A Primer on Coastal Transportation System Resilience and Adaptation to Sea Level Rise on O‘ahu Using Living Shorelines and Green Infrastructure

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A Research Report from the Pacific Southwest Region University Transportation Center

Wendy Meguro, Principal Investigator, University of Hawaii
Rebecca Ogi, Junior Research Associate, University of Hawaii

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About the Pacific Southwest Region University Transportation Center

The Pacific Southwest Region University Transportation Center (UTC) is the Region 9 University Transportation Center funded under the US Department of Transportation's University Transportation Centers Program. Established in 2016, the Pacific Southwest Region UTC (PSR) is led by the University of Southern California and includes seven partners: Long Beach State University; University of California, Davis; University of California, Irvine; University of California, Los Angeles; University of Hawaii; Northern Arizona University; Pima Community College.

The Pacific Southwest Region UTC conducts an integrated, multidisciplinary program of research, education and technology transfer aimed at *improving the mobility of people and goods throughout the region.* Our program is organized around four themes: 1) technology to address transportation problems and improve mobility; 2) improving mobility for vulnerable populations; 3) Improving resilience and protecting the environment; and 4) managing mobility in high growth areas.

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Disclosure

Principal Investigator, Co-Principal Investigators, others, conducted this research titled, "A Primer on Coastal Transportation System Resilience and Adaptation to Sea Level Rise on O‘ahu Using Living Shorelines and Green Infrastructure" at the School of Architecture and Sea Grant College Program, University of Hawaii. The research took place from June 2018 to December 2018 and was funded by a grant from the University Transportation Center Pacific Southwest Region in the amount of $20,000. The research was conducted as part of the Pacific Southwest Region University Transportation Center research program.

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Students, faculty, and professionals the University of Hawaii School of Architecture, Department of Urban and Regional Planning, Sea Grant College Program, and National Disaster Preparedness Training Center contributed to the precedent studies and design ideas. A junior research associate, Rebecca Ogi, significantly contributed to the research and drawings in this report.

Abstract

O‘ahu, Hawai‘i’s coastal hazards include accelerating erosion, sea level rise, and coastal storms that threaten to flood roadways and new rail infrastructure. Typical “hard” shoreline armoring for coastal protection results in detrimental erosion; this report presents alternatives, such as living shorelines and green infrastructure. When planning long term infrastructure for 3.2 feet of sea level rise by mid-century, the goal of living shorelines is to slow coastal erosion and reduce flooding so that coastal transportation ways may remain operational during the coming decades.

This primer provides a literature review, project precedents, and design ideas for living shorelines and green infrastructure at three coastal sites on O‘ahu. The study sites, analysis, and design methods serve as prototypes for high, medium, and low wave energy sites for reference by policy makers and future design teams. The study site locations on O‘ahu are Sunset Beach, Waikiki Beach, and Waipahu Transit Oriented Development Area.

At each site, potential living shorelines and green infrastructure strategies are evaluated based on the strategies’ function and effectiveness, quantitatively where possible. The international project precedents include built and unbuilt living shorelines and green infrastructure projects, often emphasizing their multiple uses and shared benefits. The design ideas at each study site integrate the potential living shoreline and green infrastructure strategies at a conceptual design level, communicated through drawings and physical models.

The primer also demonstrates how student learning and multi-disciplinary collaboration enhance applied research.

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A Primer on Coastal Transportation System Resilience and Adaptation to Sea Level Rise on Oʻahu Using Living Shorelines and Green Infrastructure

1.0 Executive Summary

Oʻahu's coastal hazards include accelerating erosion, sea level rise, annual high wave flooding, coastal storms, and groundwater inundation, which threaten to flood roadways, buildings, landscapes, and other infrastructure. When planning long term infrastructure for 3.2 feet of sea level rise by mid-century[i], adaptations to Hawaiʻi's coastal built environment will be necessary to minimize damage from flooding. In the past, "hard" shoreline armoring was used to protect coastal communities, but the resulting detrimental erosion prompts us to consider green design alternatives, such as living shorelines and green infrastructure.

This primer provides a methodology to identify relevant living shorelines and green infrastructure strategies for protection of various types of tropical island coastal built environments, illustrated through three sites in Hawaiʻi. The goal is to slow coastal erosion and reduce flooding so that coastal transportation ways can remain operational during the coming decades. Long-term planning for relocation and/or elevation of coastal transportation ways are also needed but are outside the scope of this study.

The primer is intended to inform and aid decision-making by Hawaiʻi's government planners and policy makers, private land-owners, developers, design teams (urban planners, architects, and landscape architects, civil engineers, transportation engineers, etc.).

This primer considers context-specific application of living shorelines for coastal protection by examining three economically and socially important site locations on Oʻahu. The replicable methodology includes:

1. Summarize coastal flood hazards at each site;
2. Identify the applicable living shoreline strategies and provide explanatory graphics;
3. Provide relevant examples of built and speculative precedent projects or research; and
4. Provide visual communication of conceptual level design ideas for site-specific application of living shoreline strategies.

Three prototypical contexts with coastal roadways are explored.

1. A recreationally significant rural coastal community location: Sunset Beach area on the North Shore of O‘ahu;
2. A current densely-developed coastal community and economic engine: Waikiki Beach on the South Shore of O‘ahu;
3. A future densely-developed Transit Oriented Development (TOD) rail station location: Waipahu at Pearl Harbor, O‘ahu.

In each area, living shorelines are examined at Sunset Beach and Waikiki Beach for their potential to protect transportation ways by physically blocking water, dissipating wave energy, and/or reducing run-up distance. The green infrastructure strategies are examined at the Waipahu TOD area for their potential to reduce flooding of the built environment, while offering multiple ecological and social shared benefits.

This primer includes strategies on living shorelines, green infrastructure, and selected “gray” infrastructure. Living shoreline strategies explored in this primer include restoration of coastal sand dunes, vegetation (groundcover, shrubs, trees), and coral reefs. Green infrastructure strategies include widening floodways, temporary water detention, and stream/river bank elevation and stabilization.

This primer also discusses combining “gray” infrastructure where there is potential to provide ecological benefit, flood protection, and prolonged use of an occasionally flooded area. Gray infrastructure strategies discussed include T-head groins, underground cisterns, multi-use berms, or elevated walkways.

2.0 Introduction

The Introduction and Motivation section describes current and future flood hazards to coastal transportation systems, sea level rise forecasts, resulting planning actions, and additional rainfall-related flood hazards. A brief description of green infrastructure for this report and living shorelines in tropical environments is provided. The section concludes with a description of each site, for categorization as a typology with qualities that may apply to many sites.

2.1 Flood Hazards to Coastal Transportation Systems

Coastal hazards that may cause flooding of roadways at the three sites studied in this primer include temporal shocks and long-term stressors.

- Shocks include
    - temporary elevation of sea levels from king tides or storm surge;
    - large wave events, such as annual high wave events;
    - storm sewer back flow due to temporary elevation of sea levels;
    - riverine flooding due to increasingly intense and frequent rainfall events (at the Waipahu site)
- Long term stressors include
    - passive flooding from elevated sea levels caused by sea level rise;
    - erosion;
    - groundwater inundation in low-lying areas.

This primer does not address flooding from catastrophic events such as hurricanes or tsunamis.

2.1.1 Sea Level Rise Impacts

Recent research and policy quantify and address the negative impacts that sea level rise will have on roadway flooding, as well as the problematic erosion caused by traditional shoreline armoring. "Based on scientific modeling of sea level rise impacts identified in the Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report issued by the State of Hawaiʻi in December 2017, the [Climate Change] Commission noted that:

Of the 9,400 acres of land located within the 3.2 foot sea level rise exposure area, over half is designated for urban land uses, making Oʻahu the most vulnerable of the Hawaiian islands;
With 3.2 feet of sea level rise, almost 18 miles of Oʻahu's coastal roads will become impassible, jeopardizing access to and from many communities; and
Oʻahu has lost more than 5 miles of beaches to coastal erosion fronting seawalls and other shoreline armoring, with many more miles of beach certain to be lost with sea level rise if widespread armoring is allowed." [ii]

A new study by scientists from the University of Hawaiʻi published in 2018, states that with the new calculation of SLR in contrast to current calculated exposed land area using the "bathtub" approach, taking into account additional coastal threats means that "At 0.98 m of SLR, projected land exposure is 2.4 times the present-day exposure on Maui; Kaua‘i and O‘ahu can expect land exposure areas that are 1.8 and 1.9 times the present-day area, respectively."[iii]

2.1.2 Sea Level Rise Planning and Directives

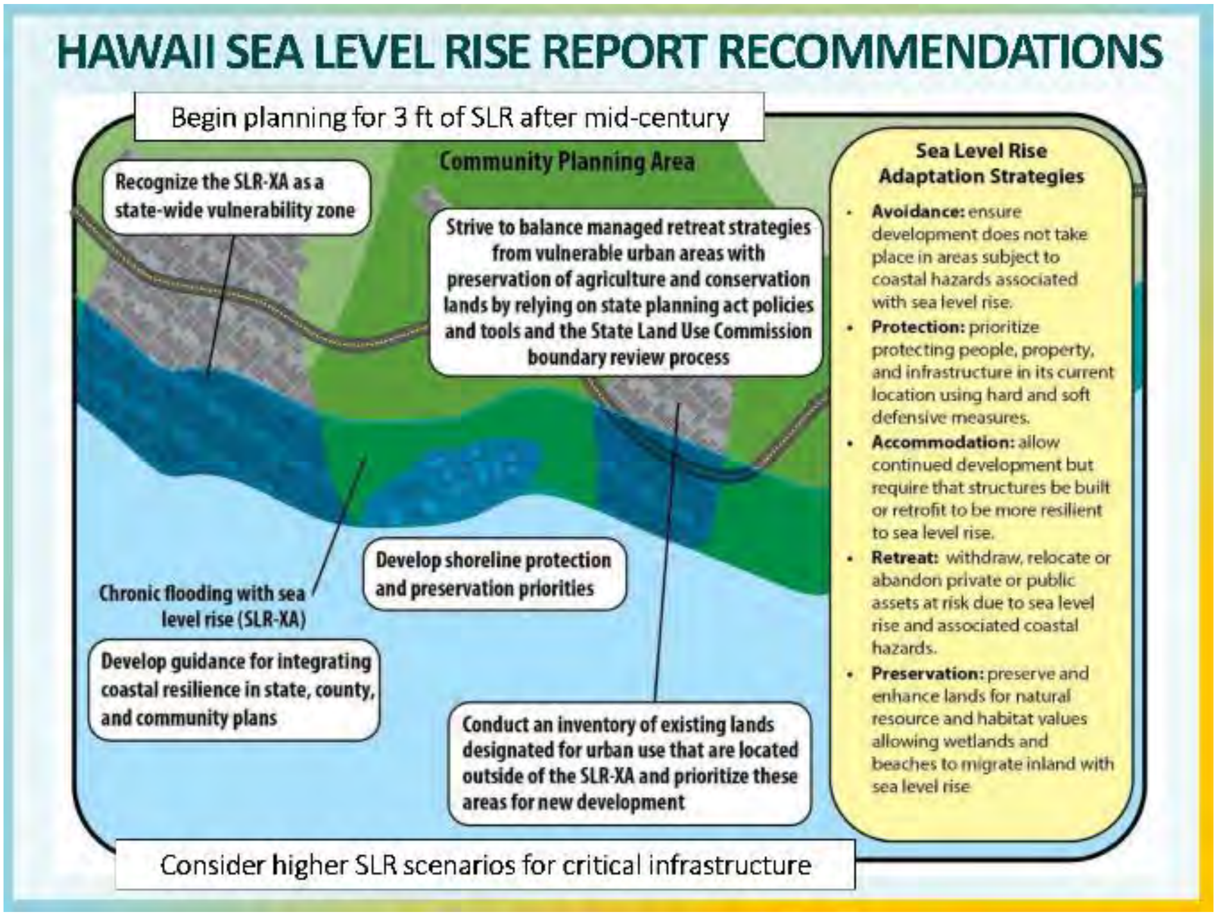
The State of Hawai‘i, Honolulu Mayor, and County Planning Departments have taken action to address sea level rise in their long-term planning. In December 2017, the State of Hawai‘i issued the Hawai‘i Sea Level Rise Vulnerability and Adaptation Report (Hawai‘i SLR Report). As illustrated in the following graphic (see Figure #), the Hawai‘i SLR report reads, "State, county, and community plans would need to determine whether to avoid risks by siting development outside areas with chronic flooding, to protect existing development through shoreline hardening, to accommodate new development through floodable design, to retreat from the shoreline by developing outside areas of chronic flooding, or to preserve the shoreline allowing landward migration of beaches, wetlands, and other natural features. Guidance is needed to help state, counties, and communities integrate sustainable and resilient land use and community development into plans and programs."

The State subsequently formed a Climate Change Commission to inform planning and policy for future climate change scenarios. In July 2018, Honolulu Mayor Kirk Caldwell issued a "formal directive to all city departments and agencies to take action in order to address, minimize the risks from, and adapt to the impacts of climate change and sea level rise." [iv]

"In its Sea Level Rise Guidance, the commission emphasized that the city should be planning for high tide flooding associated with 3.2 feet of sea level rise by mid-century, and, because of continued high global carbon emissions, take into consideration 6 feet of sea level rise in later decades of the century, especially for critical infrastructure with long expected lifespans and low-risk tolerance. The sea level rise guidelines recommended by the commission are consistent with findings by the Intergovernmental Panel on Climate Change and the National Oceanic and Atmospheric Administration (NOAA)." [iv] (See Figure *1*). The coastal roadways and future rail stations fall into the categories of infrastructure with long expected lifespans and low risk tolerance.

"An example of some considerations that could be a part of a comprehensive adaptation strategy utilizing sustainable and resilient land use practices while recognizing the SLR-XA with 3.2 feet of sea level rise[3] as a state-wide vulnerability zone."[v]

In September 2018, the Maui County Planning Department proposed new shoreline setback rules to account for erosion and sea level rise. The new rules, if passed, would allow applications in the middle of permitting to be grandfathered into new regulations, but new projects may have to conform to new shoreline setback lines. The proposal suggests "the shoreline setback line would be the erosion hazard line plus 40 feet inland … In areas without a hazard line, the setback would be 200 feet from the nearest points of the approximate shoreline as mapped by the department."



HAWAII SEA LEVEL RISE REPORT RECOMMENDATIONS

Begin planning for 3 ft of SLR after mid-century

Community Planning Area

Recognize the SLR-XA as a state-wide vulnerability zone

Strive to balance managed retreat strategies from vulnerable urban areas with preservation of agriculture and conservation lands by relying on state planning act policies and tools and the State Land Use Commission boundary review process

Chronic flooding with sea level rise (SLR-XA)

Develop shoreline protection and preservation priorities

Develop guidance for integrating coastal resilience in state, county, and community plans

Conduct an inventory of existing lands designated for urban use that are located outside of the SLR-XA and prioritize these areas for new development

Consider higher SLR scenarios for critical infrastructure

Sea Level Rise Adaptation Strategies

- **Avoidance:** ensure development does not take place in areas subject to coastal hazards associated with sea level rise.
- **Protection:** prioritize protecting people, property, and infrastructure in its current location using hard and soft defensive measures.
- **Accommodation:** allow continued development but require that structures be built or retrofit to be more resilient to sea level rise.
- **Retreat:** withdraw, relocate or abandon private or public assets at risk due to sea level rise and associated coastal hazards.
- **Preservation:** preserve and enhance lands for natural resource and habitat values allowing wetlands and beaches to migrate inland with sea level rise

Figure 1 Hawaii Sea Level Rise Report Recommendations[v]

Consideration of living shorelines and green infrastructure for protection of transportation ways may be aligned with the National Flood Insurance Program (NFIP) Community Rating System Program. The Hawaii Sea Level Rise Report recommends technical and financial support for the Community Rating System Program that “provides flood insurance premium discounts in recognition of flood risk management program elements that exceed the minimum requirements of the NFIP. Creditable activities include: land acquisitions and restoration to open space uses, relocation, flood-proofing, open space preservation, and other measures that reduce flood damages.”[vi]

2.1.3 Additional Flood Hazards

In addition to sea level rise, more frequent king tides and intense rainfall are anticipated in the coming century.

In 2018, the highest high tides of the year, “king tides”, overtopped seawalls in Waikiki, and caused storm drains to work in reverse as a conduit for ocean water to the street. The number of days per year with king tide flooding is anticipated to increase throughout the century. Sweet et al., estimated the arrival of king tide flooding at different frequencies: six, twelve, and twenty-four days per year. Flooding six days per year is estimated to arrive as early as 2024 and as late as 2038. Flooding twenty-four days per year is estimated to arrive as early as 2028 and late as 2045.[vii]

Figure 2: Waikiki storm drains backed up with sea water during a king tide event in April 2015. Photo credit: Wendy Meguro

Figure 3 The SLR-XA map diagram depicts flooded areas from 3.2 ft. sea level from passive flooding, annual high wave flooding, and coastal erosion.[viii]

El Niño events are associated with more intense rainfall in Hawai‘i and these events will become more common. According to a 2017 study on El Niño frequency predictions after the Paris Agreement stated their goal of limiting global warming to 1.5°C, “extreme El Niño events continue to increase after the GMT (global mean temperature) peaks (at 1.5°C) and stabilizes beyond 2050, from about 10 events per 100 years … at 1.5°C warming … to about 14 events per 100 years beyond 2050.”[ix]

As Wang et al. and Sweet et al. both suggest, climate change related flood hazards are expected to increase in frequency in the future. Therefore it is important to consider the simultaneous occurrence of natural hazards (e.g., the occurrence of king tides at elevated sea levels during an episode of intense rainfall).

The maps in this report show modeled flooded areas given 3.2 feet of sea level rise exposure area (SLR XA), which includes passive flooding, annual high wave events, and coastal erosion from the PacIOOS viewer (see Figure 3).

In this report, the maps with 6 feet of sea level rise are from a different source, the NOAA sea level rise viewer, and only take into account passive flooding, tidal variation, and hydrologic connectivity (not erosion). “The sea level rise scenarios are mapped on or above mean higher high water (MHHW). MHHW can be defined as the average of the highest high tide of each tidal day observed over a specific 19-year period (also referred to as the National Tidal Datum

Epoch). So in the context of the [NOAA] viewer, 0 feet of sea level rise represents the current MHHW level."

2.2 Green Infrastructure and Living Shorelines Introduction

Below are brief descriptions of living shorelines and green infrastructure as they are used for this primer.

"Living Shorelines" integrate habitat restoration techniques, coastal engineering, and conservation to mitigate coastal hazards through the incorporation of natural elements. "Hard" engineering structures such as seawalls, bulkheads, or rock revetments have been regarded as conventional solutions to protecting properties against erosion and inundation. However, hardened shorelines can have negative impacts on nearby non-armored shorelines and can ultimately lead to a complete loss of intertidal areas. In Hawaii, "for many years, the typical response to the threat of coastal erosion has been to protect the land by building a seawall... Beach sands in front of the wall can erode away entirely, leaving adjoining beach areas and unprotected property vulnerable to accelerated erosion."[x]

Living shorelines, on the other hand, have the advantage of providing coastal protection benefits to communities, while also providing ecological benefits. Living shorelines on the continental U.S. are often reference plants and other natural elements used to "stabilize estuarine coasts, bays, and tributaries."[xi] Living shoreline definition and strategies are expanded for application to tropical islands in this primer, to include restoration of coastal sand dunes, vegetation (groundcover, shrubs, trees), and coral reefs.

The Army Corps of Engineers has traditionally relied on hard infrastructure, but the Army Corps' use of nature-based infrastructure and living shorelines now outnumbers the hard structures, demonstrating its acceptance and effectiveness. "Until the latter part of the 1900s, the use of hard structures in coastal areas (sometimes termed coastal armoring), was the preferred method for reducing the effects of waves, storm surge, and erosion. However, over recent decades, U.S. Army of Corps of Engineers (USACE) beach nourishment and dune building outnumbered hard structures in terms of both the number and miles of projects constructed. Additional approaches use natural or restored habitats to help reduce the impact of waves and storm surge, and/or building design and nonstructural land-use strategies to reduce the consequences of a hazardous event."[xii]

Green infrastructure manages stormwater on-site and strives to mimic the hydrology of an undeveloped site. In this primer, we explore how green infrastructure may be used at one site to mitigate future riverine flood events that are anticipated to increase in severity with climate change. Given current flood maps, we speculate potential future flooding during temporal events such as sea level rise plus storm surge, or riverine flooding given more intense rainfall.

2.3 Living Shorelines in Hawai‘i

The Hawai‘i Sea Level Rise Vulnerability and Adaptation Report recommends that the State "develop shoreline protection, conservation, and restoration priorities and guidelines." It recognizes that "shoreline armoring is either prohibited or heavily discouraged under the Hawai‘i Coastal Zone Management Act …" and suggests potential inclusion of non-structural armoring, which would include living shorelines. "County ordinances could also require property owners to consider relocation of residences and non-structural or soft-armoring protection methods before hard armoring structures are even considered." "Further, state and local governments could adopt policies generally favoring non-structural armoring, such as beach nourishment, over hard armoring as a shoreline protection measure."[xiii]

The following quote from Chip Fletcher's book, Living on the Shores of Hawai‘i, explains why sea walls should be avoided. "For many years, the typical response to the threat of coastal erosion has been to protect the land by building a seawall. Over time though, this "solution" often leads to another problem—the loss of beaches. In Hawai‘i, dunes and sandy plains provide a primary source of sand to sustain beaches where erosion moves them inland. When a retreating beach runs up against a hard structure such as a seawall, it has no place to go. Beach sands in front of the wall can erode away entirely, leaving adjoining beach areas and unprotected property vulnerable to accelerated erosion. Miles of beach on the island of O‘ahu have already been lost, and some 70 percent of beaches in Hawai‘i are actively eroding. The beach also provides ecosystem services, such as wildlife habitat and storm surge protection. Losing the beach to erosion or a seawall could trigger a cascade of negative impacts."[xiv] Living shorelines offer moderate protection of the built environment for a limited period of time.

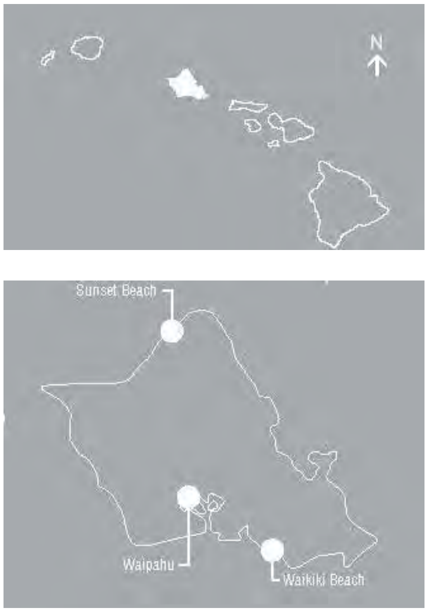


Figure 4 Maps of the Hawaiian Islands (top) and a larger map of the island of O‘ahu (bottom)

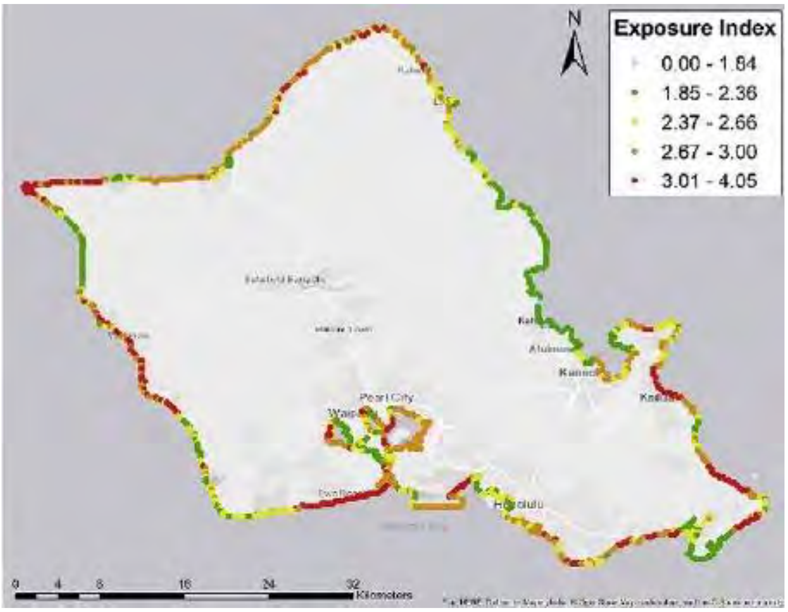


Figure 5 The Coastal Exposure Map indicates moderate and high coastal exposure vulnerability for the three locations in this study.[xv]

2.4 Site Locations and Significance

This primer explores living shorelines and green infrastructure at three prototypical contexts with coastal roadways.

1. A recreationally significant rural coastal community location: Sunset Beach area on the North Shore of O‘ahu;
2. A current densely-developed coastal community and economic engine: Waikiki on the South Shore of O‘ahu;
3. A future densely-developed Transit Oriented Development rail station location: Waipahu at Pearl Harbor, O‘ahu.

The site locations were selected not only because of their economic and social importance, but also because they represent prototypical coastal conditions with varied wave energy, roadway distance from shoreline, inland flooding risks, geology, and development density. This introductory section includes a brief description and comparison of each site; more detailed site descriptions and flood maps occur in later in the report.

The future Waipahu rail station and transit oriented development is a low wave energy site, sheltered from waves by Pearl Harbor and Pouhala Marsh. Until mid-century, shocks are likely to include rainfall and riverine flooding of areas planned for re-development. With three feet of sea level rise, flooding is likely in areas currently inhabited by detached homes. This primer explores opportunities for green spaces to serve as flood detention areas, widen the river flood way, and integrate water detention into roadway and parking lots.

Waikiki Beach represents a medium wave energy site with a man-made sandy beach. Currently, annual high wave events from summer swells, king tides, overtop seawalls and threaten to flood the densely built tourism hub. Sea level rise, groundwater inundation, and stormwater drain backflow will increase flooding in this economically significant area. This primer explores the potential for living shorelines as part of an adaptation strategy that keeps Waikiki habitable as flooding increases in frequency. We explore coral reef restoration, shrubs and trees, and beach sand restoration as potential strategies to dissipate wave energy, slow erosion, reduce wave run-up, and provide habitat.

The coastal roadway at Sunset Beach is built atop dunes. In 2017 large winter waves caused by storms eroded the bike path adjacent to this single coastal road. The surrounding rural community is valued for its world-class surfing and relies on this one road. This primer explores the potential for sand dune restoration and vegetation as part of a long-term retreat strategy to maintain the sandy beach and move built development out of harm’s way.

The three locations in this primer show moderate and high coastal exposure vulnerability in a 2018 study of Coastal Exposure of the Hawaiian Islands using GIS-based Index Modeling[xvi] (see Figure 5). This study creates a coastal exposure index based on geomorphology, relief, natural habitats, sea level change, wave exposure, surge potential, and population, using the InVEST modeling software and ArcGIS (Geographic Information Systems). This underscores the relevance of studying these three sites and the need for context-specific solutions.

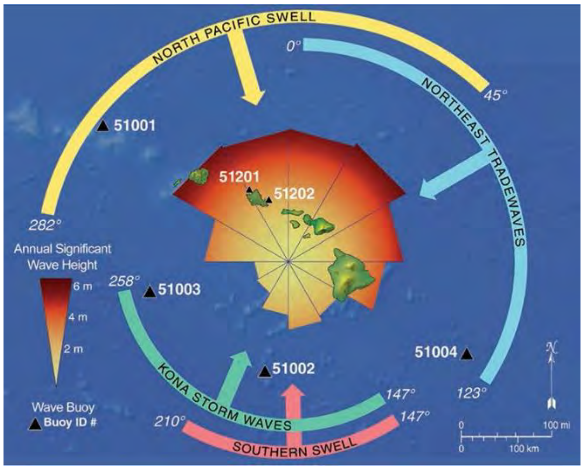


Figure 6 Hawai‘i dominant swell regimes after *Moberly and Chamberlain (1964)*[xvii], and wave-monitoring buoy locations.[xviii]

Table 1 Coastal Sites and Their Varied Characteristics

Site on O‘ahu	Significance	Wave Energy	Roadway-Shoreline Relationship	Inland Flooding Risks	Building Develop-ment Density	Geology
Sunset Beach	High recreational value. Only coastal roadway makes community vulnerable to isolation.	High, 5 meter significant wave height at offshore buoy[xix]	Separated by shifting sand dunes.	Groundwater inundation	Low	Natural sandy beach with fringing reef[xx]
Waikiki	High economic value (tourism)	Medium, 2 meter annual significant wave height at offshore buoy[xxi]	Separated by buildings	Seawater reverse flow up storm drains; groundwater inundation	High	Man-made sandy beach with coral reef
Waipahu T.O.D. Area	Denser, future transit oriented development and new rail station planned	Low, sheltered coastline at Pearl Harbor	Some roads affected by sea level rise. Rail station affected by riverine flooding.	Riverine flooding. Storm surge. Groundwater inundation	Medium	Clay-like soils

Table 2 Coastal Sites and Living Shoreline Strategies to Protect Built Environment

Site on O‘ahu	Dune Restoration	Beach maintenance	Vegetation	Coral reef restoration	Offshore breakwater
Sunset Beach	Yes, dune restoration could slow erosion.	High	Applicable to stabilize current and restored dunes.	Not applicable. High wave energy would harm coral.	Not applicable. High wave energy would damage breakwater.
Waikiki	Not applicable for relatively narrow beach.	Applicable for periodic sand replenishment .	May be applicable to stabilize sand.	Possibly applicable, especially in areas of lower wave energy.	Possibly applicable to reduce wave energy.
Waipahu T.O.D. Area	Not applicable for marsh, rivers, or canal.	Not applicable for marsh, rivers, or canal.	Applicable for bank stabilization at river edges with new elevated berms	Not applicable for low wave energy harbor environment.	Not applicable for low wave energy harbor environment.

2.5 Methodology

This university-based research was conducted during 2018 through a survey of literature and professional built work; design exercises by students; and feedback from topic experts.

1. Identify coastal hazards at each of the three sites and impacts on transportation infrastructure.
2. Identify current living shorelines and green infrastructure resiliency, adaptation best practices, and precedent projects that are relevant for the selected sites.
3. Incorporate student learning by creating a new undergraduate elective course on living shorelines for coastal protection in Hawai‘i including speculative design exercises, lectures and critique by guest experts. Collaborate with faculty and students in related courses in the Department of Urban and Regional Planning.
4. Incorporate student learning through hiring a junior research associate to assist with creating the primer.
5. Solicit feedback on draft primer from academic mentors.
6. Create a description, explanatory graphics, and 3-dimensional physical models for each living shorelines resiliency strategy, related considerations, and assessment of applicability to the sites.
7. Disseminate primer, solicit feedback, and write manuscripts to pursue publication.

3.0 Site-Specific Living Shoreline and Green Infrastructure Strategies

In this primer, suggestions for living shorelines techniques are tailored to each site’s wave energy, roadway distance from shoreline, inland flooding risks, geology, and development density.

The following three study sites serve as prototypes for high, medium, and low wave energy sites for reference by policy makers and future design teams to inform future adaptation of transportation ways from coastal erosion, flooding, and sea level rise. The potential for living shorelines and green infrastructure is studied at site locations including Sunset Beach, Waikiki Beach, and Waipahu Transit Oriented Development Area.

At each site, the first section defines sources of flooding and maps the flooded areas.

The second section explores potential living shorelines and green infrastructure strategies are explored. The literature review provides information on the strategies’ function, quantitatively where possible.

The third section includes project precedents of built and unbuilt living shorelines and green infrastructure projects, often emphasizing the multiple uses shared benefits.

The fourth section includes design ideas at each study site by applying the potential living shoreline and green infrastructure strategies at a proof-of-concept level. Design ideas are communicated through drawings, physical models, and writing.

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3.1 Sunset Beach

3.1.1 Existing Conditions

Sunset Beach represents a prototypical high wave energy, sandy beach with steeply sloped topography and bathymetry, relative to the other sites. Sunset Beach is a beach with a fringing reef and has a coastal slope of less than 20%.[xxii] Large winter waves regularly cause erosion, threatening roads and houses that are built on top of sand dunes near the shoreline. During the winter of 2015-2016, “massive El Niño-fueled winter surf hitting the North Shore, more than 11 miles of highway were closed for days due to wave overwash.”[xxiii]

Sunset Beach, along with the North Shore of O‘ahu from Haleiwa to Kahuku, was identified as highly vulnerable to coastal hazards in a 2018 study.[xxiv] The road is the only accessible through the North Shore and million dollar beachfront houses abound in this area. The North Shore is of high recreational value to visitors and locals because of its world class surfing and beautiful rural setting. Activities at Sunset Beach contribute substantially to the North Shore’s economy.[xxv]

In the 2002 publication, *Atlas of Natural Hazards in the Hawaiian Coastal Zone*, for Sunset Beach, tsunami, stream flooding, and high waves are ranked as “high” hazard types and erosion is ranked as a medium-high hazard (see Figure 8). The overall coastal hazard assessment is 5 out of 7 where 7 is highest.

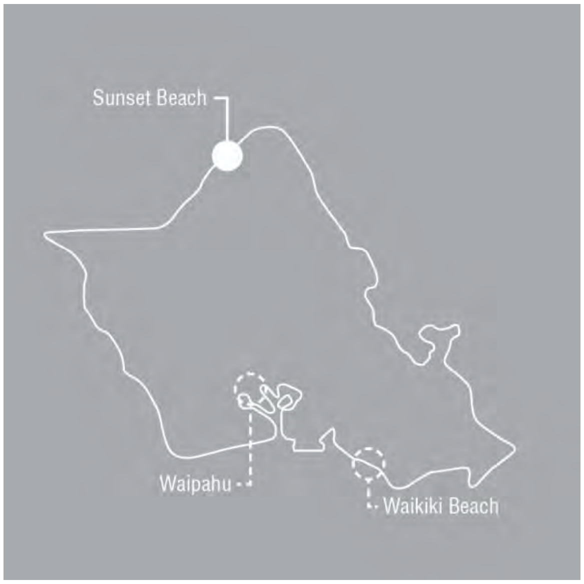

Figure 7 Map of O‘ahu with Sunset Beach highlighted.

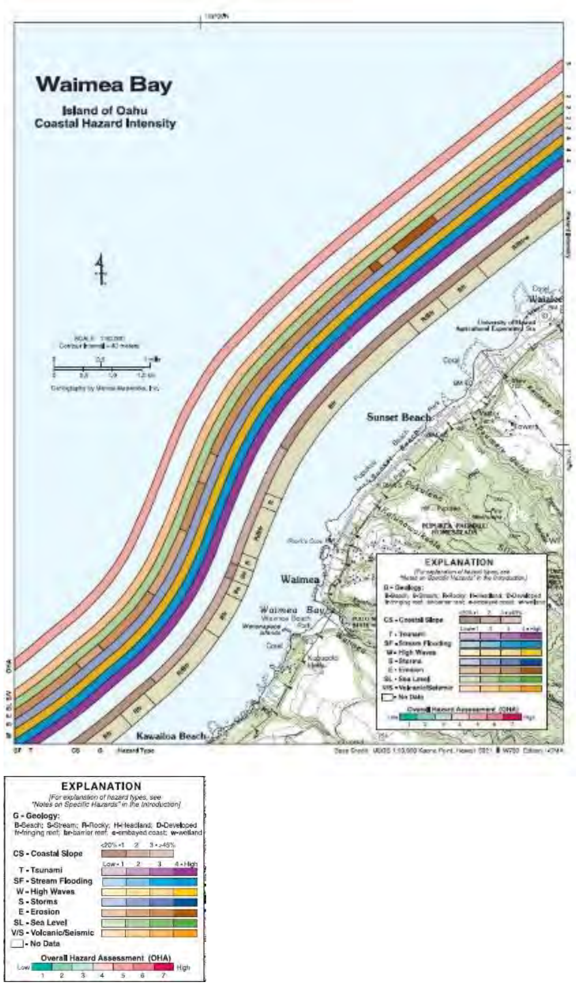

Figure 8 Map with Coastal Hazard Intensity showing area around Sunset Beach from Atlas of Natural Hazards in the Hawaiian Coastal Zone, 2002.

The following pages include photos of Sunset Beach during Spring 2018 and a map showing photo locations (see Figure 9). The photos show the erosion of the beach resulting in a crumbling asphalt bicycle path and exposure of below-grade utilities. The photos also show vegetation, typically naupaka, between the ocean and residences, which offers some buffer to oncoming waves. (See Figure 9 map and photos).

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Figure 9 Sunset Beach Existing Conditions Photo Locations Map

Sunset Beach Existing Conditions Photos

Photo A

Water-front homes face the constant threat of land erosion and water damage due to their close proximity to the eroding shoreline.

Photo credit: B. Ngo

Photo B

Vegetation may help stabilize sand, encourage the settling of wind-blown sand, and dissipate wave energy.

Photo credit: L. Gonzales

Photo C

Waves erode, expose, and damage vegetation, streets, and underground utilities.

Photo credit: S. Mendes

Photo D

The 2018 erosion due to large wave events destroyed areas of the bicycle path.

Photo credit: C. Holcom

Photo E

Erosion and steeply sloped shoreline. Photo credit: B. Ngo

Photo F

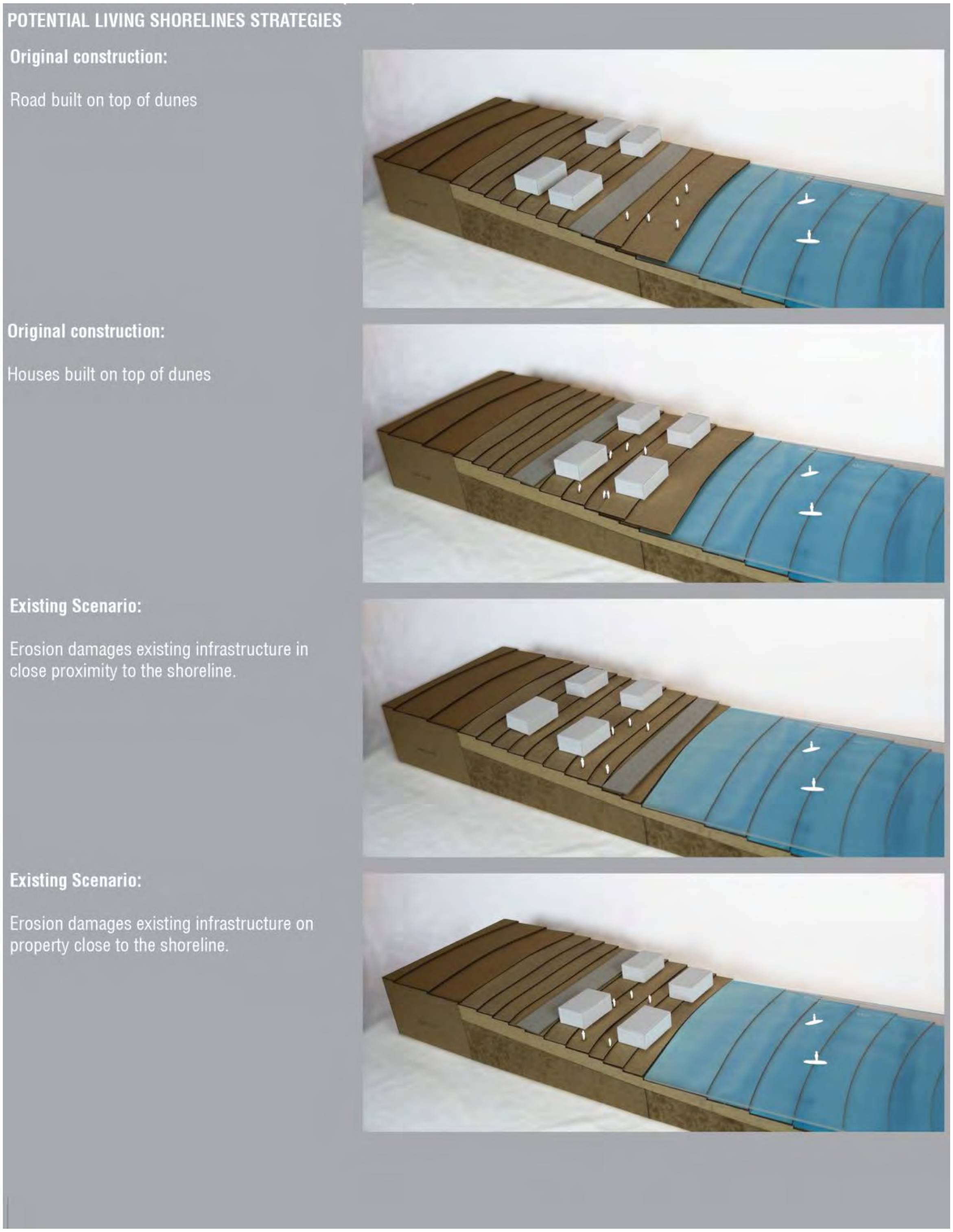
Sunset Beach looking approximately west.

Photo credit: H. Au

The following maps show the current Sunset Beach area, buildings, roads, streams, coral, topography and bathymetry (see Figure 10). The second map shows, in blue, the Sea Level Rise Exposure areas inundated with 3.2 feet of sea level rise, annual high wave flooding, and coastal erosion; the red lines indicate flooded highways (the road serving surrounding communities) (see Figure 11).

Figure 10 Sunset Beach Site Existing Conditions.
Source: Google Maps.

Figure 11 Sunset Beach wth 3.2 Ft. SLR-XA and Affected Major Roads.
Source: PacIOOS.



POTENTIAL LIVING SHORELINES STRATEGIES

Original construction:

Road built on top of dunes

Original construction:

Houses built on top of dunes

Existing Scenario:

Erosion damages existing infrastructure in close proximity to the shoreline.

Existing Scenario:

Erosion damages existing infrastructure on property close to the shoreline.

Figure 12 A scale model of Sunset Beach shows houses and a roadway threatened by erosion. Source: Models by author.

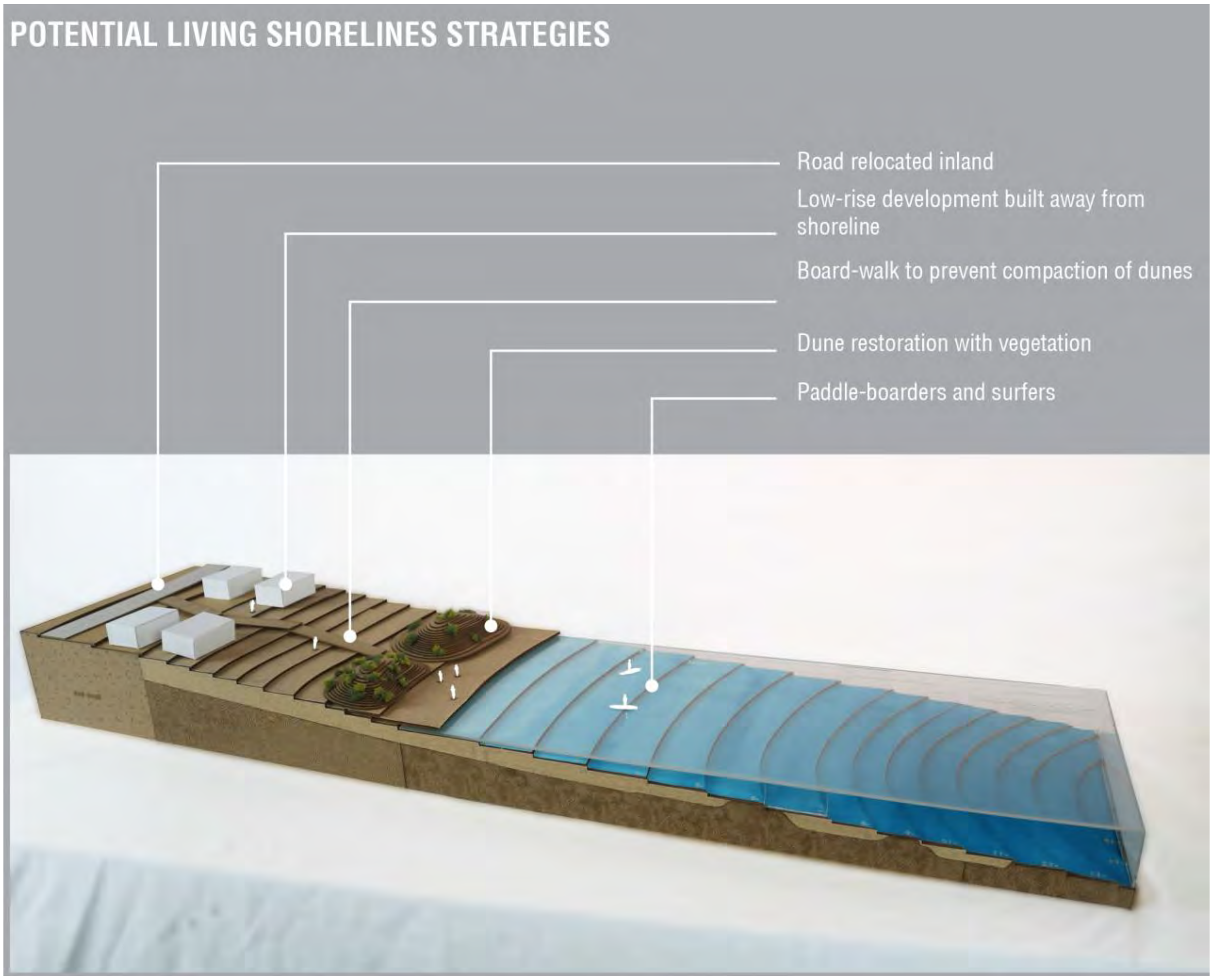


Figure 13 A scale model of Sunset Beach shows houses and road relocated, landward, new restored dunes with vegetation, and a pedestrian boardwalk. Source: Models by author.

Near-term relevant living shorelines strategies may include dune restoration in front of the roadway and houses, stabilized by groundcover, shrubs, and trees. In addition, a pedestrian walkway to protect the dunes from foot compaction might also be considered. In the long term, relocation of road, houses, and dune restoration may be considered if maintaining this recreationally-valuable beach is a priority. These strategies are illustrated through the scale site model (on the previous pages) showing 1) the original houses and road built with beach front; 2) eroded beach threatening houses and road (see Figure 12); 3) relocation of houses and road landward with new dune restoration, vegetation, and pedestrian walkways (see Figure 13). The strategy of "retreat" is also visualized in the student design proposal at the end of this Sunset Beach report section.

3.1.2 Sand Dune and Vegetation Function

Sand dunes and stabilizing vegetation can serve as flood prevention, sources of sand for migrating beaches, and ecological habitat. "Historically, dunes had backed the beaches of the North Shore, but most had been built on or removed to make way for roads and housing developments."[xxvi] Lessons learned from the alteration of dunes at the North Shore are applicable elsewhere in Hawai‘i. For example, human dune alteration is also seen in Kailua, where the dune systems have been "leveled… which compromises the dune's ecosystem and protective functions."[xxvii]

Alteration of dunes is problematic because of the sand dunes' role in natural flood prevention. "Beaches are wave-built and thus do not provide barriers at an elevation that restricts over-wash or surge during severe storms. Instead, the natural flood prevention function is provided by sand dunes, an integral component of natural sandy shore systems that are linked to the beach in cycles of sediment exchange. Sediment moves from the dune to the beach through erosion by storm waves, followed by the gradual delivery of sand from the beach to the dune by wind action and swash processes."[xxviii] The removal of dunes is also problematic because dunes would have provided sand as the beach migrates landward over time.

It is important to be aware of the relationship between plants and the formation of dunes. Typically, vegetation accompanies accretion of dunes where plants capture sand blown from shore. These plants are eventually buried and continue growing vertically. The cycle of capture, burial, and regrowth allows sand dunes to passively "grow" into their most efficient forms. However, according to a study by Thomas E. Miller, some plants, such as *Polygonum punctatum* (an introduced species in Hawai‘i[xxix]), may be associated with a decrease in dune elevation. More research should be conducted for Hawai‘i as studies on sand dunes and native vegetation are not widely documented. In Hawai‘i, through visual observation, vegetation plays a role in stabilizing sand dunes and preventing erosion from wind.

Other topics of consideration when discussing sand dunes in Hawai‘i are their ecological function and other demands for sand. In addition to coastal protection benefits, sand dunes are an important ecological feature that provides habitats for the Hawaiian monk seal, and breeding space for Hawai‘i’s sea turtles and various sea birds.

In the coming years, there may be demands for sand that may compete with dune restoration projects. Beach sand is in high demand for use in construction. Claims that quarry-sourced sand is unsuitable for construction across the state, and especially on O‘ahu, means that the demand for beach sands from sand dunes on Maui is on the rise.[xxx]

3.1.3 Sand Dune Restoration Precedent Projects

When considering sand dune restoration in Hawai‘i, the following sand dune restoration projects in Hawai‘i and on the continental US are useful precedents for comparison in scale, along with visual before and after photos.

The first sand dune restoration precedent project may be better described as temporary mounds. When large waves threatened homes along O‘ahu’s North Shore, temporary sand mounds were pushed up the beach to protect the home (see Figure 14). While this may be an effective short term strategy, long term retreat of buildings and sand dune restoration should be considered.

In the event of an oncoming storm, human intervention may assist the formation of dunes to protect infrastructure. In 2014, with the help of University of Hawai‘i Sea Grant and Department of Land and Natural Resources, homeowners obtained permits to restore the sand dunes in front of their homes, maintaining the beach and protecting their homes. During the massive surf in winter 2015–2016, the sand dunes held, and no structures were lost or permanently damaged.[xxxi] This may be a viable strategy in the next several decades in order to extend the amount of time that roadways and buildings may be used without flooding. There are precedents on the East Coast of the US, where “Naturally evolving dunes are often too low, narrow, mobile, or discontinuous to protect immediately landward infrastructure, and so they are often augmented by stabilizing them and increasing their height and volume through emplacement of sand-trapping fences or vegetation or by depositing sediment in fill operations.”[xxxii]

Figure 14 Newly restored dunes on O‘ahu's North Shore protected homes from high waves during the 2015–2016 winter.[xxxiii] Source: Hawai‘i Sea Grant.

The second sand dune restoration precedent project, the Patrick Air Force Base – Revetment and Beach Fill located in Brevard County, Florida, includes the following strategies:

- beach nourishment projects:165,000 cubic yards of sand from upland site (1998)
- hydraulic beach fill: 560,000 cubic yards of sand from an offshore sand source (2000-01)
- post-hurricane beach and dune re-nourishment: 300,000 cubic yards of sand (2005)
- sand fencing and dune vegetation

The images below show the result of using bulldozers and importation of sand onto beaches degraded by seawalls (see Figure 15 Before and after photos). Vegetation solidifies the beach nourishment effort and prevents the accelerated erosion of sand.

Figure 15 Before and after photos of beach nourishment (left) and beach and dune repair (right) at Patrick Airforce Base in Florida. Source: Olsen Associates.

While temporary dune replenishment has been conducted to protect properties, to create long-lasting shoreline protection, and to encourage the accretion of beaches, we must look at moving the shoreline built environment inland and giving space for natural processes to occur. The following project is a useful precedent for landward relocation of a parking lot and bike path and shoreline restoration.

The third sand dune precedent project, a natural shoreline infrastructure project in Seaside Park in Ventura County, California began with similar conditions to eroded shoreline roads in Hawai'i. Severe erosion and collapse of the bike path and fairground parking lot caused portions of it to be unusable, and the managed retreat project included seaside park restoration of 1,800 feet of shoreline. The parking lot and bike path that previously lined the shore were moved inland, and vegetated dunes, a cobble berm, beach nourishment (sand and cobble), were engineered to match a neighboring naturally occurring beach (see Figure 16Figure 17).[xxxiv]

Figure 16 Site in California before landward realignment of built infrastructure and restoration of the dunes and beach. The bike path and parking lot were built on fill in 1989 and eroded within 2 years. Source: Judge, J. et. al.[xxxv]

Figure 17 Project site after managed retreat and restoration of natural processes. May 2016. Source: Judge, J. et. al.[xxxiv]

A fourth restoration precedent project, a coastal restoration project at Muir Beach in California, the site was renovated completely from creek to shore. While the scale of this project is much larger than sand dune restoration, it illustrates how sand dunes can be part of a larger, overall strategy, relevant to the North Shore of O‘ahu that includes thriving ecosystems from mountains to ocean. A new floodplain plan was developed to remove man-made levee and promote natural flooding by creating soft edge channels (see Figure 18). Sand dunes were encouraged to develop using sand fences and vegetation.[xxxvi] While the scale of this project is much larger than sand dune restoration, it illustrates how sand dunes can be part of a larger, overall strategy, relevant to the North Shore of O‘ahu that includes thriving ecosystems from mountains to ocean.

Figure 18 Coastal dune and floodplain restoration of Redwood Creek at Muir Beach, California was intended to promote increased and wholesome ecosystem function.

Figure 19 The speculative future rendering above shows restored dunes with buildings elevated on stilts. Credit: Ennead F.R.E.D. team FARROC New York competition "Leading Innovation" winner.[xxxvii]

The fifth sand dune restoration precedent project illustrates the potential for dune creation without bulldozers at property owners' initiative. In New Jersey, beach-front property owners have been passively building up their backyard dunes using sand fences, vegetation, and leftover Christmas trees for over 30 years.[xxxviii] The initial effort to protect their homes from wind resulted in dunes about 25 feet high and 120-150 feet wide. Superstorm Sandy reduced the dune width by about 50 feet, and only one property sustained water damage from tidal break. Although the scale of the dunes are larger than the currently available area at Sunset Beach, the project gives an indication of the potential scale of future managed retreat strategies at Sunset Beach. It is also evident that dune width and height play a crucial role in effective storm protection.

The sixth sand dune restoration precedent is a speculative design competition in Far Rockaway, New York, where coastal development was flooded and destroyed by superstorm Sandy. The design proposal includes restoring the dunes and vegetation, and elevating buildings, walkways, and roadways above the ground plane (see Figure 19). The ground plane is designed for recreation and habitat, and flood waters can move through without destroying the development.xxxvii[xxxvii]

3.1.4 Student Design Ideas for Sunset Beach

Undergraduate students at the University of Hawai‘i School of Architecture in an elective course on Coastal Communities and Flood Resilience conducted a six-week exercise to create a design proposal sea level rise adaptation. The following student design idea for Sunset Beach recognizes that houses and roadways are within the 3.2 foot sea level rise exposure area (see blue area in Figure 20) and affected by coastal erosion (see red line in Figure 20). The modified aerial image illustrates the design proposal where houses and roadways are relocated landward, and the existing neighborhoods are outlined in orange dashed lines, for reference (see Figure 21).

The idea by student Cristina Holcom to adapt to sea level rise includes 1. Retreat; 2. Rise; 3. Revitalize.

1. **Retreat**: Both homes and roads are moved landward in order to avoid damage from sea level rise and flooding. Development is relocated to the base of the mountainside, outside of the sea level rise exposure area. The road is relocated at a minimum of 100 feet from the expected sea level rise exposure area.
2. **Rise**: Any structures remaining in the sea level rise exposure area that do not retreat landward would require wet-flood-proofing and elevation in order for flood waters to flow through or beneath.
3. **Revitalize**: Along the coast, a new significant vegetated area could serve as a wave buffer, farming, and recreational zone. Proposed native plants, such as hala and naupaka kahakai can help stabilize the soil, slow erosion, and buffer wave energy. Farming is proposed to replace the retreating homes, and recalls previous farming land uses. Revitalization of a coastal bike path and open green space would create a place for recreation for residents and visitors.

With 3.2 feet of sea level rise, green space decreases in area significantly - more so on the western edge. But the new implementations are still held in place. New vegetation should help delay estimated erosion, and major roads and homes are at a safe distance for the scope that this project covers.

This proposal is drastic and wide spread, increasing built density landward and creating an open space coastal buffer. Of course, beyond the scope of this class, such large proposals would require input and coordination with land owners, community members, and related stakeholders.

Figure 20 Sunset Beach with blue SLR-XA and red erosion line.
Source: PacIOOS.

Figure 21 The modified aerial image illustrates the design proposal in which houses and roadways are relocated landward, and the existing neighborhoods are outlined in orange dashed lines, for reference. Source: Student C. Holcom

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3.2 Waikiki Beach

3.2.1 Existing Conditions

Waikiki Beach represents a prototypical medium wave energy, sandy beach with flatter sloped topography and bathymetry, relative to the other sites. The iconic visitor destination is densely populated and of high economic value, located at on the south shore of O‘ahu. Waikiki Beach is estimated to be worth over $2 billion in annual visitor expenditures.[xxxix]

Waikiki is a developed beach with fringing reef; its coastal slope is less than 20%.[xl] At Waikiki Beach, the hazard types ranked as “high” include tsunami, stream flooding, and storms in the 2002 *Atlas of Natural Hazards in the Hawaiian Coastal Zone* (see Figure 23). The more recent, 2017, Hawai‘i Sea Level Rise Report and mapping indicate that a number of the potentially flooded structures on O‘ahu are hotels located in Waikiki. “Elevated water levels in spring and summer of 2017… caused beach overwash and erosion at Waikiki.” [xli] The report recommends, “Private and public entities in Waikiki and parts of Honolulu should begin to factor in long-term preparedness for sea level rise adaptation including dealing with basement flooding, beach restoration at Waikiki Beach, and even consideration of how best to prepare for higher sea levels in the future.”

Moderate waves cause beach erosion and this man-made beach requires periodic replacement of the sand, called beach nourishment. Waikiki has several man-made shoreline conditions, including sandy beach, sea walls, groins and beaches with man-made breakwaters. In this primer, we study an area near Fort DeRussy Beach Park (see Figure 25), which currently has a sandy beach and tall buildings close to the shoreline. The area is projected to experience limited major roadway flooding, moderate minor roadway flooding, and building flooding with 3.2 feet of sea level rise, annual high wave flooding, and coastal erosion. The aerial map shows flooded areas in the sea level rise exposure area (SLR-XA) in light blue, flooded major roads in red, and coral in orange dots (see Figure 26)[xlii]. With 6 feet of sea level rise (see Figure 27), much of Waikiki is inundated and all of the major and minor roads near Fort DeRussy Beach park are flooded.

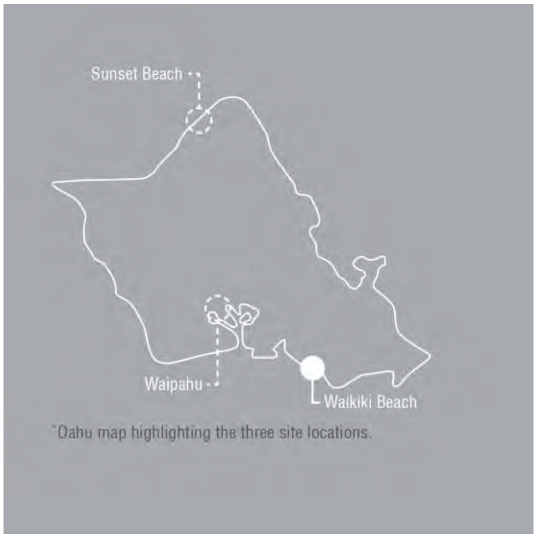

Figure 22 Map of O‘ahu with Waikiki Beach highlighted.

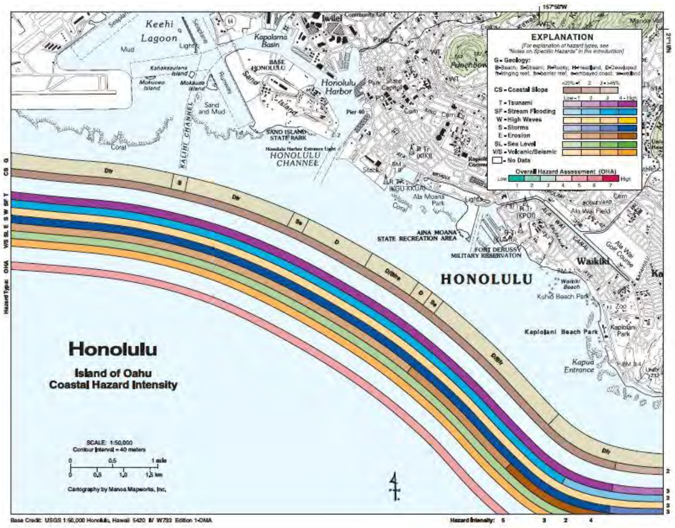

Figure 23 Map with Coastal Hazard Intensity showing area around Waikiki Beach. “High” hazards include tsunami, stream flooding, and storms.[xliii]

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Figure 24 Waikiki Existing Conditions Photo Location Map

Waikiki Existing Conditions Photos

Photo G

Normally, stormwater inlets and pipes convey stormwater to the ocean, but with high tides and wave events, the sea water emerges out of the stormwater inlet onto the street. This will become more common with sea level rise.

Photo credit: W. Meguro

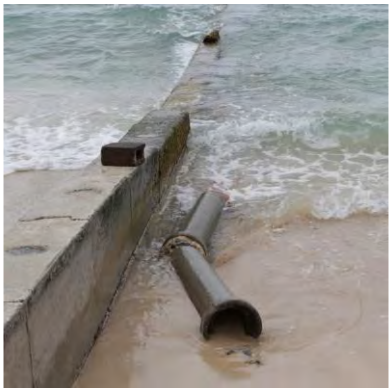


Photo H

"The dynamic movement of sand can expose once-buried underground utility lines." Wrote C. Fletcher, in "Living on the Shores of Hawai'i" p 259.

Photo Credit: C. Guarin

Photo I

Even sea-walls made of concrete cannot avoid erosion along the shore. This ocean access stair will soon no longer be usable without constant maintenance and repair.

Credit: K. Yamamotoya

Photo J

Vertical sea-walls and erosion at Waikiki. Photo credit: H. Au

Photo K

Naupaka kahakai (Scaevola sericea) grows land-ward of a boardwalk in Waikiki. Vegetation along the shore may help reduce wave energy that affects coastal properties.

Photo credit: H. Au

Photo L

Buildings experiencing flooding from high tide and king tide events put up temporary walls to protect their underground floors.

Photo credit: S. Mendes

The following maps show the current Waikiki Beach area near Fort DeRussy, including buildings, roads, streams, coral, topography and bathymetry (see Figure 25). The second map shows, in light blue, the Sea Level Rise Exposure Areas inundated with 3.2 feet of sea level rise, annual high wave flooding, and coastal erosion; the red lines indicate flooded highways (see Figure 26). The third map shows, in dark blue, widespread inundation 6 feet of sea level rise (see Figure 27).

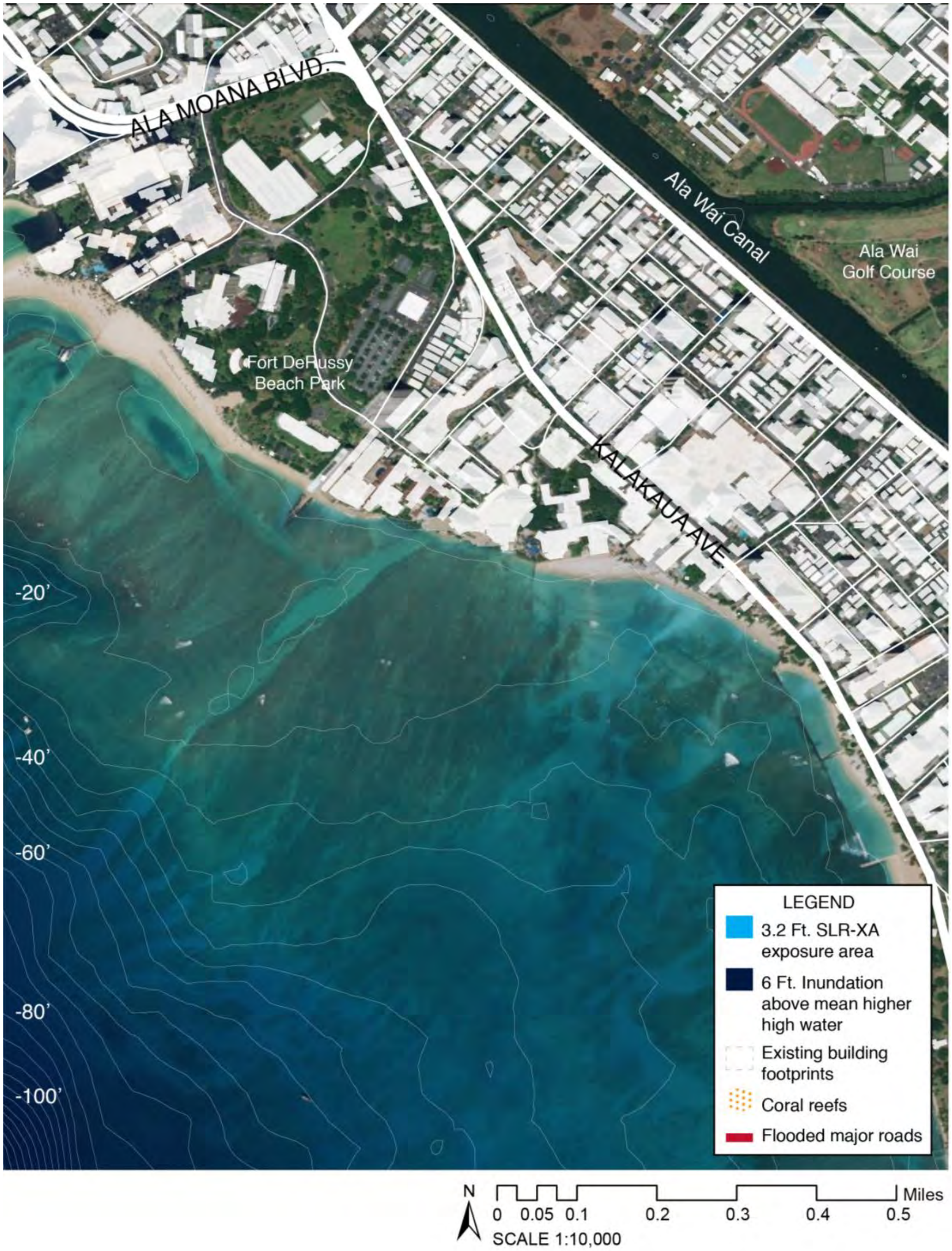


Figure 25 Waikiki Beach Study Site Aerial Map – Existing Conditions

Figure 26 Waikiki Beach Study Site with 3.2 Ft. SLR and Flooded Major Roads

Figure 27 Waikiki Beach Study Site with 6 Ft. SLR and Flooded Major Roads

Photos of the area’s existing conditions show evidence of elevated water levels and erosion. The adjacent aerial map keys the locations of the photos (see Figure 24). The stormwater drains currently experience backflow with high tides and large wave events (see Figure 24 Photo G). Concrete sea walls and groins degrade from wave action (see Figure 24 Photo I and J). Eroded sand reveals previously buried pipes (see Figure 24 Photo H). Some coastal properties currently have naupaka along the beach front, which may buffer waves (see Figure 24 Photo K). Building operators attempt to protect their properties from king tides with temporary flood walls and sand bags (see photo L).

This primer on living shorelines at Waikiki beach is a portion of the recommended effort toward evaluating options for long-term sea level rise adaptation. Kirk Caldwell, Mayor of Honolulu, has stated that the high economic value and dense urban development in Waikiki make retreat unlikely, at least in the coming decades. In situ adaptation strategies to mitigation flooding should be developed and implemented soon in order to minimize flooding for as long as possible.

Living shorelines are one strategy to reduce erosion, reduce the distance of wave run-up, and reduce flooding of roadways and buildings. For Waikiki, relevant living shorelines strategies to reduce wave energy may include coral reef restoration, introduction of shrubs and trees, and beach sand restoration (see Figures 28 and 30). As described in the introduction, armoring shorelines with sea walls should be avoided because of the resulting erosion (see Figure 29).

Many beaches on O‘ahu have already been lost, and some 70 percent of beaches in Hawai‘i are actively eroding.[xliv] Coastal armoring placed in an area of existing erosional stress will cause the beaches fronting the armoring to diminish. Coastal armoring is designed to protect the upland, but does not prevent erosion of the beach profile seaward of the armoring. Thus an eroding beach will continue to erode. If the armoring had not been placed, the width of the beach would have remained approximately the same, but with increasing time, would have been located progressively landward.[xlv]

For the man-made beach of Waikiki, where modifications to the shoreline with groins and walls already exist, combining living shorelines with typical “hard” infrastructure techniques might provide a solution. While they are beyond the scope of this report, several ideas are acknowledged here. T-head groins could be designed for a site’s wave energy and direction to encourage sand accretion on either side of the groin (see Figure 29). The T-head groins could be composed of rocks that foster marine life, creating habitat.

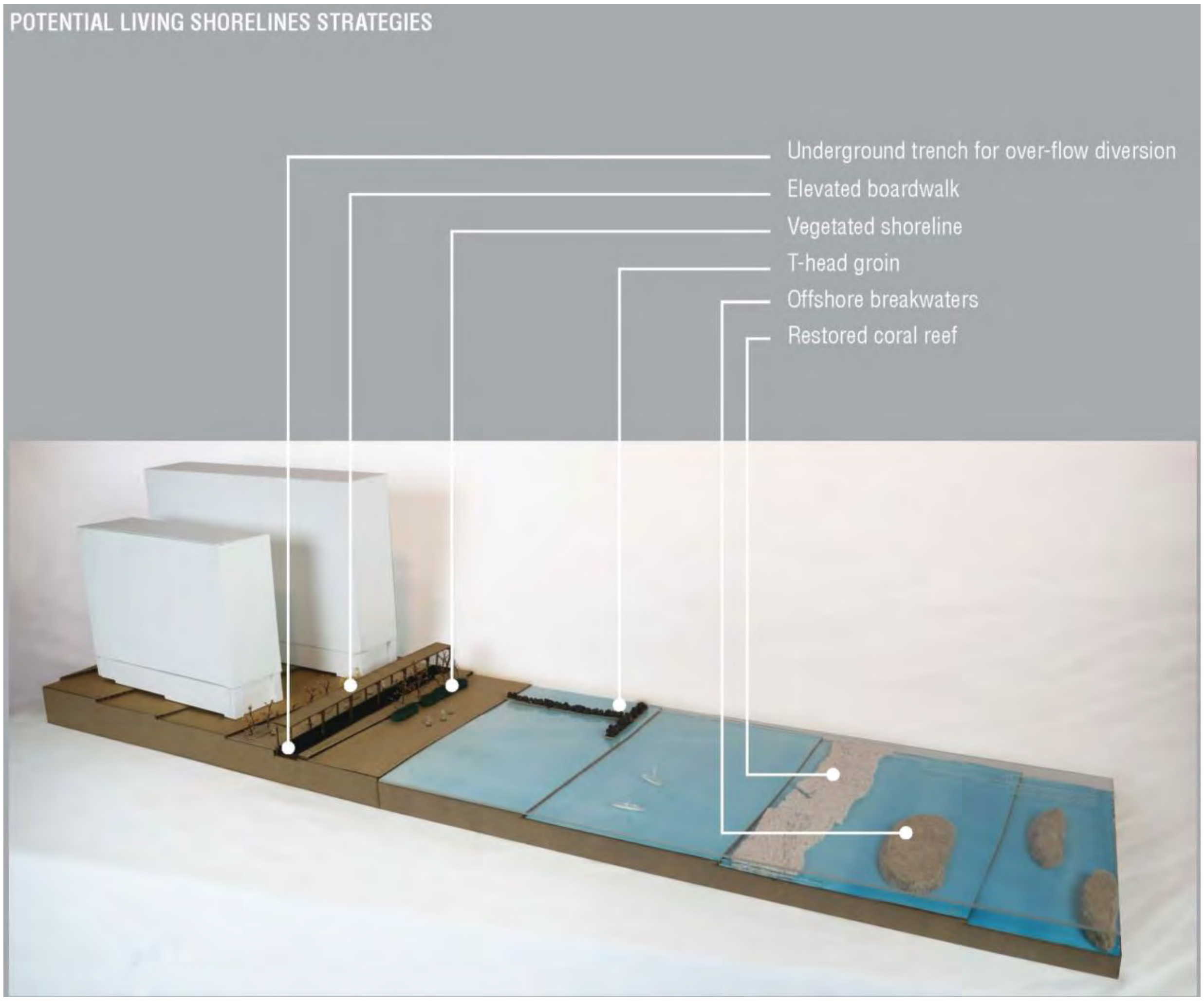
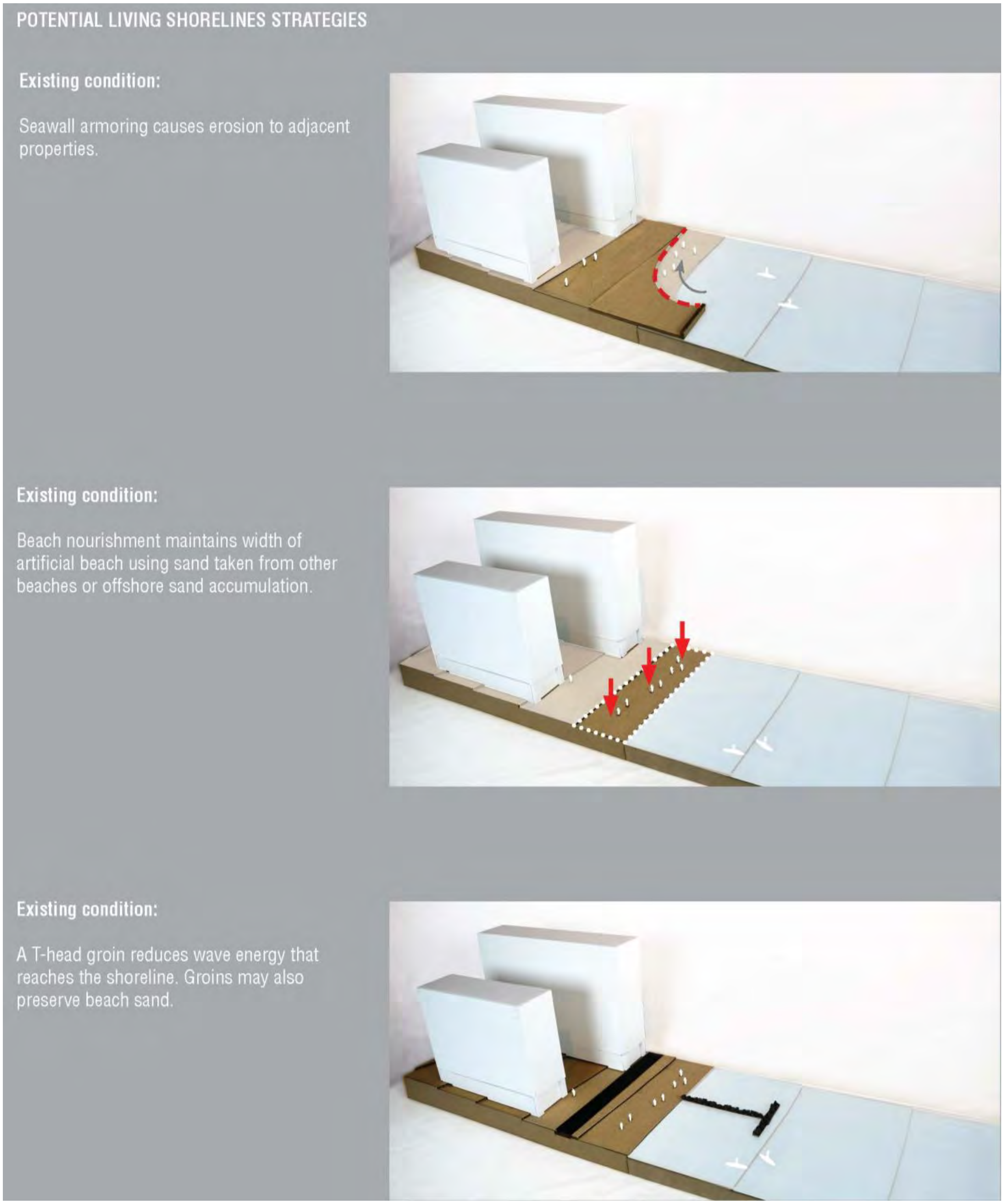


Figure 28 Potential living shorelines and landscape strategies at the Waikiki site.
Models created by Wendy Meguro and student researcher Liem Tran.



POTENTIAL LIVING SHORELINES STRATEGIES

Existing condition:

Seawall armoring causes erosion to adjacent properties.

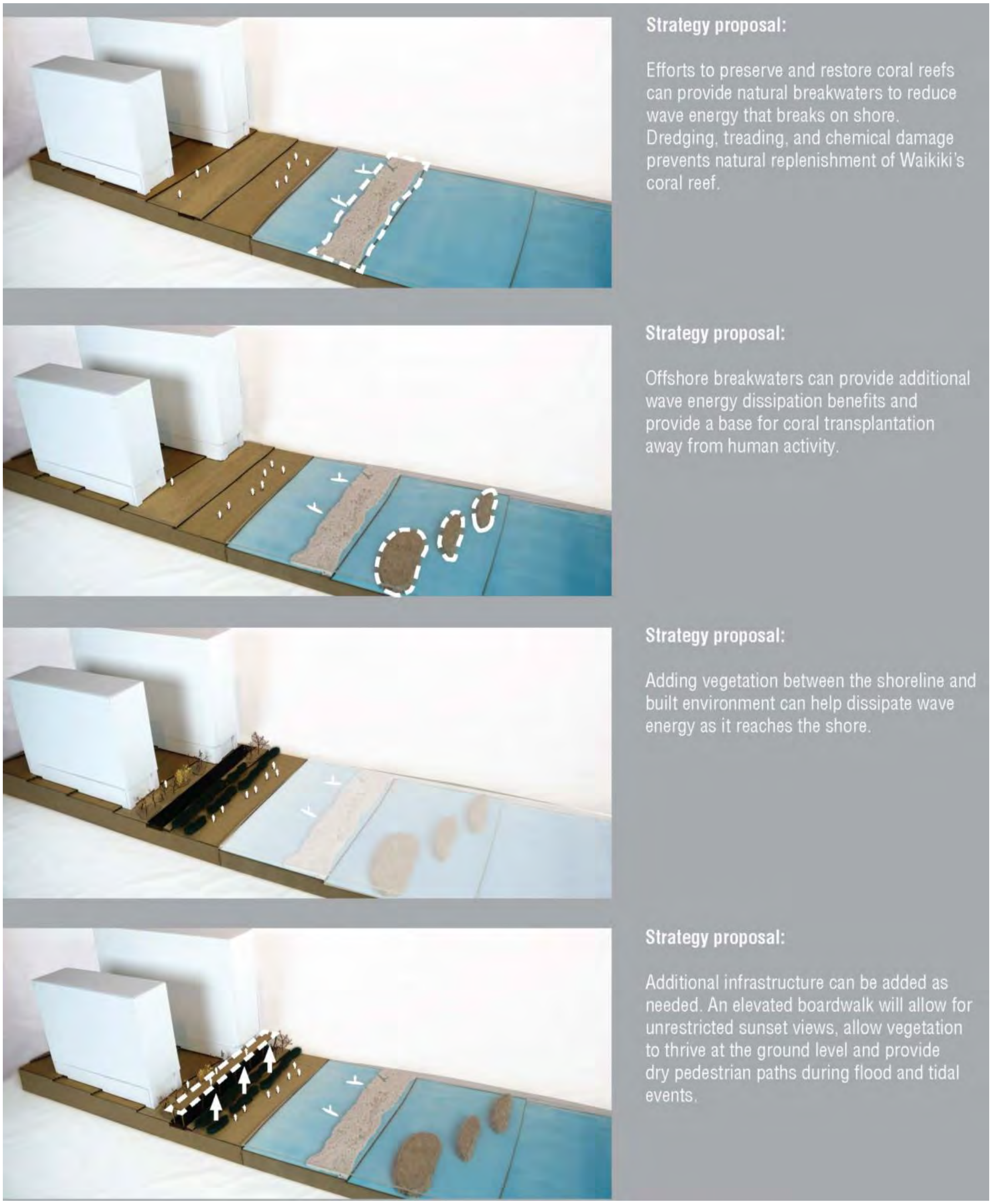
Existing condition:

Beach nourishment maintains width of artificial beach using sand taken from other beaches or offshore sand accumulation.

Existing condition:

A T-head groin reduces wave energy that reaches the shoreline. Groins may also preserve beach sand.

Figure 29 Waikiki Beach includes sea walls, beach nourishment, and groins.
Models created by Wendy Meguro and student researcher Liem Tran.



Strategy proposal:

Efforts to preserve and restore coral reefs can provide natural breakwaters to reduce wave energy that breaks on shore. Dredging, treading, and chemical damage prevents natural replenishment of Waikiki's coral reef.

Strategy proposal:

Offshore breakwaters can provide additional wave energy dissipation benefits and provide a base for coral transplantation away from human activity.

Strategy proposal:

Adding vegetation between the shoreline and built environment can help dissipate wave energy as it reaches the shore.

Strategy proposal:

Additional infrastructure can be added as needed. An elevated boardwalk will allow for unrestricted sunset views, allow vegetation to thrive at the ground level and provide dry pedestrian paths during flood and tidal events.

Figure 30 Potential living shoreline strategies include coral restoration, submerged breakwaters, vegetation, and an elevated boardwalk.

Models created by Wendy Meguro and student researcher Liem Tran.

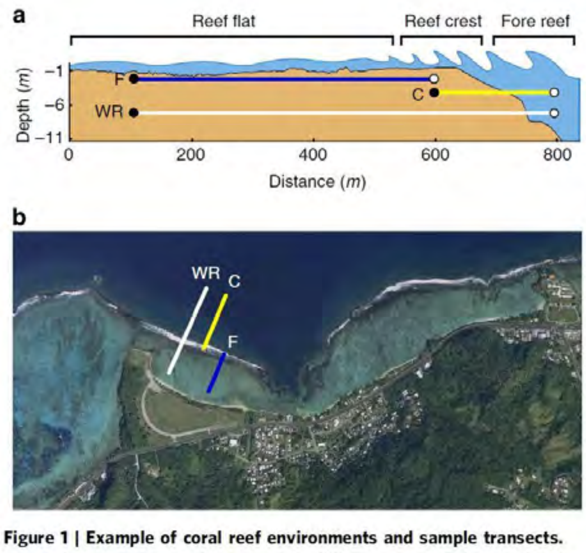
3.2.2 Protective Benefits of Coral Reefs

Coral reefs provide ecological marine habitat and are a major attractor for Hawai‘i’s tourism economy. The reefs are an important cultural and sustenance resource, and can also offer protective benefits by reducing wave energy. Although anecdotes of the wave dissipating potential of coral reefs are plentiful, quantified information on the effect of coral reefs is modest. The following is a summary of research papers found that quantify site-specific effects of coral reefs on wave energy.

First, a paper titled “The Effectiveness of Coral Reefs for Coastal Hazard Risk Reduction and Adaptation” studied 225 coral reefs in the Pacific, Atlantic, and Indian oceans. The authors found that the whole reef which includes the fore-reef, reef crest, and reef flat (see Figure 31) reduced wave energy and wave height by 97% and 84%, respectively.[xlvi] Even if the reef flats in Waikiki do not extend as far from shore as the reef flats in the study, the study noted that “50% of the reduction in both wave energy and height occurred within < 150 m (500 ft) from the reef crest...” (see Figure 33). Aerial photos show that the reefs in Waikiki extend further than 500 feet from shore. If Waikiki conditions are similar to the 225 coral reefs studied, then the coral reefs reduce wave energy and height by at least 50%, which alone is a significant protective benefit.

The study’s findings seem relevant for Waikiki’s typical low to medium wave energy. “The effects of the whole reef in dissipating wave energy were linear from small through hurricane-level waves, that is, the reefs reduced a consistent 97% percent of the incident wave energy.”[xlvi] Although it is outside of the scope of this study, a possible concern would be if large hurricane-level waves destroyed the coral and negated its protective benefits.

The paper also notes other factors that intuitively make sense: reefs closer to the ocean’s surface and reefs with higher surface complexity were more effective in dissipating wave energy.xlvi[xlvi]



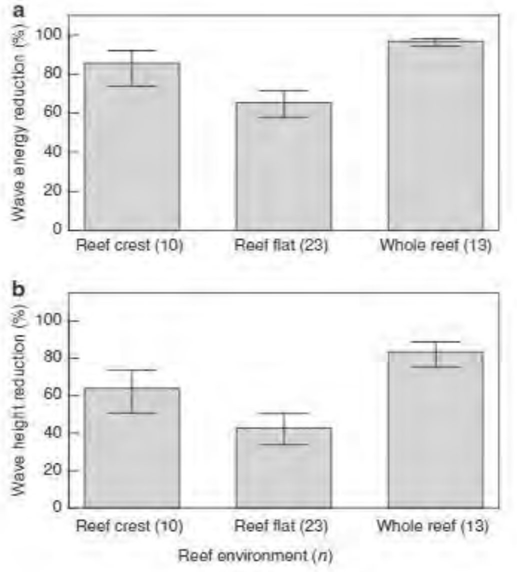


Figure 31 The section drawing and aerial satellite view are examples of coral reef environments and sample transects from the study "The Effectiveness of Coral Reefs for Coastal Hazard Risk Reduction and Adaptation."[xlvii]

Figure 32 The graphs above show the percentage in wave energy and wave height reduction for the reef areas indicated in the diagrams at the left.[xlvii] Source: "The Effectiveness of Coral Reefs for Coastal Hazard Risk Reduction and Adaptation."

Second, research in the Seychelles provides quantitative information that reef decay can result in increased wave energy. The paper, "Coral mortality increases wave energy reaching shores protected by reef flats"xlvii tracked the progression of reef decay and erosion over twenty years and fourteen sites in the Seychelles. The physical characteristics of coral mortality included crumbling of coral, which increased the gap between the top of the coral and sea level; eroded coral with less friction to waves; and dying reef crest corals. It found that the simultaneous erosion of coral reefs and rising sea levels increased the distance of the ocean's surface from the corals and allowed more wave energy to reach shores (see Figure 33).

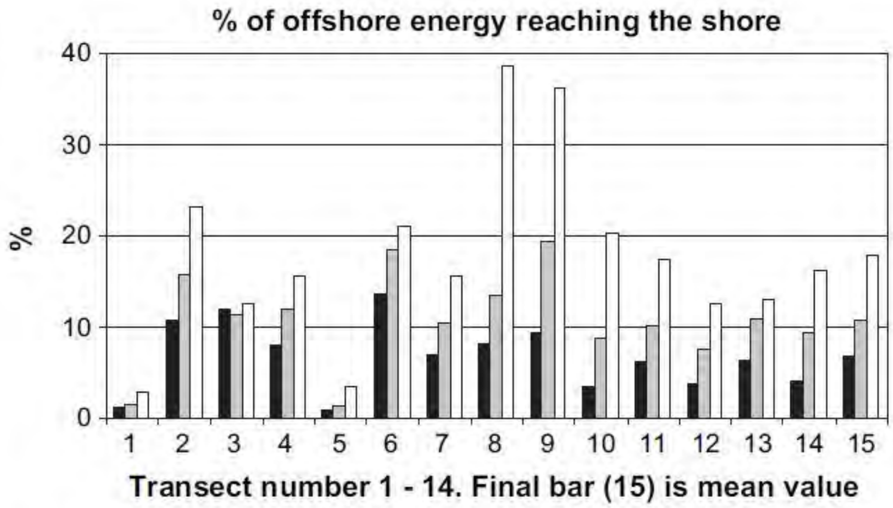


Fig. 6. Percent of offshore wave energy which reaches the shores behind each reef. Site labelled 15 at right is average of all reefs. Black bars = 1994; grey bars = 2004; white bars = 2014. Order of sites is 1–14, left to right, as for Table 3.

Figure 33 The graph above shows the increase in wave energy reaching the shore from 1994, to 2004, to 2014 as coral reef decay and erode. By decreasing wave energy, coral reefs help protect the coastal communities from flooding and erosion. [xlviii]

A third research paper indicates that “coral reef structural complexity provides important coastal protection from waves under rising sea levels”[xlix] through the study and simulation of four locations in the South Pacific. As compared to other coastal settings, coral reefs result in “high hydraulic roughness, greater frictional dissipation of waves, and greater coastal protection service.” Given the trend of coral reef erosion, by 2100 the simulations at the case study sites and predicted back-reef wave heights will be 2.4 times greater than today.

With regard to Waikiki, this raises a question about the sea level rise maps: what future coral reef heights and friction coefficients are assumed when calculating the area of flooding with the annual high wave event flooding with the future 3.2 feet of sea level rise?

It is relevant to recognize that quantitative research on the role of coral in wave attenuation is limited, as illustrated in a 2005 paper where out of over 400,000 papers on reef ecology and geology in the last 20 years, only 10% addressed the role of reefs in wave attenuation, wave energy or wave breaking with data.[l] Despite limited quantitative data, the papers above are useful to indicate that healthy coral reefs can significantly decrease wave energy, and warrant further site-specific evaluation in locations like Waikiki.

3.2.3 Coral Reef Restoration Function

Given the potential protective, wave-dissipating benefits of coral reefs, this section questions the viability of coral reef restoration in Waikiki by summarizing research and precedent projects in and outside of Hawai‘i.

In comparison, coral reef restoration is not a viable option for the Waipahu site. The coral does not offer a protective benefit because of the low wave energy due to the harbor and marsh. In contrast, Sunset Beach has high wave energy, which, as the historical study below notes, is not conducive to coral growth. A 1998 study of Holocene Coral Reef Accretion in Hawai‘i[li] indicates that, during the historical Holocene era, patterns show that coral vertical accretion in sheltered bays (Kaneohe Bay and Hanauma Bay) is about 2 mm/year. In contrast, accretion is practically 0 mm/year during the entire Holocene era at Mamala Bay and Sunset Beach, where wave exposure is higher, even at optimal depth.

In order to restore coral reefs at Waikiki, more research is needed to understand the factors limiting current coral growth and actions needed to promote healthy coral reefs. Coral reef health is influenced by a number of human-related factors, including water quality and ocean temperature, human trampling, and vessel grounding. These factors would need to be improved in order to create a hospitable environment for coral to grow in Waikiki. Policy makers and community members could promote coral health by protecting near shore water quality by reducing or eliminating pollutants and sediment[lii] in stormwater runoff, and chemicals in sunscreen. Policy makers and community members could also curb greenhouse gas emissions, which cause rising ocean temperatures, resulting in detrimental coral bleaching events. Human trampling on coral reefs and vessel grounding may be avoided through education. Protection of coral reefs should be highest priority and, when necessary, the restoration of coral reefs should be considered.

3.2.4 Coral Reef Restoration Precedent Projects

The process of coral restoration includes growing coral in a nursery or dredging and transplanting it to the location of interest. The following sections summarize research on coral transplantation and a large-scale coral restoration project.

The active research in Hawai‘i on coral restoration indicates that it is a strategy that should be considered in the suite of tools for coastal protection. Promising research by the Hawai‘i Institute of Marine Biology and the Department of Aquatic Resources (DAR) Coral Restoration Nursery indicates that coral restoration may be a viable strategy for low to medium wave energy shorelines with degraded coral. A study of the “Effectiveness of coral relocation as a mitigation strategy in Kaneohe Bay, Hawai‘i,” from 2005-2016, found that transplanted coral from a dredged site to donor site was successful prior to a bleaching event (see Figure 34). “This suggests that transplantation or potentially using fragments in a nursery could be successfully employed around the state assuming these corals do not experience increasing bleaching or other devastating events."[liii]

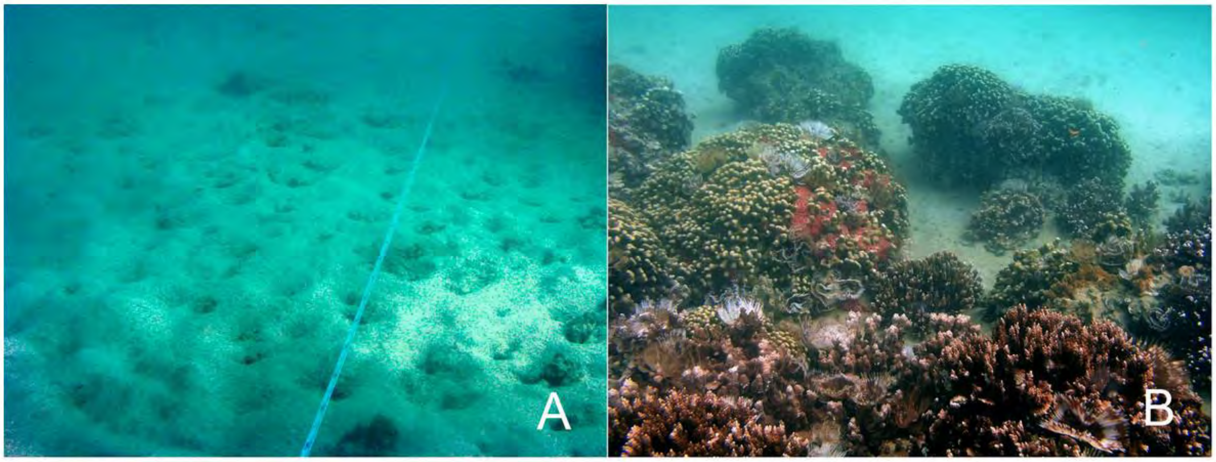


Figure 34 Coral restoration site in Kaneohe before image (2006) and after image (2012). Image source: Department of Aquatic Resources.

The DAR coral nursery is "using techniques that will reduce the time it takes to grow transplantable corals to about one year [rather than the typical ten or more years]. We are hopeful this will help recover reefs which have been seriously degraded by human impacts…"[liv] (see Figure 35). Perhaps this would be useful in Waikiki where human impacts on coral include human trampling and vessel grounding.

Figure 35 Coral fragment propagation at the DAR coral nursery.[lv]

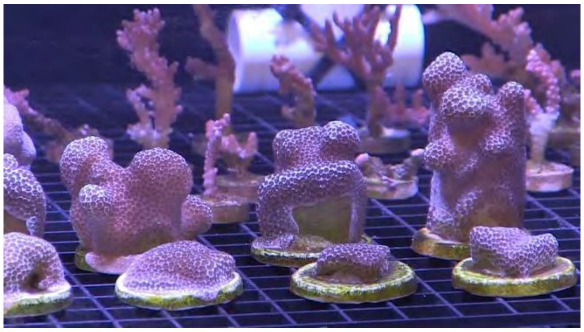


Figure 36 Coral fragment propagation at the DAR coral nursery.[lv]

A third study suggests that low wave energy is conducive to coral transplantation. A study on "Growth and Mortality of Coral Transplants on Maui"[lvi], which included south-facing shore locations, noted that when wave energy is low, the corals gain mass, but winter storm events caused breakage, abrasion, and overturned the coral transplants, increasing coral mortality. If coral were transplanted in Waikiki, planting it during low winter swells and building protective barriers such as submerged breakwaters to provide calmer water for coral growth might be helpful. Issues with submerged breakwaters, such as changes to the Waikiki surf breaks would need to be addressed.

Other coral propagation techniques are showing success world-wide, which indicates a hopeful future for coral restoration in Hawai‘i. For example, in a 2014 article[lvii], researchers used a coral microfragments growing technique to dramatically accelerate growth in the nursery. These corals were planted on dead coral heads and skeleton reefs, first at a smaller scale, and then in some of the first-large scale efforts to restore massive corals in the wild. Located in the Florida Keys, the corals are thriving and planting will continue indefinitely.

One of the successful coral colony transplants on degraded reefs in Florida and the Caribbean may be particularly relevant to Hawai‘i. One of the Caribbean coral species, *Acropora*[lviii], is rare but exists in Hawai‘i (Northwest Hawaiian Islands, Kaua‘i, and Hawai‘i Island[lix]). Perhaps it could also be successfully propagated and restored in Hawai‘i.

The Potential Role of Artificial Reefs

If coral conservation and restoration methods do not have sufficient vertical accretion, man-made artificial reefs may be considered for the purpose of wave attenuation and shoreline erosion prevention. Several strategies may be considered, including “reefballs” and 3D printed reefs (see Figure 37).

Reefballs mimic the benefits of naturally occurring coral reefs by providing shelter for fish. This typically increases biomass in the immediate vicinity of its installation and provides erosion protection functions. In calm water conditions, reefballs may provide a suitable substrate for coral transplantation and growth. Reefballs are not suitable for areas with higher wave energy because it may prevent adhesion or damage established reefs, and sediment may smother coral. Roughly 500,000 reefballs costing tens of millions of dollars have been placed in marine environments as aids in increasing marine fish stocks[lx]. In Hawai‘i, perhaps nurseries may develop “pre-conditioned” reefballs for transplant onto depleted reefs. Artificial reefs may be 3D printed to mimic the structure of natural reefs for engineered benefits.

Figure 37 A deployed reefball in Antigua attracts and becomes habitats for various species of wildlife.[lxi]

3.2.5 Economic Value of Healthy Coral Reefs and Cost of Coral Reef Restoration

While this primer does not thoroughly research costs, a short summary of the value of healthy coral reefs and the costs of coral reef restoration are briefly discussed.

Healthy coral reefs are a major attraction for tourists visiting Hawai‘i’s “paradise”. The colorful polyps that decorate popular snorkeling, scuba, and tour areas also create habitat for other marine life. Tourists drawn in by Hawai‘i’s unique experiences supported 204,000 jobs and generated 16.7 billion dollars in expenditures in 2017.[lxii] The Hawai‘i Coral Reef Initiative Research Program (HCRI-RP) says “nearshore reefs annually generate about $800 million in gross revenues (or $364 million in added value)” solely in economic values.[lxiii]

In a limited number of research papers found that the cost of coral reef restoration varies by a factor of at least two. In one study, the initial phase, growing coral fragments in underwater nurseries, had a median cost of US$28,082/ha. The second phase, including out-planting of fully grown corals, had a median cost of US$45,445/ha (at a base year 2010).[lxiv]

A research paper by Levi et al. “Mid-water rope nursery—Testing design and performance of a novel reef restoration instrument” studied “small coral fragments attached to a rope, creating an easily constructed nursery bed that is rapid and inexpensive.” A subsequent response to that paper by Bayraktrarov et al.[lxiv] gave the most detailed breakdown of coral restoration costs available in the literature. Including the second phase, growing coral fragments and colonies, monitoring and propagating colonies plus out-planting and maintenance, cost $38,664 per hectare in 2007 dollars. The paper reports that the value in 2010 dollars is $45,445. Using the website, usinflationcalculator.com, if converted to 2018 dollars, the cost of a coral nursery and maintenance costs are approximately $52,516 per hectare. Bayraktarov et al. noted that for extensive restoration projects (e.g., after ship grounding or other severe reef damaging events) a median value for restoration was calculated at $165,607 per hectare. When calculated in 2018 dollars, the cost increases to $191,391 per hectare.

Continued research on coral restoration specific to Hawai‘i is being conducted by the University of Hawaii and DAR. By utilizing their research a more accurate estimation of restoration costs can be calculated for Hawaii.

3.2.6 Challenges to Coral Reef Restoration

The following topics related to coral reef restoration are beyond the scope of this primer, and would need to be addressed at future specific sites under consideration for coral reef restoration.

- Coral degradation due to terrestrially-sourced erosion, chemical poisoning, ocean warming and acidification, and stormwater runoff pollutants
- Effect of coral restoration on recreational surf conditions
- Design and engineering of coral restoration or artificial reefs
- Waikiki beach sand erosion smothering coral reefs[lxv]

Despite efforts to restore coral reefs in Hawaii, the continuously changing global environment may create an unsuitable habitat for corals in the future. Complications such as increasing sea temperatures, ocean acidity, and rising sea levels may hinder the growth and resilience of coral populations. Increased frequency of warm ocean temperatures during El Niño events[lxvi] may also increase coral bleaching events.

3.2.7 Vegetated Shorelines

The application of vegetation to shorelines in Waikiki has the potential to dissipate wave energy and slow erosion, offering moderate near-term protection to roadways and buildings. In addition, vegetation can create habitat and educate passers-by. In contrast, as described in the introduction, typical “hard” infrastructure such as concrete sea walls, rip-rap, and rocks cause erosion of beach sands. As is the case with coral reefs, applying a buffer strategy with the greatest depth and complexity provides more effective wave energy dispersion. This section and the report appendix include a description of salt and drought tolerant ground covers, shrubs, and trees in Hawai‘i that may be considered for incorporation into coastal landscapes.

New vegetation between the shoreline and relatively close buildings or roadway would require careful consideration in its location and extents. One consideration is to provide coveted space for beach goers. A second consideration is the opportunity to create landscapes that educate visitors and residents about native plants and their role in flood mitigation. New landscape designs provide opportunities to “improve weakened ecological structure and function … In a world where aging infrastructure and rising tides are leading to new investment in coastal construction, there is a new opportunity to improve urban coastal habitat. The restored vegetation can reflect our new physical conditions, the need to be resilient to climate change and rising sea levels."[lxvii]

3.2.8 Protective Benefits of Vegetated Shorelines

In a study by Guannel et al.[lxviii], researchers used "an integrated modelling approach for quantifying how vegetation modifies near-shore processes—including the attenuation of wave height, mean and total water level—and reduces shoreline erosion during storms." The researchers studied the effect of two vegetation scenarios: scenario one—"Sea Grass Meadow Fronting a Dune-Backed Sandy Beach" (see Figure 38); and scenario two—"Mangrove Forest on a Mud Bed" (see Figure 39). Although sea grass and mangroves are not native coastal vegetation in Hawai‘i, the method of one-dimensional computer modeling to test the effects of vegetation on wave height is a relevant method that could be applied in Hawai‘i. As seen in Fig. 40, overall wave height (H_s) and mean water levels (ŋ) are reduced with the presence of vegetation (green line) versus no vegetation (blue line). In the case of scenario two, we see similar results of lowered wave height and mean water in comparison to the no vegetation simulation. However, scour is lowered in the case of the applied mangrove forest (see Figure 39). This may suggest a lowered rate of sand loss by erosion through a stabilization of sand.[lxix]

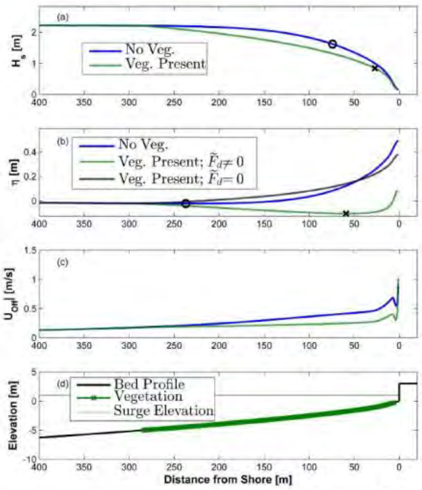


Figure 2. Wave model outputs for storm B (Table 1), for the seagrass bed offshore of a sandy beach example. (a) Profiles of wave height and location of wave breaking in the presence and absence of vegetation (circle and cross, respectively). (b) Profiles of mean water level and location of minimum setdown (circle and cross), in the absence of vegetation, and in the presence of vegetation when vegetation-induced stress are taken into account ($\tilde{F}_d \neq 0$) and neglected ($\tilde{F}_d = 0$). (c) Profiles of depth averaged undertow. (d) Elevation profile showing the 3 m high dune and the seagrass meadow location.

Figure 38 Simulated wave attenuation. [lxix]

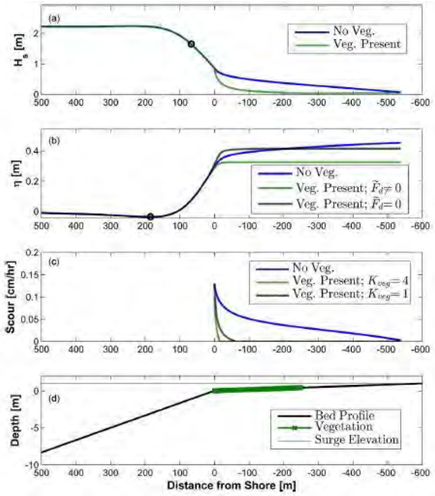


Figure 5. Wave model outputs for storm B (see Table 1), for the mangrove forest example. (a) Profiles of wave height and location of wave breaking (circle). (b) Profiles of mean water level and location of minimum setdown (circle), in the absence of vegetation, and in the presence of vegetation when vegetation-induced stress are taken into account ($\bar{F}_d \neq 0$) and neglected ($\bar{F}_d = 0$). (c) Profiles of rate of mud bed scour. Effects of biota on critical bed shear stress are taken into account when $K_{veg} = 4$, and neglected when $K_{veg} = 1$. (d) Depth profile showing the location of the mangroves.

Figure 39
Computer simulation compares shoreline mangrove forest (green line) to no vegetation (blue line). [lxix]

3.2.9 Suggested Flora Species Options for Near Shore Application

Evolution in the Hawaiian Islands has resulted diverse flora and fauna that are specifically adapted to coastal environments. The following list of groundcover, shrubs, and trees was compiled from several references by identifying plants with the following criteria: native or have low invasive risk; salt tolerant; and can survive in coastal zones. Alongside the qualities in the table, plant selection criteria would also likely include color, texture, and maintenance required. Groundcover such as pohuehue could potentially help stabilize sand and reduce erosion (see Figure 40). Shrubs and trees with dense root, trunk and branch structures, such as hala trees (see Figure 41) or naupaka (see Figure 42), could dissipate wave energy during periodic high wave events, and reduce the wave run up.

Figure 40 Pohuehue
Photo: W. Meguro

Figure 41 Hala
Photo: W. Meguro

Figure 42 Naupaka
Photo: H. Au

The suggested flora species list was compiled using multiple sources that identify low-invasive risk, low-water, and salt tolerance (see Table 3). The 2016 Maui County Planting Plan is a 240 page document with planting requirements and protocol along with an extensive suggested plant list for public spaces organized by plant size. The Maui County Planting Plan is the base suggested plant list that was further narrowed down or supplemented for the purpose of this report. Invasive species research is publicly available through the Hawaii Pacific Weed Risk Assessment (HPWRA) website. As of July 2018, nearly 2,000 species were assessed for invasive risk. The suggested flora species list notes the invasive risk number from HPWRA where less than 0 is considered very low risk, 0-3 low risk, and 3+ high risk. Some species such as *Lagerstroemia indica* or commonly called the crepe myrtle was given a weed risk value of 6 through the assessment evaluation. However, crepe myrtle is not an aggressive spreader despite its high invasive risk value; therefore, it is rated “low” post-evaluation.

Next, plants were selected using criteria for low water requirements and salt tolerance using the reference book, The Watersmart Garden: 100 Great Plants for the Tropical Xeriscape. The book features plants found in Hawaii describes plants’ water requirements by assigning them “zones” numbered 1-4 (1 requires the most water, 4 the least). It also describes plants’ salt tolerance (appendix D) defined as: “indicates tolerance of onshore, salt-laden winds” (denoted as “OS” in following table); or “indicates tolerance of such winds with protection from direct contact, such as a strong windbreak or a structure”[lxx] (denoted as “WB” in following table). Other information about salt tolerance and commonality was sourced from “Flowers of the Pacific Island Seashore: A Guide to the Littoral Plants of Hawaii, Tahiti, Samoa, Tonga, Cook Islands, Fiji, and Micronesia.”

Table 3 Flora Species List

Scientific Name	Common Name	Zone[lxxi]	Salt tol.[lxxi]	Invasive Risk[lxxii]	Notes	Toxic[lxxi]	Thorns[lxxi]	Irritant[lxxi]
Ground Covers + Shrubs								
Capparis sandwichiana	Maiapilo			Native	Salt spray tolerant[lxxiii]			
Cyperus javanicus	Ahuawa			Native	Brackish water, saltwater, salt spray tolerantlxxiii			
Ipomoea pes-caprae subsp. brasiliensis	Beach morning glory/ pohuehue			Native				
Plectranthus amboinicus	Cuban oregano		WB	L (HWPRA)				
Small Shrubs: 2-6 ft								
Crassula ovata	Jade plant	Z4	OS	L (HWPRA)				
Lycium sandwicense	Ohelo kai			Native				
Myoporum sandwichense (creeping form)	Naio (creeping)	Z4	OS	Native				
Plumeria obtusa x rubra	Plumeria "Petite Pink"	Z3		L (HWPRA)	Sp. obtusa rated (-5, low)lxxii, sp. rubra rated (-6, low)lxxii			
Wikstroemia uva-ursi	Akia	Z3		Native				
Medium shrubs: 6-10 ft								
Plumbago auriculata	Blue plumbago	Z3	WB	L (HWPRA)	Originally given a rating of 6, but rated "low" post evaluationlxxii			
Rhaphiolepis indica	Indian hawthorn	Z3	WB	L (HWPRA)				
Rondeletia odorata	Rondeletia	Z3		L (HWPRA)				
Scaevola taccada	Beach naupaka	Z4	OS	Native				
Strelitzia reginae	Bird of paradise	Z3	WB	L (HWPRA)				
Large Shrubs: 10+ feet								
Carissa macrocarpa	*Natal plum*	*Z3*	*OS*	L (HWPRA)			***Thorns***	
Codiaeum variegata	Garden croton	Z3		L (HWPRA)				
Dodonaea viscosa	A'ali'i	Z4	WB	Native				
Holmskioldia sanguinea	Cup and saucer	Z3		L (HWPRA)				

Nerium oleander	*Oleander*	*Z4*	*WB*	L (Hawaii)	*Rated "low" post evaluationlxxii*	***Toxic***		***Irritant***
Small trees: 15-30 ft								
Bauhinia tomentosa	Yellow bell orchid tree	Z3		L (HWPRA)				
Caesalpinia pulcherrima	*Peacock flower*	*Z4*		L (HWPRA)	*Rated "low" post evaluationlxxii*	***Toxic***	***Thorns***	
Cassia roxburghii	Red cassia	Z3		L (HWPRA)				
Cordia sebestena	Geiger tree	Z3		L (HWPRA)				
Dendrolobium umbellatum	Horse bush			L (HWPRA)	Also called Desmodium umbellatum Rated "low" post evaluationlxxii			
Ficus carica	Common fig	Z3		L (HWPRA)				
Gardenia brighamii	Mau o hele	Z4		Native				
Guaiacum officinale	Lignum vitae	Z3		L (HWPRA)				
Lagerstroemia indica	Crepe myrtle	Z3		L (HWPRA)	Rated "low" post evaluationlxxii			
Myoporum sandiwicense	Naio	Z4	OS	Native				
Pandanus tectorius	Hala			Native				
Plumeria obtusa (Bahamas)	*Plumeria*	*Z4*	*OS*	L (HWPRA)		***Toxic***		***Irritant***
Tabebuia aurea	Yellow trumpet tree	Z3		L (HWPRA)				
Medium trees: 30-50 ft								
Colvillea racemosa	Colville's Glory	Z3		L (HWPRA)				
Cordia subcordata	Kou			Native				
Delonix regia	Royal Poinciana	Z3		L (HWPRA)				
Guettarda speciosa	Beach gardenia			L (HWPRA)	Found on all archipelagoes except Hawaiilxxiii			
Lysiloma	False	Z4	OS	L (HWPRA)				

latisiliquum	tamarind							
Plumeria obtusa	*Plumeria*	*Z3*	*WB*	L (HWPRA)		***Toxic***		
Plumeria rubra	*Plumeria*	*Z3*	*WB*	L (HWPRA)		***Toxic***		
Pseudobombax ellipticum	Shaving brush tree	Z3		L (HWPRA)				
Terminalia catappa	Indian almond			L (HWPRA)	Rated "low" post evaluationlxxii			
Thespesia populnea	Milo			H (HWPRA)	Introduced but culturally significant			
Large Trees: 50+ ft								
Barringtonia asiatica	Poison fish tree			L (HWPRA)	Rare in cultivation in Hawaiilxxiii			
Cassia x nealiae	Rainbow shower tree	Z3	WB	L (HWPRA)				
Cocos nucifera	Coconut tree (niu)			L (HWPRA)				

Note: Zones 1 and 2[lxxi] are omitted from this list. Empty "zone" cells refer to plants not discussed in The Watersmart Garden: 100 Great Plants for the Tropical Xeriscape.

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3.3 Waipahu

3.3.1 Existing Conditions

The Waipahu future Transit Oriented Development (TOD) area is a low-wave energy environment, sheltered by Pearl Harbor and Pouhala Marsh. Currently, the area is developed at a suburban level, with detached houses and low-rise residential and commercial areas. Future, denser mid-rise development is planned around a rail stop, which is already constructed. The area studied in this document is the ½ mile radius around the rail stop, the Transit Oriented Development (TOD) area.

Unlike the other two study sites, the goal is not to dissipate wave energy to protect coastal communities. At Waipahu Transit Oriented Development (TOD), flooding of roadways and buildings occurs when elevated water levels overtop streams and canal banks. Occurring in isolation or simultaneously, temporary flood shocks include storm surge, king tides, intense rainfall, and stormwater runoff; and long-term flood stressors such as sea level rise. Flooding would threaten the existing and proposed roadways, buildings, and rail transit area. Impervious buildings, roads, and slow-draining clay soils exacerbate flooding in the area.

Relevant flood protection strategies in Waipahu may include green infrastructure methods such as passive stormwater management in bioswales and rain gardens, floodable landscapes that allow water to recharge groundwater aquifers. These strategies may be combined with gray infrastructure flood mitigation strategies, such as water detention in underground cisterns and building flood protection, which are briefly mentioned in this report.

This report examines the potential for green infrastructure to reduce damage caused by temporary flooding that is anticipated to increase in frequency during the next several decades. Large-scale built environment planning and retreat strategies are needed to address areas that will be permanently flooded from sea level rise and and areas affected by groundwater inundation. The information provided here may help the State or City follow the Hawaii Sea Level Rise report recommendation to "Develop design standards for existing and proposed land uses that limits urban growth and increases flood resiliency within the [sea level rise exposure area] SLR-XA"[lxxiv] by avoiding future development in the SLR-XA.

Figure 43 Waipahu TOD Site Existing Conditions Map

Waipahu Existing Site Photos

Photo M

Vegetation along stream edges provides habitat to support bio-diversity. However, allowing vegetation to grow rampant and pollution to accumulate can cause upstream backup of flood water as it travels downstream

Credit: K. Yamamotoya

Photo N

The smooth-walled drainage canals causes floodwater to flow rapidly downstream, transporting pollutants and sediment with little opportunity for settling or filtration.

Credit: K. Yamamotoya

Photo O

A different section of the same canal pictured above has a natural, rather than hard edge. Vegetation along the canal edge provides increased surface area to slow down water movement.

Credit: L. Gonzales

Photo P

Aging infrastructure may not be able to withstand the increased projections of flooding in Waipahu. The Pearl Harbor bike path bridge over Wailani Canal may be deteriorating due to accumulation of stagnant water.

Photo credit: S. Mendes

Photo Q (Off map)

Lack of effective grading and stormwater conveyance infrastructure results in persistent ponding during heavy rain events, which is problematic for pedestrians, drivers, and residents.

Photo credit: N. Nishimura

Photo R

Soil in portions of Waipahu contain high amounts of clay, which results in low water absorption rates.

Photo credit: H. Au

The ½ mile radius study site's position (see Figure 44) between several freshwater streams and canals results in an increased vulnerability to damage caused by rain events .The study site is located between Waikele stream which runs to the west of Hawaii's Plantation Village into Pouhala Marsh; Kapakahi stream along Waipahu Depot Road to the east end of Pouhala Marsh; Wailani drainage canal along the west edge of Waipahu District Park through Ted Makalena Golf Course into Pearl Harbor, and an unnamed waterway parallel to Wailani drainage canal along the Pearl Harbor Bike Path. Major green spaces include Hans L'Orange Park, Hawaii's Plantation Village, Waipahu District Park, Ted Makalena Golf Course, and Pouhala Marsh Wildlife Sanctuary.

The photos of the existing site show stagnant, ponding stormwater, likely due to the clay soils' limited permeability. The photos also show varying stream edge conditions, including concrete channels and natural edges, some with significant litter and debris (see Figure 44 on preceding pages). The modern retrofitting of streams into hard canals, channelizing streets with impermeable pavement and paving vast expanses of land has caused rainfall to move rapidly move toward the coastal environment. "Brackish-water species adapted to tolerate estuary conditions cannot take this chemical and material stress and ultimately disappear. Many of these species and the organisms they feed on are marine fishes, so with the decline of estuaries come san impact to our coastal fishery, the reef, and even offshore species."[lxxv]

The following series of maps show flooded areas in the Waipahu Transit Oriented Development areas due to rainfall and sea level rise. The following map (see Figure 45 and 46) shows the planned Transit Oriented Development area in orange, the Pouhala rail station in black, the light blue 3.2 foot sea level rise exposure area, the dark blue 6 foot sea level rise area. The map (see Figure 47) depicts SLR at 3.2 feet, 4 feet, and 6 feet.

With 3.2 feet of sea level rise, the elevated water levels in streams and canals, result in flooding of smaller roadways and buildings adjacent to the streams and in unattached low-lying areas. The flooded areas include smaller roads, detached homes, and low-rise commercial buildings.

With 4 feet of sea level rise, a significant number of residential roads and detached homes will be flooded near the intersection of the Wailani Stream Drainage Canal and the unnamed stream. Waipahu District Park further inland near Wailani Drainage Canal and Farrington Highway will also flood.

With 6 feet of sea level rise, widespread flooding of roads, detached homes, commercial areas, future Transit Oriented Development areas, and parks and golf courses will occur (see Figure 46).

Please note the different mapping methods. The map showing the 3.2 foot and 4 foot Sea Level Rise Exposure Area (SLR XA), include passive flooding, annual high wave events, and coastal erosion from PacIOOS viewer. The 6 foot sea level rise maps from NOAA show modified bathtub flooding including "local tidal variability and hydrological connectivity."

In addition to sea level rise maps, it is relevant to also consider riverine flooding at the Waipahu site. In collaboration with the University of Hawaii's Department of Urban Planning's Fall 2017 practicum students[lxxvi], flood simulations for the study site were run through FEMA's software, HAZUS, "a GIS-based software model which produces loss estimates for … floods, … based on state-of-the-art scientific and engineering knowledge and software architecture"[lxxvii](see Figures 47, 48, 49). The riverine flood maps show flood events of varying severity: 1% annual chance rainfall event (100-year flood); 3% annual chance rainfall event (30-year flood); and 100% annual chance rainfall event (1-year flood). The 1-year river flood area primarily affects properties adjacent to the streams (see Figure 47). However, the 30-year and 100-year riverine flood events cause widespread flooding in the future TOD area, particularly south of the rail station (see Figures 48 and 49).

The Federal Emergency Management Agency (FEMA) Flood Insurance Rate Map (FIRM) showing flood zones (see Figure 49). Flood risk zones subject to inundation from the 1%-annual chance flood are designated as special flood hazard areas (SFHAs) on the Federal Insurance Rate Maps (FIRMs) produced by FEMA. "It is important though that the reader understands that event-based coastal flooding with sea level rise would expand the landward extent of these [special flood hazard areas] SFHAs."[lxxviii]

Figure 44
Waipahu TOD Site Map
Proposed TOD Plans

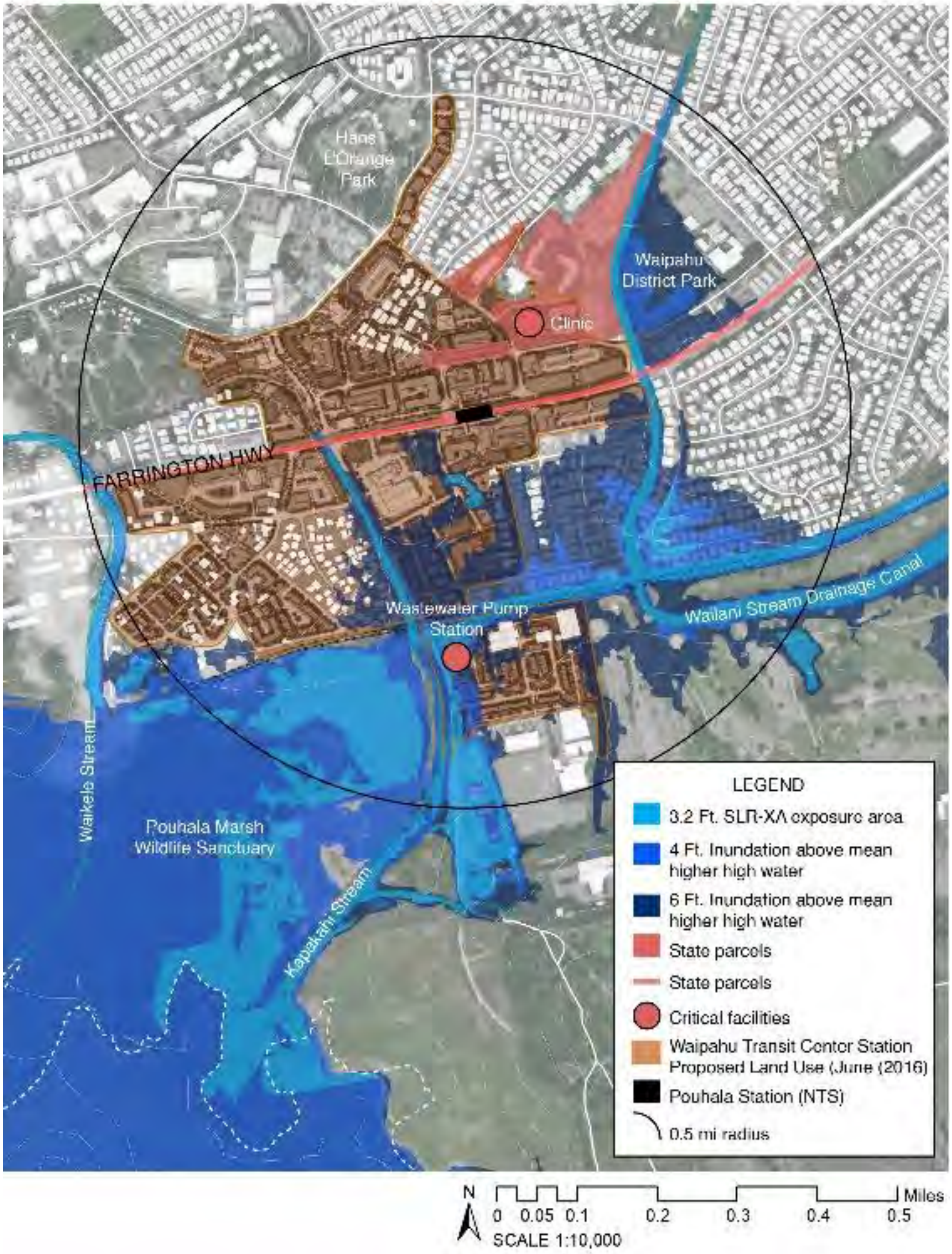


Figure 45
Waipahu TOD Site Map: SLR with Affected Major Roads and TOD Parcels

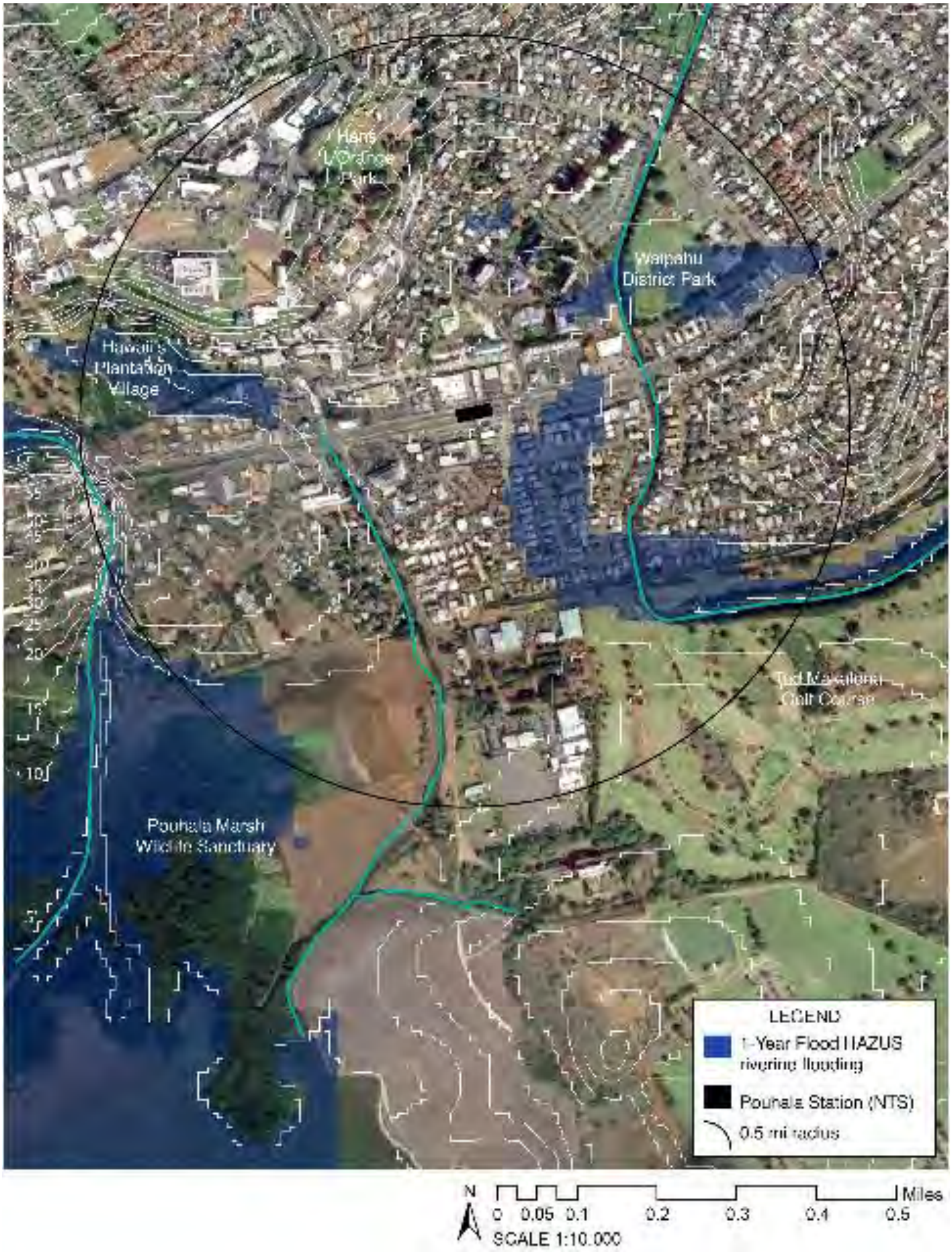


Figure 46
Waipahu TOD Site Map: Hazus Riverine Flooding Simulation – 1 Year Flood

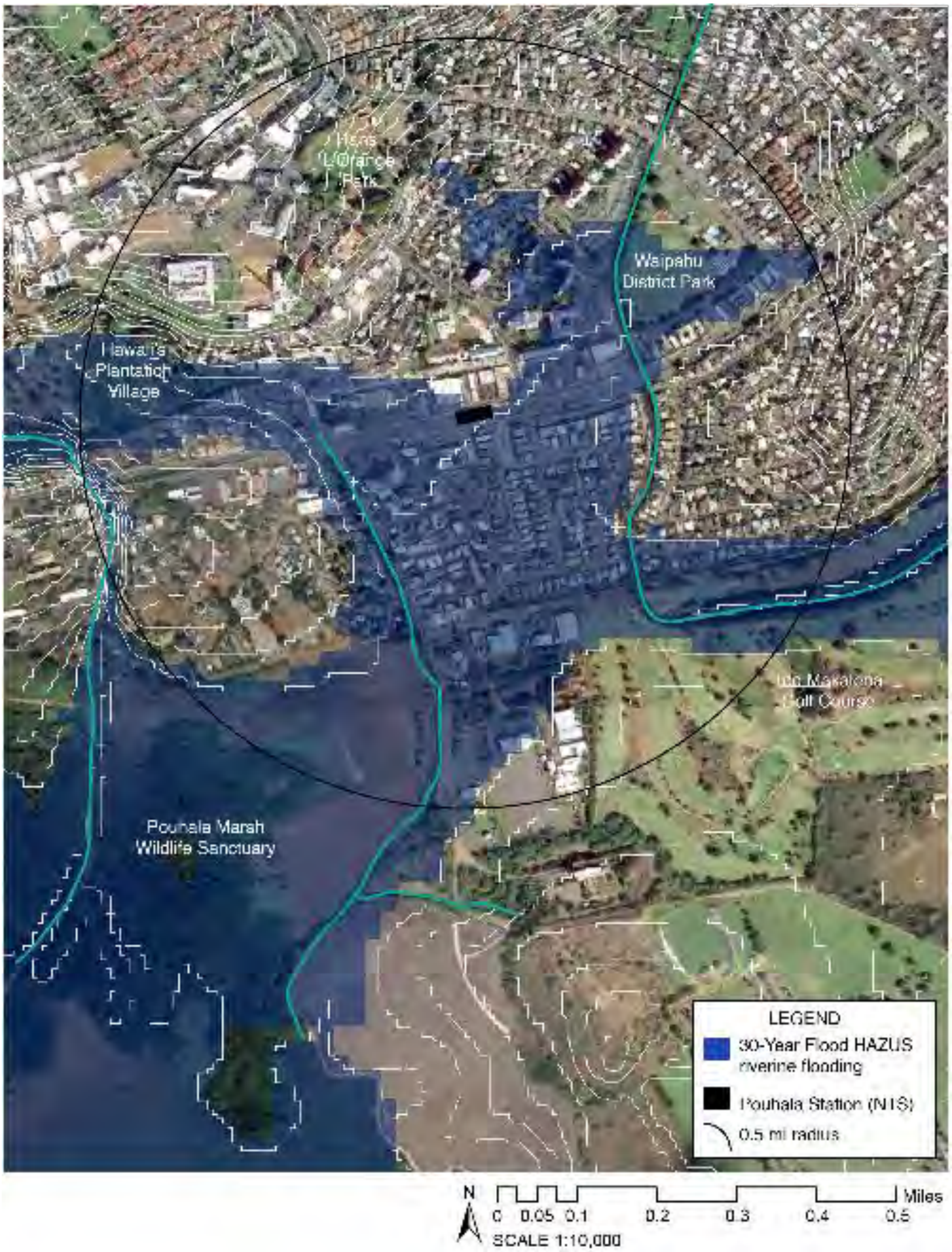


Figure 47
Waipahu TOD Site Map: Hazus Riverine Flooding Simulation – 30 Year Flood

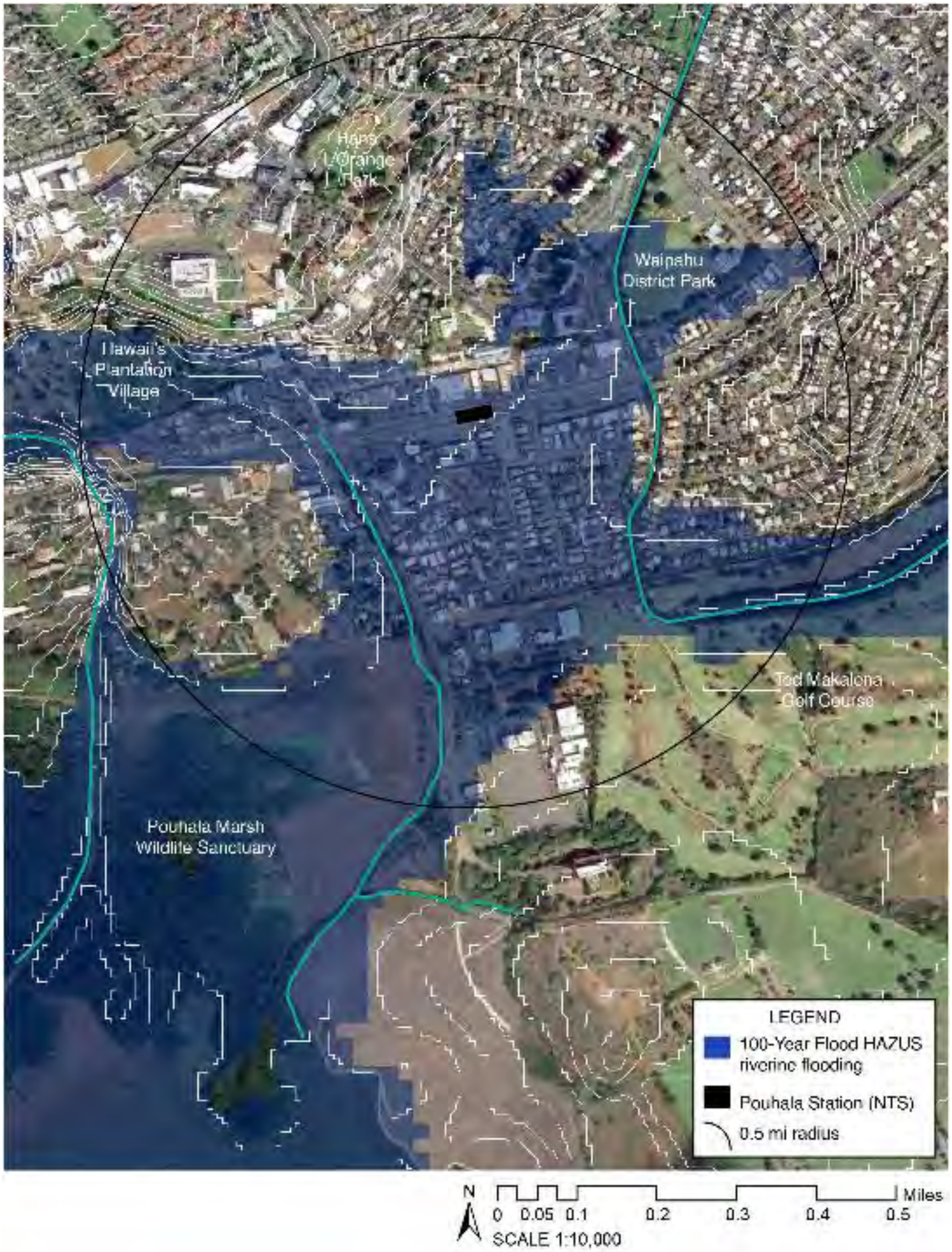


Figure 48
Waipahu TOD Site Map: Hazus Riverine Flooding Simulation 100-Year Flood

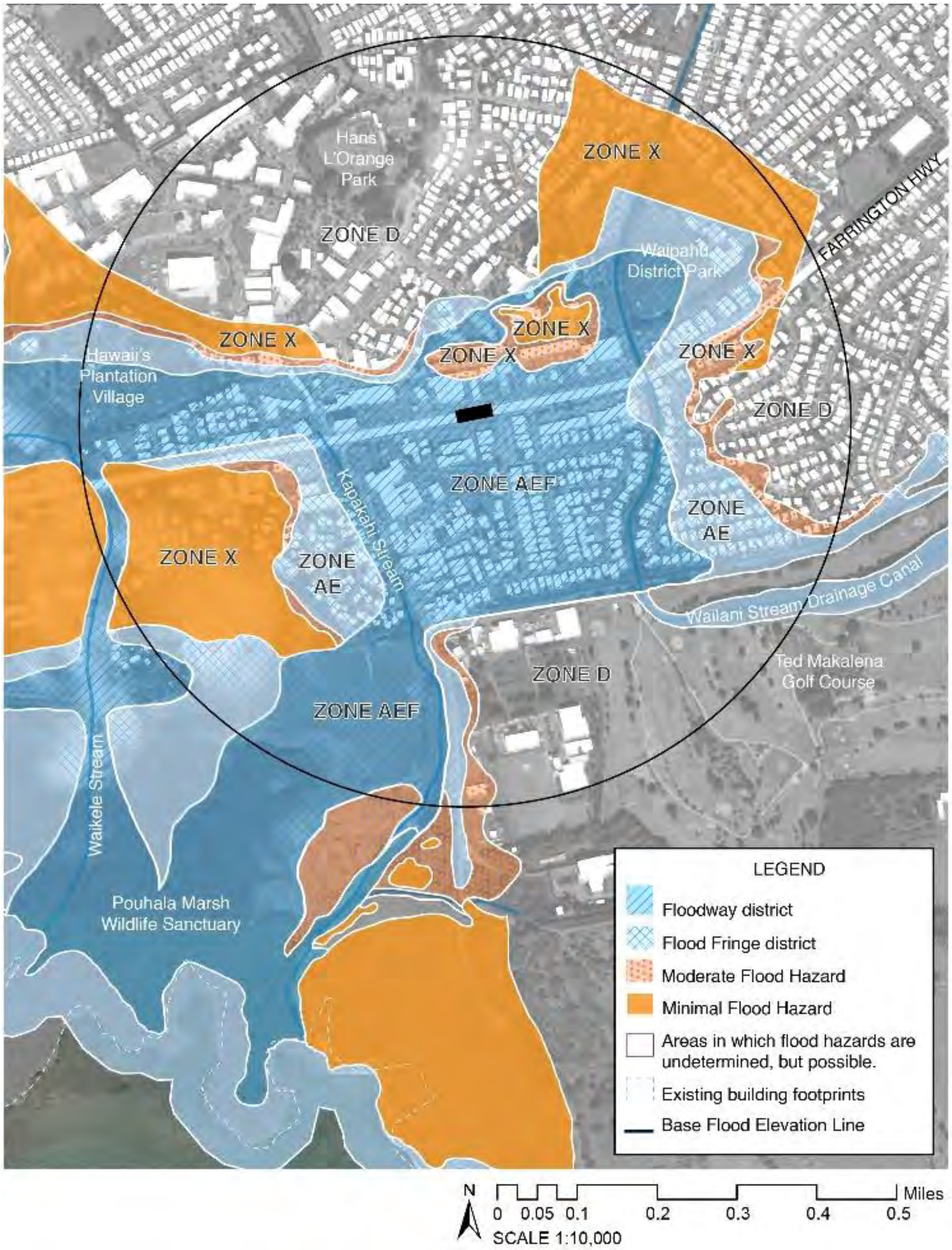


Figure 49
Waipahu FEMA Flood Zones from Flood Insurance Rate Map

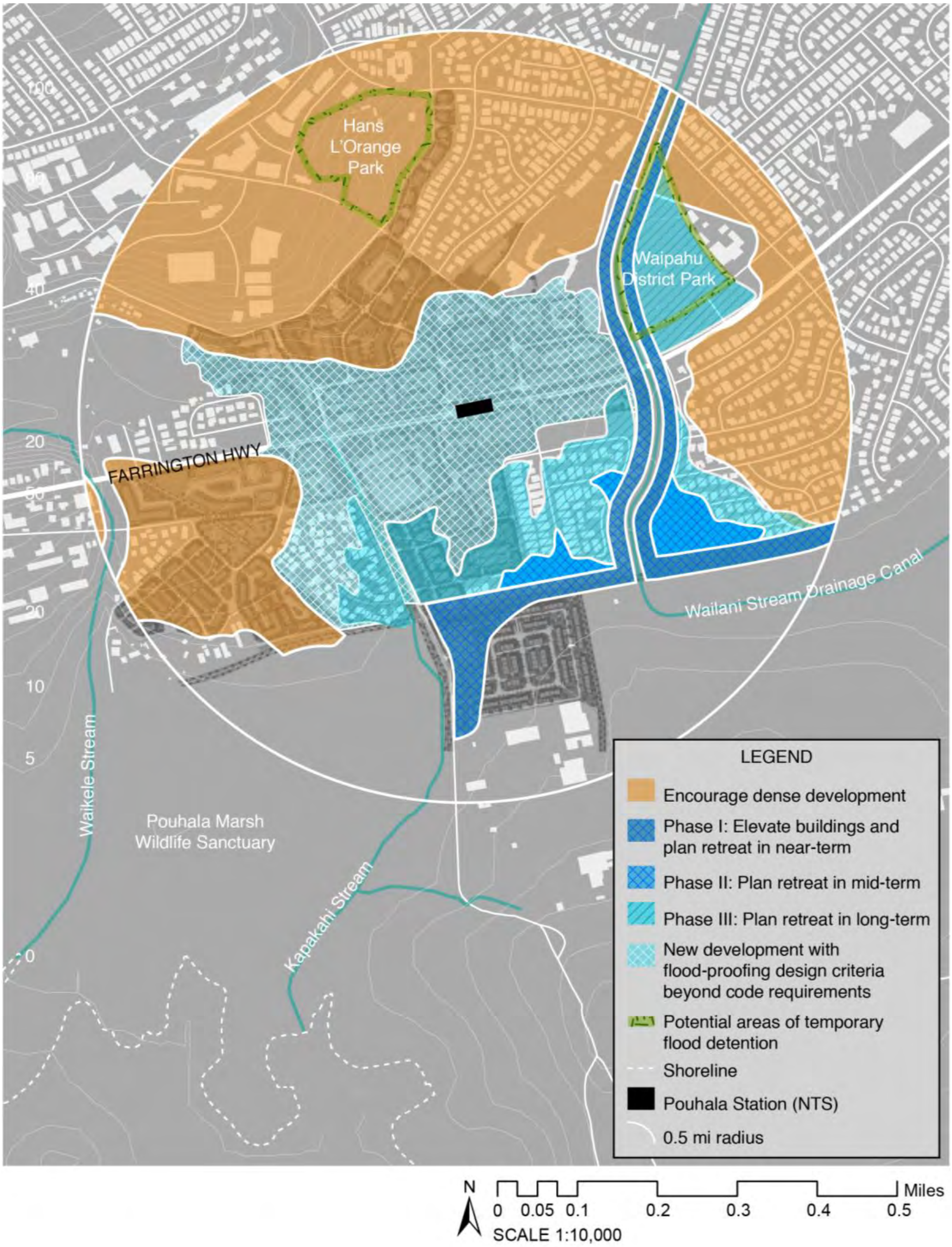


Figure 50
Waipahu TOD Area Potential Strategies Diagram

3.3.2 Potential Strategies Introduction

This primer expands upon green infrastructure planning strategies as an alternative to typical gray, hard infrastructure to reduce near-term episodic flood damage to transportation ways. To mitigate flooding of the roadways and new rail station in the Waipahu TOD area, planning-scale strategies for near-term adaptation and protection, long-term retreat are explored here. Once areas become permanently flooded by sea level rise, a different approach will be required to retreat, elevate, or otherwise adapt transportation ways.

For each of the following strategies, principles and precedent projects are presented. First, we consider managing stormwater by encouraging infiltration and detention in on-site bioswales. Second, we examine flood water detention through deliberate design of large, floodable spaces. Third, we explore widening the stream floodways and elevating the stream banks to reduce overtopping, and present precedent projects. We also briefly mention non-green infrastructure strategies, which may be relevant at the Waipahu site, such as underground cisterns, and permeable pavement.

3.3.3 Bioswales

Green infrastructure strategies aims to mimic natural hydrology to contend with the large areas of impervious surfaces and contaminated stormwater runoff. The subject of green infrastructure is well documented, and this primer describes opportunities to incorporate one type of green infrastructure, bioswales, near the roads and rail guideway in the Waipahu TOD area.

A bioswale is a “stormwater control feature that uses a combination of an engineered basin, soils, and vegetation to slow and detain stormwater, increase groundwater recharge, and reduce peak stormwater runoff.”[lxxix]. Bioswales filter sediment and pollution that flow off streets before they enter storm drains, streams, and ultimately the ocean. The following “Section Drawing A-C” illustrates conceptual incorporation of bioswales immediately adjacent to a roadway and in a parking lot (see Figure 73). The following “Figure 51: Section A” lower section drawing titled “Potential Future Design” illustrates a potential vegetated bioswale below the elevated rail guideway below structural columns (see Figure 51).

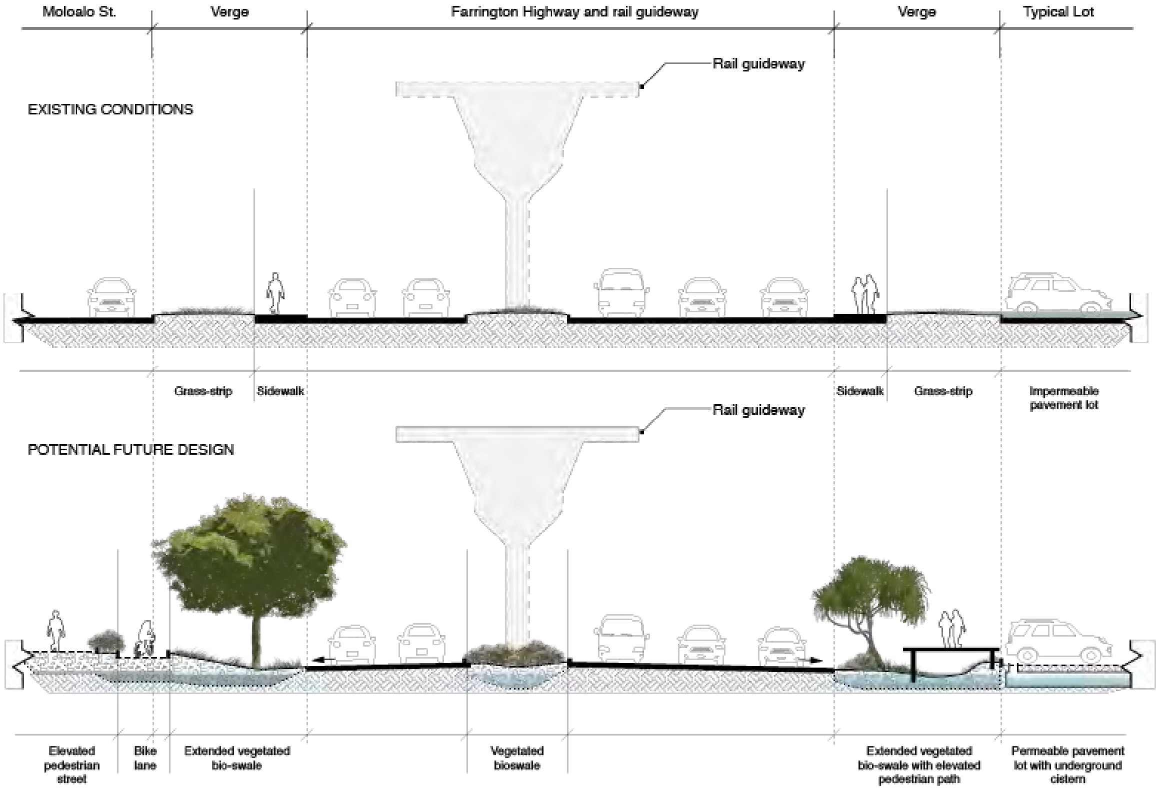


Figure 51:
Section A: Waipahu TOD Site Rail Guideway/Farrington Hwy Section

Several images of precedent projects below demonstrate how bioswales are integrated into roadway and elevated highway designs. Figure 52 shows a heavily vegetated bioswale at a lower elevation than the surrounding the large roadway, sidewalk, and parking lot in Milwaukee, WI. Figure 53 shows a bioswale with curb cuts integrated in a dense urban area between buildings, sidewalk, and road in Milwaukee, WI. Figure 54 shows a bioretention basin approximately four feet deep with curb cuts and overflow outlet to storm sewer in a detached house residential community in Seattle, WA (see Figure 54) shows a bioswale, curb, cut, and pervious asphalt at the Center for Sustainable Landscapes in Pittsburgh, PA. Figure 56 shows the sidewalk, bioswale, bicycle, filter strip, and road in Long Island, NY is a useful precedent for Waipahu TOD multi-modal transportation. Figure 57 shows the precedent project named "HOLD" by DLANDSTUDIO direct stormwater downspouts runoff to gravel sedimentation basins and remediative plants.lxxx The elevated highway with downspouts are a useful precedent for the elevated rail in Waipahu. Below are photos of useful precedent bioswales located adjacent to various types of transportation ways: roads, sidewalks, bicycle lanes, parking lots, and below elevated highways.

Figure 52
Bioswale between the roadway, sidewalk, and parking lot in Milwaukee, WI. Photo: W. Meguro

Figure 53
Bioswale with curb cuts adjacent to urban buildings, sidewalk, and road in Milwaukee, WI. Photo: W. Meguro

Figure 54
Vegetated stormwater detention basin in Seattle, WA. Photo: W. Meguro

Figure 55
Bioswale, curb, cut, and pervious asphalt at the Center for Sustainable Landscapes in Pittsburgh, PA. Photo: W. Meguro

Figure 56
The sidewalk, bioswale, bicycle, filter strip, and road in Long Island, NY is a useful precedent for Waipahu TOD multi-modal transportation. Photo: W. Meguro

Figure 57
The precedent project, HOLD, by DLANDSTUDIO direct stormwater downspouts runoff to gravel sedimentation basins and remediative plants.[lxxxi] Image: DLANDSTUDIO

Another relevant precedent for the Waipahu TOD area is the method used to identification of the best performing stormwater management designs to guide future development produced through a municipal study in Wisconsin. The city of La Crosse, Wisconsin published a study, “Using Green Infrastructure to Mitigate Flooding in La Crosse, WI: An Assessment of Climate Change Impacts and System Wide Benefits” [lxxxii] in which they utilized the EPA’s Storm Water Management Model to test the effectiveness of permeable pavement and bio-retention areas under different storm scenarios. Their study concluded that a deeper storage gravel bed in bio-retention areas and wider use of permeable streets mitigate flooding from increasingly intense storm events. The following resulting tangible design guidance is helpful to municipal planners and design teams.

- Permeable pavement with a 4 foot gravel storage bed was determined to be the highest performing system in the basin that can be used to meet the City’s objectives for flood control.
- Implementing permeable pavement on 25 percent of the potential street area represents the knee-of-the-curve solution to mitigate flooding from the 3-month, 2-hour storm event.
- Implementing permeable pavement on 75 percent of the potential street represents the knee-of-the-curve solution to mitigate flooding from the 10-year, 2-hour storm event.

While the design storms in the study above are specific to La Crosse, Wisconsin, a similar analysis could be undertaken for Waipahu. The suggestions for bioswales could be incorporated into the TOD new and re-development requirements.

3.3.4 High Volume Above-Grade Water Detention Areas

When re-developing the half-mile radius surrounding the new rail station, there is an opportunity to utilize large open spaces for multiple benefits, including stormwater detention, recreation, and habitat creation. Parks or plazas are ideal amphibious spaces – serving as public space during dry times and floodable space during rainy times to store, infiltrate, and slowly release significant volumes stormwater to municipal systems. One may consider redesigning Waipahu's major green spaces to better receive and detain stormwater runoff from surrounding areas. Areas of interest include Hans L'Orange Park, Waipahu District Park, Hawaii's Plantation Village, and Ted Makalena Golf Course (see Figure 44 for map). The following precedent projects demonstrate multiple protective, ecological, and social benefits.

Copenhagen's Enghaveparken public park is an example of a multi-functional park that is designed to accommodate community gathering during dry seasons, and 24,000 cubic meters of water during rainy seasons.[lxxxiii] Currently under construction, and estimated to be completed in 2019, the design for the park was envisioned through a design competition and won by the team Third Nature (see Figure 58). The design aims to maintain the original structure of the park and visibly manage stormwater by using the park as a retention basin and directing remaining water to a closed underground reservoir.

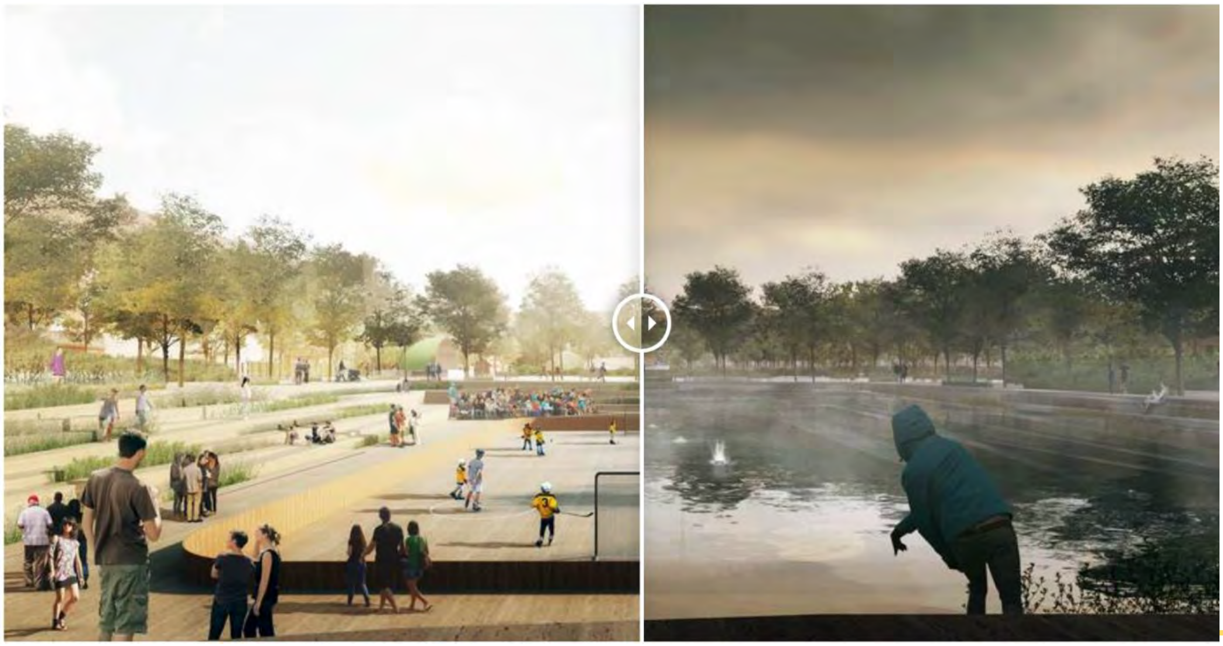


Figure 58
The competition winning entry by Third Nature for Enghaveparken shows a sunken space used for recreational public gathering when dry, and to hold stormwater during heavy rains. Image credit: Third Nature.

The following study method is a useful precedent for iterative design, analysis, and resulting guidelines for urban stormwater wetlands in Waipahu. The MIT Center for Advanced Urbanism study considers regional-scale digital simulation to design engineered green spaces, to the “capture and purify stormwater while delivering ecosystem and recreational benefits.”[lxxxiv] Researchers at MIT released the “Design Guidelines for Urban Stormwater Wetlands” report in 2018 a study on maximizing efficiency of wetlands through digital modeling and simulation for Los Angeles, California and Houston, Texas sites. A large portion of this study looks at the engineered approach to “optimal topographic forms” (see Figure 59) to minimize water pollution. However, their guidelines also encourage the combination of three elements: new habitats, public programming, and recreation to create a “unique palette for design” which results in “programming opportunities for people and nature”.[lxxxv]

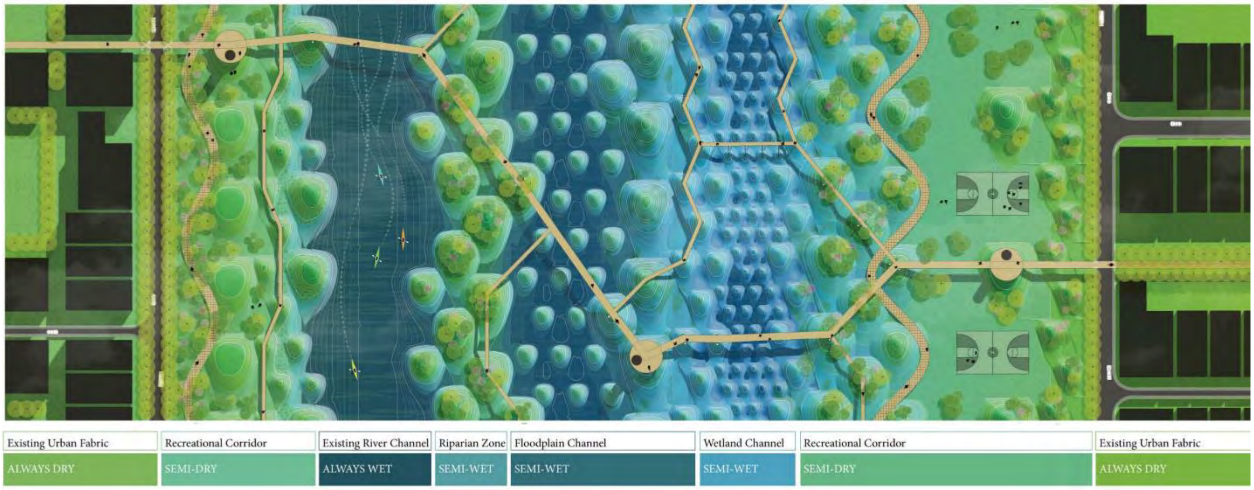


Figure 59 Analysis image from MIT’s “Strategies for Urban Stormwater Wetlands” shows a portion of a redesigned stream corridor utilizing optimized topographical elements that suports human and ecological functions.

The following photos demonstrate public green spaces that support human recreation while directing stormwater runoff to slow and infiltrate in low-lying areas. There is a bioswale adjacent to playing fields at Manoa District Park in Honolulu, HI (see Figure 60). There is a constructed wetland with pedestrian bridges (not shown) for stormwater management at Brooklyn Bridge Park in New York City, NY (see Figure 61).

Figure 60
Green space with swale in Honolulu, HI. Photo: W. Meguro.

Figure 61
Floodable landscape for stormwater management in Brooklyn Bridge Park, NY. Photo: W. Meguro

Floodable public spaces comprised of hardscape may be more appropriate than a green space in some urban contexts. Water Square Benthemplein in Rotterdam, NL was designed and constructed by De Urbanisten for the Rotterdam Climate Initiative and demonstrates how a municipality can use infrastructure to serve multiple benefits (see Figure 62). The square "combines water storage with the improvement of the quality of urban public space."[lxxxvi] The square is used for recreation, in dry weather. In wet weather, gutters direct water to three basins in a "dramatically gush the rain water visibly onto the square."[lxxxvi] Stormwater either "flows into an underground infiltration devices"[lxxxvi] or is detained and slowly released to the municipal combined sewer system. The description of the project timeline is helpful in understanding the steps and schedule relevant for similar studies and potential application at the Waipahu Transit Oriented Development (TOD) area. The Water Square project moved from research in 2005, to policy in 2007, to a pilot study in 2008, to a publication in 2010, to design in 2011-2012, and opening in 2013.

Figure 62 Floodable urban space, Water Square, in Rotterdam, NL Square by De Urbanisten.[lxxxvi]

3.3.5 Widen Stream Floodways and Elevate Stream Banks

A potential strategy to prevent overtopping of stream and canal banks is to increase the width of the floodway adjacent to the waterways, and increase the height/elevation of the stream banks. Modification to the Wailani and Kapakahi streams widths and banks presents an opportunity for flood protection, ecological restoration, human transportation, and recreation.

Section diagrams illustrating the forthcoming concepts are illustrated in the following pages in Section A at Kapakahi Stream and Section B at Wailani Stream Drainage Channel. These sites were selected because the built environment adjacent to the waterways will be inundated with 3.2 feet of sea level rise.

Challenges include modification of the existing stream channel or bed, and relocation of existing detached homes adjacent to the streams. Managed retreat or property buy-out should prioritize the properties projected to be flooded soonest.

Widening the flood way could increase the volume of the stream, as compared to the current channelized streams. See Figure 63 for a section diagram of the floodway, the "expanded channel in which water flows during floods."[lxxxvii] In addition, the stream banks could be elevated in an effort to protect surrounding areas from stream overtopping. The potential expansion of the floodway and elevated bank height would require calculation of anticipated water volumes, and the conceptual idea is presented here.

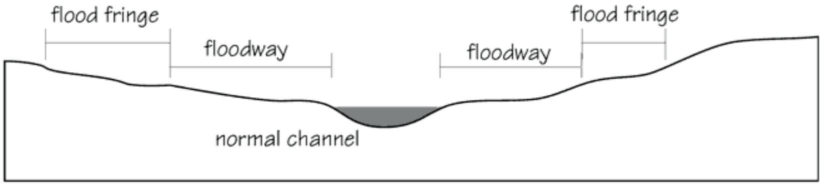


Figure 63 Section diagram

The section diagram above from Building Green describes the engineering terms for segments of a river basin, including the floodway.lxxxvii

Potentially changing portions of Kapakahi and Wailani streams from concrete channels to natural stream banks may have potential for ecological restoration (see Figure 44 Photo N and Photo O). Concrete channelized streams are problematic because faster moving water swiftly carries sediment and pollutants downstream, to the detriment of estuaries, coastal fisheries, reefs, and offshore species.[lxxxviii] The channelized stream "offers no habitat to native species" and encourages development within adjacent flood plains.[lxxxviii] Future modified stream banks could be modified to restore the natural ecology. "Ideally, streams in Hawai`i should have natural beds and banks. Cool, clear water should meander through features such as pools and riffles that also provide habitat to native species. Naturally overhanging vegetation should provide shade from the hot subtropical sun for the indigenous ecology."[lxxxviii]

In addition, newly elevated stream banks may serve a variety of purposes for human transportation and recreation, such as a biking and walking path, nature walk with signage (see Figure 72). The streams could serve as a mauka to makai, mountains to ocean, contiguous green way and alternative transportation way.

3.3.6 Precedent Projects: Elevated Stream Banks, Stream De-channelization, and Recreation

The following built project point to the potential success of dechannelizing streams and designating a flood plain adjacent to the stream. In Singapore, a 1.7 mile channelized canal was revived into a 1.8 mile, natural meandering stream, in order to reduce peak flooding while increasing water security by slowing and collecting stormwater runoff (see Figure 64)"In a feat of sequenced engineering, [landscape architect Herbert] Dreiseitl managed to re-engineer soils, add bio-engineered plant systems along with trees, break up the existing concrete channel and reuse the rubble to stabilize the entire system — all while the river was still running."[lxxxix] In addition to reducing dangerous flooding, biodiversity increased, adjacent property values rose, and people in the city have much-desired access to nature. This is an excellent example of public infrastructure that also serves ecological and human recreation purposes.

The canal in Singapore resembles the channelized stream that runs alongside Waipahu District Park. One may envision the stream dechannelized, with planned temporary stormwater flood detention in large Waipahu District Park to prevent or reduce downstream flooding near the new rail stop.

Figure 64 A stream de-channelization and park project in Singapore is a useful precedent for Wailani Stream and Kapakahi Stream in Waipahu.

Figure 65 Before and After Kallang River de-channelization.[xc]

Another precedent project, is a winning Rebuild By Design entry called, "Hunts Point Lifelines" by PennDesign / Olin et. al. The process is a useful precedent because of the analysis of flood depths and integration of waterfront functions to create a floodable green space along the water's edge. A part of the multi-faceted design features a levee built adjacent to a river. It features walkable space and access to the water on dry days and a protected walkway during flooding events (see Figure 66).

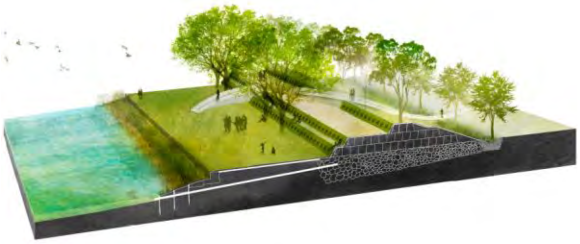
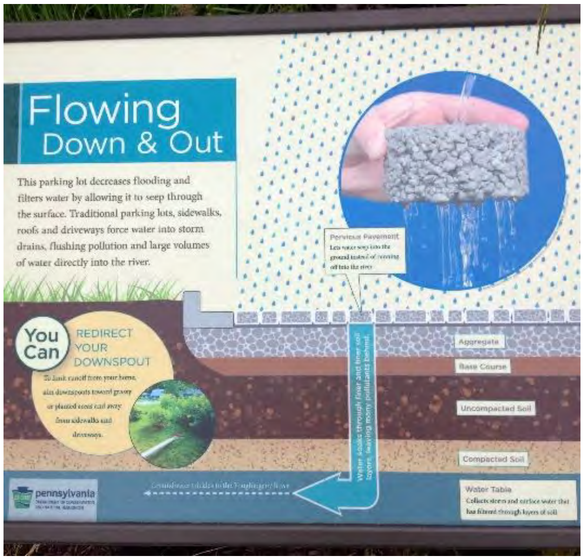


Figure 66 PennDesign/Olin's design for a Multi-use levee.[xci]



This parking lot decreases flooding and filters water by allowing it to seep through the surface. Traditional parking lots, sidewalks, roofs and driveways force water into storm drains, flushing pollution and large volumes of water directly into the river.

To limit runoff from your home, aim downspouts toward grassy or planted areas and away from sidewalks and driveways.

Water soaks through finer and finer soil layers, leaving many pollutants behind.

Collects storm and surface water that has filtered through layers of soil

Figure 67 Illustration section drawing of permeable paving stormwater infiltration by the Pennsylvania Department of Conservation and Natural Resources. Photo: W. Meguro

3.3.7 Selected Gray Infrastructure Introduction

Selected gray infrastructure strategies that are relevant to roadways are briefly presented here for consideration to compliment green infrastructure in a comprehensive flood-mitigation plan.

3.3.8 Permeable Pavement

When re-developing the Waipahu TOD area, large impermeable areas, such as less-trafficked roads, parking lots, and public plazas should be evaluated for permeable paving. Permeable pavement is "a paved surface with a higher than normal percentage of air voids to allow water to pass through it and infiltrate into the subsoil"[xcii]. A section drawing on signage by the Pennsylvania Department of Transportation illustrates the layers below permeable paving including a base course, uncompacted soil, compacted soil, and finally the water table (see Figure 67). Materials such as paving stones, or grass pavers may be used in lieu of typical asphalt (see Figures 68 and 69).

Figure 68 Permeable grass-crete in parking lot in Honolulu, HI. Photo: W. Meguro

Figure 69 Permeable paving in parking lot in Pennsylvania. Photo credit: W. Meguro

Areas such as sidewalks, parking lots, driveways, alleys, bike paths, or patios with light vehicular traffic are recommended, since permeable paving may be more susceptible to compression and its air voids are necessary to allow water to pass through it. In Waipahu's residential neighborhoods, there are many areas with light vehicular traffic, such as residential driveways and residential road shoulders used for walking and parallel parking (see Figure 44 Photo R).

One consideration in Waipahu are the anecdotes from a community meeting residents that soils are slow to drain and have a high clay content and low water permeability. Soils may be dredged and more porous gravel layers installed below permeable paving in order to create space for water infiltration. Sub-surface perforated pipes may also slowly transport water to stormwater sewers or retention basins. Section drawing A-B illustrates new permeable paving in an existing parking lot (see Figure 72).

In areas of extensive flooding such as the residential neighborhood north of the Ted Makalena Golf Course, bio-retention using permeable paving atop a gravel storage bed may store stormwater runoff and flooding from riverine overtopping (see Figure 73).

Additionally, planning and design teams must consider the water table depth on a site by site basis to determine if on-site water infiltration is a feasible strategy.

3.3.9 High Volume Water Detention Areas

Utilizing large underground cisterns to temporarily store large quantities of stormwater runoff, riverine flooding, or storm surge water may mitigate flooding of roadways. Water would be pumped out and the space cleaned after a flood event. Section drawings illustrating potential new underground cisterns are illustrated in Section A-D (see Figure 72).

One of the world’s most well-known examples of underground cisterns is Japan’s G-Cans project. The system consists of five silos, each 65 meters deep and 32 meters in diameter, and 6.5 kilometers of connecting tunnels that lead to a 25.4 meter high by 177 meter long “Underground Temple.” Tokyo’s G-Cans have a capacity to store a 200-year flood event below city streets (see Figure 70). After a storm event, large pumps actively pump the floodwater into the Edogawa River.[xciii]

Another example of below-grade large volume water storage is a museum carpark in Rotterdam (see Figure 72). The car park accommodates 1,150 cars and also houses “one of the largest underground water reservoirs in the Netherlands, a reservoir with a capacity of 10,000m^3” [xciv] (over 2.64 million gallons).

Figure 70
Water storage tank in Japan's G-Cans project. Source: Dddeco.

Figure 71
Diagram of Japan's G-Cans project.[xcv]

Figure 72
MuseumPark Car Park water storage in
Rotterdam, Netherlands[xcvi]

3.4.0 Potential Strategies Section Drawings

The following portion of this report takes a closer look at Waipahu using section drawings to illustrate potential applications of the green infrastructure strategies discussed. The Waipahu site map shows the location of the section drawings with a line (see Figure 73). Section A is a section drawing of Kapakahi Stream near the Waipahu Convenience Center. Section B addresses the residential section with high levels of predicted flooding. These areas are selected for illustration because they will experience flooding from sea level rise or storm surge soonest.

At the top of each page, a section drawing depicts the existing site conditions. Each section drawing below it displays potential green infrastructure strategies for flood mitigation at roadways.

Each section drawing is divided into portions denoted with vertical lines. Each portion should be considered as a singular strategy. The entirety of a section drawing is not a cohesive prescription, but rather a series of options. For example, permeable pavement is a singular design strategy and can be applied in combination with a terraced floodway, or with a simple sloped floodway.

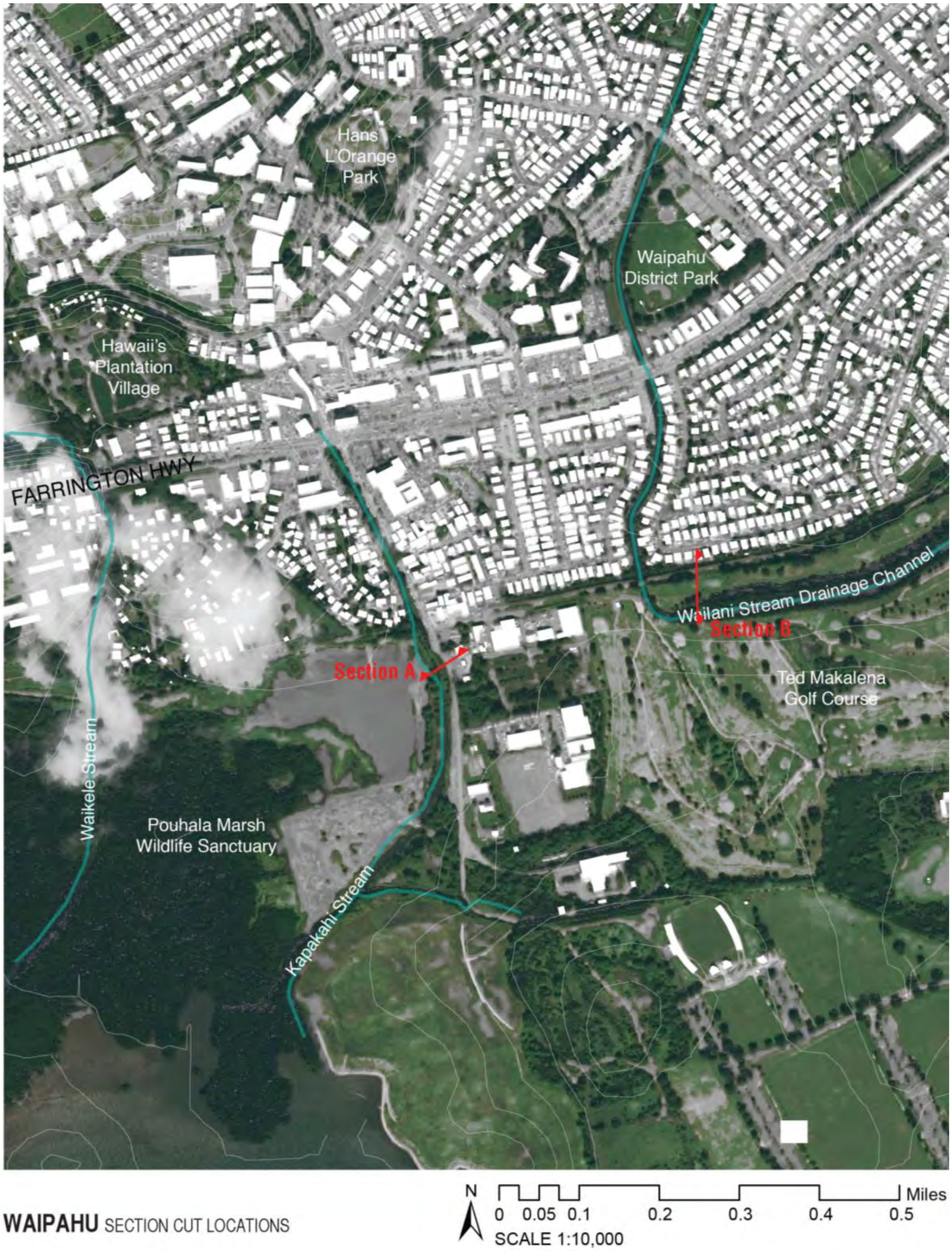


Figure 73 Waipahu Map of Section Cut Locations

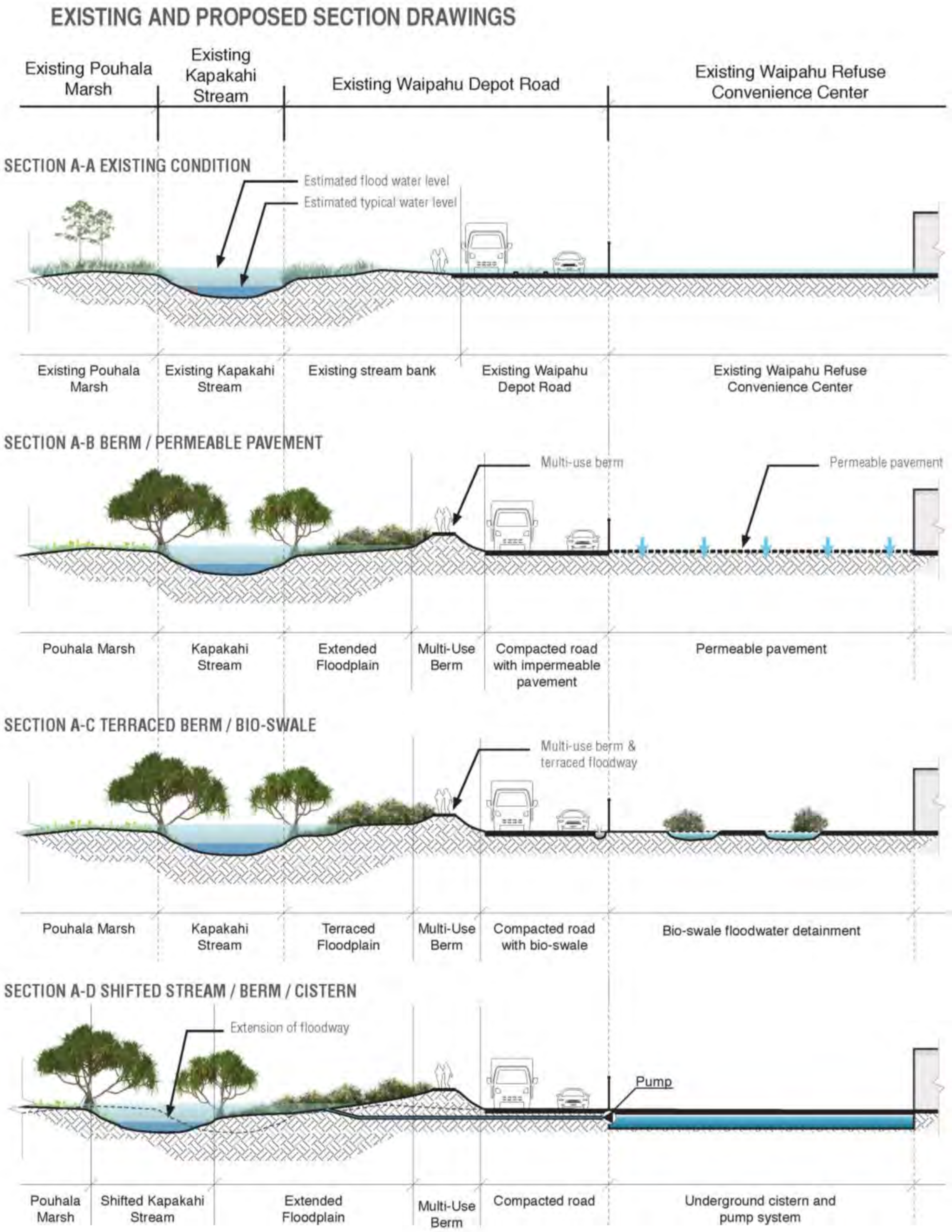


Figure 74 Waipahu Section Drawing A at Kapakahi Stream

SECTION A-A Existing Condition

Current conditions along Kapakahi stream varies greatly as portions are underground, severely overgrown, or heavily polluted. Sea level rise, river, and storm surge flooding occurs around streams and their neighboring low-lying areas. Flooding will negatively impact residences, commercial businesses, and public infrastructure if current conditions are not adapted accordingly. High clay content soil in combination with expansive asphalt coverage prevents proper drainage of water. Streams are clogged with vegetation and trash, and roads are susceptible to disuse due to elevated flooding.

The following proposal strategies should be considered individually, not grouped per section. Strategies should be considered on a site-by-site basis.

Please refer to Appendix A for small scale maps of flood impacts on infrastructure and the TOD plan, and existing FEMA zones.

SECTION A-B Multi-use berm / permeable pavement

By extending the floodplain around Kapakahi stream, the stream will be able to handle a higher volume of flood water, thereby decreasing velocity. A berm is proposed in the remaining schemes as elevated walkways provide a means of transportation when vehicular roads become flooded. Permeable pavement should be incorporated in low lying areas to reduce ponding on large lots. Native vegetation well suited for saline environments should be given highest priority when selecting species for planting. Trees such as hala, and shrubs such has `ohelo kai and `ahu`awa are hardy species.

SECTION A-C Terraced multi-use berm / bio-swale

Terraced floodplains allow for use of elevated platforms when dry, and permit the flow of water during flood events. Benefits are similar to the extended floodplain mentioned above. Bioswales are forms of green infrastructure that have been widely implemented on urban streets across the globe. Swales are miniature ecologies that capture and filter water through microbial processes and the natural uptake of water by plants. Many designs of bioswales exist and each are created to achieve different outcomes for site specific needs. Bioswale implementation is versatile and can be implemented on paved lots, along streets, for residential use, and more.

Section A-D Shifted and expanded flood-plain / multi-use berm / cistern

The entire floodplain can be extended into Pouhala Marsh and allow for greater volume capacity. Although sections of Kapakahi stream are underground, expanding the stream can be advantageous along all sections to reduce bottlenecking.

Grey infrastructure should be considered to use in conjunction to green infrastructure. Cisterns and pumps may be useful around soils with high clay content to absorb excessive levels of flooding.

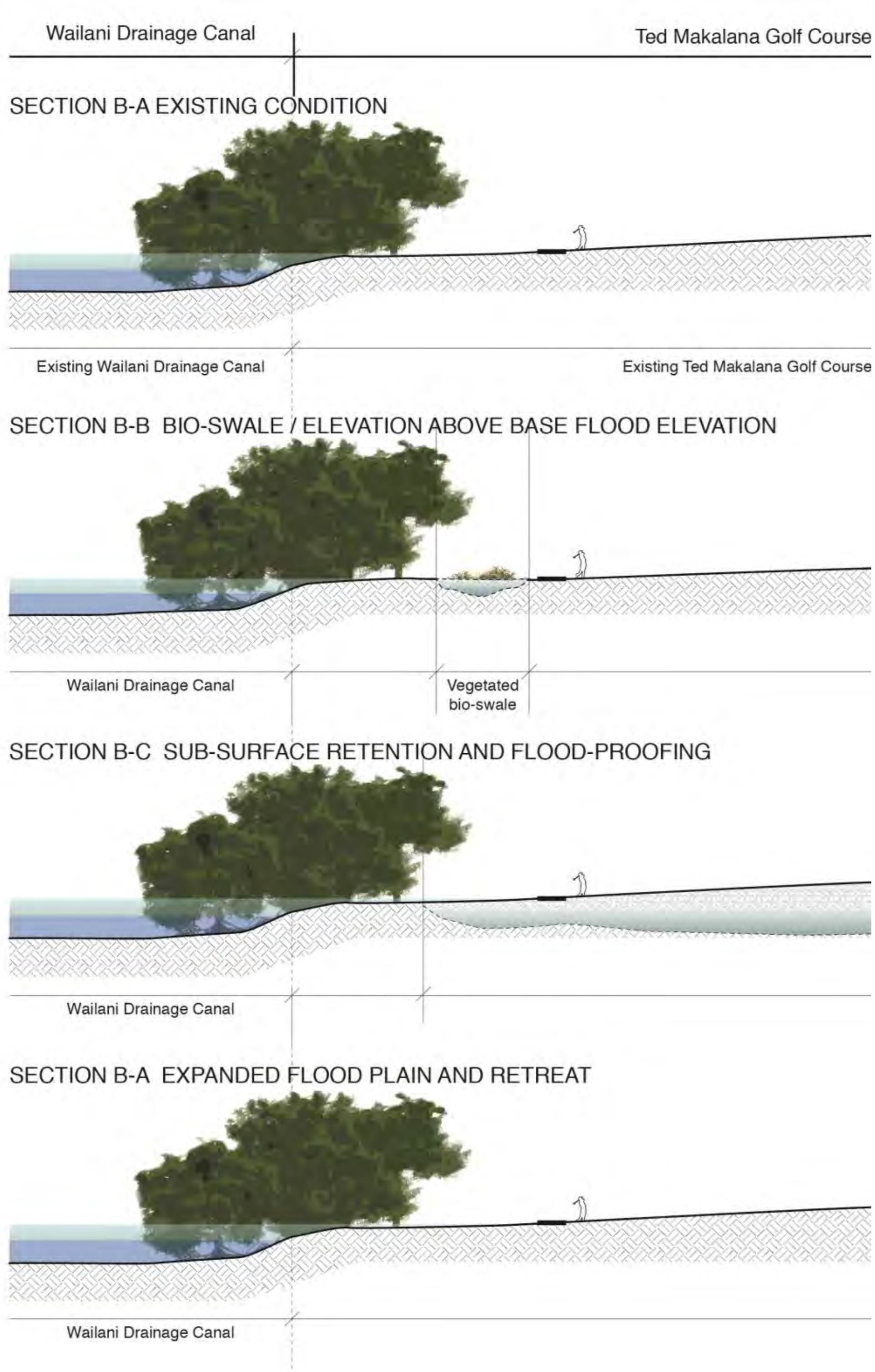


Figure 75 Waipahu Section Drawings B at Ted Makalana Golf Course

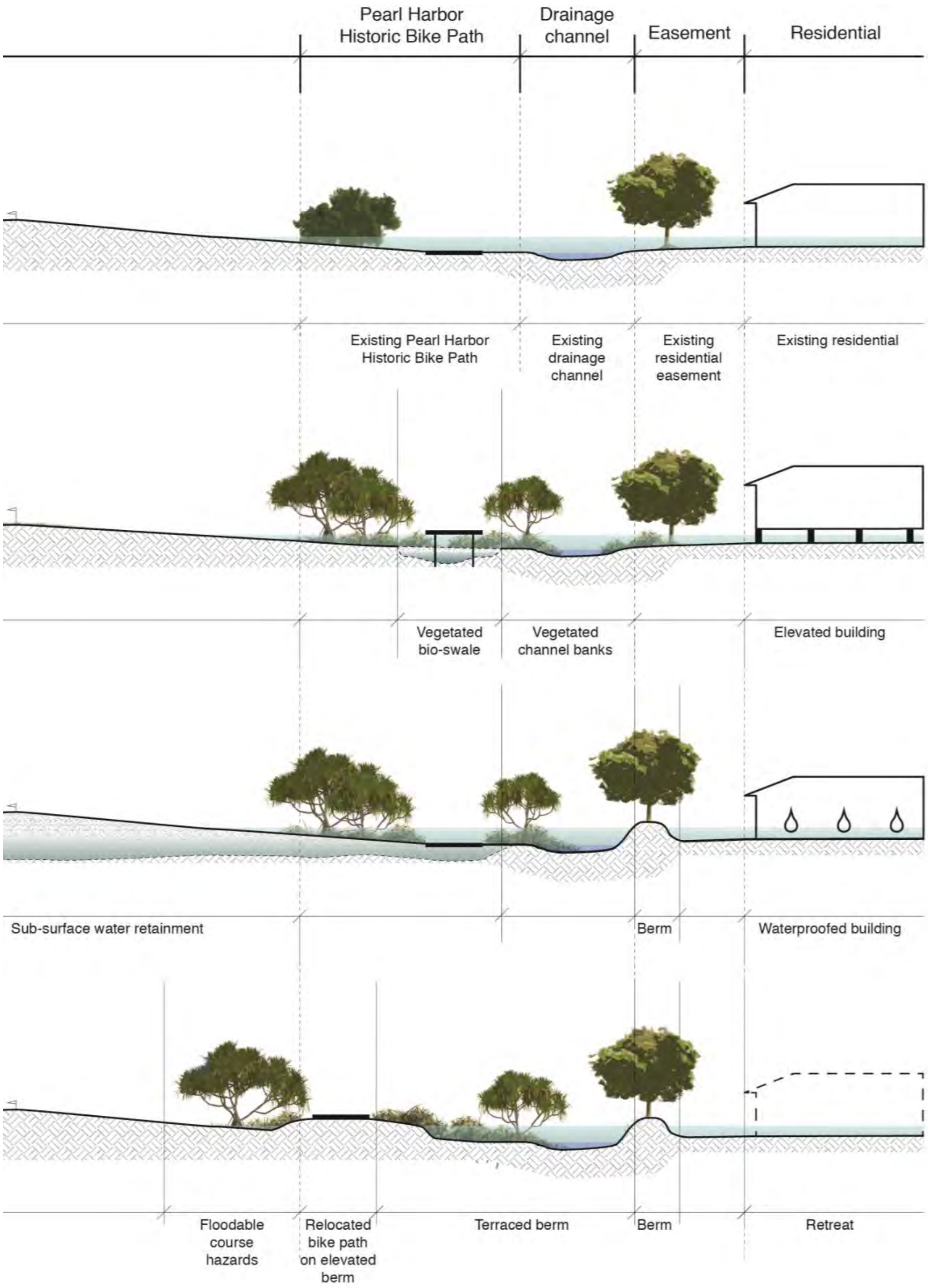


Figure 76 Waipahu Section Drawings B at Ted Makalana Golf Course (continued)

SECTION B-A Existing Condition

Section drawings “B” are spread over two pages, and should be viewed on pages facing each other. Flooding along the canal between Wailani stream and nearby residences is a big contributor to wide spread flooding in the nearby low-lying areas. This channel is often filled with large debris and trash, has low flow rates, and is both narrow and shallow. Many residences (refer to Appendix A - Waipahu RES maps) will experience flood-related damage. Redesigning the site may open up opportunities for improved public experiences on the bike path, and improved health and safety.

SECTION B-B Bio-Swale / Elevation Above Base Flood Elevation

Elevated buildings and roads should allow water to flow beneath, especially for buildings within FEMA zone AEF - where development within he floodway (F) must ensure “no increases in upstream flood elevations” (FEMA). Bioswales may be installed along the bike path, and within the golf course to aid in storage of floodwater.

SECTION B-C Sub-Surface / Retention and Flood-Proofing

Opportunity lies within the large expanse of the Ted Makalena Golf Course. Allowing the golf course to flood can ease pressures on the small channel. By allowing flood design on golf course property, the channel may be given space to be properly designed.

Buildings may also be designed to be dry-or wet- flood-proofed. Buildings within floodways must be wet-flood-proofed to allow movement of water. However, dry-flood-proofing requires sealing lower level to prevent water infiltration.

SECTION B-D Expanded Floodplain / Retreat

Berms may be able to protect residences from stream overtopping. However, simply increasing the height of stream banks may cause an increase in stream velocity. Therefore, a combination of widening the channel and increasing the height of a berm may help contain those floodwaters. The elevated berm may be outfitted with recreational elements such as a biking or jogging lane. In cases of chronic flooding, property owners may choose to retreat and relocate activities.

4.0 Conclusion

Oahu, Hawaii's coastal hazards include accelerating erosion, sea level rise, and coastal storms that threaten to flood roadways and new rail infrastructure. Typical "hard" shoreline armoring for coastal protection results in detrimental erosion; this report presents alternatives, such as living shorelines and green infrastructure. When planning long term infrastructure for 3.2 feet of sea level rise by mid-century1, the goal of living shorelines is to slow coastal erosion and reduce flooding so that coastal transportation ways can remain operational during the coming decades.

This primer provides a replicable methodology to identify relevant living shorelines and green infrastructure strategies for protection of various types of tropical island coastal built environments, illustrated through three following sites in Hawai‘i.

1. A recreationally significant rural coastal community location with one coastal road and high wave energy: Sunset Beach area on the North Shore of O‘ahu;
2. A current densely-developed coastal community and economic engine with moderate wave energy: Waikiki Beach on the South Shore of O‘ahu;
3. A future densely-developed Transit Oriented Development (TOD) rail station location with low wave energy: Waipahu at Pearl Harbor, O‘ahu.

The primer's replicable method includes the following steps.

1. Convey the characteristics and flood vulnerabilities at each prototypical site through maps, drawings, and physical models.
2. Proposes relevant living shorelines, green infrastructure, and selected gray infrastructure strategies.
3. Provide examples from existing literature on research, similar built precedents, and government policies to support the preliminary hypothesis that the strategy is relevant for the site.
4. Visualize how the strategy may be integrated into a prototypical site by creating new modified site maps, drawings, and physical models.

The living shoreline strategies explored in this primer include restoration of coastal sand dunes, vegetation (groundcover, shrubs, trees), and coral reefs. Green infrastructure strategies include widening floodways adjacent to rivers, temporary water detention, and stream/river bank elevation and stabilization. Gray infrastructure strategies discussed include T-head groins, underground cisterns, multi-use berms, or elevated walkways.

In addition, the architecture and planning students learn about coastal flooding and propose design scenarios through course work and research on this project. Selected student and junior associate researcher maps and drawings are included in this primer.

Data Management Plan

Data for this study is bibliographic in nature and can be found in the reference pages.

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