Site	Last day of good data [YD]	Cumulative days for each condition						
		C0	C1	C2	C3	C4	C5	C6
Honolua Shallow	419	105.0	17.7	7.9	14.6	4.5	44.3	1.9
Kahana Deep	376	62.0	13.4	4.2	11.6	2.8	19.3	1.9
Kahana Shallow	327	13.0	0.0	0.0	4.3	2.8	5.1	0.0
Māhinahina Shallow	339	25.0	4.0	0.0	9.0	2.8	5.1	0.0
Honokōwai Deep	372	58.0	11.2	4.2	11.6	2.8	17.6	1.9
Honokōwai Shallow	337	23.0	3.8	0.0	7.6	2.8	5.1	0.0
Kā‘anapali Deep	457	142.0	29.9	9.8	20.2	5.0	57.3	1.9
Wahikuli Shallow	345	31.0	4.0	0.0	9.0	2.8	9.2	0.0

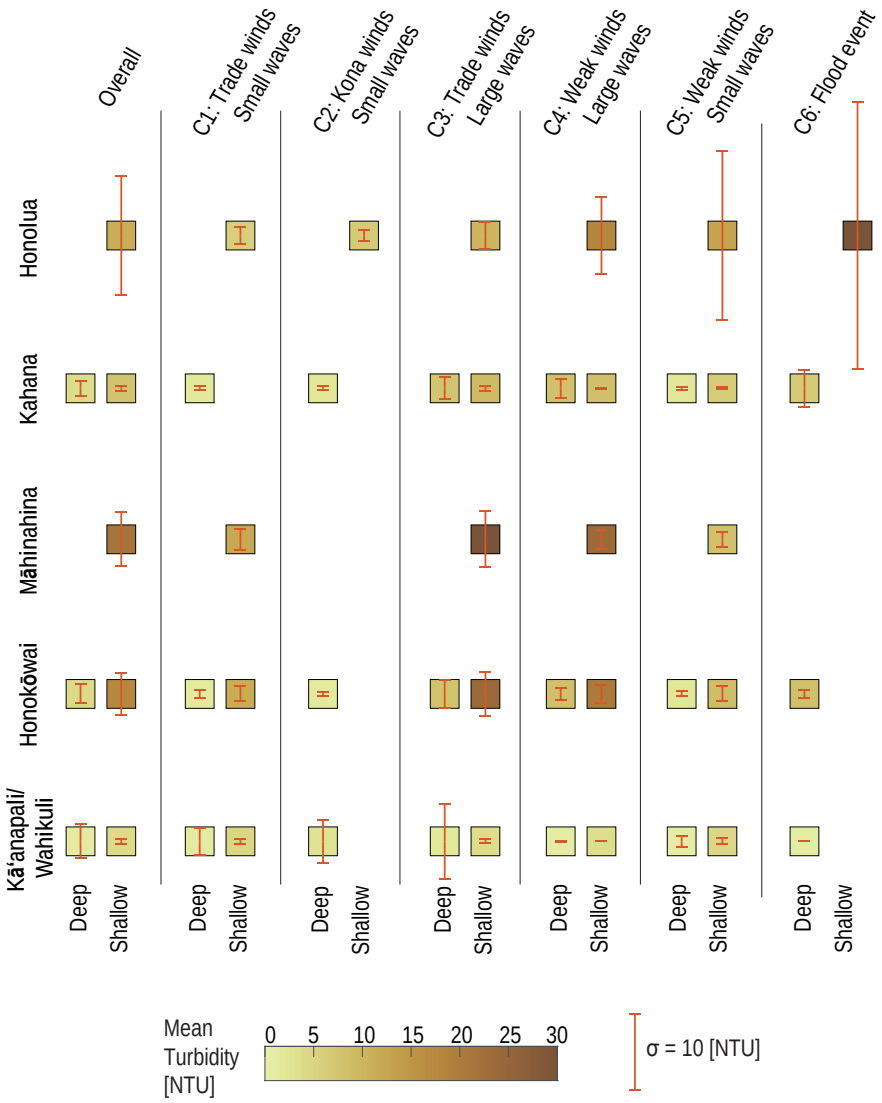


Figure 18. Diagram showing mean turbidity by site (rows) and by meteorological-oceanographic condition (columns), in Nephelometric Turbidity Units (NTU). Red error bars indicate ±1 standard deviation (σ). Deep and shallow sites are shown. For the bottom row, the offshore site is Kā‘anapali Deep and the nearshore site is Wahikuli Shallow.

it was the only nearshore site that had valid data during this event (fig. 18). Honolua Shallow also exhibited a much higher variability in near-bed turbidity than the other sites, pointing to the event-driven turbidity dynamics at this site.

The combined wave-current bed shear stress, τ_{wc}, was calculated as $\tau_{wc} = \rho \times u_{wc}$, where ρ is seawater density and u_{wc} is the combined wave-current friction velocity, which was determined using the Madsen (1994) iterative method. The relationship among wave-current bed shear stress, near-bed turbidity, and water levels was examined for each of the study sites (fig. 19). Sites along the middle section of the study area (Kahana Deep, Kahana Shallow, Māhinahina Shallow, Honokōwai Deep, and Honokōwai Shallow) show a similar pattern where increased bed shear stresses correlate with increased near-bed turbidity (fig. 19*A–B*, *E–G*). Water levels did not vary with either bed shear stress or turbidity, except in the case of Kahana Shallow, which also was the only site with depth-limited waves. Like at the other sites, turbidity at Honolua Shallow and Kā‘anapali Deep increases with greater bed shear stress, but unlike at the other sites, large turbidity events occur that are not driven by wave-current induced bed resuspension (fig. 19*C–D*). At Wahikuli Shallow, bed shear stresses generally were low, and no relationship to either turbidity or water levels was discernible (fig. 19*H*).

The combined wave-current bed shear stress also was used as a proxy for potential resuspension and sedimentation during the six forcing conditions. A critical shear stress threshold, $\tau_{crit} = 0.17$ newtons per square meter (N/m^2), was used to identify times when the combined wave-current bed shear stresses would likely erode fine-grained ($D <$ 0.063 mm) bed material and (or) keep suspended sediment in suspension. This τ_{crit} threshold was determined using a grain density of 2,650 kilograms per cubic meter (kg/m^3), which is characteristic of sediment originating from the West Maui watershed (Storlazzi and Jaffe, 2008). For each of the six forcing conditions, we determined the fraction of time that the wave-current bed shear stress exceeded the critical threshold (fig. 20). In general, large wave conditions (C3 and C4) and the flood event (C6) led to the greatest amount of resuspension. Under these conditions, bed shear stresses at

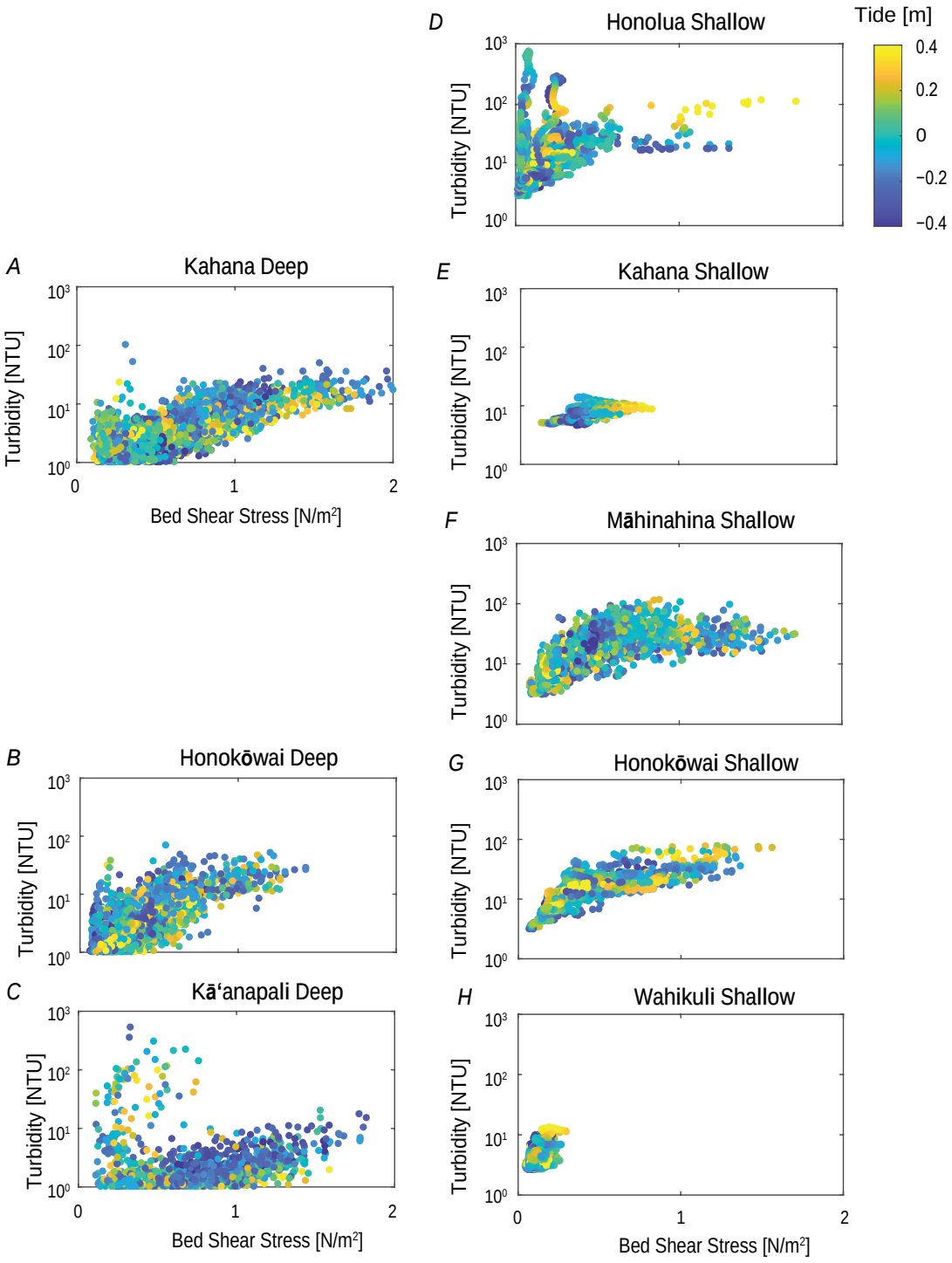


Figure 19. Scatter plots showing relationships between wave-current bed shear stress, in newtons per square meter (N/m²), and resulting near-bed turbidity, in Nephelometric Turbidity Units (NTU). Colors indicate water level (tide), in meters (m) above mean sea level.

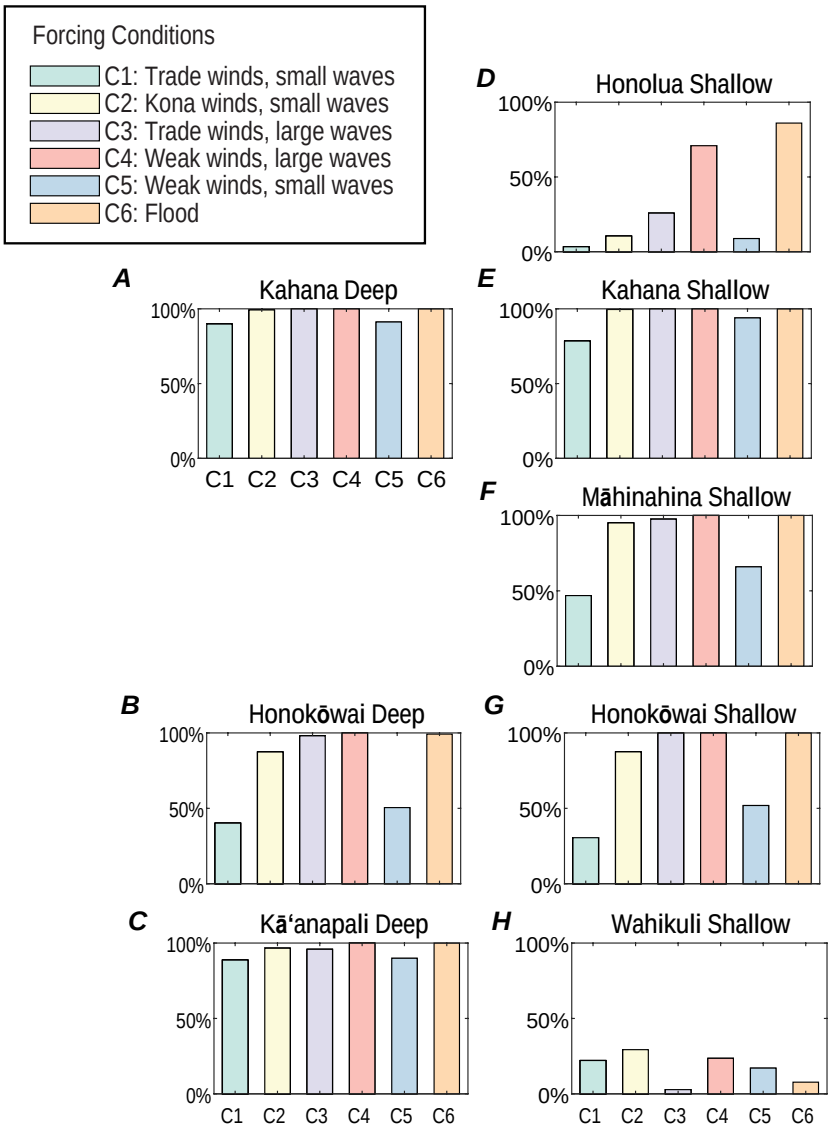


Figure 20. Bar graphs showing fraction of time, in percent, that wave-current bed shear stress exceeds the critical threshold for fine-grained, terrigenous sediment resuspension.

the Kahana, Māhinahina, and Honokōwai sites (both shallow and deep sites) exceeded the threshold for resuspension almost 100 percent of the time. Apart from Wahikuli Shallow, the trade winds and small waves (C1) and weak winds and small waves (C5) conditions resulted in the least amount of resuspension. The direction of winds and waves may influence the amount of resuspension, as the Kona winds and small waves condition (C2) generally led to a greater proportion of resuspension, despite waves remaining small. Bed shear stresses at Kahana Deep and Kā‘anapali Deep prevent settling of fine-grained sediment nearly all the time, regardless of forcing conditions. At Kā‘anapali Deep—an exposed site offshore of Hanaka‘ō‘ō Point—strong currents were a major contributor to bed shear stresses. Under resuspension conditions, the bed shear stress from currents alone was, on average, 83 percent (±1 standard deviation 64 percent) as strong as the wave-induced bed shear stress. In contrast, at Kahana Deep, the magnitude of the current-induced bed shear stress was, on average, 26 percent (±25 percent) of that from waves, and at Honokōwai Deep it was, on average, only 13 percent (±13 percent) the wave-induced bed shear stress.

The resuspension conditions at Honolua and Wahikuli Shallows differed from other study sites. At Honolua Shallow, bed shear stresses remained low except under unusual conditions, such as weak winds and large waves (C4), as well as the flood event (C6) (fig. 20*D*). This likely reflects the sensitivity of this site to wave direction. At Wahikuli Shallow, very little resuspension occurs, regardless of the oceanographic conditions, but the greatest resuspension occurs under Kona winds and small waves (C2) (fig. 20*H*). This is

likely because Wahikuli Shallow is more exposed to southerly winds and waves and is mostly protected from waves out of the north and northwest.

Taking the turbidity and bed shear stress patterns together, Kahana Deep, Kahana Shallow, and Kā‘anapali Deep are sites where bed shear stresses generally remain sufficiently high to prevent settling of fine-grained, terrigenous sediment. At Māhinahina Shallow, Honokōwai Shallow, and Honokōwai Deep, Kona winds, large waves, and flood events (C2, C3, C4, and C6) result in resuspension conditions, however, these conditions occur infrequently (approximately 24 percent of the time during the study). Under the more prevalent conditions of trade winds or weak winds and small waves (C1 and C5), bed shear stresses at Māhinahina Shallow, Honokōwai Shallow, and Honokōwai Deep exceed the threshold for resuspension about one-half the time. In addition, mean near-bed turbidity was highest overall at Māhinahina and Honokōwai Shallows, suggesting that, though it is unclear if sedimentation is a concern at these sites, the suspended-sediment concentrations may be elevated and chronic. Honolua and Wahikuli Shallows are sites that experience relatively low suspended-sediment concentrations in the water column but may be more prone to sedimentation. For Honolua Shallow, turbidity events coincide with flood events, but, under typical conditions (C1 and C5), resuspension rarely occurs (<25 percent of the time), indicating this material may not be efficiently removed from reefs. For Wahikuli Shallow, both turbidity and the potential for resuspension are relatively low.

Modeled Sediment Transport

The models were used to investigate the varying effects that individual and combined stream sediment plumes have on different reef areas along the West Maui coastline. Here, two major effects to corals from terrestrial-derived sediment are considered—sediment settling on corals and light attenuation from increased turbidity. To address the effect of terrestrial sediment settling on reefs, we examined the amount of net sedimentation (as net sediment mass deposited per unit area) during the simulation period. To address the effect of turbidity in the water column from suspended terrestrial sediment, we examined both the concentration of suspended sediment present in the water column (as depth-averaged concentrations per unit area) as well as the fraction of sunlight that reaches the seabed (as percentage of surface irradiance). We examined the temporal and spatial patterns of these flood-driven sediment effects on reefs and which stream outfalls were the primary sources of that sediment. We then investigated these patterns during simulated rainfall-driven flood event scenarios to examine how different meteorological and oceanographic conditions affect corals. Lastly, we compared two watershed scenarios—Baseline and Restoration scenarios—to assess the potential effects of restoration measures on mitigating the negative effects of terrestrial sediment on nearshore coral reefs.

Temporal Patterns

To capture how the terrestrial sediment settlement and water column concentrations vary with time, we focused on three temporal “snapshots” from the 10-day simulation: (1) the day of the flood (day 0), (2) 1 day post-flood (day 1), and (3) 7 days post-flood (day 7).

Sedimentation.—Sedimentation patterns during and after flood events varied among the different reefs (fig. 21*A–D*). The Honolua reef received most of its sedimentation coincident with the flood (day 0). This is likely due to the proximity of the reef to the Honolua Stream outfall; the sediment load from Honolua Stream has minimal transit time to reach the adjacent reef. Both the Honolua and Wahikuli reefs are relatively sheltered (behind headlands) and, thus, were only affected by sedimentation sourced from their respective single stream outfalls located at the shoreline. Some reefs, such as Māhinahina and Honokeana, were not affected by sedimentation until at least one day after a flood event. These also were the reefs whose flood-driven sedimentation was sourced from several different streams. The Kapalua reef experienced negligible sedimentation. The effect of large waves coinciding with flood events also varied by reef (fig. 21*B*, *D*). At Honolua and Wahikuli reefs, large waves resulted in decreased sedimentation on days 1 and 7, but hardly any change in initial sedimentation on day 0. At Honokeana reef, large waves nearly eliminated any sedimentation. In contrast, sedimentation at Māhinahina and Honokōwai reefs actually increased under large waves. The effects of watershed restoration measures were quantified by examining the difference between the Baseline and Restoration scenarios (fig. 21*E–F*). The greatest reduction of sedimentation from restoration occurred at the Honokeana, Māhinahina, and Honokōwai reefs, generally in the days following the flood event (days 1 and 7; fig. 21*E–F*).

Suspended-Sediment Concentration.—The depth-averaged suspended-sediment concentration (SSC) present in the water column over each reef also was examined on days 0, 1, and 7 post-flood (fig. 22*A–22D*). The source of SSC over reefs showed similar patterns to that of sedimentation. Most of the SSC over Honolua and Wahikuli reefs originated from nearby Honolua and Wahikuli Stream outfalls, respectively, whereas SSC at the Honokeana, Māhinahina, and Honokōwai reefs was sourced from multiple streams. SSC was negligible at Kapalua reef. SSC for most reefs was highest on day 0, except for Honokeana, for which it was highest on day 1. The Honolua reef experienced the highest SSC, which was sixfold greater than at other reefs. For most reefs, there was no discernible effect of large waves coincident with the flood (fig. 22*B*, *D*); the only meaningful difference occurred at Honokeana reef, which experienced a decrease in SSC in the Flood+Waves scenario. The effects of the Restoration scenario on SSC were small at Honokeana and Honokōwai reefs in the Flood Only scenario (fig. 22*E*) and further decreased under the Flood+Waves scenario (fig. 22*F*).

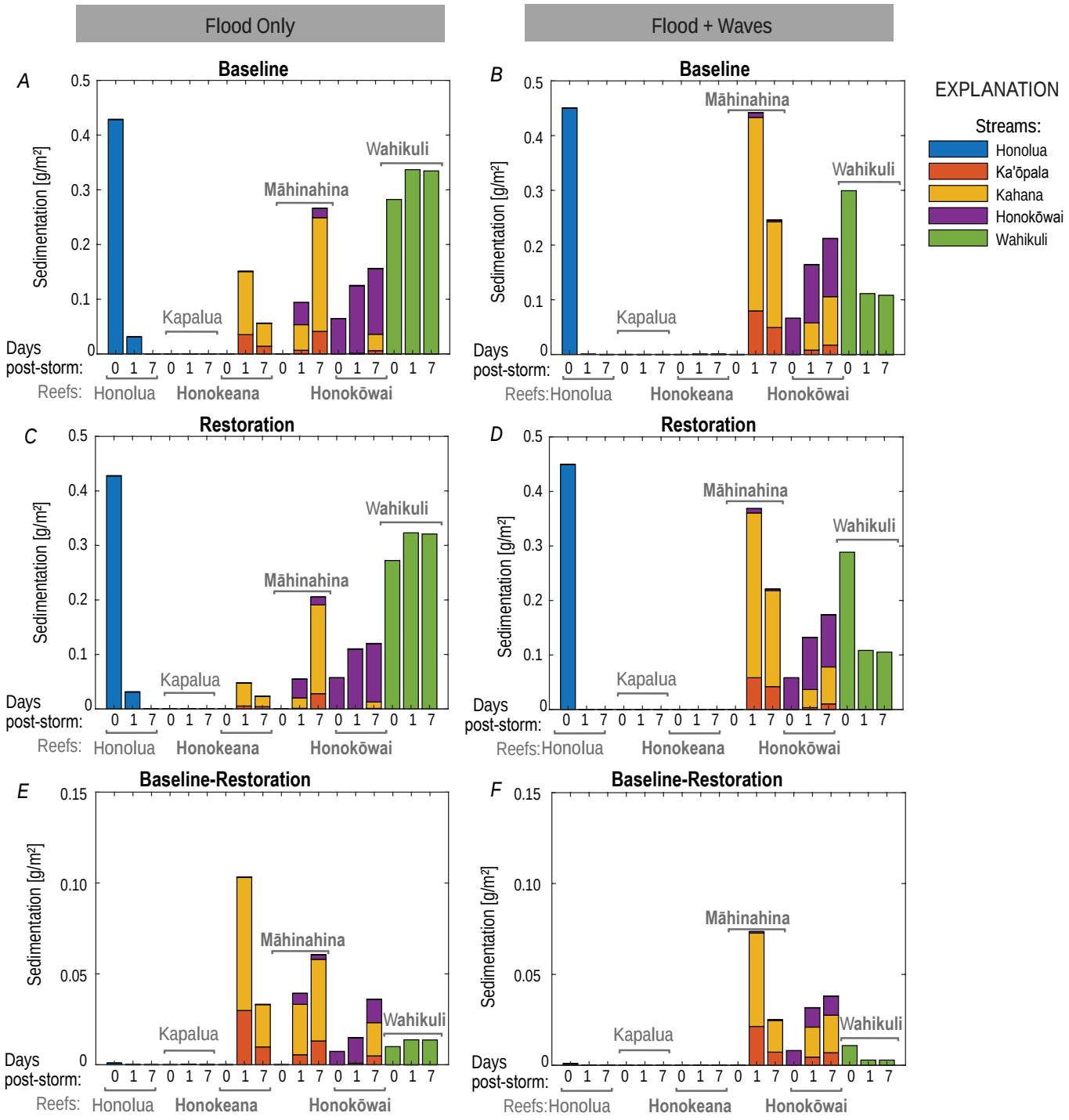


Figure 21. Bar graphs showing amount of sedimentation (in grams per square meter [g/m²]) on the six reef areas (gray text and brackets) for the Flood Only (*A*, *C*, *E*) and Flood+Waves (*B*, *D*, *F*) conditions. Sedimentation is shown for three times—day 0 of the flood event, day 1 post-flood, and day 7 post-flood. *A, B*, Baseline scenarios. *C, D,* Restoration scenarios. *E, F*, Difference between Baseline and Restoration scenarios. Colors show stream source of sediment.

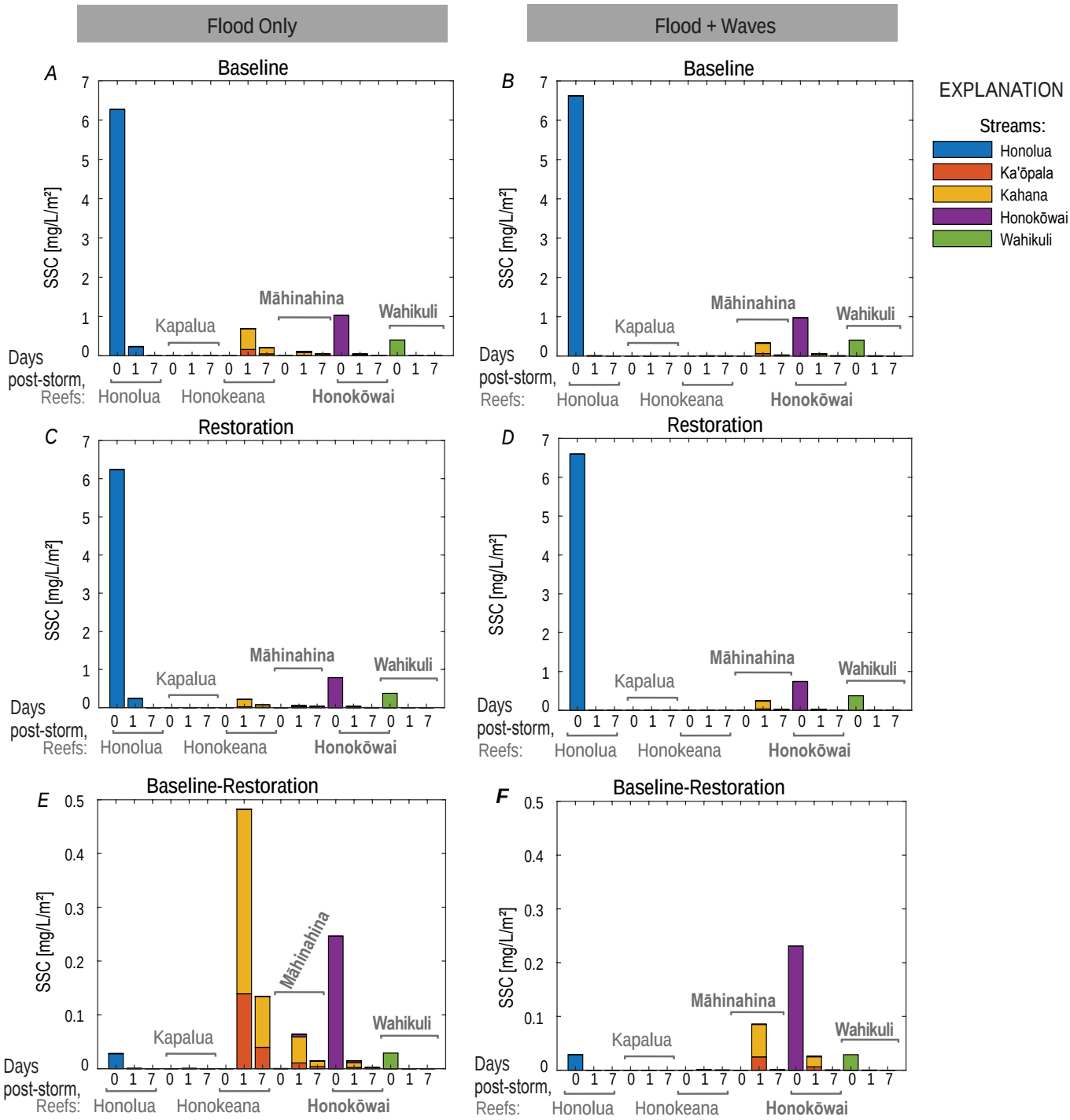


Figure 22. Bar graphs showing amount of depth-averaged suspended-sediment concentration (SSC; in milligrams per liter per square meter [mg/L/m^2]) on the six reef areas (gray text and brackets) for the Flood Only (*A*, *C*, *E*) and Flood+Waves (*B*, *D*, *F*) conditions. SSC is shown at three times—day 0 of the flood event, day 1 post-flood, and day 7 post-flood. *A, B*, Baseline scenarios. *C, D*, Restoration scenarios. *E, F*, Difference between Baseline and Restoration scenarios. Colors show stream source of sediment.

Spatial Patterns

Sedimentation.—Spatial patterns of total sedimentation on the seabed 7 days post-flood are shown for each model scenario in figure 23 (see appendix 10 for larger versions of each map in fig. 23). Sedimentation on the seabed and reefs throughout the West Maui study area 7 days post-flood show somewhat consistent spatial patterns across the different flood and restoration scenarios (fig. 23*A–D*). We identified four primary regions of sedimentation—(1) inshore of the Māhinahina reef, (2) along the offshore boundary of the Māhinahina and Honokōwai reefs, (3) within the most protected part of the Wahikuli reef, and (4) a broad patch farther offshore, beyond the reef areas.

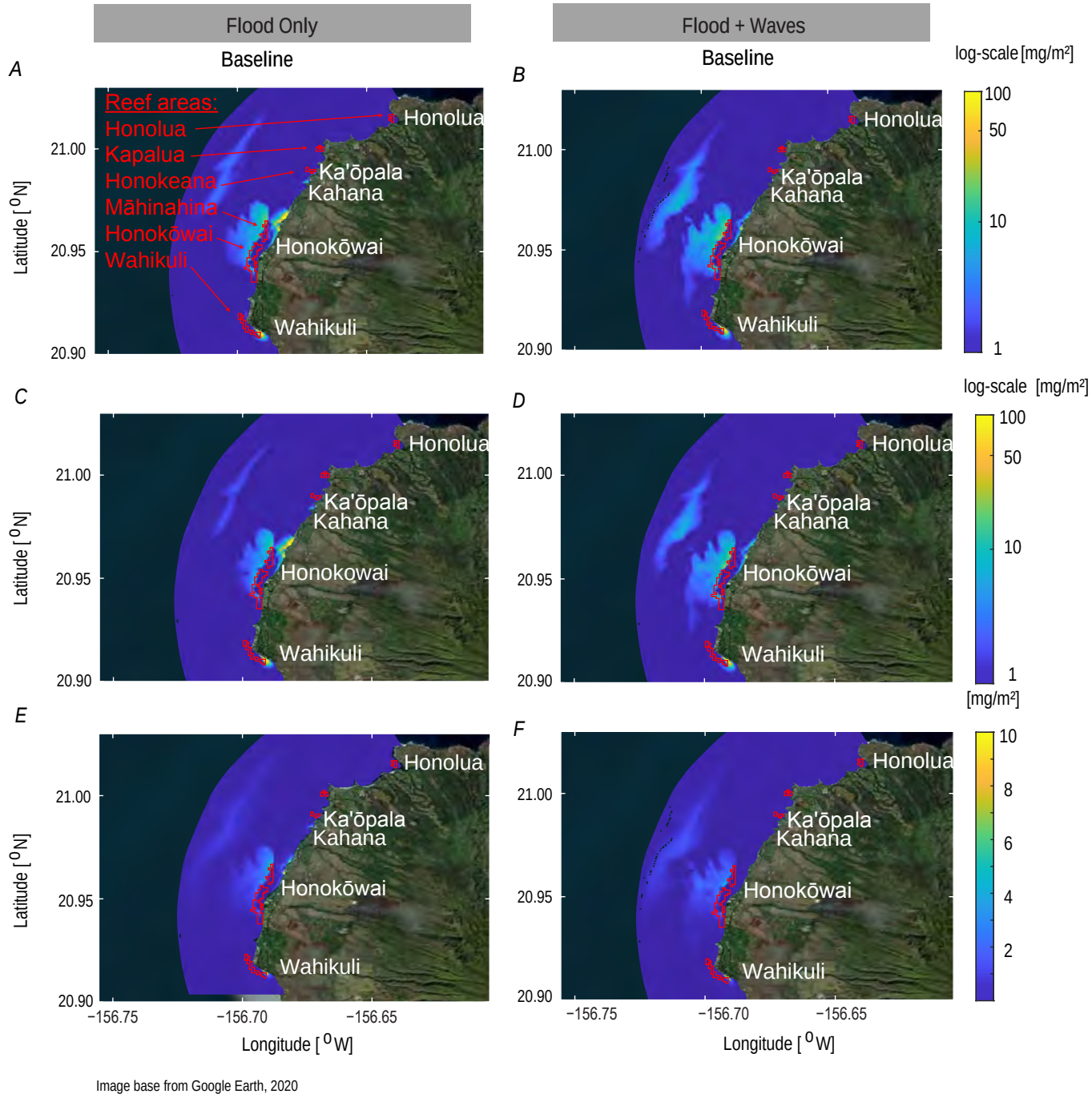


Figure 23. Maps of West Maui study area showing total amount of sedimentation (in milligrams per square meter [mg/m²]) at the end of model simulations (day 7 post-flood) for Flood Only (*A*, *C*, *E*) and Flood+Waves (*B*, *D*, *F*) scenarios. Stream outfall locations are labeled in white and reef areas are outlined and labeled in red. *A*, *B*, Baseline scenarios. *C*, *D*, Restoration scenarios. *E*, *F*, Difference between Baseline and Restoration scenarios. Note total sedimentation is shown with a log scale in parts *A–D* and a linear scale in parts *E–F*. See appendix 10 for larger versions of these maps.

Nearshore sedimentation is greater under the Flood Only scenario (fig. 23*A, C*), whereas far offshore sedimentation increases under the Flood+Waves scenario (fig. 23*B, D*). The greatest reduction in sedimentation in the Restoration scenario occurred for the region along the offshore boundary of the Māhinahina and Honokōwai reefs (fig. 23*E*). With the inclusion of large waves during the flood event, the Restoration scenario only results in a small decrease in sedimentation in the nearshore Wahikuli reef area (fig. 23*F*, appendix figure 10.3*B*). The stream outfall source of sedimentation was identified for deposited sediment greater than 3 milligrams per square meter (mg/m^2) (fig. 24; see appendix 11 for larger versions of each map in fig. 24). The patch of sediment inshore of the Māhinahina reef originated from the Ka‘ōpala and Kahana Streams. The patch of sediment along the offshore boundary of the Māhinahina and Honokōwai reefs was sourced from Ka‘ōpala, Kahana, and Honokōwai Streams. The sediment patch on the southmost section of the Wahikuli reef originated from Wahikuli Gulch. With the addition of large waves during the flood event, the broad patch located farther offshore is composed of sediment from the Ka‘ōpala, Kahana, and Honokōwai Streams.

Suspended-Sediment Concentrations (SSC).—The effects of suspended sediment in the water column were evaluated spatially by examining the average fraction of surface irradiance that reached the seabed; this metric also is referred to as light attenuation (fig. 25; see appendix 12 for larger versions of each map in fig. 25); small percentages

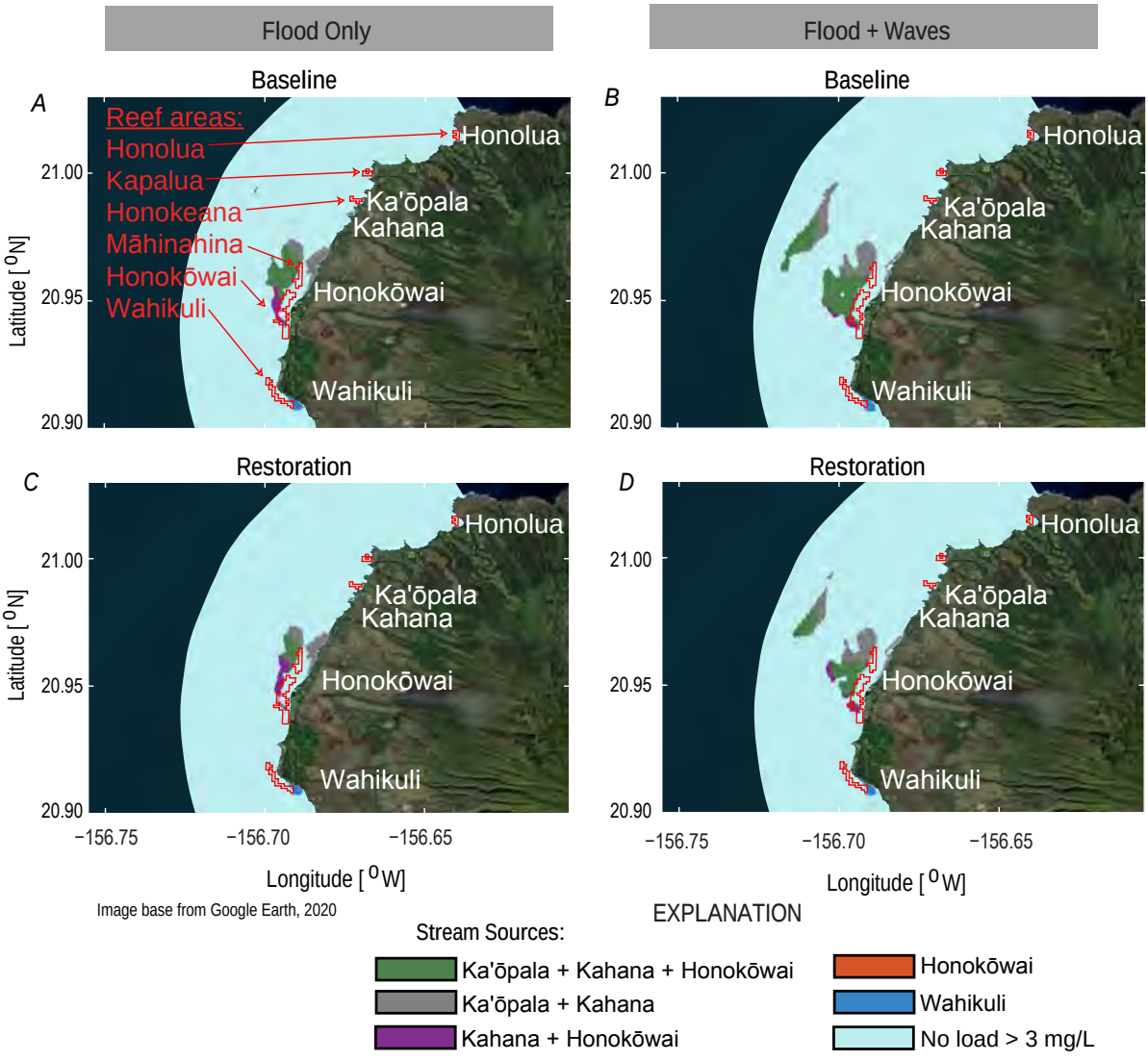


Figure 24. Maps of West Maui study area showing stream sources for total sedimentation at the end of model simulations (day 7 post-flood) for Flood Only (*A*, *C*) and Flood+Waves (*B*, *D*) scenarios. Stream sources only shown for total sedimentation greater than 3 milligrams per square meter (mg/m^2). Stream outfall locations are labeled in white and reef areas are outlined and labeled in red. *A, B*, Baseline scenarios. *C, D*, Restoration scenarios. See appendix 11 for larger versions of these maps. mg/L, milligrams per liter.

indicate very little light reaching the seabed. In contrast to the sedimentation spatial patterns shown in figure 23, the greatest amount of light attenuation caused by SSC occurred along the coastline, primarily between the Māhinahina and Honokeana reefs (fig. 25*A*, *C*). With the addition of large waves, nearshore turbidity and thus light attenuation is largely decreased (fig. 25*B*, *D*). Notably, the Restoration scenario decreases light attenuation (indicated by an increase in the amount of surface irradiance reaching the bed) in the nearshore region by as much as 40 percent (fig. 25*E*). We note, however, that this region is not within the perimeters of the reef areas. Because the inclusion of larger waves already decreases the degree of light attenuation caused by SSC, the Restoration scenario has a smaller effect (fig. 25*F*).

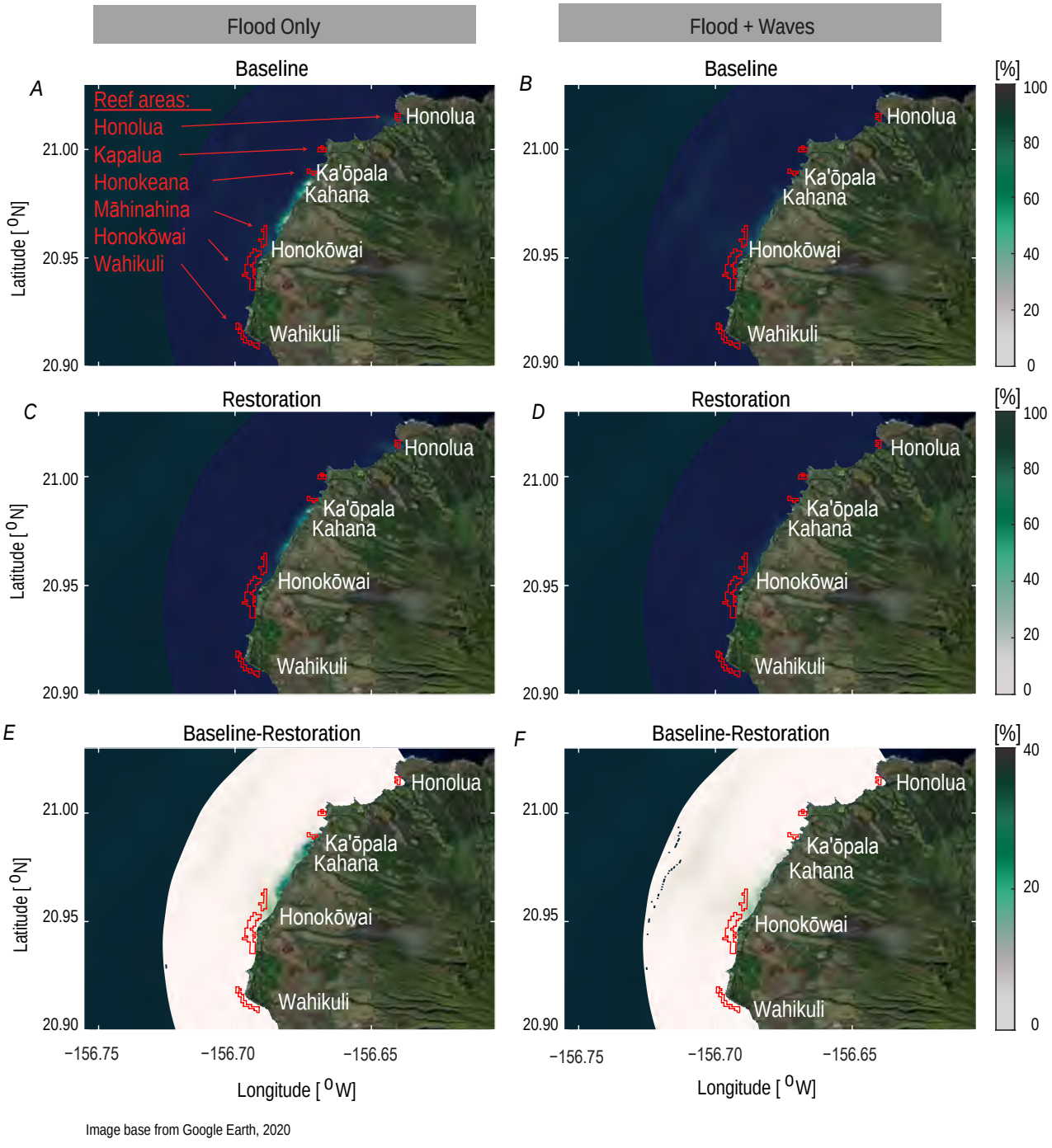


Figure 25. Maps of West Maui study area showing fraction of surface irradiance that reaches the seabed (averaged over entire model simulation), in percent, for Flood Only (*A*, *C*, *E*) and Flood+Waves (*B*, *D*, *F*) scenarios. Small percentages indicate very little light reaching the seabed. Stream outfall locations are labeled in white and reef areas are outlined and labeled in red. *A*, *B*, Baseline scenarios. *C*, *D*, Restoration scenarios. *E*, *F*, Difference between Baseline and Restoration scenarios. See appendix 12 for larger versions of these maps.

Exposure

The effects of sediment from stream outfalls on reefs also were examined by simulating the exposure of each reef to high sedimentation and SSC. The exposure was quantified by fraction of time during each simulation day that a reef experienced levels of sedimentation greater than 10 mg/m^2 of reef area and SSC greater than 10 milligrams per liter per square meter (mg/L/m^2) of reef area. The exposures of the reefs to low levels of sedimentation (>1 mg/m^2) and low SSC (>1 mg/L/m^2) also are shown in appendix 13.

Sedimentation.—Under baseline watershed conditions, a flood event with small waves resulted in reefs being exposed to deposited sediment exceeding 10 mg/m^2 less

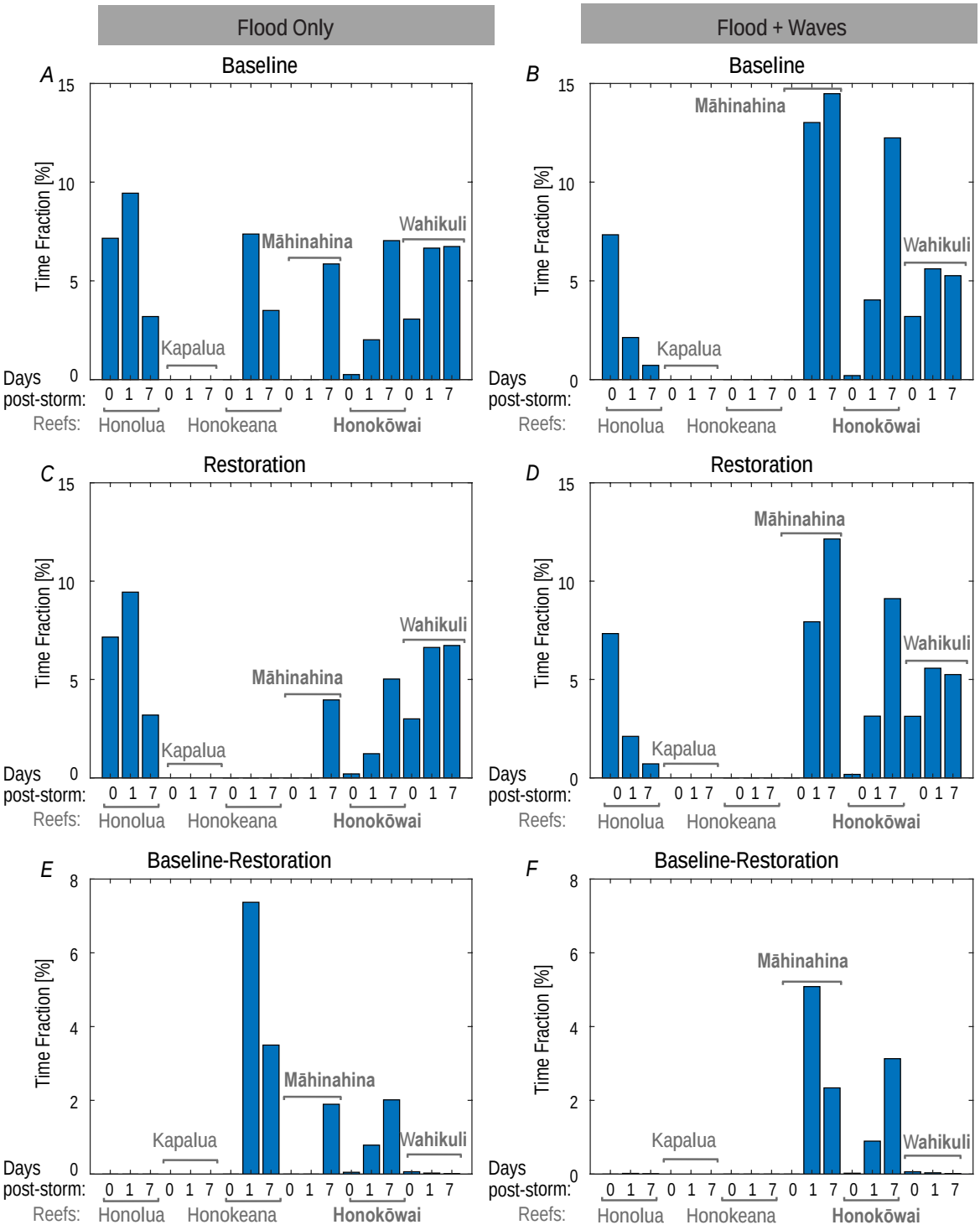


Figure 26. Bar graphs showing fraction of time (in percentage of total flood simulation time for a given day) reefs are exposed to sedimentation above 10 milligrams per square meter of reef area for each of the six reefs (gray text and brackets) for the Flood Only (*A*, *C*, *E*) and Flood+Waves (*B*, *D*, *F*) scenarios. Fraction of time is shown for three time steps—day 0 of the flood event, day 1 post-flood, and day 7 post-flood. *A*, *B*, Baseline scenarios. *C*, *D*, Restoration scenarios. *E*, *F*, Difference between Baseline and Restoration scenarios.

than 10 percent of the time, and most reefs experienced the highest exposure on days 1 or 7 post-flood (fig. 26*A*). With the inclusion of large waves (Flood+Waves scenario), sedimentation exposure decreased at Honolua reef, particularly on days 1 and 7 post-flood, and exposure at Honokeana reef did not occur (fig. 26*B*). In contrast, exposure at Māhinahina and Honokōwai reefs nearly doubled in the Flood+Waves scenario. With watershed restoration, the greatest reduction in sedimentation exposure under small waves (Flood Only scenario) occurred at the Honokeana reef (fig. 26*C*, *E*),

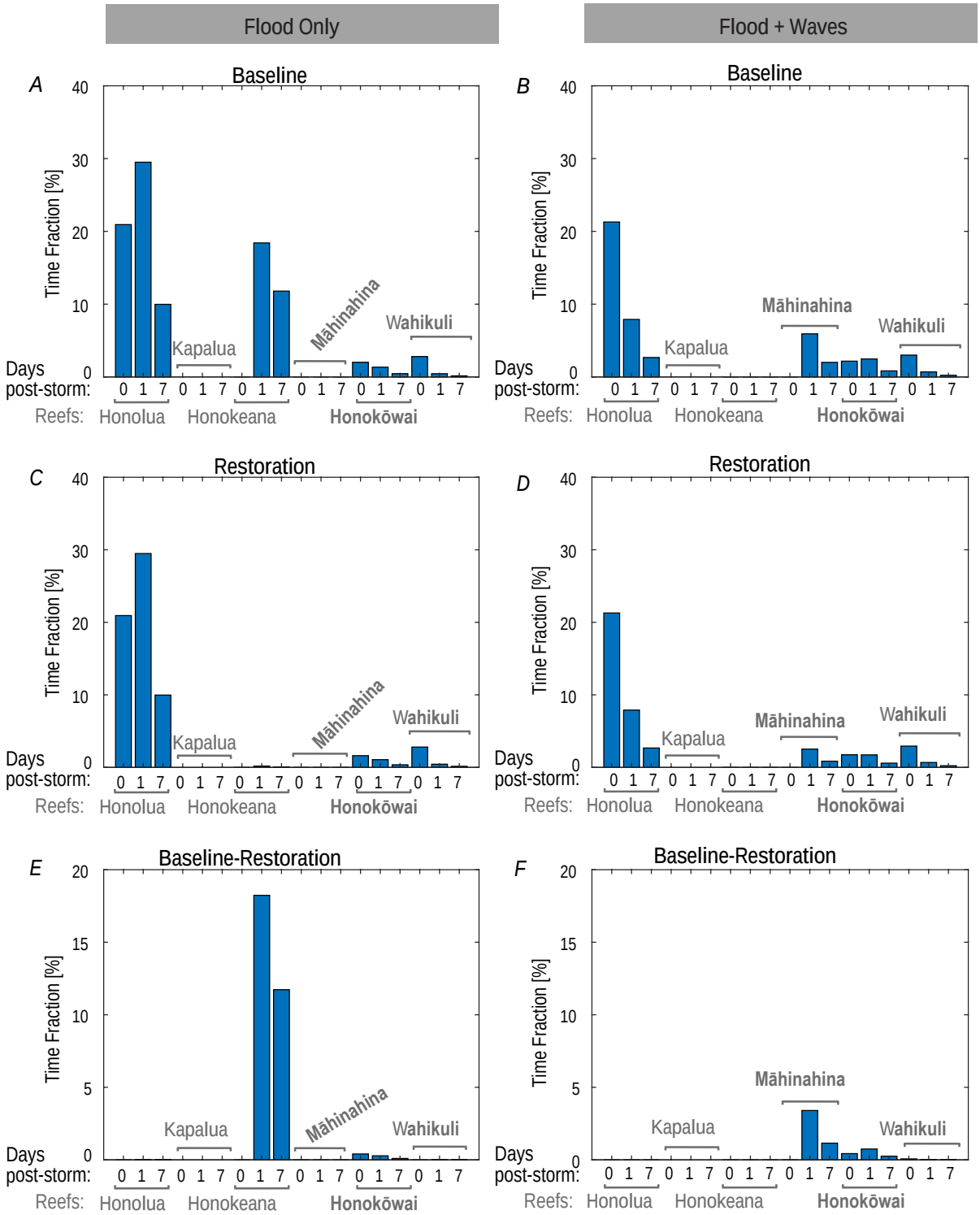


Figure 27. Bar graphs showing fraction of time (in percentage of total flood simulation time for a given day) reefs are exposed to suspended-sediment concentrations (SSC) above 10 milligrams per liter per square meter of reef area for each of the six reef areas (gray text and brackets). Fraction of time is shown for three time steps—day 0 of the flood event, day 1 post-flood, and day 7 post-flood. *A*, *B*, Baseline scenarios. *C*, *D*, Restoration scenarios. *E*, *F*, Difference between Baseline and Restoration scenarios.

whereas the greatest reduction during flood events with large waves occurred at Māhinahina reef (fig. 26*D, F*).

Suspended-Sediment Concentrations (SSC).—Under the Baseline and Flood Only scenario, the Honolua reef was exposed to SSC exceeding 10 mg/L/m² approximately 20 percent of the time on day 0 of the flood event, (fig. 27*A*). The Honokeana reef had moderate exposures of about 18 percent of the time on day 1 and about 13 percent of the time on day 7 post-flood. With the inclusion of large waves, the exposures at these reefs were substantially decreased, by over one-half at Honolua (for day 1 post-flood) and entirely eliminated at Honokeana reef (fig. 27*B*). In contrast, the exposure of Māhinahina reef to high SSC changed from negligible in the Flood Only scenario to about 5 percent of the time in the Flood+Waves scenario (on day 1 post-flood). Under the Flood Only scenario, greatest reduction in SSC exposures under the Restoration scenario occurred at the Honokeana reef, where exposure levels were almost entirely reduced (fig. 27*C, E*). Under the Flood+Waves scenario, the Restoration scenario only had a small decrease from the Baseline scenario at Māhinahina reef, and negligible effect at other reefs (fig. 27*D, F*).

Discussion

Reef Summaries

This section summarizes the modeling results for each of the reef areas: Honolua, Kapalua, Honokeana, Māhinahina, Honokōwai, and Wahikuli (tables 13–18). For each reef area, the stream source or sources, resulting total amount of sedimentation and suspended sediment concentrations, and exposure of the reefs due to sedimentation and suspended sediment concentrations are described for different watershed and oceanographic conditions. The first condition listed is the Baseline watershed condition under the Flood Only scenario ("Baseline" column in tables 13–18). Then, two additional conditions are considered: the Baseline watershed condition under the Flood+Waves scenario ("Flood+Waves" column), and watershed Restoration under either the Flood Only or Flood+Waves conditions ("Restoration" column). For these additional conditions, any changes between them and the first Baseline-Flood Only scenario are listed. The term "No change" indicates zero magnitude change, while "Negligible" indicates a non-zero but not statis tically significant change.

Table 13. Modeling results for Honolua reef, West Maui, during Baseline, Large Wave, and Restoration scenarios.

[g/m², gram per square meter; mg/m², milligram per square meter; mg/L/m², milligram per liter per square meter]

Parameter	Baseline	Flood+Waves	Restoration
Sedimentation			
Source	Honolua Stream	No change	No change
Total amount	Large (>0.4 g/m²) on day 0 of flood event	Negligible	Negligible
Exposure (>10 mg/m²)	Limited (7–9 percent of the time) on day 0 of flood and day 1 post-flood	Large (about 80 percent) decrease on day 1 post-flood; moderate (about 30 percent) decrease on day 7 post-flood	Negligible
Suspended-sediment concentrations			
Source	Honolua Stream	No change	No change
Total amount	Large (>6 mg/L/m²) on day 0 of flood event	Negligible	Negligible
Exposure (>10 mg/L/m²)	Moderate (20–30 percent of the time) on day 0 of flood event and day 1 post-flood	Moderate decrease (to <10 percent of the time) on days 1 and 7 post-flood	Negligible

Table 14. Modeling results for Kapalua reef, West Maui, during Baseline, Large Wave, and Restoration scenarios.

[mg/m², milligram per square meter; mg/L/m², milligram per liter per square meter]

Parameter	Baseline	Flood+Waves	Restoration
Sedimentation			
Source	None detected	None detected	None detected
Total amount	None detected	None detected	None detected
Exposure (>10 mg/m²)	None detected	None detected	None detected
Suspended-sediment concentrations			
Source	None detected	None detected	None detected
Total amount	None detected	None detected	None detected
Exposure (>10 mg/L/m²)	None detected	None detected	None detected

Table 15. Modeling results for Honokeana reef, West Maui, during Baseline, Large Wave, and Restoration scenarios.

[g/m^2, gram per square meter; mg/m^2, milligram per square meter; $mg/L/m^2$, milligram per liter per square meter]

Parameter	Baseline	Flood+Waves	Restoration
		Sedimentation	
Source	Kahana (majority) and Ka‘ōpala Streams	Near total reduction	Reduction of Kahana Stream source
Total amount	Small amount (<0.2 g/m^2) deposited days 1–7 after flood event	Near total reduction	Large reduction (50–70 percent) for days 1 and 7 post-flood
Exposure (>10 mg/m^2)	Small exposure (3–8 percent of the time) on days 1 and 7 post-flood	Total reduction	Total reduction
		Suspended-sediment concentrations	
Source	Kahana (majority) and Ka‘ōpala Streams	Total reduction	Reduction of Kahana Stream source
Total amount	Small (<1 $mg/L/m^2$) on days 1 and 7 post-flood	Total reduction	Large (>50 percent) reduction (in Flood Only scenario)
Exposure (>10 $mg/L/m^2$)	Moderate exposure (12–18 percent of the time) on days 1 and 7 post-flood	Total reduction	Total reduction

Table 16. Modeling results for Māhinahina reef, West Maui, during Baseline, Large Wave, and Restoration scenarios.

[g/m^2, gram per square meter; mg/m^2, milligram per square meter; $mg/L/m^2$, milligram per liter per square meter]

Parameter	Baseline	Flood+Waves	Restoration
		Sedimentation	
Source	Kahana (majority), Ka‘ōpala, and Honokōwai Streams	Increased Kahana and Ka‘ōpala Stream contributions, particularly on day 1 post-flood	Negligible change
Total amount	Moderate (about 0.25 g/m^2) deposited on day 7 post-flood	Large increase (80 percent) in sedimentation, particularly on day 1 post-flood	Moderate (10–20 percent) reduction, mostly of Kahana Stream-sourced sediment
Exposure (>10 mg/m^2)	Limited (7 percent of time) on day 7 post-flood	Large increase (to 13–15 percent of time) for both days 1 and 7 post-flood	Large (about 50 percent) reduction
		Suspended-sediment concentrations	
Source	Kahana (majority), Ka‘ōpala, and Honokōwai Streams	Slight increase in Kahana Stream contribution	Negligible change
Total amount	Negligible	Slight increase	Slight reduction
Exposure (>10 $mg/L/m^2$)	Negligible	Slight increase (to 3–5 percent of the time)	Moderate (about 30 percent) reduction in Flood+Waves scenario)

Table 17. Modeling results for Honokōwai reef, West Maui, during Baseline, Large Wave, and Restoration scenarios.

[g/m^2, gram per square meter; mg/m^2, milligram per square meter; $mg/L/m^2$, milligram per liter per square meter]

Parameter	Baseline	Flood+Waves	Restoration
Sedimentation			
Source	Honokōwai Stream (majority), and small contributions from Ka‘ōpala and Kahana Streams	Increased contribution from Kahana Stream on days 1 and 7 post-flood	Negligible change
Total amount	Small, increasing from days 0 to 7 post-flood (from <0.10 to about 0.15 g/m^2)	Slight increase on days 1 and 7 post-flood	Moderate (about 20 percent) decrease
Exposure (>10 mg/m^2)	Limited, increasing from days 0 to 7 post-flood (from about 1 to 7 percent of the time)	Large (about 80 percent) increase by day 7 post-flood	Moderate (about 20 percent) decrease
Suspended-sediment concentrations			
Source	Honokōwai Stream (majority)	No change	No change
Total amount	Largest on day 0 (about 1 $mg/L/m^2$)	Negligible	Moderate (about 25 percent) decrease on day 0
Exposure (>10 $mg/L/m^2$)	Very limited (<2 percent of the time)	Negligible	Moderate (25–50 percent) decrease

Table 18. Modeling results for Wahikuli reef, West Maui, during Baseline, Large Wave, and Restoration scenarios.

[g/m^2, gram per square meter; mg/m^2, milligram per square meter; $mg/L/m^2$, milligram per liter per square meter]

Parameter	Baseline	Flood+Waves	Restoration
Sedimentation			
Source	Wahikuli Stream	No change	No change
Total amount	Large (about 0.3 g/m^2), relatively constant from day 0 to 7 post-flood	Large reduction (about 200 percent) on days 1 and 7 post-flood	Negligible
Exposure (>10 mg/m^2)	Limited (3–7 percent of the time), increasing on days 1 and 7 post-flood	Negligible	Negligible
Suspended-sediment concentrations			
Source	Wahikuli Stream	No change	No change
Total amount	Small (<0.5 $mg/L/m^2$) only on day 0 of flood event	Negligible	Negligible
Exposure (>10 $mg/L/m^2$)	Minimal (<3 percent of the time)	Negligible	Negligible

Flood Restoration Scenarios

With watershed restoration, the greatest reduction in sediment effects on reefs occurred at Honokeana (Flood Only scenario) and Māhinahina (Flood+Waves scenario)—reefs that were affected by sediments from multiple streams. Sediment affecting Honokeana reef originated from Ka‘ōpala and Kahana Streams, and sediment reaching Māhinahina reef came primarily from Kahana Stream as well as Ka‘ōpala and Honokōwai Streams. Sediment from the Kahana, Ka‘ōpala, and Honokōwai Streams also comprised the largest sedimentation footprint in the study area (fig. 24). Watershed restoration produced the smallest effect on sediment effects at Honolua and Wahikuli reefs. These reefs are at the northern and southern edges (respectively) of the study area and are only affected by sediment from a single stream outfall (Honolua Stream and Wahikuli Gulch, respectively). These two streams also were the only ones that did not have dam modification included as a simulated restoration measure (fig. 7). The reef site that experienced no discernible effect from either sedimentation or suspended-sediment concentration (SSC) was Kapalua reef, which is an exposed site with no nearby major stream outfall.

Large waves during a flood event led to decreased post-storm sedimentation in the nearshore areas and greater post-storm sedimentation offshore of the reefs (figs. 23, 24). This distribution likely indicates that wave-driven resuspension of sediment occurs in the nearshore regions and is then transported farther offshore, where it can settle. The Māhinahina and Honokōwai reefs were the only reef sites that experienced an increase in sedimentation with the occurrence of large waves during flood events (fig. 21). These two reefs are farther offshore than the others and closest to the offshore patches of sediment deposited after a Flood+Waves scenario (fig. 23*B, D*). Large waves during simulated flood events also decreased mean (over the entire simulation period) suspended-sediment concentrations, which in turn decreased the amount of light attenuation (fig. 25). This effect was greatest in the nearshore area between Kahana and Honokōwai reefs, where the fraction of surface irradiance reaching the seabed improved by nearly 60 percent, but there was no discernible decrease in SSC within reef areas under increased wave forcing (fig. 22).

Integration of Measurements and Modeling

In model simulations, large waves during the flood event led to a decrease in suspended-sediment concentrations between Kahana and Honokōwai study sites. This may seem at odds with the measurements from this area, which show that near-bed turbidity increases with increasing wave heights. However, it is important to keep in mind that the model results only consider sediment entering coastal waters from the five stream sources and do not simulate sediment already present on the seabed. In addition, wave heights in the Flood+Waves simulations increased for only 8 hours during the 1-day flood event (fig. 6*D*). The measured wave record indicates that most wave events last for several days; at Kahana Deep, wave events with $H_s > 1$ m had durations ranging from 14 hours to 9 days, with a mean of 2 days (fig. 17*D*). During the flood event on year day (YD) 354 (fig. 9*E*), wave heights > 1 m lasted for just longer than 2 days. The positive correlation between wave energy and increasing near-bed turbidity in the measurements illustrates a process not captured by the model simulations, in which material that is already deposited on the seabed is resuspended by wave action and subsequently transported by prevailing currents. Furthermore, even during relatively calm conditions (C5; weak winds, small waves), the coastal region between Kahana and Honokōwai study sites experiences bed shear stresses capable of resuspending fine-grained terrigenous material more than 50 percent of the time (fig. 20*A–B, E–G*). Thus, long after a flood event has occurred, these sites likely continue to experience chronic effects from sediment, particularly from material in suspension. The multiple stream sources affecting the area between Kahana and Honokōwai study sites, coupled with the near-bed turbidity dynamics shown in the observations, suggest strong connectivity and transport pathways along this region of the coast. Previous work found a nearshore circulation pattern whereby nearshore turbid waters flow southward from the Kapalua study site to the Honokōwai study site (Storlazzi and others, 2006), further indicating the interconnectedness of sediment dynamics along this part of the West Maui coastline.

In contrast, the Honolua and Wahikuli study sites are relatively sheltered, are only influenced by a single stream source, and primarily experience flood-event driven sediment effects. Because turbidity data for the Honolua study site during the flood event on YD 354 were valid, we can compare the measured and simulated flood-driven sediment dynamics at this site. In the model simulations, flood events resulted in a large amount of both sedimentation and SSC at the Honolua reef on day 0 of the flood event (figs. 21, 22). The measurements show a similar pattern—during the flood event on YD 354, the near-bed turbidity at Honolua Shallow spiked to more than 400 Nephelometric Turbidity Units (NTU) (40 times greater than the overall median value of 10 NTU) within 3 hours of the rainfall peak. But what happens to this large initial input of sediment into Honolua Bay in the days and weeks following a flood event? Unlike the sites between the Kahana and Honokōwai study sites, the conditions inside Honolua Bay are seldom conducive to the resuspension of fine-grained, terrigenous sediment (fig. 20). This conclusion also is supported by near-bed turbidity measurements, which are not well correlated with bed shear stress (fig. 19*D*). Thus, the primary effect of sediment on Honolua reef is likely sedimentation, not chronic light attenuation due to SSC. Previous work in Honolua Bay found that sediment deposited on the inner reef remained in the bay for at least 6 months (Dollar and Grigg, 2004). There also is a documented recirculation pattern in the bay that could further enhance the retention of any sediment released into the bay (Storlazzi and

Presto, 2005). In addition to the lack of physical scouring and export of sediment from the bay, the amount of sedimentation at this study site is relatively high, with the model simulations indicating that flood-driven sedimentation at Honolua reef exceeds that of any other site (fig. 21). A recent sediment budget analysis for West Maui watersheds indicated that Honolua Bay had the one of the highest annual fine-grained sediment loads to the nearshore, second only to Kahana Stream, and also had the greatest maximum sediment load from a hypothetical decadal storm (Stock and Cerovski-Darriau, 2021). There also has been a stark decrease in coral health and cover in Honolua Bay over the past several decades (Rogers and others, 2015). Coral cover in Honolua Bay has decreased at a greater rate than at other monitored Maui reefs, with a change from 42 percent coral cover in 1995 to only 9 percent in 2005 (Hawaii Department of Aquatic Resources, 2007).

Conclusions

Coral reefs along the West Maui coastline are in decline owing in part to the detrimental effects from terrestrial sediment. Local, State, and Federal agencies are motivated to use research, restoration, and management actions to better protect and preserve coral reefs in this area. But in order to address terrestrial sediment dispersal from watersheds and the subsequent effect on coral reefs, it is first critical to understand how coastal ocean hydrodynamics (waves and currents) control the transport, dispersal, settling, and removal of sediment from coral reef areas. To elucidate these dynamics, the USGS and Deltares cooperated on a joint observation- and model-based experiment to resolve and simulate the hydrodynamics and terrestrial sediment dynamics in this area. The objective of this work was to provide information on terrestrial sediment dispersal and residence times over nearshore coral reefs for present conditions as well as potential watershed restoration scenarios.

Model simulations project that Honokeana and Māhinahina reefs experience the greatest reduction in sediment effects from theoretical watershed restoration. And when large waves coincided with a flood event, post-storm sedimentation generally was reduced in the nearshore region but increased in the region offshore of the reefs. The measured and simulated sediment dynamics demonstrate a demarcation between reefs sheltered within embayments (Honolua reef) or behind points (Wahikuli reef) and those along the relatively open coastline between Kapalua and Kāʻanapali (Kapalua, Honokeana, Māhinahina, and Honokōwai reefs). The sheltered sites are affected by terrestrial sediment from single stream outfalls, with most of the sediment delivered within hours of a flood (rain) event. Once this sediment enters the nearshore, it settles out and remains within the reef area for a prolonged period owing to a lack of wave or current-driven bed shear stress. Thus, the primary effect of sediment on reefs within these sheltered areas is sedimentation. In contrast, reefs along the open coastline (between Kapalua and Kāʻanapali) are more exposed to waves and terrestrial sediment from multiple stream sources. At these reefs, fine-grained terrestrial sediment can rarely settle but instead remains in suspension. Thus, even long after a flood event has occurred, these sites are chronically exposed to light attenuation from suspended sediment.

These analyses underscore the importance of understanding how coastal ocean hydrodynamics can lead to different sediment dynamics and stressors for coral reefs along the same region of the West Maui coastline. These differing factors indicate that watershed restoration and mitigation strategies might need to vary among the different reefs and streams. An important next step is to determine management goals for these reefs—what are target reductions of sedimentation, suspended-sediment concentrations, or the resulting light attenuation? Then, using the coupled hydrodynamic-sediment model, we can examine which watershed restoration scenarios for each stream will achieve those targets. It is also important to incorporate knowledge of how coastal dynamics will alter with climate change. For example, models project that mean significant wave heights around the Hawaiian Islands will decrease slightly by 2100, but mean peak wave periods could increase, particularly during the boreal spring months of March–May (Storlazzi and others, 2015b). In addition, rainfall has been decreasing in the Hawaiian Islands for the past 30 years (Chu and others, 2010), but with greatly varying precipitation patterns on each island (Timm and others, 2015). With this decrease in rainfall, it is projected that Hawai‘i will experience more drought, and that when rain events occur, they will be exceptionally intense, potentially causing more flooding, runoff, and sedimentation (Leta and others, 2018).

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Appendix E - USGS Open File Report

Appendixes

Appendix 1. **Acoustic Wave and Current Profiler Information**

Table 1.1. Nortek 600 kilohertz upward-looking acoustic wave and current profiler (AWAC) details.

[kHz, kilohertz; m, meter; %, percent; Hz, hertz]

Parameter	Value
Beams' signal to noise ratio (s/n)	6,278, 6,492, 6,623
Transmitting frequency	614 kHz
Depth of transducer	10 m
Blanking distance	0.5 m
Height of first bin above bed	2.0 m
Bin size	1.0 m
Number of bins	10
Measurement load	25 percent
Compass update rate	0:20:00.00 minutes
Profile ensemble interval	0:20:00.00 minutes
Profile average interval	0:10:00.00 minutes
Wave ensemble interval	1:00:00.00 hour
Wave number of samples	1,024
Wave sampling rate	1 Hz
Sound speed calculation	Set salinity, updating temperature via sensor
Analog input 1 (seapoint)	Standard
Power output	Enabled
Power level	High
Coordinate system	East-north-up (ENU)

Data processing.—The acoustic wave and current profiler (AWAC) current and wave data were converted using the Nortek AWAC program and the wave data were processed using the QuickWave program. All further analyses were performed using MATLAB. All spurious data above the water surface were removed for visualization and analysis.

Appendix 2. Other Sensor and Processing Information

Table 2.1. Marotte HS drag-tilt current meter details.

[Hz, hertz]

Parameter	Value
Serial numbers	B1230, B1233, B1245, B1262, B1293
Sampling interval	1 Hz
Burst samples	1,024
Burst period	0:20:00.00 minutes

Table 2.2. RBR Virtuoso Dwave (RBR-Wave) logger details.

[Hz, hertz]

Parameter	Value
Serial numbers	055049, 055050, 055053, 055058, 055064
Sampling interval	1 Hz
Burst samples	1,024
Burst period	1:00:00.00 hour

Table 2.3. RBR Virtuoso turbidity (RBR-Tu) sensor details.

Parameter	Value
Serial numbers	054126, 054170, 054273, 054277, 054278
Mode	AVERAGE
Sampling period	0:05:00.00 minutes
Number of samples averaged	20
Burst period	0:20:00.00 minutes

Data processing.—The Marotte current data were exported to ASCII[4] format using Marotte software. The RBR-Wave and RBR-Tu current data were exported to ASCII using the RBR Ruskin software. Further quality control and data analyses were performed using MATLAB.

[4]ASCII, American Standard Code for Information Interchange.

Appendix 3. **Hydrodynamic Model—Nesting and Configuration**

Delft3D-FLOW (water levels, currents, salinity, and temperature).—The hydrodynamic model used four different nested model grids—the Hawaii (L1; 5-kilometer [km] grid) domain, the Maui (L2; 1-km grid) domain, the WMaui (L3; 200-meter [m] grid) domain, and the Nearshore (L4; 40-m grid) domain (see fig. 2 of main text). The L2–L4 nested models were forced at the boundaries by Riemann invariants that contain information about both vertical displacement and horizontal flow. From L3 to L4, the vertical layer definition changed from 20 z-layers (fixed depth) to 10 sigma layers (equidistant), with water-column values correspondingly interpolated. The nesting routines for the Delft3D-FLOW models were based on MATLAB routines available in OpenEarthTools (https://svn.oss.deltares.nl/repos/openearthtools).

SWAN (wave height, wave period, and wave direction).—Nesting for the SWAN models is based on full two-dimensional wave spectra. This was done by first introducing observational points into the larger model domain for each grid cell of the smaller model domain where spectral information was needed. Subsequently, the outputs from SWAN were combined into one spectral wave boundary condition and were provided to the smaller model domain.

Appendix 4. Hydrodynamic Model—Bathymetry

Bathymetry for the Hawaii, Maui, and WMaui (L1–L3) models were sourced from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NOAA, 2009). The bathymetry for the local coastal model was constructed from a digital elevation model of Lahaina (Taylor and others, 2008), which has a resolution of 1/3 arc second and is referenced to mean high water (MHW). The depth values were converted to mean sea level (MSL) by applying an offset of 0.238 meter (m), which was the difference between MHW and MSL for this area as determined by NOAA gage datums. Depths were then interpolated onto the curvilinear coastal grid (fig. 4.1). The grid of the coastal model extends to an offshore depth of at least 30 m. Along the north end of the offshore boundary, the seabed drops to about 150 m, but is shallower at the south end of the offshore boundary. To allow unrestricted flow into the model through the south boundary, the domain was extended south beyond a ridge that has a depth of about 20 m.

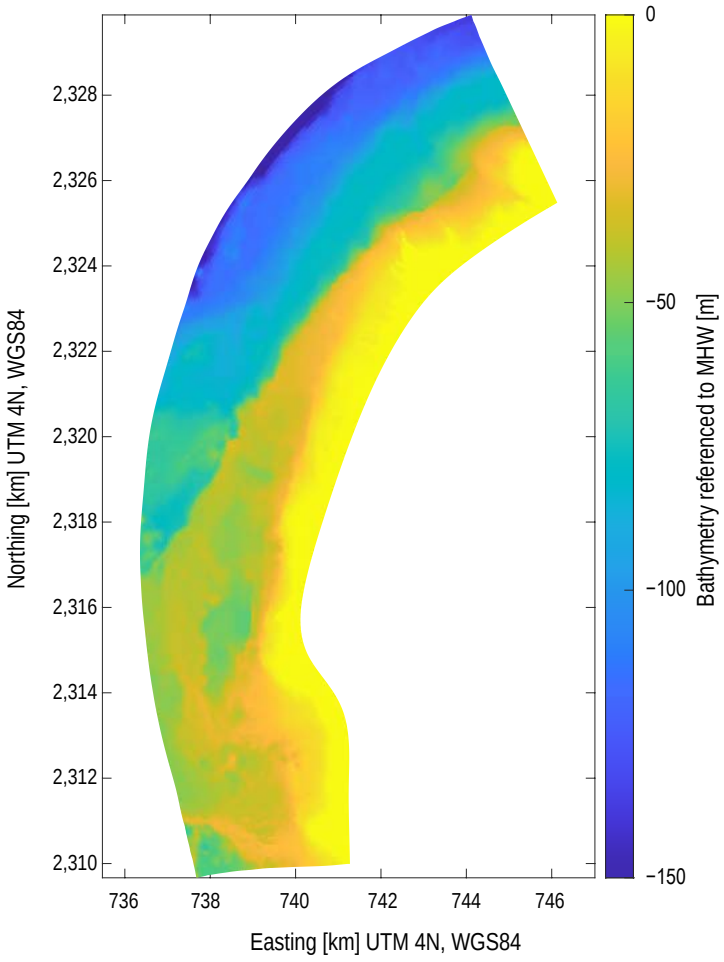


Figure 4.1. Map plot showing the bathymetry of the coastal model derived from a digital elevation model of Lahaina, offshore West Maui, Hawai‘i (Taylor and others, 2008). Abbreviations: UTM 4N, Universal Transverse Mercator zone 4N; WGS84, World Geodetic System 1984; m, meter; km, kilometer; MHW, mean high water.

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Appendix 5. Hydrodynamic Model—Physical Parameter Settings

Delft3D-FLOW (water levels, currents, salinity, and water temperature).—Salinity and water temperature were included in the model as oceanic fluxes. No atmospheric heat fluxes from radiation were included. Bed roughness was modeled with the depth-independent Chézy roughness formulation. The Chézy coefficient, C, is related to the dimensionless friction coefficient, c_f, using $C = \sqrt{g/c_f}$, where g is gravitational acceleration. The Nearshore (L4) model used a spatially varying c_f, which was estimated from Vargas-Angel and others (2017), using the conversion in table 5.1.

Table 5.1. Hydrodynamic roughness coefficients as a function of coral cover.

Coral cover	Dimensionless roughness coefficient (c_f)	Chézy roughness coefficient (C)
10–50 percent	0.10	9.9
50–90 percent	0.13	8.7
90–100 percent	0.15	8.1
None (sand)	0.003	55

Turbulence and vertical mixing were computed using the k-ε model (Uittenbogaard and others, 1992). Horizontal mixing (viscosity and diffusivity) was uniformly set to 100 square meters per second (m^2/s).

Delft3D-WAVE (wave height, period, and direction).—The Hawaii (L1), Maui (L2), and WMaui (L3) models (see fig. 2 of main text) were run using spectral wave model Delft3D-WAVE (using SWAN version 41.10). The following other model settings were applied:

1. Communication time step—Wave computations were performed every 60 minutes. The SWAN model was run in stationary mode so that waves had sufficient time to propagate completely from the offshore boundaries to the coast. This time step also was appropriate because offshore waves and wind properties do not change greatly within a 60-minute period. Wave forces were computed based on dissipation, and Delft3D-FLOW and SWAN models communicate every 60 minutes. For the Delft3D-WAVE computations, water level, velocity, and wind were taken and extended from the Delft3D-FLOW results.

2. White capping and wave growth—During model validation, Delft3D-WAVE was run in the third-generation mode with wind input, quadruplet interactions, and white capping. Nonlinear, saturation-based white capping combined with wind input of Yan (1987) was applied. In flood scenarios, wave growth by wind was switched off in order to control the peak frequency at which waves propagate through the study area; because of this, white capping and quadruplet interactions were switched off for flood scenarios. For deep-water physics, the combination of wind input and saturation-based white capping proposed by van der Westhuysen and others (2007) was used.

3. Bed roughness—A constant semi-empirical expression for Joint North Sea Wave Project (JONSWAP) results typical for sandy bottoms of 0.038 square meter per cubic second (m^2/s^3) was used.

4. Accuracy—The numerical accuracy was set to 1 percent for relative and absolute wave height differences, requiring at least 99 percent of the wet grid cells. The maximum number of iterations was set to 20.

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Appendix 6. Hydrodynamic Model—Validation of Hawaii (L1) Model

Meteorological Forcing

Besides observations, several weather models exist that hindcast meteorological conditions. The advantage of using weather models over measurements is the spatial coverage; the spatial variance in meteorological forcing is important for driving hydrodynamic models. The atmospheric model used was ERA5, a 5th-generation atmospheric reanalysis of the global climate that is produced by the Copernicus Climate Change Service (C3S) at the European Centre for Medium-Range Weather Forecasts (C3S, 2018). Wind speed, wind direction, and atmospheric pressure from ERA5 were applied in all model simulations. Calibration of the meteorological conditions was not carried out in this study.

Waves

Spectral wave boundaries from ERA5 were used for the Hawaii (L1) model domain. ERA5 meteorological outputs were linearly interpolated for modeled significant wave height (H_s), peak wave period (T_p), and dominant wave direction using boundary segments of 50 kilometers (km), which approximately matched the resolution of the ERA5 model.

Water Levels, Salinity, and Water Temperature

Tidal information was obtained from the Oregon State University TOPEX/Poseidon global inverse solution (TPXO 8.0). TPXO is a global tide model that uses the Laplace tidal equations and incorporates along-track averaged satellite altimetry data (Egbert and Erofeeva, 2002). TPXO uses a global grid with 0.25° resolution, on which the resulting tides are computed as complex amplitudes of the Earth-relative, sea-surface elevations for 13 harmonic tidal constituents. The tidal data were then interpolated to the Hawaii (L1) model boundaries. To include large-scale oceanic circulation effects, the Hawaii (L1) model was forced using the HYbrid Coordinate Ocean Model (HYCOM; http://hycom.org/) horizontal current velocities, water temperature, and salinity outputs (HYCOM Consortium, 2018). HYCOM is a three-dimensional (0.5° resolution), operational, data-assimilative system ocean model. Hydrodynamic forcing (water level and current) from HYCOM and TPXO were combined to create three-dimensional Riemann boundary conditions. A time step of 10 minutes was used to create the combined time series.

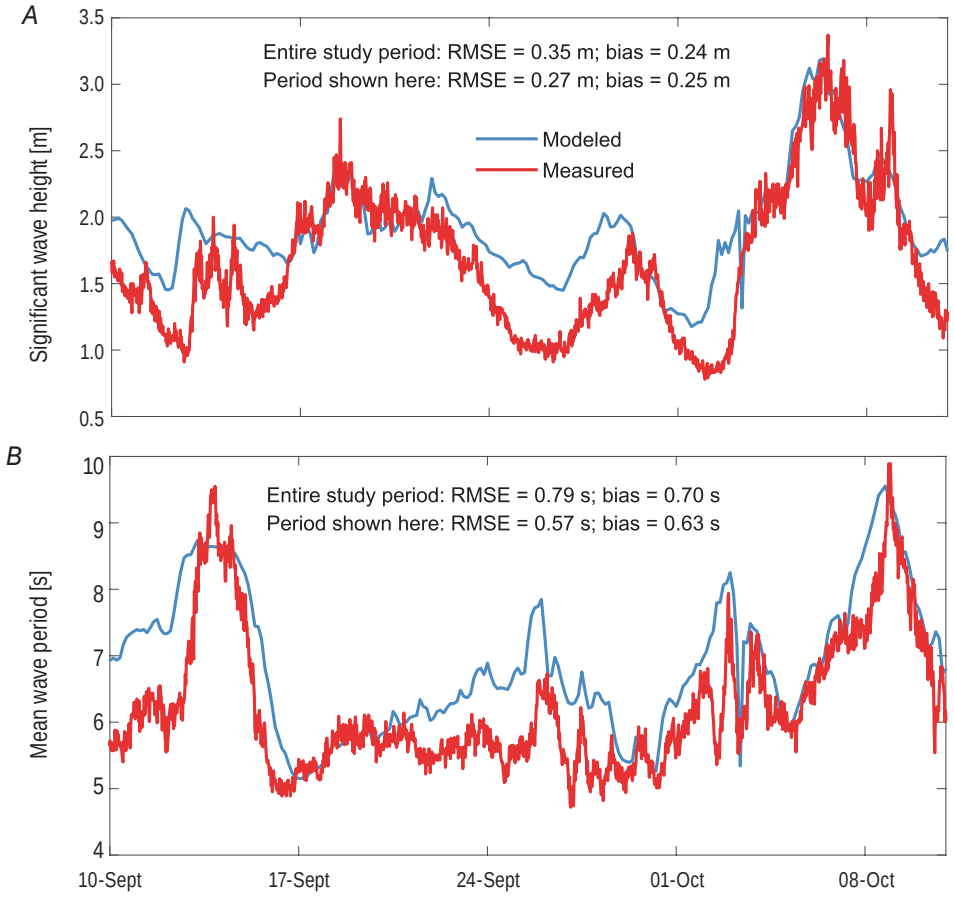


Figure 6.1. One-month time-series plots showing a comparison of wave parameters from the large-scale Hawaii hydrodynamic model and measurements from Mōkapu Point, O'ahu, Hawai'i. *A*, Significant wave height (H_s), in meters (m). *B*, Mean wave period (T_m), in seconds (s). Root mean square error (RMSE) and bias for each parameter over the entire study period and the selected time period are given. GMT, Greenwich mean time; Sept, September; Oct, October.

Validation of Offshore Water Levels and Waves

The mean wave height (H_m) and mean wave period (T_m) in the Hawaii (L1) model were validated against buoy measurements at Mōkapu Point, O‘ahu. For validation purposes, T_m is a better measure than the peak wave period (T_p) because it is a better representation of the full wave spectrum than the peak period. The modeled significant wave height (H_s) and T_p follow the trends in the measurements well, and the peaks are particularly well covered (fig. 6.1). In general, the model slightly overestimates both wave height and wave period.

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HYCOM Consortium, 2018, HYbrid Coordinate Ocean Model (HYCOM): HYCOM consortium website, accessed May 1, 2018, at http://hycom.org/.

Appendix 7. Extinction Coefficient for Offshore West Maui

The extinction coefficient, *K*, used in the model was calculated based on Storlazzi and others' (2015a) measurements, which reported how different sediment types, grain sizes, and concentrations affect light availability for photosynthesis in coral reef ecosystems. Table 7.1 presents the depth-averaged *K* values for different grain sizes, concentrations, and colors used in the model.

The oxidized volcanic terrigenous sediment of West Maui is reddish, so the *K* values for red sediment color were used for both sand and mud. Extinction coefficients were plotted against sediment concentrations to determine the linear correlation (fig. 7.1).

1. K_{mud} = 0.0896 × mud concentration (milligrams per liter [mg/L])
2. K_{clay} = 0.0896 × clay concentration (mg/L)
3. K_{sand} = 0.0062 × sand concentration (mg/L)

A background extinction, K_{bk}, was determined to be 0.04 per meter offshore West Maui. The background extinction was set to zero in the models so that any light reduction resolved in the model is due to stream sediment discharges. This results in the following formula for calculating *K* in the water column offshore West Maui:

$$K_{total} = K_{bk} + (0.0896 \times K_{mud}) + (0.0062 \times K_{clay)} + (0.0062 \times K_{sand})$$

Reference Cited

Storlazzi, C.D., Norris, B.K., and Rosenberger, K.J., 2015a, The influence of grain size, grain color, and suspended-sediment concentration on light attenuation—Why fine-grained terrestrial sediment is bad for coral reef ecosystems: Coral Reefs, v. 34, p. 967–975, https://doi.org/10.1007/s00338-015-1268-0.

Table 7.1. Depth-averaged extinction coefficient (*K*) statistics for different sediment colors, grain sizes, and concentrations.

[All *K* values are in units per meter; from Storlazzi and others (2015a). σ, standard deviation; mg/L, milligram per liter; –, not determined]

Grain size	Concentration (mg/L)	Red		Tan		White		Clear	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ
None	0	–	–	–	–	–	–	1.983	1.371
Mud	10	3.580	1.072	4.066	1.353	2.815	0.908	–	–
Mud	100	11.235	3.219	7.172	1.435	6.121	1.222	–	–
Mud	1,000	19.560	16.919	13.299	3.732	12.428	3.449	–	–
Sand	10	2.004	0.993	1.718	1.009	2.165	1.134	–	–
Sand	100	1.689	0.838	1.739	0.814	2.382	1.236	–	–
Sand	1,000	7.899	1.788	5.197	1.125	4.302	0.889	–	–

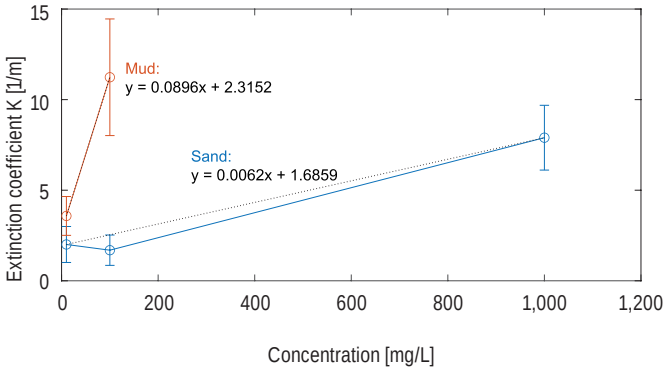


Figure 7.1. Plot of extinction coefficient (K), in values per meter (1/m) ± one standard deviation, versus concentration, in milligrams per liter (mg/L), of mud (orange) and sand (blue). Data from Storlazzi and others (2015a).

Appendix 8. Time-Series Plots of Measurements from Three Offshore (Deep) Sites—Honokōwai, Kahana, and Kā‘anapali

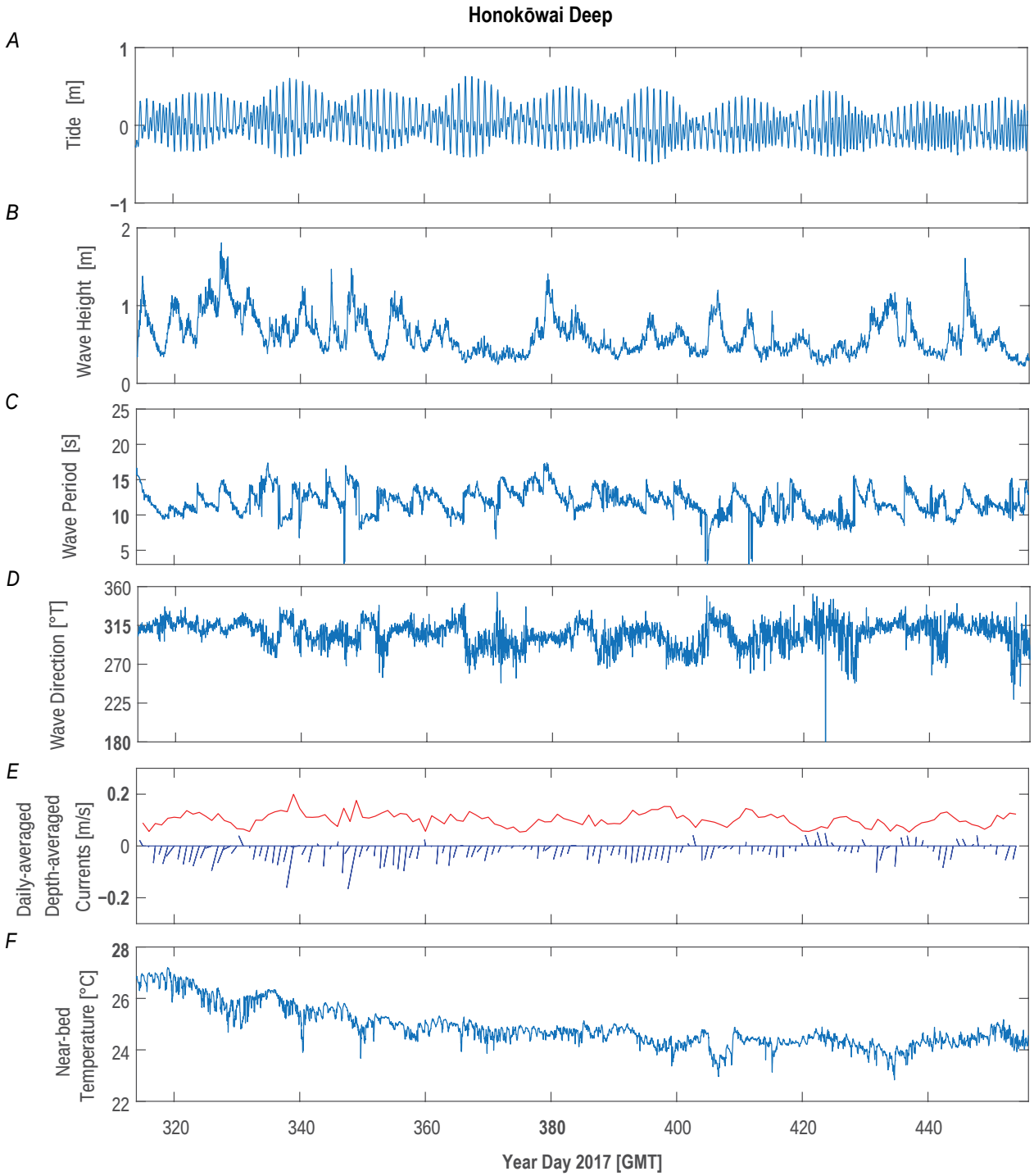


Figure 8.1. Time-series plots of oceanographic measurements during the study period from the Honokōwai Deep study site. *A*, Tide water levels, in meters (m). *B*, Significant wave height, in meters. *C*, Peak wave period, in seconds (s). *D*, Wave direction at peak period (direction of origination), in degrees clockwise from true north (°T). *E*, Daily- and depth-averaged current velocity (blue), in meters per second (m/s), and velocity direction, in degrees clockwise from true north (in direction of flow; north is up; length scales with current velocity magnitude); daily- and depth-averaged current magnitude (red), in meters per second. *F*, Near-bed water temperature, in degrees Celsius. GMT, Greenwich mean time.

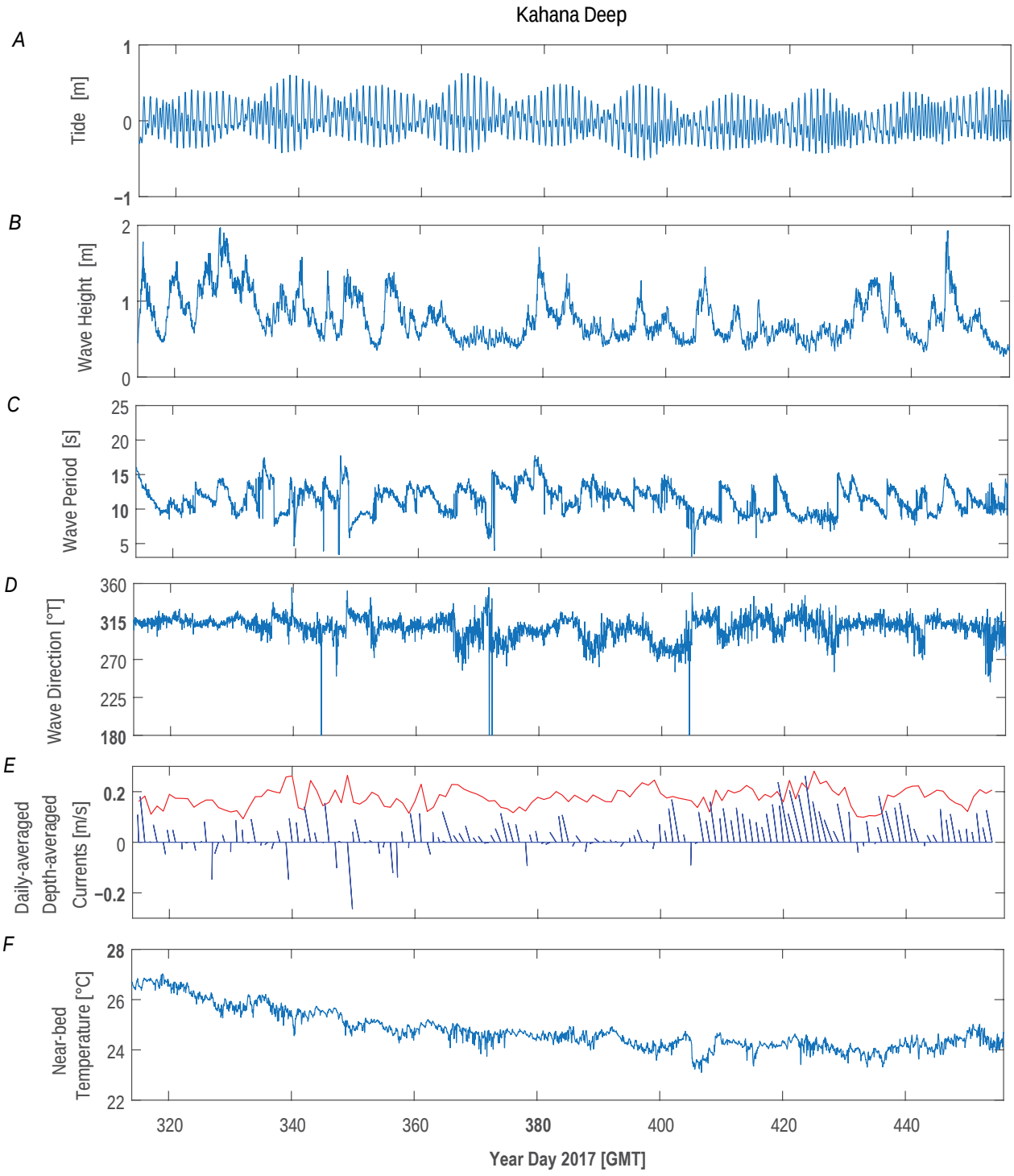


Figure 8.2. Time-series plots of oceanographic measurements during the study period from the Kahana Deep study site. *A*, Tide water levels, in meters (m). *B*, Significant wave height, in meters. *C*, Peak wave period, in seconds (s). *D*, Wave direction at peak period (direction of origination), in degrees clockwise from true north (°T). *E*, Daily- and depth-averaged current velocity (blue), in meters per second (m/s), and velocity direction, in degrees clockwise from true north (in direction of flow; north is up; length scales with current velocity magnitude); daily- and depth-averaged current magnitude (red), in meters per second. *F*, Near-bed water temperature, in degrees Celsius (°C). GMT, Greenwich mean time.

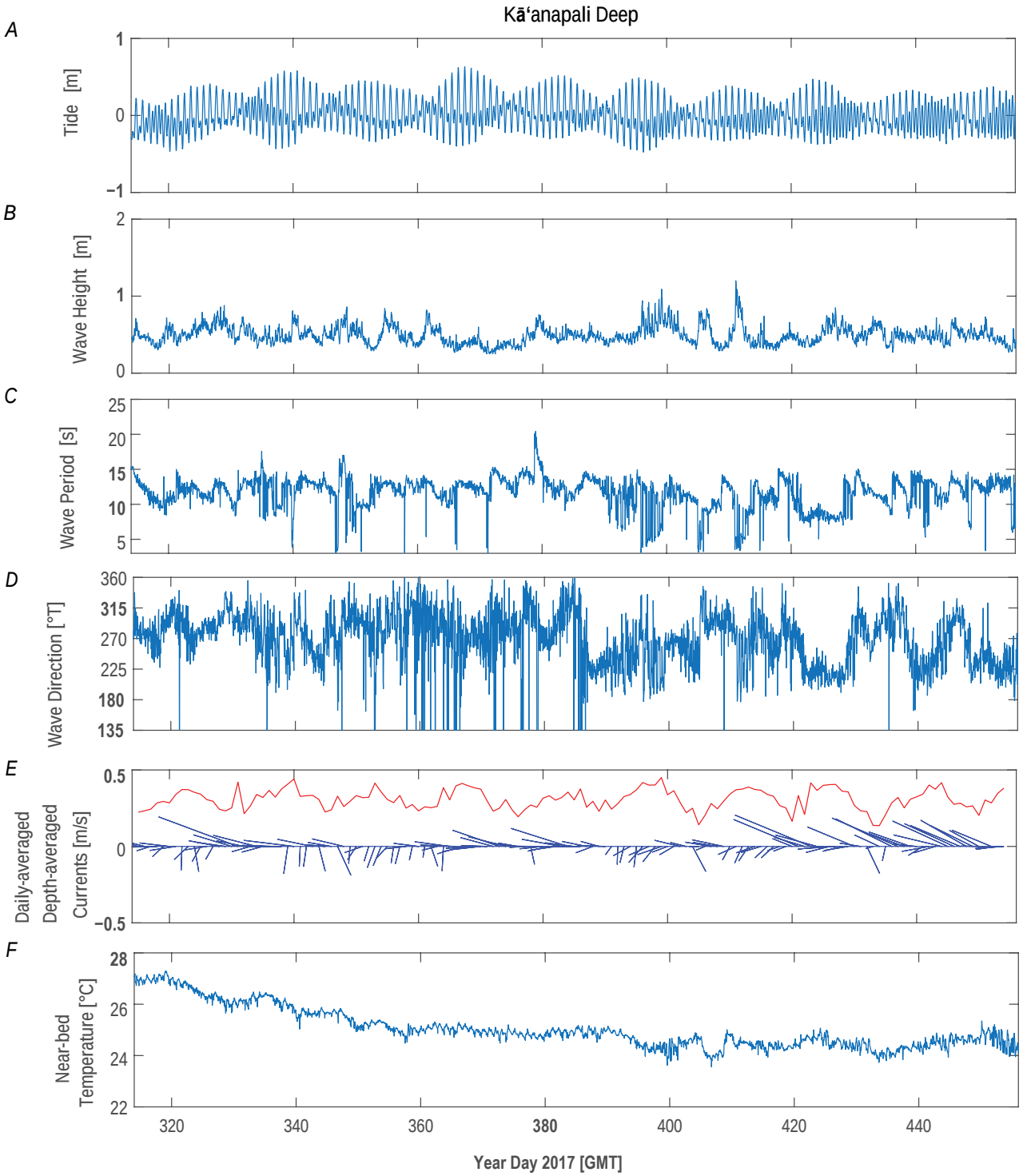


Figure 8.3. Time-series plots of oceanographic measurements during the study period from the Kā‘anapali Deep study site. *A*, Tide water levels, in meters (m). *B*, Significant wave height, in meters. *C*, Peak wave period, in seconds (s). *D*, Wave direction at peak period (direction of origination), in degrees clockwise from true north (°T). *E*, Daily- and depth-averaged current velocity (blue), in meters per second (m/s), and velocity direction, in degrees clockwise from true north (in direction of flow; north is up; length scales with current velocity magnitude); daily- and depth-averaged current magnitude (red), in meters per second. *F*, Near-bed water temperature, in degrees Celsius (°C). GMT, Greenwich mean time.

Appendix 9. Time-Series Plots of Measurements from Five Nearshore (Shallow) Sites—Honolua, Kahana, Māhinahina, Honokōwai, and Wahikuli

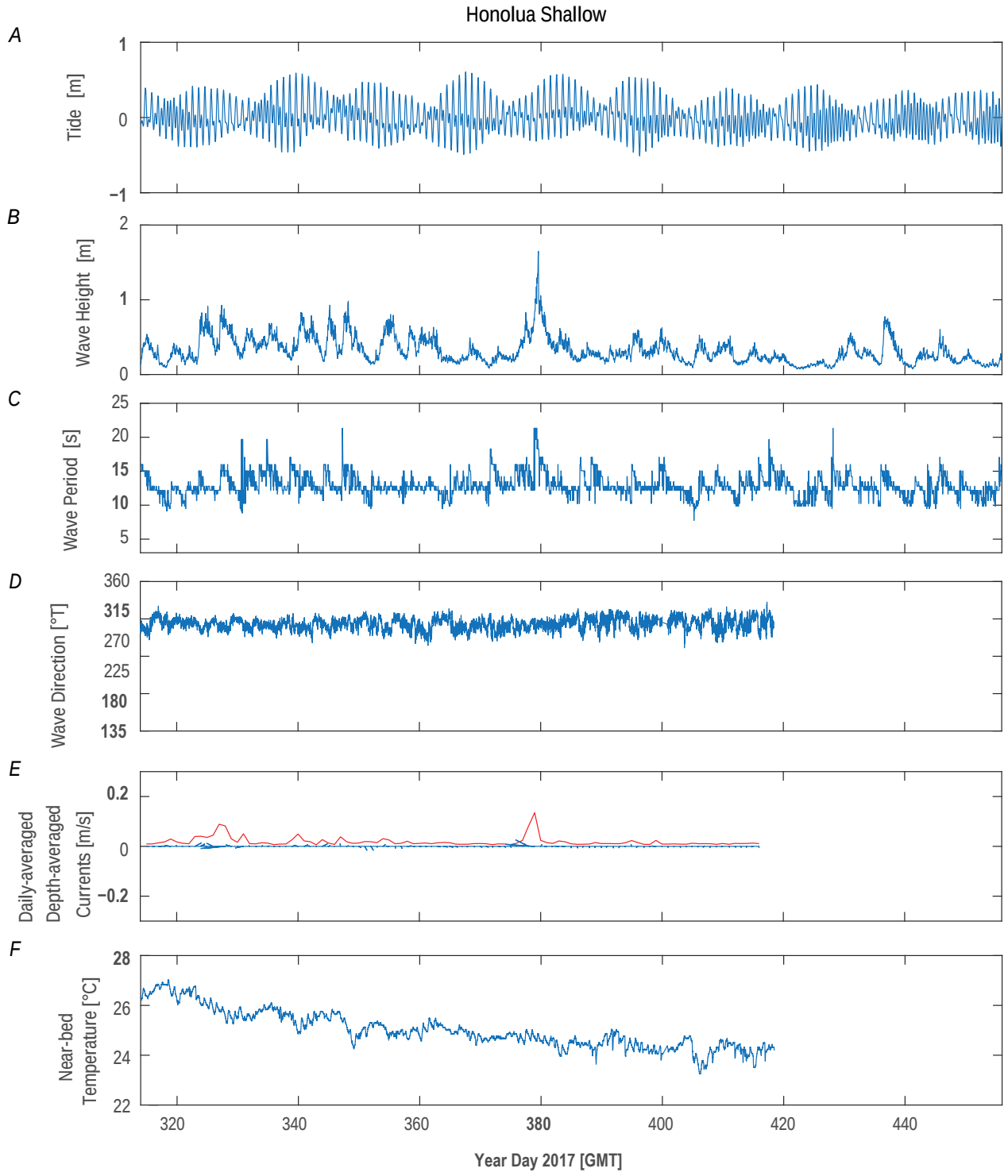


Figure 9.1. Time-series plots of oceanographic measurements during the study period from the Honolua Shallow study site. *A*, Tide water levels, in meters (m). *B*, Significant wave height, in meters. *C*, Peak wave period, in seconds (s). *D*, Wave direction at peak period (direction of origination), in degrees clockwise from true north (°T). *E*, Daily- and depth-averaged current velocity (blue), in meters per second (m/s), and velocity direction, in degrees clockwise from true north (in direction of flow; north is up; length scales with current velocity magnitude); daily- and depth-averaged current magnitude (red), in meters per second. *F*, Near-bed water temperature, in degrees Celsius (°C). GMT, Greenwich mean time.

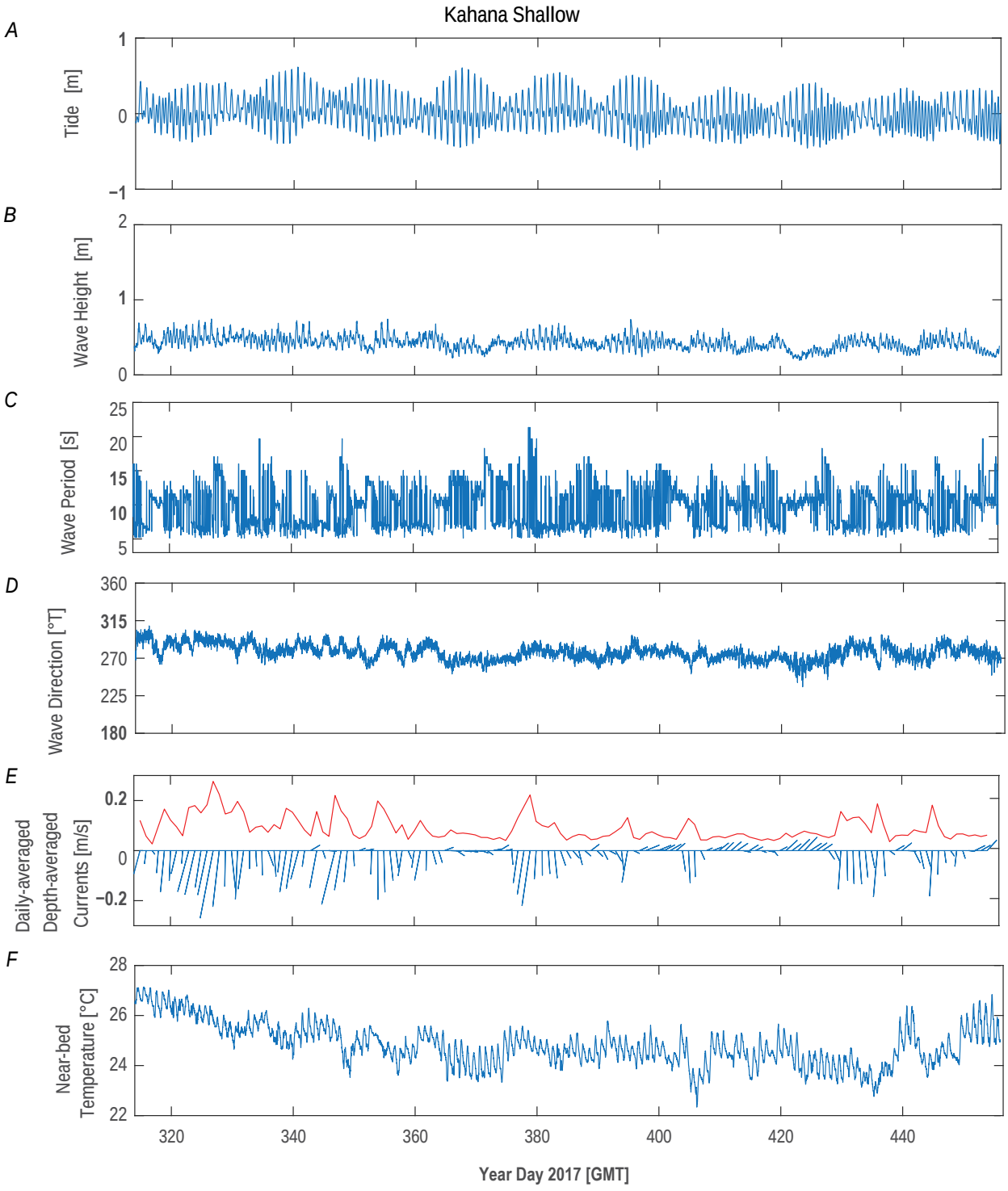


Figure 9.2. Time-series plots of oceanographic measurements during the study period from the Kahana Shallow study site. *A*, Tide water levels, in meters (m). *B*, Significant wave height, in meters. *C*, Peak wave period, in seconds (s). *D*, Wave direction at peak period (direction of origination), in degrees clockwise from true north (°T). *E*, Daily- and depth-averaged current velocity (blue), in meters per second (m/s), and velocity direction, in degrees clockwise from true north (in direction of flow; north is up; length scales with current velocity magnitude); daily- and depth-averaged current magnitude (red), in meters per second. *F*, Near-bed water temperature, in degrees Celsius (°C). Other abbreviation: GMT, Greenwich mean time.

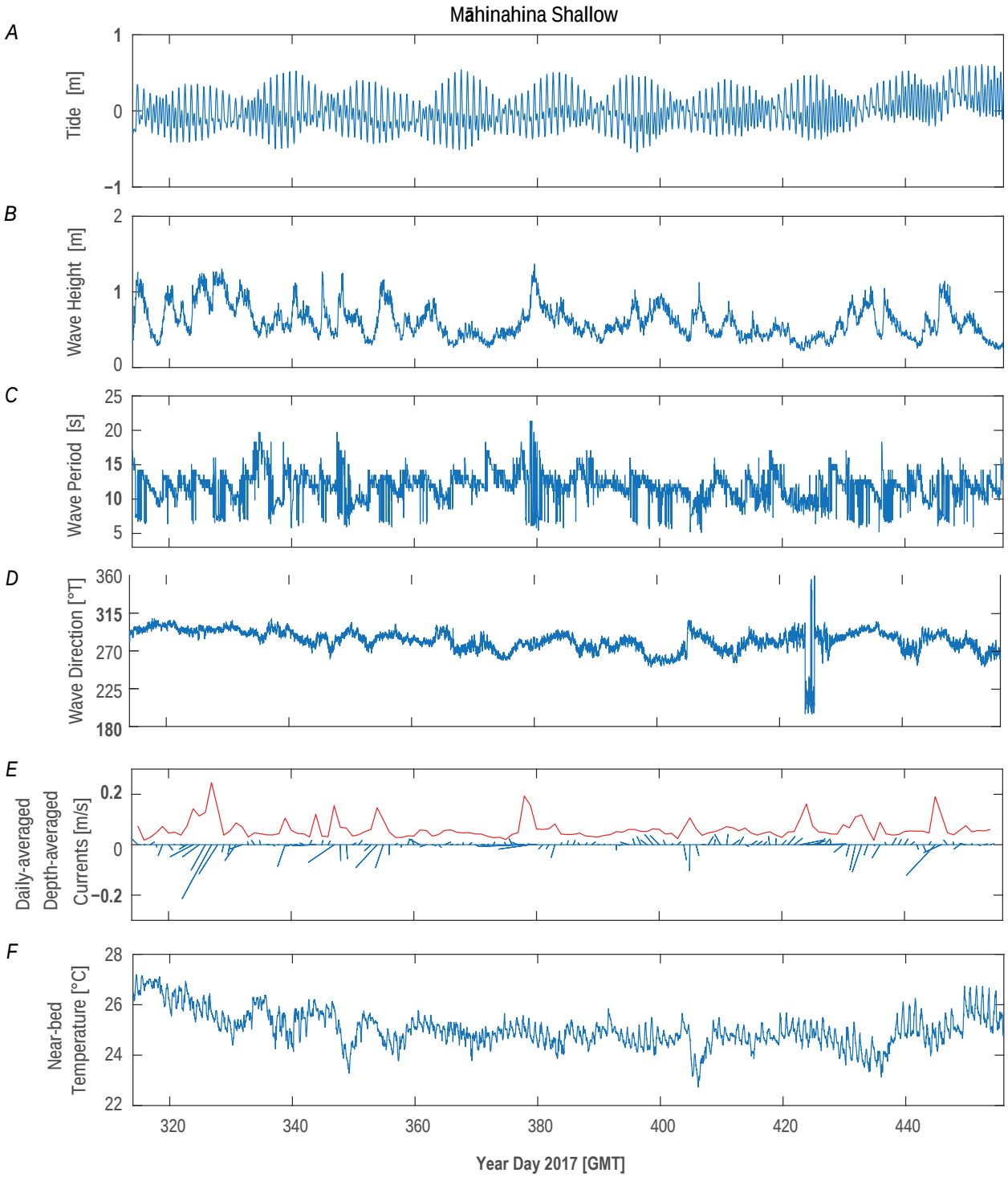


Figure 9.3. Time-series plots of oceanographic measurements during the study period from the Māhinahina Shallow study site. *A*, Tide water levels, in meters (m). *B*, Significant wave height, in meters. *C*, Peak wave period, in seconds (s). *D*, Wave direction at peak period (direction of origination), in degrees clockwise from true north (°T). *E*, Daily- and depth-averaged current velocity (blue), in meters per second (m/s), and velocity direction, in degrees clockwise from true north (in direction of flow; north is up; length scales with current velocity magnitude); daily- and depth-averaged current magnitude (red), in meters per second. *F*, Near-bed water temperature, in degrees Celsius (°C). GMT, Greenwich mean time.

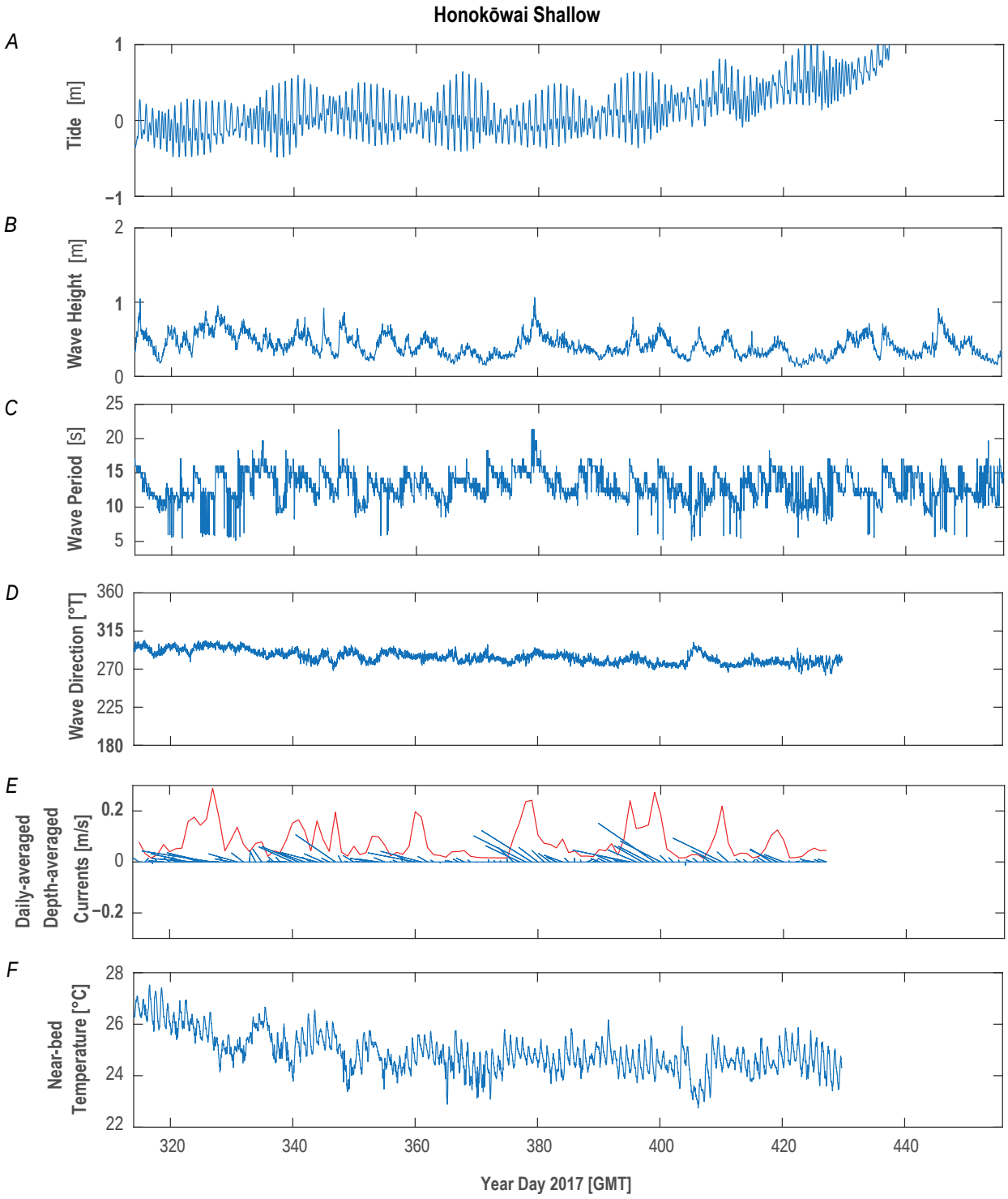


Figure 9.4. Time-series plots of oceanographic measurements during the study period from the Honokōwai Shallow study site. *A*, Tide water levels, in meters (m). *B*, Significant wave height, in meters. *C*, Peak wave period, in seconds (s). *D*, Wave direction at peak period (direction of origination), in degrees clockwise from true north (°T). *E*, Daily- and depth-averaged current velocity (blue), in meters per second (m/s), and velocity direction, in degrees clockwise from true north (in direction of flow; north is up; length scales with current velocity magnitude); daily- and depth-averaged current magnitude (red), in meters per second. *F*, Near-bed water temperature, in degrees Celsius (°C). Other abbreviation: GMT, Greenwich mean time.

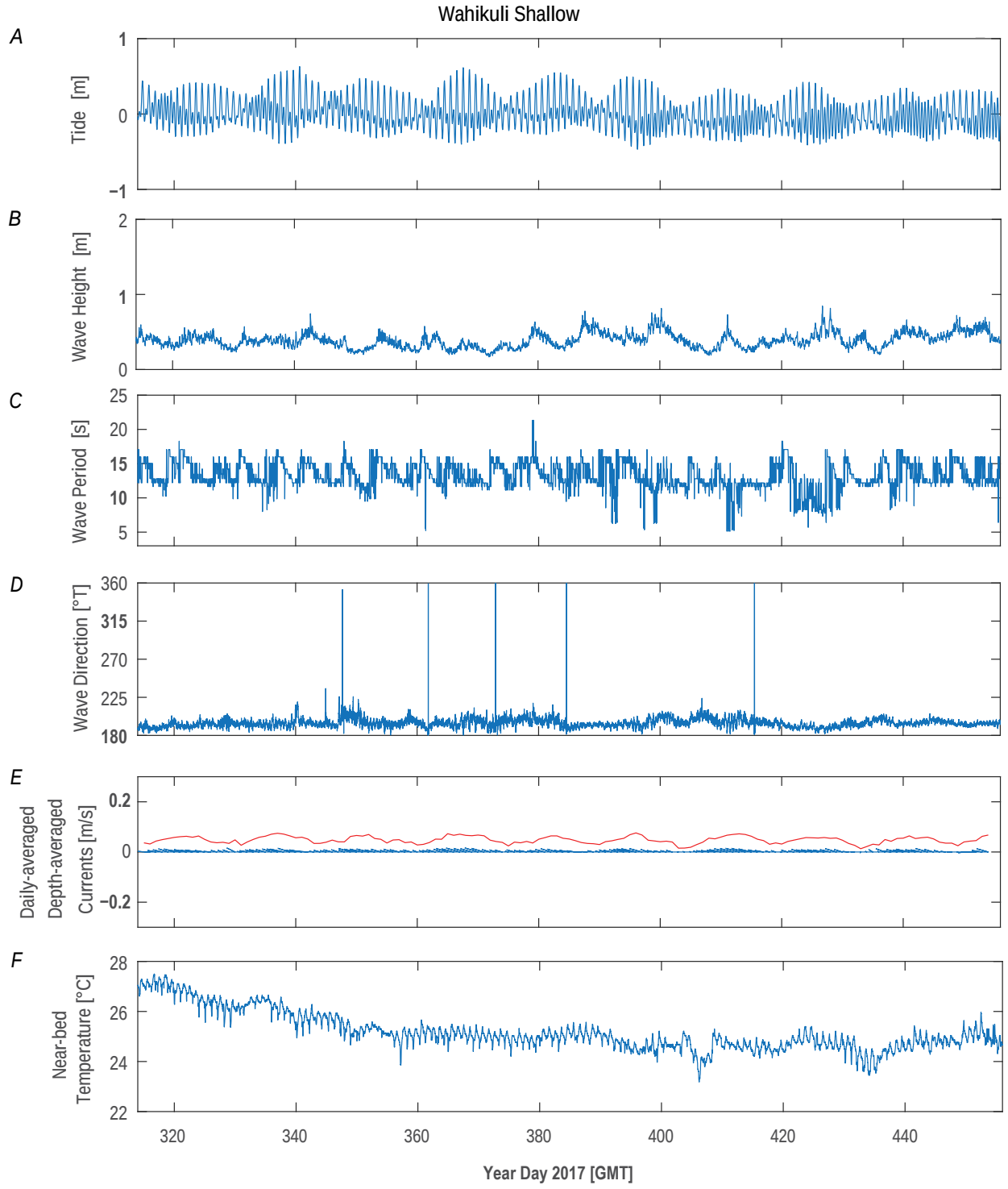


Figure 9.5. Time-series plots of oceanographic measurements during the study period from the Wahikuli Shallow study site. *A*, Tide water levels, in meters (m). *B*, Significant wave height, in meters. *C*, Peak wave period, in seconds (s). *D*, Wave direction at peak period (direction of origination), in degrees clockwise from true north (°T). *E*, Daily- and depth-averaged current velocity (blue), in meters per second (m/s), and velocity direction, in degrees clockwise from true north (in direction of flow; north is up; length scales with current velocity magnitude); daily- and depth-averaged current magnitude (red), in meters per second. *F*, Near-bed water temperature, in degrees Celsius (°C). GMT, Greenwich mean time.

Appendix 10. Larger Versions of Figure 23 Panels

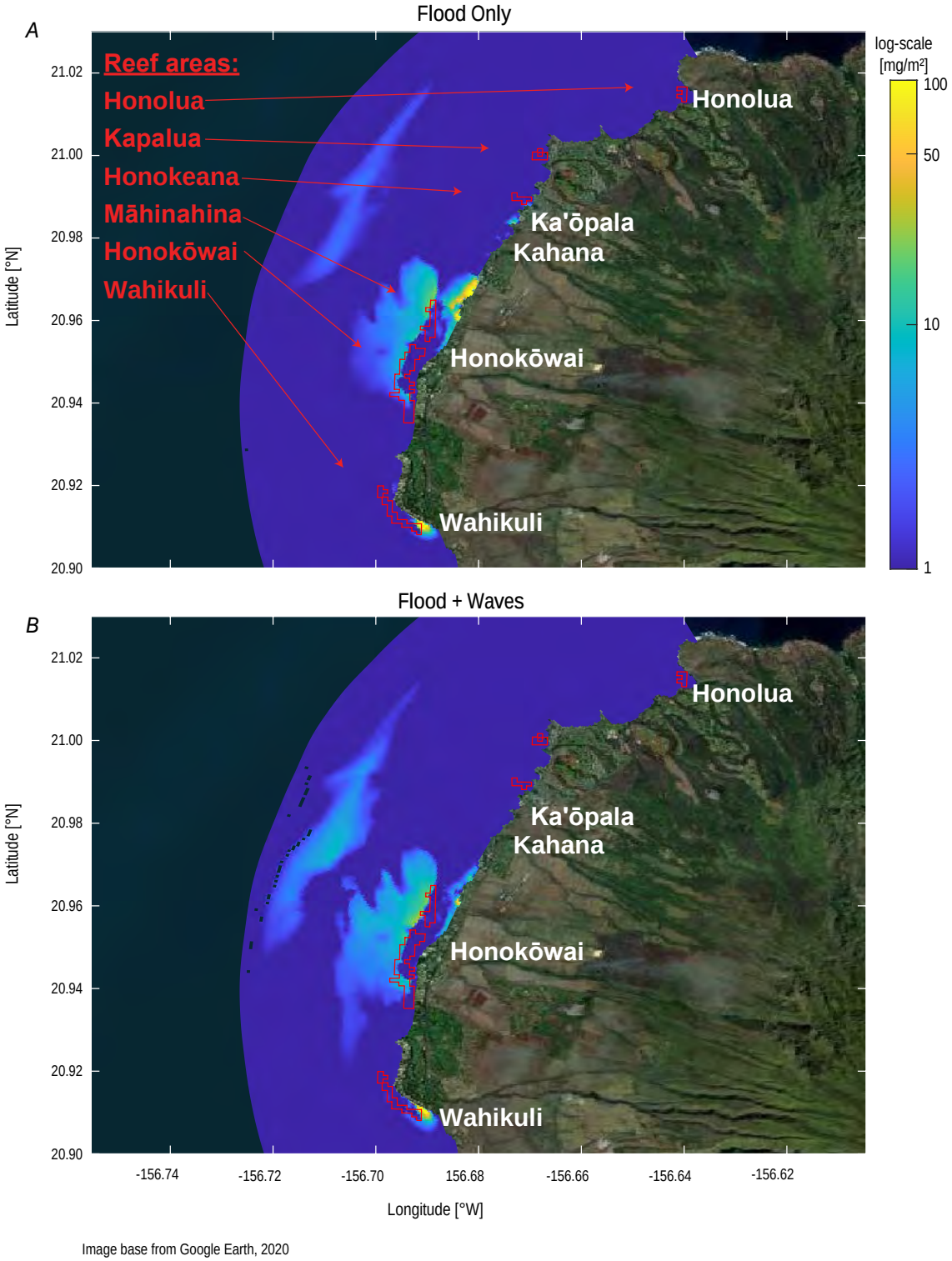


Figure 10.1. Maps of West Maui study area showing the total amount of sedimentation (in milligrams per square meter [mg/m^2]) at the end of model simulations (day 7 post-flood) under Baseline watershed conditions for Flood Only (*A*) and Flood+Waves (*B*) scenarios. Stream outfall locations are labeled in white and reef areas are outlined and labeled in red. Note total sedimentation is shown with a log scale.

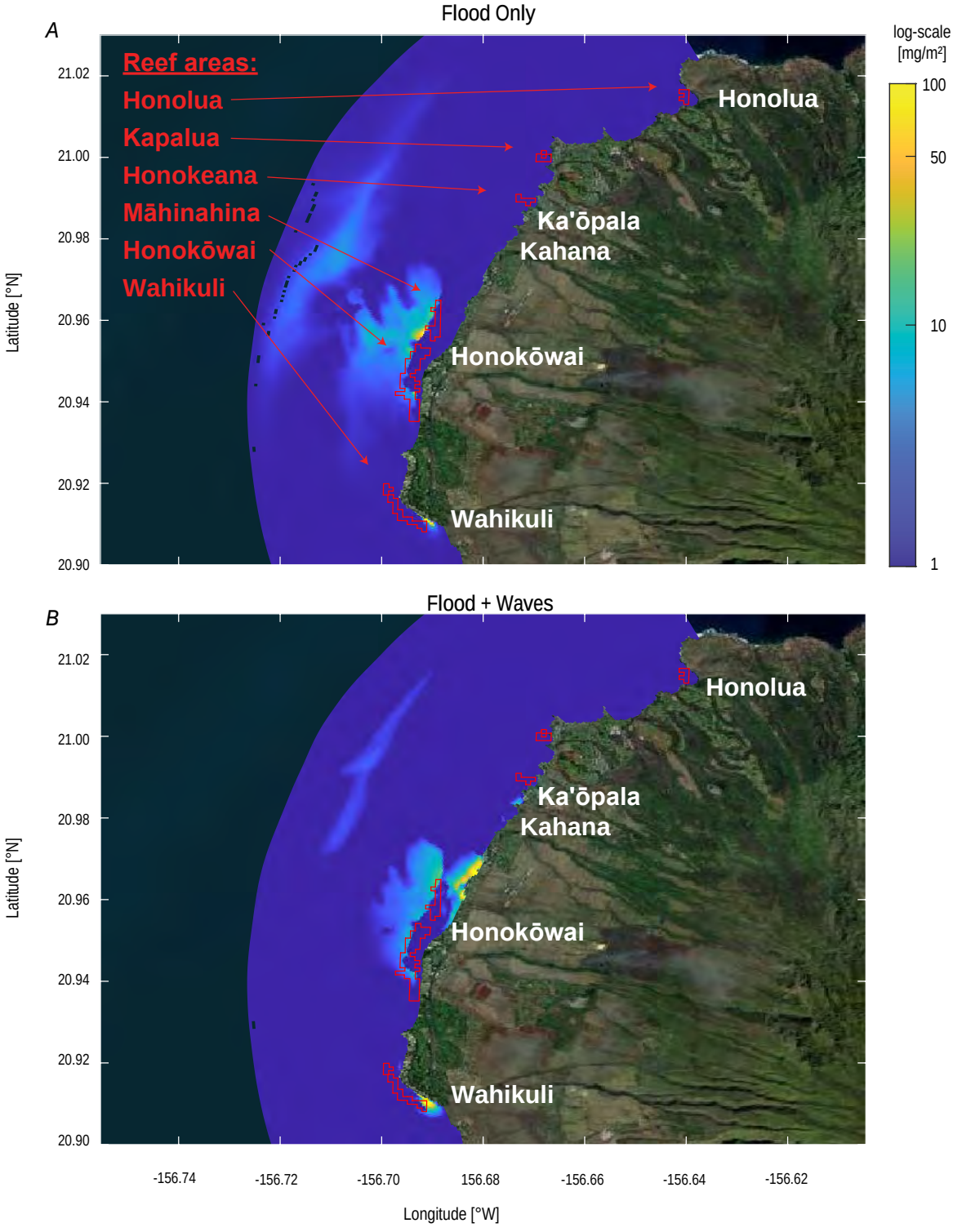


Figure 10.2. Maps of West Maui study area showing the total amount of sedimentation (in milligrams per square meter [mg/m^2]) at the end of model simulations (day 7 post-flood) under Restoration watershed conditions for Flood Only (*A*) and Flood+Waves (*B*) scenarios. Stream outfall locations are labeled in white and reef areas are outlined and labeled in red. Note total sedimentation is shown with a log scale.

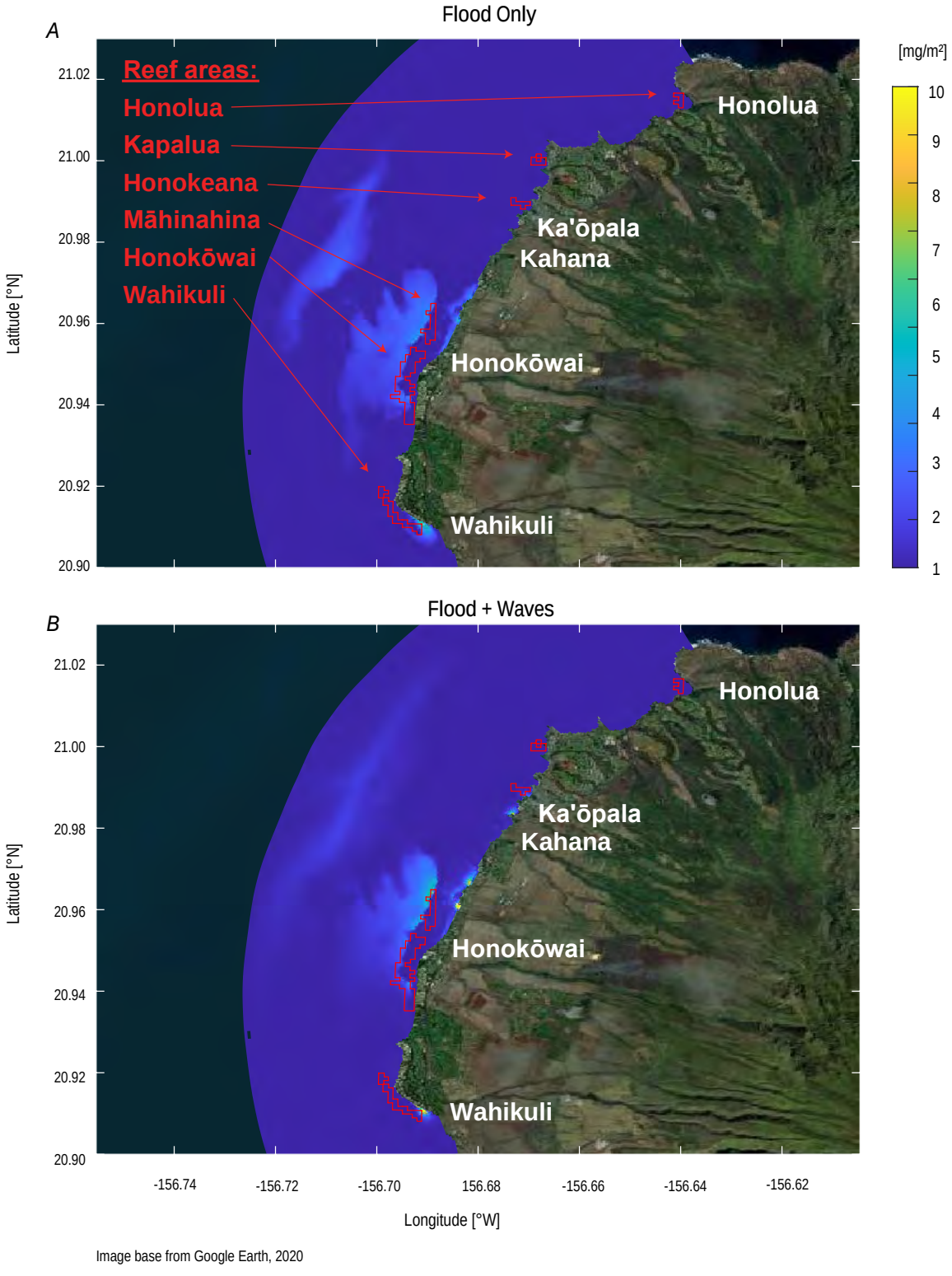


Figure 10.3. Maps of West Maui study area showing the difference in the total amount of sedimentation (in milligrams per square meter [mg/m^2]) at the end of model simulations (day 7 post-flood) between the Baseline and Restoration watershed conditions for Flood Only (*A*) and Flood+Waves (*B*) scenarios. Stream outfall locations are labeled in white and reef areas are outlined and labeled in red. Note total sedimentation difference is shown with a linear scale.

Appendix 11. Larger Versions of Figure 24 Panels

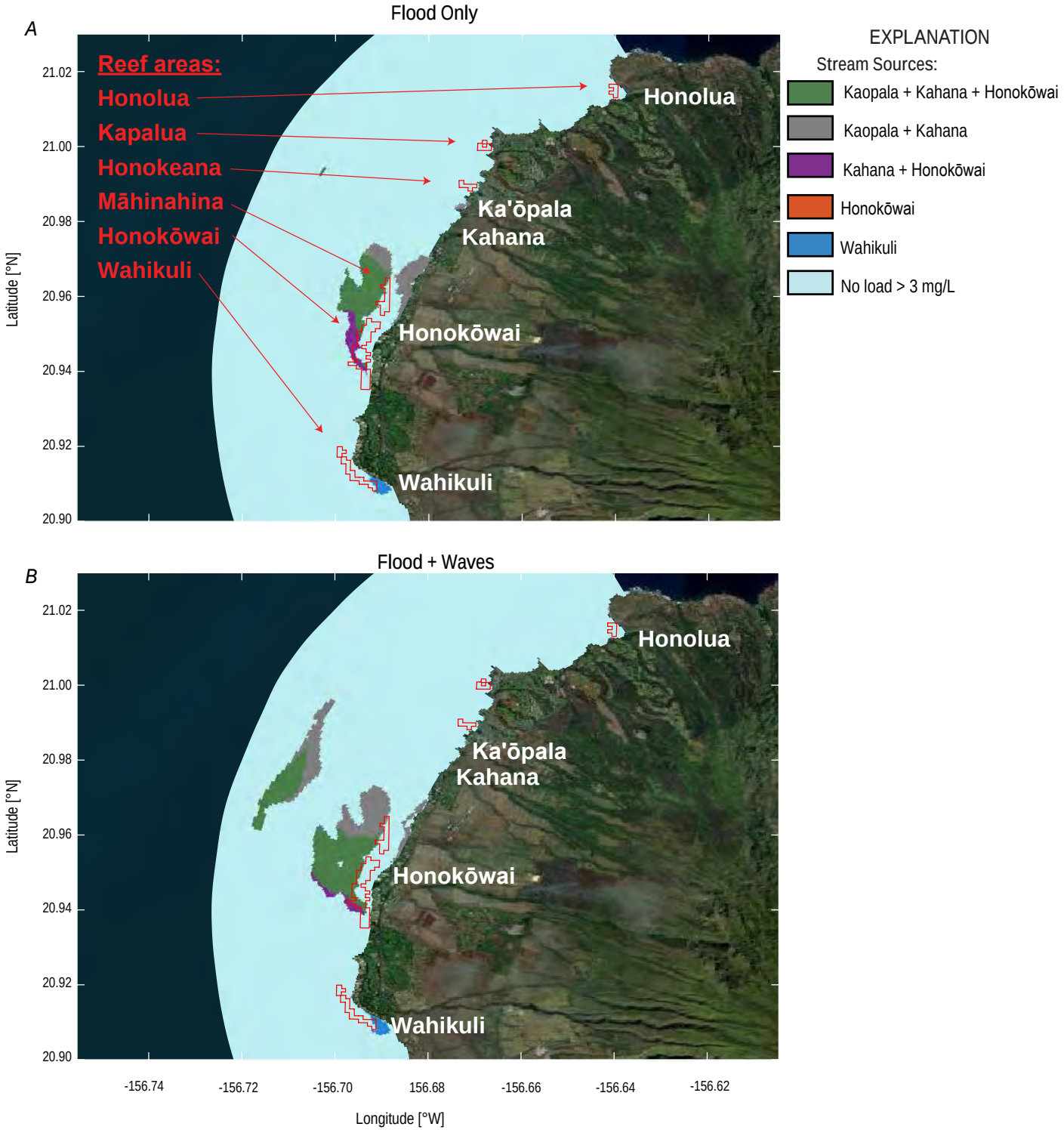


Image base from Google Earth, 2020

Figure 11.1. Maps of West Maui study area showing stream sources for total sedimentation at the end of model simulations (day 7 post-flood) under Baseline watershed conditions for Flood Only (*A*) and Flood+Waves (*B*) scenarios. Stream sources only shown for total sedimentation greater than 3 milligrams per square meter (mg/m^2). Stream outfall locations are labeled in white and reef areas are outlined and labeled in red.

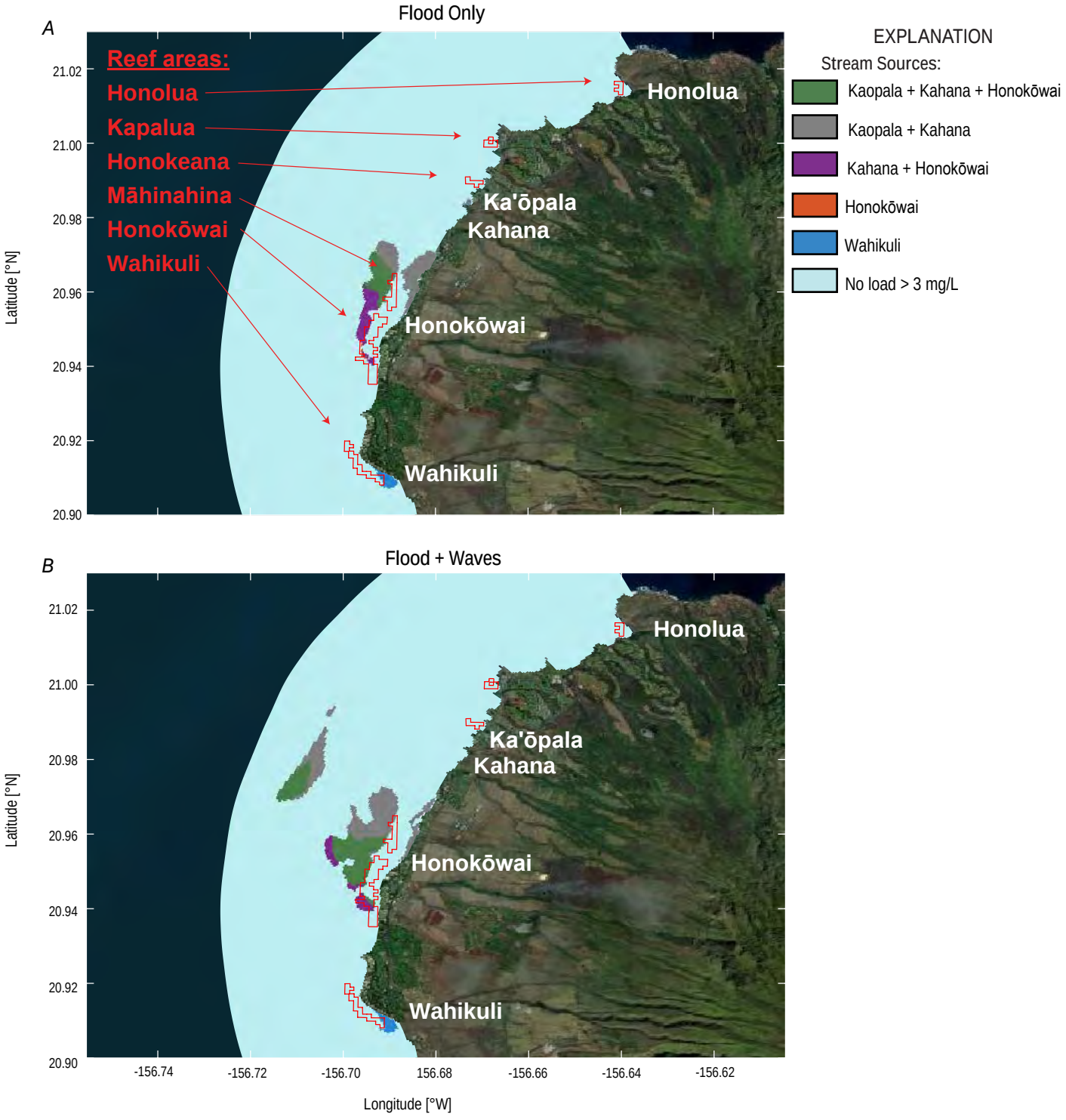


Image base from Google Earth, 2020

Figure 11.2. Maps of West Maui study area showing stream sources for total sedimentation at the end of model simulations (day 7 post-flood) under Restoration watershed conditions for Flood Only (*A*) and Flood+Waves (*B*) scenarios. Stream sources only shown for total sedimentation greater than 3 milligrams per square meter (mg/m^2). Stream outfall locations are labeled in white and reef areas are outlined and labeled in red.

Appendix 12. Larger Version of Figure 25 Panels

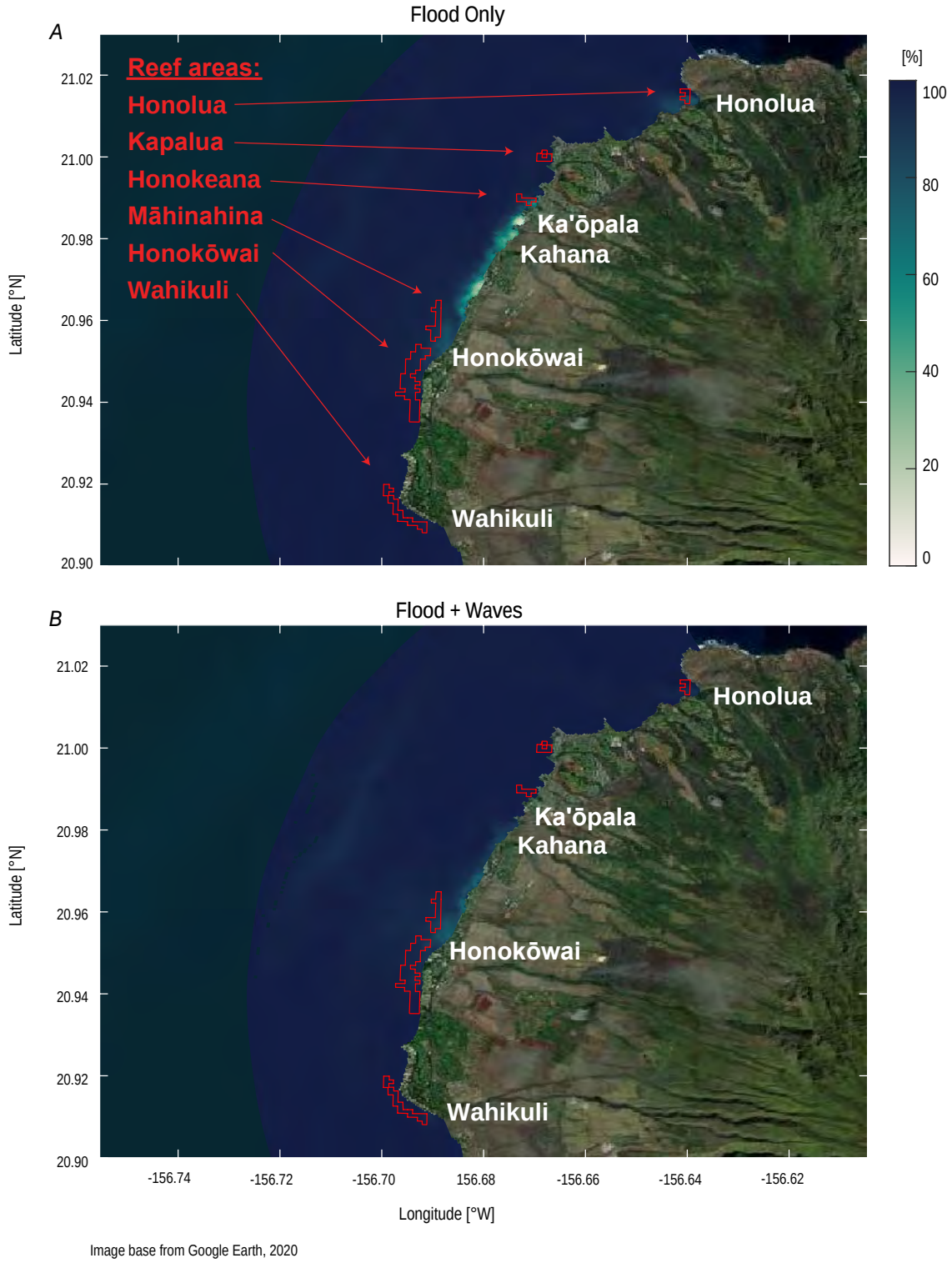


Figure 12.1. Maps of West Maui study area showing fraction of surface irradiance that reaches the seabed (averaged over entire model simulation), in percent, under Baseline watershed conditions for Flood Only (*A*) and Flood+Waves (*B*) scenarios. Small percentages indicate very little light reaching the seabed. Stream outfall locations are labeled in white and reef areas are outlined and labeled in red.

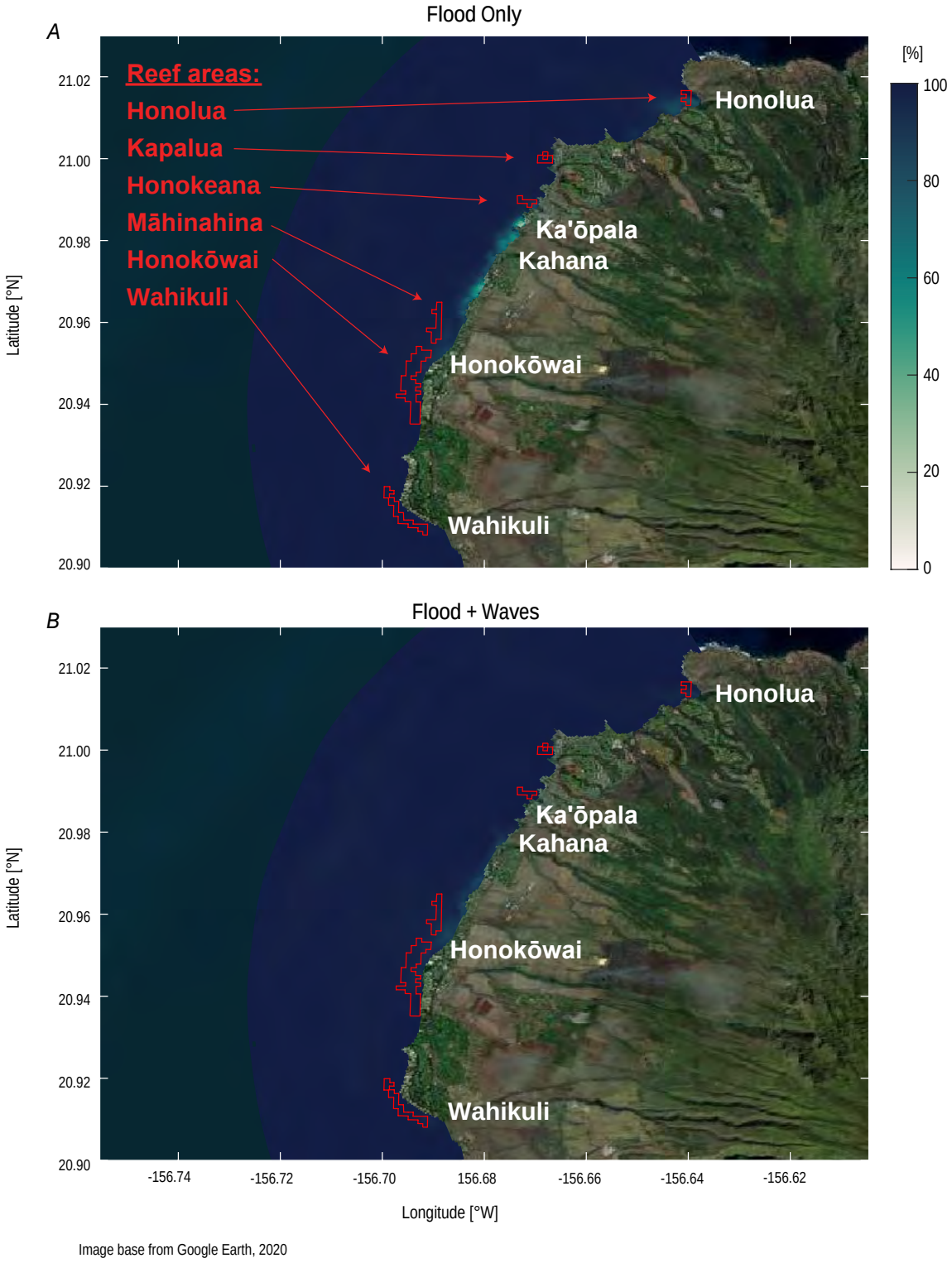


Figure 12.2. Maps of West Maui study area showing fraction of surface irradiance that reaches the seabed (averaged over entire model simulation), in percent, under Restoration watershed conditions for Flood Only (*A*) and Flood+Waves (*B*) scenarios. Small percentages indicate very little light reaching the seabed. Stream outfall locations are labeled in white and reef areas are outlined and labeled in red.

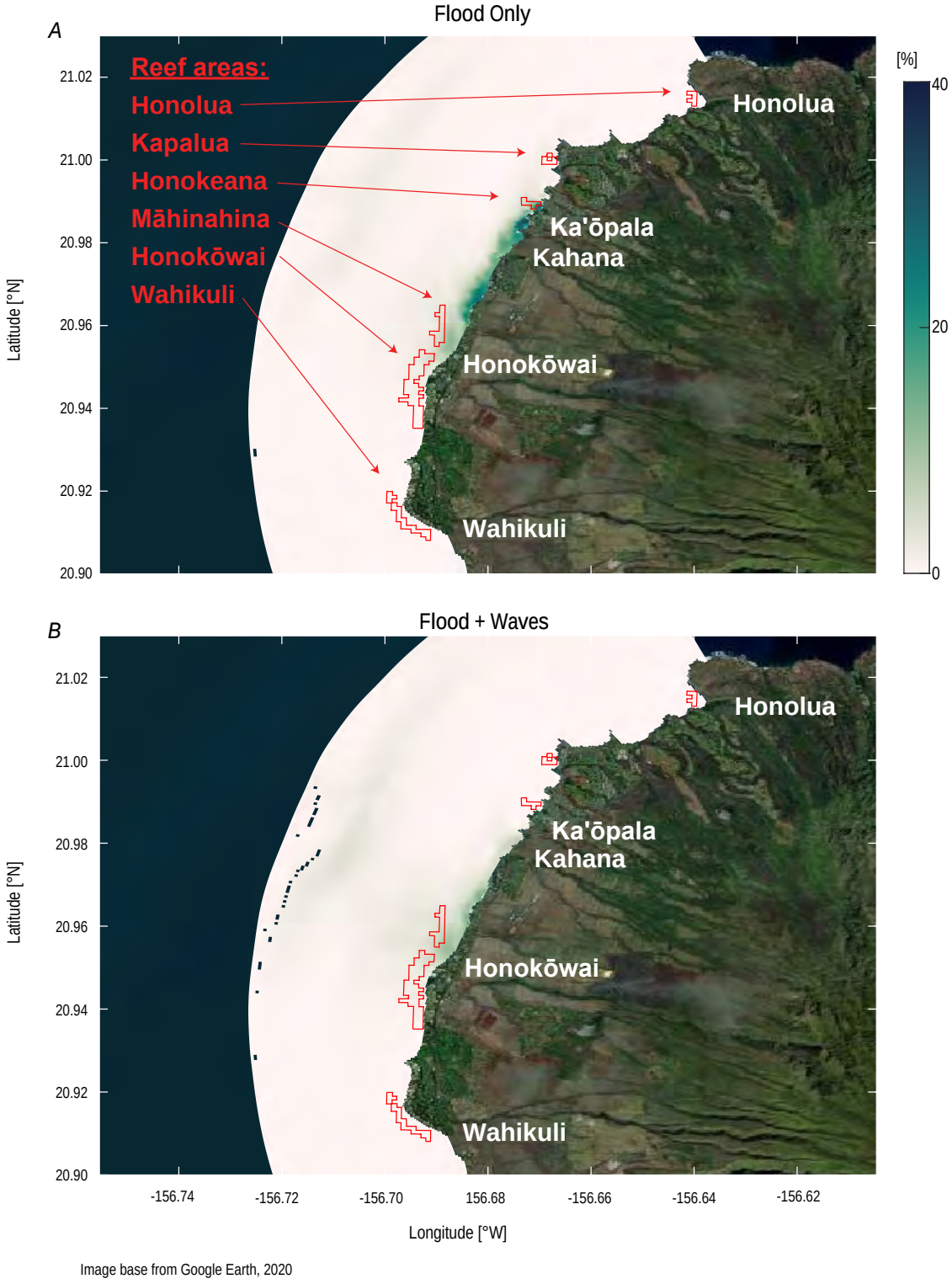


Figure 12.3. Maps of West Maui study area showing the difference in fraction of surface irradiance that reaches the seabed (averaged over entire model simulation), in percent, between Baseline and Restoration watershed conditions for Flood Only (*A*) and Flood+Waves (*B*) scenarios. Stream outfall locations are labeled in white and reef areas are outlined and labeled in red.

Appendix 13. Exposure of Coral Reef Areas to Terrestrial Sediment

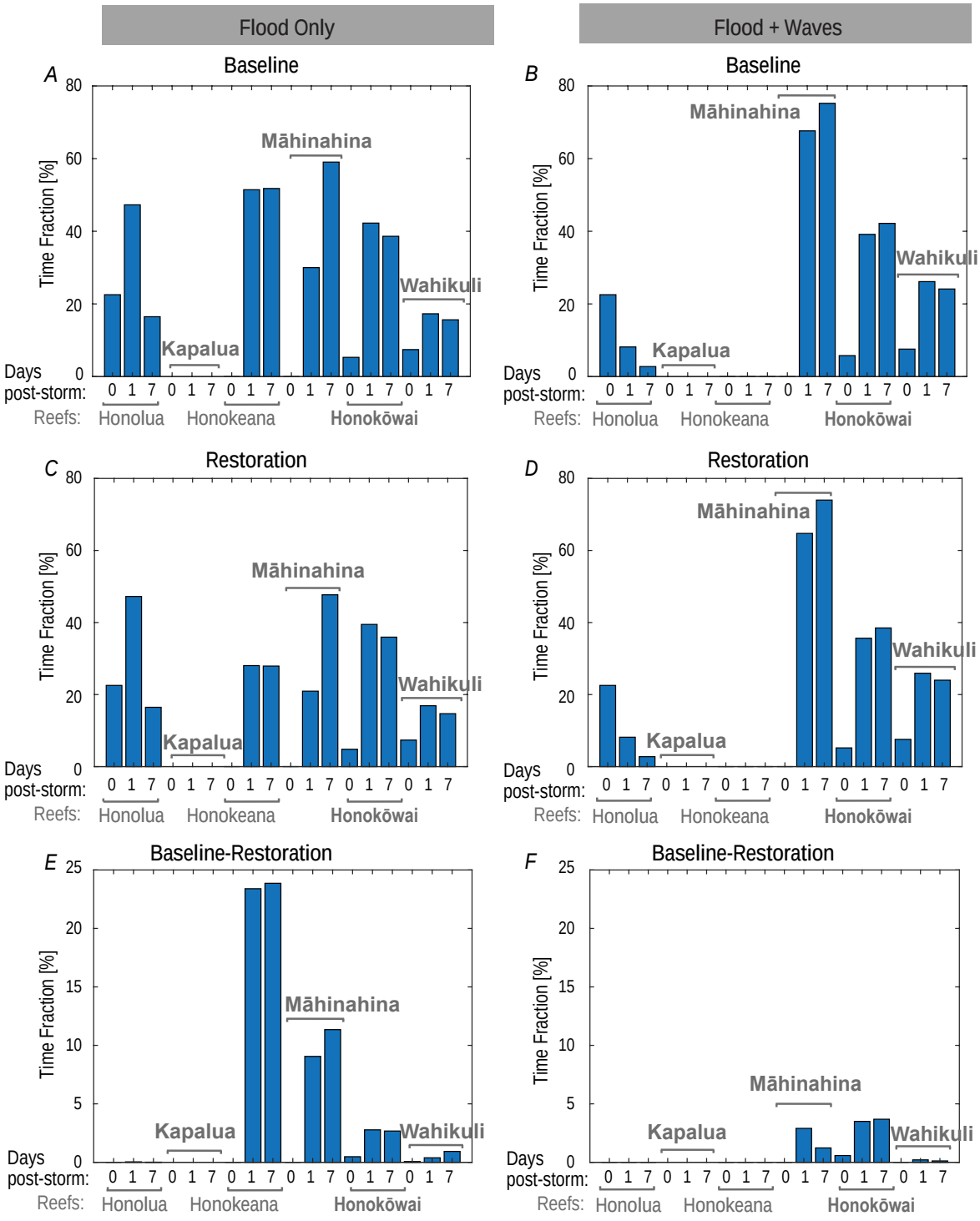


Figure 13.1. Bar graphs showing fraction of time (in percentage of total flood simulation time for a given day) reefs are exposed to sedimentation above 1 milligram per square meter of reef area for each of the six reefs (gray text and brackets) for the Flood Only (*A*, *C*, *E*) and Flood+Waves (*B*, *D*, *F*) scenarios. Fraction of time is shown for three time steps—day 0 of the flood event, day 1 post-flood, and day 7 post-flood. *A*, *B*, Baseline scenarios. *C*, *D*, Restoration scenarios. *E*, *F*, Difference between Baseline and Restoration scenarios.

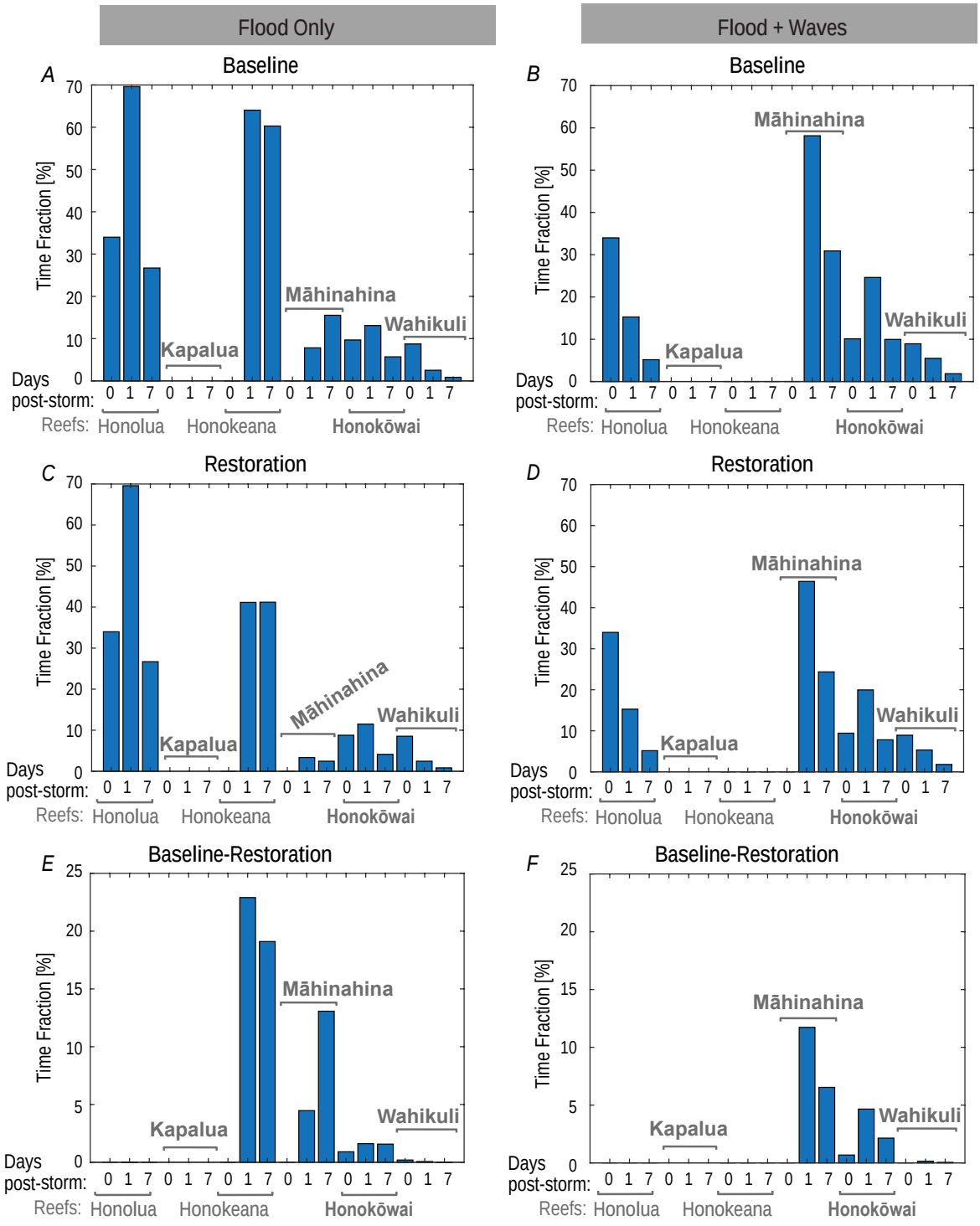


Figure 13.2. Bar graphs showing fraction of time (in percentage of total flood simulation time for a given day) reefs are exposed to suspended-sediment concentrations above 1 milligram per liter per square meter of reef area for each of the six reef areas (gray text and brackets). Fraction of time is shown for three time steps—day 0 of the flood event, day 1 post-flood, and day 7 post-flood. *A*, *B*, Baseline scenarios. *C*, *D*, Restoration scenarios. *E*, *F*, Difference between Baseline and Restoration scenarios.

Appendix E - USGS Open File Report

Moffett Field Service Center, California
Manuscript approved for publication December 27, 2022
Edited by Claire E. Ashcraft
Layout by Kimber Petersen

USGS

Storlazzi and others—Observations along West Maui, Hawai'i (2017–2018), and Modeling Effects of Potential Watershed Restoration—Open-File Report 2022–1121

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https://doi.org/10.3133/ofr20221121

Appendix E - USGS Open File Report