Design for Flooding:

Māpunapuna Industrial Park

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To my parents.

Mom, thank you for being my confidant and best friend. Now we can start traveling the world together like we planned!

Dad, you really are a wise man. Thank you for being my strength and teaching me confidence throughout the years.

I love you both dearly and cannot imagine getting here this far without your unconditional love and support. Thank you for giving me the push I needed when things got hard and cheers when they were great.

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ABSTRACT

Floods are one of the most hazardous natural disasters in Hawai‘i, largely due to the islands' dramatic landscapes and the proximity of urban development to the coastlines. Hawai‘i's vulnerability is also amplified because it is one of the most isolated places in the world and outside government emergency response may not be immediately available. Some current flood mitigation and adaptation measures include channelized and dammed streams, elevated structures, the use of flood-proof building materials, and statewide warning systems, all of which are conventional, engineering-focused, and monofunctional. These approaches alone are not well equipped to withstand severe flooding events and allow for post-disaster recovery. Because of Hawai‘i's isolation, its exposure to different types of flooding hazards, and its growing populations, future mitigation and adaptation strategies must be multi-functional, able to withstand severe flooding events while also addressing the needs of the communities.

This research provides an array of design strategies for enhancing Hawai‘i's resilience from future floods based on the works of Roger H. Charlier and Christian P. De Meyer, co-authors of *Coastal Erosion: Response and Management*, the United States Army Corps of Engineers (USACE), and the Environmental Protection Agency (EPA). Design precedents showcasing shoreline protection, floodable and floating architecture, stormwater management, and ecological restoration projects were analyzed; each incorporated specific design strategies into bold, holistic flood-responsive designs.

Phases of a conceptual, redeveloped master plan of Māpunapuna, an industrial district on O'ahu prone to flooding from rainfall, event-based surges from the ocean, and the effects of sea level rise, demonstrate the implementation of the selected design strategies and lessons taken from the research in order to enhance the district's resilience to future floods. Overall, the speculative final design is an example of an innovative, responsive design resilience to floods that can be explored in Hawai‘i and other coastal communities with similar conditions.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

Floods are a common natural hazard in Hawai‘i. Because of the islands’ dramatic landscapes, dense and growing coastal developments, and impacts of climate change, flood risks are increasing. However, despite numerous close calls with hurricanes and tsunamis, the state’s flood mitigation and adaptation measures are average at best. Urban areas and infrastructures do not reflect the importance of resilience. As design professionals, are we adequately addressing flood risk that properly reflects Hawai‘i’s geographical location and characteristics?

In Hawai‘i, current solutions for reducing flood risk include channeled and dammed streams, sea walls, ripraps, and insurance coverage for flood-compliant designed structures. These measures alone, however, do not effectively mitigate flood impacts. Furthermore, altering the natural landscape, as with modified streams, sea walls, and ripraps, in time, has adverse effects on the physical environment causing erosion, permanent loss of beaches, and the worsening of flood conditions. Moreover, providing flood insurance encourages residents to reside closer to the shores, thus increasing exposure to severe coastal inundation. Prior to the existence of dense urban development and the growing effects of climate change, the islands’ natural landscapes effectively processed floodwater through coastal wetlands, beaches, coral reefs, and inland vegetation. At the same time, these enhanced ecologies provided additional food and material resources.

To date, mitigation and adaptation flood-reduction measures usually translate into structural, engineered measures that are limited in scope. This research acknowledges that flood mitigation and adaptation measures can be successful if strategies are varied and represent a more holistic approach to flood mitigation. Thus, the purpose of this dissertation investigation is first to identify and develop design strategies that effectively address the multiple implications of flooding—physical, environmental, and socio-economic—and then to demonstrate their significance through a conceptual design proposal for Māpunapuna, Hawai‘i.

The dissertation is divided into two sections: research (chapters 2-4) and design (chapters 5-8).

Chapter 2 provides insight into the broad context of floods, examining conditions that lead to floods as a hazard and investigating causes, consequences, and existing flood mitigation and adaptation strategies. Chapter 3 examines flooding in the regional setting of Hawaiʻi, identifying common flood hazards and applied mitigation and adaptation strategies. Chapter 4 presents innovative design precedents that highlight features that relate to mitigation and adaptation design, including shoreline protection, floating architecture, floodable architecture, stormwater management control, and ecological restoration. Chapter 5 discusses design principles derived from the research portion and formulates an array of design strategies and measures for Hawaiʻi. Chapter 6 analyzes Māpunapuna's existing conditions and chapter 7 introduces the conceptual master plan. Speculative design interventions for Māpunapuna are divided into three phases following the timeline of sea level rise based on findings from the Climate Science Special Report. Finally, chapter 8, concludes the research and discusses the lessons learned through the process.

CHAPTER 2: FLOODS

The significance of this chapter is to understand the problem of floods, starting with defining the terminology and understanding what makes them a risk. Subsequently, the discussion shifts towards identifying the causes, consequences, and existing mitigation and adaptation strategies of floods. As coastal cities continue to grow, and the effects of climate change worsen, in particular sea level rise, current urban infrastructures are becoming increasingly more obsolete—stormwater and sewage systems are becoming overwhelmed during abnormally wet weather, coastal protective measures are becoming outmoded by more violent storms, and roads are becoming more susceptible to flooding during these events. Therefore, are existing urban infrastructures addressing future changes in the climate and will they be resilient to the effects in the future? Flooding is common throughout Hawai‘i, but these occurrences are gradually worsening due to rainfall combined with the effects of urban development and sea level rise.

2.1 Determining Floods as Hazards

The National Oceanic and Atmospheric Administration (NOAA) defines a flood as "any high flow, overflow, or inundation by water which *causes* or *threatens damage*," while the International Federation of Red Cross and Red Crescent Societies, the largest humanitarian association in the world, classifies floods as a hazard, or a "*threatening* event, or probability of occurrence of a *potentially damaging phenomenon* within a given time period and area" (emphases mine).[1,2] According to these definitions, a flood is understood as a hazard because of its potentially damaging impact on human settlements. In natural settings, however, ecosystems in flood-prone areas often adapt to inundation cycles. For example, most mangrove species are conditioned to be submerged with root growth systems that are dependent on local tide levels. Unlike vegetation that thrives in freshwater conditions, these species have also become accustomed to the salinity of the water.[3] Thus, the global perspective of flooding as a hazard is a human interpretation based on the measurable loss of socio-economic assets.[4]

Joern Aerts, author of *Climate Adaptation and Flood Risk in Coastal Cities*, suggests a flood hazard's outcome is influenced by many variables, including size and population of the affected area, flood category and frequency, quality of flood defense and control systems, as well as the community's ability to react.[5] Authors Keith Smith and Roy Ward, in their book

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[1] "Glossary - F," National Oceanic and Atmospheric Administration's National Weather Service, accessed December 3, 2017, http://w1.weather.gov/glossary/index.php?letter=f (emphasis mine).
[2] "Types of Disasters: Definition of Hazard," International Federation of Red Cross and Red Crescent Societies, accessed December 3, 2017, http://www.ifrc.org/en/what-we-do/disaster-management/about-disasters/definition-of-hazard/.
[3] "Adaptation of Mangrove Trees," NOAA Ocean Service Education, accessed December 3, 2017, https://oceanservice.noaa.gov/education/kits/estuaries/media/supp_estuar07d_mangrove.html.
[4] Keith Smith and R. C. Ward, Floods: Physical Processes and Human Impacts (Chichester ; New York: Wiley, 1998), 19.
[5] Jeroen C. J. H. Aerts, ed., Climate Adaptation and Flood Risk in Coastal Cities, Earthscan Climate (Abingdon, Oxon ; New York: Earthscan, 2012), 5.

Floods: Physical Processes and Human Impacts, discuss these variables and categorize them into two distinct groups: physical exposure—the characteristics of the flood—and human vulnerability—the affected socio-economic factors (Table 2.1).

Table 2.1 Physical exposure and human vulnerability factors

PHYSICAL EXPOSURE	HUMAN VULNERABILITY
• Flood category • Frequency	• Quality of flood defenses and control systems • Community awareness • Emergency response • Size of affected area • Population density

Source: Data from Smith and Ward 1998.

According to Smith and Ward, it is not the event alone that determines the result of a flood, but rather the balance between variables of physical exposure and human vulnerability. Figure 2.1 demonstrates the dynamics of the variable's relationship using the example of a river's flow. Hazard is represented where the flow crosses the damage threshold, above or below the band of tolerance of socio-economic factors. A rapid and steep increase in flow is interpreted as a flood and a sudden decrease, a drought. When applying such a comparison to a coastal location, however, a different interpretation may be required. Higher tide levels, exceeding the daily average, have the potential to inundate shoreline properties while lower tide levels can provide temporary amenities such as tide pools or greater beach coverage. In both scenarios, a steady flow within the band of tolerance can be perceived as a resource while an influx is a hazard.

Figure 2.1 Relationship between a river's flow and time.

Source: adapted from Keith and Ward [6]

Smith and Ward continue to explain that the relationship between physical exposure and human vulnerability has the potential to change over time. Figure 2.2 presents three different potential scenarios. In Figure 2.2a, the band of socio-economic tolerance remains continuous while the water flow steadily increases over time, surpassing the boundaries. The relationship in Figure 2.2a portrays the limitations of existing channel restrictions on the capacity of a body of water. Within the next diagram, Figure 2.2b, the band of socio-economic tolerance remains continuous while the water flow is constant but intensifies over time. The correlation displayed in Figure 2.2b depicts a change in the climate, such as heavier rains or an increase in storm activity. Lastly, Figure 2.2c shows a socio-economic band of tolerance that becomes narrower over time, while water flow remains constant. The narrowing of the socio-economic band of tolerance represents the risk of development on flood-prone areas.[7]

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[6] Smith and Ward, *Floods*, 20.
[7] Ibid.

Figure 2.2 Different circumstances of flooding.

Source: adapted from Smith and Ward[8]

This correlation is demonstrated in the example of the 2008 flood in Cedar Rapids, Iowa, the city's worst flood in recorded history, with crest levels measured at ten feet higher than the previous record peak of twenty feet in 1929.[9] An estimated 18,623 individuals were affected, and 5,390 residential properties damaged or destroyed. The June 2008 flood was catastrophic due to a combination of natural events leading up to it—winter snow amounts were greater than normal, significant flooding occurred during the preceding months including torrential rains in June, and, most importantly, the recovery time between events was insufficient.[10,11] The soil gradually became saturated and unable to retain water. In response, and in order to better prepare the community for future flood events, Cedar Rapids developed

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[8] Ibid., 21.
[9] "2008 Flood Review," National Weather Service, accessed December 3, 2017, https://www.weather.gov/dvn/flood2008_Overview.
[10] Ibid.
[11] "Midwest Floods of 2008 in Iowa and Wisconsin: Building Performance Observations, Recommendations, and Technical Guidance," accessed December 3, 2017, https://www.fema.gov/media-library-data/20130726-1722-25045-0903/fema_p_765.pdf.

a new master plan that included improvements such as updated evacuation methods and building codes, new flood maps, community cooperation procedures, and designation of appropriate areas of retreat. This master plan was designed to decrease potential flood hazards and increase the resilience of the community.[12]

2.2 Causes and Influences of Flooding

As summarized in the previous section, there were a number of circumstances combined to cause the 2008 Cedar Rapids floods. However, the primary cause was precipitation in the form of rain and snow. Throughout most parts of the world, rain is the primary source of flooding. While there are many other circumstances and variables that affect flooding events, this section addresses only those most relevant to the design application site, Māpunapuna. Rainfall is currently the primary source of flooding in Hawaiʻi. In the long term, sea level rise will also become a primary source of flooding in low-lying coastal areas, like Māpunapuna. Finally, the effects of urban development, especially in areas like Māpunapuna, encompass a range of influences that indirectly exacerbate flood conditions.

2.2.1 Rainfall

Rainfall is one of the leading causes of flooding throughout the world. Typically, a natural environment becomes flooded when soils and vegetation are oversaturated, and bodies of water begin to overflow their banks.[13] Event-based flooding, originating from hurricanes and tropical storm events, can contribute large amounts of rainfall to affected areas, as was the case in Texas during hurricane Harvey in August 2017. According to the National Weather

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[12] "2008 vs 2016 Floods," Iowa Flood Center, accessed December 3, 2017, http://iowafloodcenter.org/2008-vs-2016-floods/.

[13] Smith and Ward, *Floods*, 10-12.

Service (NWS), some areas in the southeast of Texas received as much as 40 inches of rain within 48 hours and Cedar Bayou, in Houston, received a total of 51.88 inches).[14] Large watershed areas, such as those across Texas, take time to efficiently drain. Thus, when large amounts of rain fall within a short period of time, this can be a problem, especially for urban areas that are unable to keep up with the drainage.

In Hawaiʻi, circumstances are similar, however with smaller and more dynamic watersheds. Most of the islands' watersheds begin at the top of the steep mountains and carry hundreds of inches of water rapidly down to the coastal regions (Figure 2.4). The smaller drainage areas of these watersheds result in periodic flooding. Due to the urbanization of several of the main islands, rainfall events, especially heavy ones, often lead to flash flooding with effects such as localized inundation, large quantities of sediment at confluences, and pollution. Local weather forecasts often caution viewers, especially those in vehicles, to be wary of inundated areas; vehicles can stall in floodwaters and even get carried away in swifter currents.

A study that examined heavy rainfall on the larger Hawaiian islands over a fifty year period reveals a statewide 27 percent decrease in frequency of high-intensity rain events but an overall increase in frequency of low-intensity rain events.[15,16] Another study, analyzing rainfall patterns over the past 60 years on the main islands, shows a decrease in intensity of rain activity on Oʻahu and Kauaʻi, an increase in intensity on the island of Hawaiʻi, and variable intensity on Maui.[17] The variability of rainfall patterns made apparent through these studies

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[14] National Weather Service, "Major Hurricane Harvey - August 25-29, 2017," National Weather Service, accessed December 8, 2017, http://www.weather.gov/crp/hurricane_harvey.
[15] O. Elison Timm et al., "Projection of Changes in the Frequency of Heavy Rain Events over Hawaii Based on Leading Pacific Climate Modes," *Journal of Geophysical Research: Atmospheres* 116, no. D4 (February 27, 2011): D04109, https://doi.org/10.1029/2010JD014923.
[16] Pao-Shin Chu, Ying Ruan Chen, and Thomas A. Schroeder, "Changes in Precipitation Extremes in the Hawaiian Islands in a Warming Climate," *Journal of Climate* 23, no. 18 (May 20, 2010): 4881-4900, https://doi.org/10.1175/2010JCLI3484.1.
[17] Ibid.

reflects the number of influences that affect the Central North Pacific (CNP) region, including topography, mid-latitude weather systems, storms and cyclones, El Nino-Southern Oscillation (ENSO), and Pacific Decadal Oscillation (PDO).[18]

Future projections are just as inconsistent depending on the methodologies applied. In "Climate Change in Hawaii: A summary of climate change and its impacts to Hawai'i's ecosystems and communities," the authors provide an explanation for the amount of uncertainty regarding calculating future rainfall conditions*:*

> Global climate and circulation computer models (GCMs), including those used by the Intergovernmental Panel on Climate Change and others, are often too geographically broad to resolve specific regions such as Hawai'i. Climate scientists simulate regional changes by adapting global models to smaller scales. Most experts in climate change science are cautious when asked to make regional predictions, especially on extended timescales into the future. Downscaling GCMs can bring the risk of enhancing any inherent weakness or errors of the parent model but they can also help resolve uncertainty in regions with complex topography, such as Hawai'i. These problems, however, do not make regional simulations worthless, as long as their limitations are understood.[19]

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[18] U.S Environmental Protection Agency, *Climate Change Indicators in the United States, 2016*, Fourth, 2016, https://www.epa.gov/sites/production/files/2016-08/documents/climate_indicators_2016.pdf.
[19] University of Hawaii at Manoa Sea Grant College Program, *Climate Change Impacts in Hawaii - A Summary of Climate Change and Its Impacts to Hawaii's Ecosystems and Communities*, 2014, 25.

Figure 2.3 Mean annual rainfall in the state of Hawaiʻi

Source: Rainfall Atlas of Hawaiʻi[20]

Figure 2.4 Heavy rains in the Koolaus result into intermittent water falls.

Source: Hawaiian Style Art[21]

[20]Thomas W. Giambelluca et al., "Online Rainfall Atlas of Hawaiʻl," *Bulletin of the American Meteorological Society* 94, no. 3 (March 2013): 313-16, https://doi.org/10.1175/BAMS-D-11-00228.1.

[21] *Koolau Waterfalls*, digital image, accessed March 29, 2018, https://www.etsy.com/listing/223521795/koolau-waterfalls?utm_source=OpenGraph&utm_medium=PageTools&utm_campaign=Share.

One report projects that, by the end of the twenty-first century, Maui and the island of Hawaiʻi will become wetter while Kauaʻi and Oʻahu will become slightly drier.[22] Another predicts that, while the southern shoreline of Oʻahu will experience an increased frequency rainfall through 2040, rain events will become less extreme.[23] A third analysis concludes that dry months will become wetter while normally wet winter months will become drier.[24,25] If these projections hold true, rainfall events in Māpunapuna may become less regular but more intense. Consideration of these predictions is crucial to the design component of the dissertation as conceptual designs will depend on present and future conditions of the site.

2.2.2 Urban Development

The effects of urbanization are significant to flood events. Smith and Ward argue "flood hazards are created by countless individual locational decisions which encourage the settlement and economic development of floodplains and flood-prone coastal areas." The development of flood-prone areas in more developed countries, for instance, may be influenced by benefits such as waterfront views, immediate access, and proximity to activities of leisure or commerce.[26] In most major coastal cities, coastal-based industries such as fisheries, tourism, and shipping, make up a significant portion of the city's GDP. However, more development results in more extraction of and alterations to the natural environment.

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[22] Victoria Keener, *Regional Climate Scenarios and Trends for the U.S. National Climate Assessment. Part 8: Climate of the Pacific Islands*, 2013.
[23] Chase W. Norton, Pao-Shin Chu, and Thomas A. Schroeder, "Projecting Changes in Future Heavy Rainfall Events for Oahu, Hawaii: A Statistical Downscaling Approach," *Journal of Geophysical Research: Atmospheres* 116, no. D17 (September 16, 2011): D17110, https://doi.org/10.1029/2011JD015641.
[24] Axel Lauer et al., "Downscaling of Climate Change in the Hawaii Region Using CMIP5 Results: On the Choice of the Forcing Fields," *Journal of Climate* 26, no. 24 (July 30, 2013): 10006–30, https://doi.org/10.1175/JCLI-D-13-00126.1.
[25] M. Takahashi et al., "High and Low Rainfall Events in Hawaiʻi in Relation to Large-Scale Climate Anomalies in the Pacific: Diagnostics and Future Projections," n.d.
[26] Smith and Ward, *Floods*, 26.

Critical components such as soils and vegetation are needed for water to drain correctly and to buffer impacts from surges.[27] With the alteration and removal of these systems, developments and populations become more vulnerable to natural hazards. While coastal residential properties, such as those in Hawai'i and Florida, are highly favorable due to the immediate access and views, flood risks also increase.

In less developed countries, reasons to settle in flood-prone areas are often more fundamental, such as agriculture. Vietnam, for instance, relies on inhabiting "alluvial river deltas and low-lying coastal plains" for its wet-rice farming.[28] These areas are susceptible to flood hazards but are also vital to the livelihood of numerous inhabitants. Other common causes of serious flood events in less developed countries include poor planning and lack of proper infrastructure maintenance provided by government entities.

2.2.3 Global Mean Sea Level

Sea level rise pertains to the increase in global mean sea level (GMSL) due to the increasing volume of the world's oceans. Sea level rise worsens coastal flood impacts; elevated sea levels allow high tides or surging waters to encroach further onto land while simultaneously elevating groundwater tables (Figure 2.5). Eventually, sea level rise will lead to permanent inundation, significantly affecting many coastal developments like Hawai'i (see discussion in section 3.5).

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[27] C.P Konrad, "Effects of Urban Development on Floods," U.S Geological Survey Publications Warehouse - USGS, accessed December 6, 2017, https://pubs.usgs.gov/fs/fs07603/.
[28] Smith and Ward, *Floods*, 29.

Figure 2.5 Coastal flooding exacerbated by sea level rise.

Source: NASA[29]

According to John A. Church and Neil J. White, the global mean sea level has increased by 8 to 9 inches since 1880, 3 inches of this occurring since 1993.[30] Similar findings were recorded in the U.S. Global Change Research Program's (USGCRP) recently updated Climate Science Special Report (CSSR) about "the state of science relating to climate change and its physical impacts."[31] The USGCRP documented an increase in global mean sea level of approximately 7 to 8 inches since 1900, "with about 3 of those inches occurring since 1993."[32] Both sets of findings indicate that global mean sea level increased at the greatest rate during the late twentieth century.[33]

The rapid development of sea level rise in the last century is the result of human-induced climate change. Large concentrations of greenhouse gas (GHG) emissions have

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[29] "New NASA Web Portal Shines Beacon on Rising Seas," NASA/JPL, accessed April 2, 2018, http://www.jpl.nasa.gov/news/news.php?feature=6254.
[30] John A. Church and Neil J. White, "Sea-Level Rise from the Late 19th to the Early 21st Century," *Surveys in Geophysics* 32, no. 4 (September 1, 2011): 585-602, https://doi.org/10.1007/s10712-011-9119-1.
[31] USGCRP, "Climate Science Special Report," accessed March 15, 2018, https://science2017.globalchange.gov/chapter/front-matter-about/.
[32] W.V. Sweet et al., "Ch. 12: Sea Level Rise. Climate Science Special Report: Fourth National Climate Assessment, Volume I" (U.S. Global Change Research Program, 2017), https://doi.org/10.7930/J0VM49F2.
[33] Robert E. Kopp et al., "Assessing New Jersey's Exposure to Sea-Level Rise and Coastal Storms: Report of the New Jersey Climate Adaptation Alliance Science and Technical Advisory Panel," 2016, https://doi.org/10.7282/T3ZP48CF.

accumulated in the atmosphere causing global mean surface temperatures to increase over time. Subsequently, warmer atmospheric temperatures melt glaciers and ice sheets adding volume to the ocean, and heat ocean temperatures causing seawater to become less dense and to expand.[34] Initially, these contributed equally to sea level rise; however, recent observations indicate "ice melt now contributes about twice the amount than that of thermal expansion." The Greenland and Antarctic glaciers and ice sheets are responsible for about 34 percent of the world's sea level rise.[35]

For coastal developments, sea level rise projections are important; they can predict which areas are at risk and approximately when coastal lands may be in jeopardy. The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) introduced four scenarios of GHG emissions called representative concentration pathways (RCPs) (Table 2.2). Each scenario simulates a timeframe where global annual GHG emissions reach a peak and then begin to decline. They range from RCP2.6, the least global annual GHG emission due to effective climate change mitigation efforts, to RCP8.5, the most severe output of global annual GHG emissions reflecting no attempt to mitigate climate change impacts.[36]

Sea level rise planning documents, such as the *Hawai'i Sea Level Rise Vulnerability Adaptability Report*, use the 3.2-foot rise forecast to assess the potential impacts of sea level rise.

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[34] *Climate Change Indicators in the United States, 2016*, 34.
[35] W. Sweet et al., "Global and Regional Sea Level Rise Scenarios for the United States," Report, 2017, USGS Publications Warehouse, http://pubs.er.usgs.gov/publication/70190256.
[36] Intergovernmental Panel on Climate Change, ed., "Introduction," in *Climate Change 2013 - The Physical Science Basis* (Cambridge: Cambridge University Press, 2014), 147-48, https://doi.org/10.1017/CBO9781107415324.007.

Table 2.2 Representative Concentration Pathway (RCP)

SCENARIO	INTERPRETATION
RCP2.6	Stringent mitigation scenario
RCP4.5	Immediate scenario
RCP6	Immediate scenario
RCP8.5	Business as usual

Source: Data from IPCC 2014.

Since the release of the AR5, climate science research has progressed, leading to the development of refined model projections of sea level rise scenarios. The CSSR published an update of global mean sea level rise projections for the United States, establishing six scenarios relative to 2000 (Table 2.3). Applied data originates from "19-year averages of GMSL centered at the identified year" and factors in the rate of melting of the glaciers and ice sheets.[37] Table 2.4 lists the six GMSL rise scenarios, comparing their probability of occurrence with those of the AR5 RCPs.

Table 2.3 GMSL rise scenarios in meters (feet) relative to 2000.

SCENARIO	2020	2030	2050	2100
Low	0.06 (0.2)	0.09 (0.3)	0.16 (0.5)	0.30 (1.0)
Intermediate-Low	0.08 (0.3)	0.13 (0.4)	0.24 (0.8)	0.50 (1.6)
Intermediate	0.10 (0.3)	0.16 (0.5)	0.34 (1.1)	1.0 (3.3)
Intermediate-High	0.10 (0.3)	0.19 (0.6)	0.44 (1.4)	1.5 (4.9)
High	0.11 (0.4)	0.21 (0.7)	0.54 (1.8)	2.0 (6.6)
Extreme	0.11 (0.4)	0.24 (0.8)	0.63 (2.1)	2.5 (8.2)

Source: Data from Doken, Fahey, Hibbard, Horton, Kopp. LeGrande, Maycock, Romanou, Stewart, Sweet, Wuebbles 2017.

[37] Sweet et al., "Ch. 12," 342-43.

Table 2.4 Interpretation of GMSL rise scenarios

SCENARIO	INTERPRETATION
Low	Continuing current rate of GMSL rise, as calculated since 1993 Low end of *very likely* range under RCP2.6
Intermediate-Low	Modest increase in rate Middle of *likely* range under RCP2.6 Low end of *likely* range under RCP4.5 Low end of *very likely* range under RCP8.5
Intermediate	High end of *very likely* range under RCP4.5 High end of *likely* range under RCP8.5 Middle of *likely* range under RCP4.5 when accounting for possible ice cliff instabilities
Intermediate-High	Slightly above high end of *very likely* range under RCP8.5 Middle of *likely* range under RCP8.5 when accounting for possible ice cliff instabilities
High	High end of *very likely* range under RCP8.5 when accounting for possible ice cliff instabilities
Extreme	Consistent with estimates of physically possible "worst case"

Source: Data from Doken, Fahey, Hibbard, Horton, Kopp. LeGrande, Maycock, Romanou, Stewart, Sweet, Wuebbles 2017.

The RCP scenario predictions fall well below the scenarios projected in the CSSR because AR5's maximum predicted scenario of 3.2 feet is used as the intermediate scenario in the CSSR. The CSSR indicates that a sea level rise of 8 feet is "physically plausible" by the end of the century. Nevertheless, there is a growing consensus within the scientific community that sea levels will continue to increase past 2100, no matter what course of action is taken in the interim, as the effects of climate change take centuries to mitigate[38]

Sea level rise is a global phenomenon, yet its impacts are not uniform. Some regions are affected more than others based on geographical conditions such as the landmass's uplift and subsidence, ocean currents, wind patterns, and gravitational pull. A study on the United States' coastlines from 1960 to 2015, reflects the variation of sea level rise at the regional scale. Locations along the Atlantic Ocean and the Gulf of Mexico have the highest rating of sea

[38] Sweet et al., "Ch. 12."

level change (6.01 inches—8 inches; >8 inches), while Pacific coastlines have a mixed range of declining sea levels (-8 inches—0 inches) and subtly increasing levels (0.01 inches—2 inches; 2.01 inches—4 inches; 4.01 inches—6 inches) (Figure 2.6).[39] This is also the case for Hawai‘i. Data recorded over the last century show an approximate increase of 5 to 6 inches on O‘ahu and Kaua‘i, 8 inches on Maui, and 12 inches on the island of Hawai‘i.[40] The variability here reflects the ages of the islands. O‘ahu and Kaua‘i are the oldest and have a more gradual rate of sea level rise while Hawai‘i, which is still growing due to volcanic activity, has the highest rate of rise.

Figure 2.6 Sea level rise rates in the U.S

Source: EPA[41]

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[39] *Climate Change Indicators in the United States, 2016*, 34.
[40] NOAA, “Tides & Currents,” accessed March 21, 2018, https://tidesandcurrents.noaa.gov/sltrends/sltrends.html.
[41] *Climate Change Indicators in the United States, 2016*, 35.

It may be difficult to understand the significance of a 3- to 8-foot rise in sea levels; however, sea level rise mapping tools, such as NOAA's Sea Level Rise Coastal Viewer, can provide hypothetical outlooks on the extent and impacts of sea level rise. Because Māpunapuna is in the lower coastal regions of Hawaiʻi, it is critical for the conceptual design to take into consideration increasing sea levels to ensure the community's resilience during future flooding events. The Sea Level Rise Coastal Viewer's highest parameter is currently 6 feet. Due to the mapping tool's parameters, the conceptual design will follow the CSSR's High scenario timeline forecasting a 6-foot sea level rise by 2100 (see discussion in chapter 7).

In the long run, sea level rise will intensify and irreversibly impact both manmade and natural environments. Numerous coastal cities, including those in Hawaiʻi, Florida, Maryland, New Jersey, and Virginia, are beginning to experience these effects. One of most common effects of sea level rise is the increased frequency of "sunny day" or tidal flooding, where "tides are exceptionally high in combination with high waves and/or other oceanic and atmospheric phenomena."[42] Properties, roads, and stormwater systems in lower coastal areas are most affected. The following list, compiled by the University of Hawaiʻi's School of Ocean and Earth Science and Technology, details additional impacts of sea level rise (emphases mine):

- Inundation – SLR may cause increased wave over-topping, tsunami inundation, and hurricane storm surge with negative impacts to low-lying environments, ecosystems, and developed areas including roads and communities.

- Erosion – SLR may lead to changes in coastal sediment transport and storage resulting in erosion of beaches, dunes, bluffs, estuarine shorelines, and tidal wetlands. Fine sediment released by erosion may impact coastal water quality, and combined with ocean acidification and warming cause negative impacts to reefs.

[42] Hawai'i Climate Change Mitigation and Adaptation Commission, "Sea Level Rise Vulnerability and Adaptation Report," n.d., 23.

- Salt Intrusion – SLR may cause salt intrusion into aquatic ecosystems, wetlands, low-land agriculture (taro, loʻi and rice), and coastal plain groundwater systems.

- Drainage Problems - SLR may raise the groundwater table leading to increased flooding, poor drainage, and storm damage where rainfall and high ocean levels converge.

- Community Displacement and Cultural Heritage - Threats to traditional lifestyles of indigenous communities in the region (including destruction of coastal artifacts and structures, reduced availability of traditional food sources and subsistence fisheries, and the loss of the land base that supports Pacific Island cultures) will make it increasingly difficult for Pacific Island cultures to sustain their connection with a defined place and their unique set of customs, beliefs, and languages.[43]

2.3 Consequences

Floods can have many damaging effects on a community and its built environment. Smith and Ward, in *Floods Physical Processes and Human Impacts*, organize flood-related losses into two groups: direct and indirect; each group has four subcategories: tangible, intangible, primary, and secondary (Figure 2.7).[44] Direct losses refer to damages that occur during and immediately after the event, while indirect losses refer to those that develop over time. Tangible and intangible losses refer to socio-economic damages. Tangible losses involve the potential loss of economic value, while intangible losses focus on the potential repercussions on human populations. Primary and secondary losses deal with the sources of the losses. Primary losses originate from the event itself, while secondary losses encompass those that are "at least one causal step removed from the flood."[45]

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[43] http://www.soest.hawaii.edu/coasts/sealevel/index.html University of Hawaii at Manoa School of Ocean and Earth Science and Technology, "Sea Level Rise," *Sea Level Rise* (blog), October 28, 2017, http://www.soest.hawaii.edu/coasts/sealevel/index.html.
[44] Smith and Ward, *Floods*, 34.
[45] Ibid.

[46] Ibid., 15.

Figure 2.7 Flood loss categories

Source: adapted from Smith and Ward[46]

[46] Ibid., 15.

2.3.1 Direct Losses

Direct losses, the most recognizable form of flood loss, comprise the physical outcomes on a property or person. Damages inflicted on properties, whether from the force of the floodwaters or the period of inundation, are considered primary tangible losses. The level of investment and development to a property determines its potential physical damage value. For example, the buildings throughout Waikiki have a high level of potential tangible loss due to the density of the area and amount of Gross State Product (GSP) generated for the state of Hawaiʻi; during 2002, about 8 percent (roughly $3.6 billion) of the state's GSP originated from Waikiki alone.[47] Similarly, in rural areas, farmland properties have a high level of potential tangible loss because of the financial value of crops, livestock, equipment, and critical agricultural infrastructures. Damage could incur both loss of investment and unfavorable decline in future yields.[48]

Secondary tangible losses pertain to the recovery efforts of the event. Reconstruction can be costly and prolonged due to a high demand for materials and workers, lack of resources, and decrease in property value. However, this type of loss can be may prevented or minimized through encouragement of public interest and procurement of financial support for rebuilding.

Primary intangible losses concern the number of fatalities, or mortality rate, of a flood event.[49] According to the United Nations Office for Disaster Risk Reduction and the Center for Research of the Epidemiology of Disasters (CRED) in their report, *The Human Cost of Weather Related Disasters, 1995-2015*, floods were responsible for the third highest number disaster-related deaths worldwide between 1995 and 2015, after storms and extreme temperatures.

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[47] Department of Business, Economic Development & Tourism, "The Economic Contribution of Waikiki," Debedt E-Reports, 2003, http://files.hawaii.gov/dbedt/economic/data_reports/e-reports/econ_waikiki.pdf.
[48] Smith and Ward, *Floods*, 45.
[49] Ibid., 47.

Because the report is an overview, however, the precise causes of death and details of the unique global events were not provided.

Dr. Jean French presented a study on flash flood mortality rates in the United States occurring between 1969 and 1998.[50] He compiled data from 16 survey reports and identified five causes of flood-related deaths: drowning, trauma, heart attack, electrocution, and burial in mud (Table 2.5Table 2.5 Circumstances of flash flood-related deaths, U.S, 1969-1981). Drownings were responsible for 93 percent of the fatalities, which primarily occurred to those swept directly into water or to those caught in trapped or submerged vehicles.

Injuries and illnesses related to floods are considered secondary intangible losses.[51] Injuries, obtained from debris carried by floodwaters or during evacuation, can be as minor as a sprain or as severe as a puncture wound. Illnesses emerge during the aftermath, often originating from viral and bacteria infested from poor water quality. Floods can overwhelm water infrastructures, causing the overflow of pollution, exposing survivors to infectious bacteria. Existing literature indicates that flood-related epidemiological outbreaks primarily occur in countries where water and sanitation systems are not well maintained. Unlike water-borne diseases, mental health disorders caused by flood-related trauma are well-documented. The amount of stress-related illnesses flood survivors experience is vast. One of the most common disorders, especially for younger flood survivors, is post-traumatic stress disorder (PTSD).[52]

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[50] J French et al., "Mortality from Flash Floods: A Review of National Weather Service Reports, 1969-81.," *Public Health Reports* 98, no. 6 (1983): 584-88.
[51] Smith and Ward, *Floods*, 47.
[52] Sarb Johal and Zoe Mounsey, "A Research-Based Primer on the Potential Psychosocial Impacts Offlooding," *Disaster and Prevention and Management* 25, no. 1 (2016): 104-10.

Table 2.5 Circumstances of flash flood-related deaths, U.S, 1969-1981

CIRCUMSTANCES OF DEATH	NUMBER	PERCENTAGE
Drownings	177	93
Car-related	80	46
Swept into water (in home, at campsite or when crossing bridge)	81	46
Rafting or sailing	4	2
Stormwater	2	1
During evacuation (not involving car)	4	2
Performance rescue	6	3
Trauma	2	1
Heart Attack	7	4
Electrocution	2	1
Buried in mud	2	1
Total	100	100

Source: Data from Doken, Fahey, Hibbard, Horton, Kopp. LeGrande, Maycock, Romanou, Stewart, Sweet, Wuebbles 2017.

2.3.2 Indirect Losses

Indirect losses, in contrast to direct losses, develop and become evident over time. Primary tangible losses here refer to the "disruption of economic and social activities, especially in urban areas, immediately after a flood."[53] For instance, inundated or damaged roads, airports, and ports may prohibit businesses to resume their daily activities, which may in the long run delay income. Damage to infrastructures is a critical component of this loss category. In agricultural communities, the consequences are similar; delays or interruptions in annual yields may diminish profit in the long term.

Secondary tangible losses refer to the "long-term effects of floods." Different from the previous category of loss, this focuses on the effects of altered spending habits of flooded

[53] Smith and Ward, *Floods*, 51.

communities, which may change due to property loss, financial damages, and reconstruction costs. Over time, these changes can negatively affect an area's economy, especially problematic for communities dependent on retail and tourism.[54]

According to Smith and Ward, "indirect intangible losses are the most difficult of all to identify… partly because they are bound up with the traditional adjustment strategies adopted by people regularly exposed to flood hazard."[55] For instance, those who live in areas frequently affected by floods may lower their standards of living in order to minimize potential losses. Victims may show greater acceptance of the loss of property and belongings. These individuals may not feel as much shock and may be less burdened by the stresses of recovery than those who experience greater losses. Another form of indirect intangible loss is extensive out-migration after an event. Survivors that can afford to may relocate for greater security and stability, leaving behind those who lack resources or courage to move. For example, only about 47 percent of the population of New Orleans returned after Hurricane Katrina (Figure 2.8).[56]

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[54] Ibid.
[55] Ibid., 53.
[56] Narayan Sastry and Jesse Gregory, "The Location of Displaced New Orleans Residents in the Year After Hurricane Katrina," *Demography* 51, no. 3 (June 2014): 753-75, https://doi.org/10.1007/s13524-014-0284-y.

Figure 2.8 Population displacement in following the aftermath of hurricane Katrina.

Source: The New York Times[57]

[57] The New York Times, ***Katrina's Diaspora***, digital image, accessed December 6, 2017, http://graphics8.nytimes.com/images/2005/10/02/national/nationalspecial/02diaspora_graphic.gif.

2.4 Adaptation and Mitigation Strategies

Flooding has been a part of the human experience since the earliest documented settlements. For instance, in the third millennium in ancient China, a system of dikes and channels were constructed to tame the floodwaters of the Yellow River, now called Huang He.[58] Over the next millennia, many more dikes and channels were built and were largely successful in regulating floodwaters and permitting life to thrive along the river. However, through a combination of overuse, neglect, and deteriorating soil conditions exacerbated by several years of harsh weather ending with a succession of big storms, the system failed in 1931. This event was known as China's Sorrow; fatalities were estimated to reach 2 million, while about 52 million people were affected.[59] In another example, the development of New Orleans into one of the United States' largest port cities was highly dependent on a series of levees constructed by the United States Army Corps of Engineers (USACE) beginning in 1928. This system, however, did not prove lasting. Past flooding events, which demonstrated system failures, were often overlooked, and in 2005, the levees and sea walls in and around New Orleans failed against the effects of Hurricane Katrina. About 80 percent of the city was inundated with floodwaters from the extended period of heavy rainfall and the storm surge.[60] In New Orleans' case, the prime reason for levee and sea wall failure was largely due a system failure as a sum of the levees were incomplete

Flood control measures are not a permanent solution. Various factors change over time and as mentioned in section 2.1, the balance between physical exposure and human vulnerability determines the outcome and frequency of the hazard. In both examples above, shifts in the climate and deteriorating soil conditions were not accounted for during the

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[58] John Withington, *Flood* (London: Reaktion Books, 2013), 20-25.
[59] Arthur De C. Sowerby, "China's Sorrow," The China Story, accessed November 15, 2017, https://www.thechinastory.org/ritp/chinas-sorrow/.
[60] "Hurricane Katrina," History, accessed December 6, 2017, http://www.history.com/topics/hurricane-katrina.

original implementation of the structures, thus intensifying the magnitude of these unprecedented events.

This section briefly describes the benefits and drawbacks of the flood mitigation and adaptation strategies of retreat, protection, accommodation, and green stormwater infrastructures. Each strategy was analyzed through the lens of selected precedents to demonstrate their potential for addressing different flooding scenarios. The terminology derives from *Coastal Erosion: Response and Management*, by Roger H. Charlier and Christian P De Meyer, the USACE's "Coastal Risk Reduction and Resilience", and work published by the Environmental Protection Agency (EPA).

2.4.1 Retreat

The first category of mitigation and adaptation strategies is retreat, which can be understood as "abandonment in vulnerable areas and resettlement of inhabitants."[61] There are three measures of retreat, each of which reflects a different level of involvement from the government and different development limitations (Table 2.6).

The first measure involves the largest scale of action and involvement from the government. The government prevents any future development in vulnerable areas via: purchasing lands, enforcing land use restrictions, avoiding redevelopment in regions affected by past natural disaster events, or reducing incentives for developing in sensitive zones. At this scale of resettlement, affected inhabitants must be compensated. Several countries (i.e., India and the United States) carry out this form of retreat by transforming vulnerable lands into nature reserves or establishing considerable setbacks for future developments.[62] Overall, this

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[61] Roger Henri Charlier and Christian P. de Meyer, *Coastal Erosion: Response and Management*, Lecture Notes in Earth Sciences 70 (Berlin ; New York: Springer, 1998), 22.
[62] Ibid.

measure strives to create buffer zones along coastal areas of development to make them more resilient in the long term.

The second measure offers developers some control and slightly limits the government's role. Developers are aware of the risks and uncertainties of building in vulnerable areas and accept that abandonment will eventually occur. According to Charlier and De Meyer, this measure of retreat is executed through "regulations that prohibit private construction of protective structures" and "conversion of land ownership to long-term or conditional leases, which expire when the sea reaches a particular level or when the property owner dies."[63] This is best understood as a planned phase-out and is the most accommodating measure for all parties involved.

The last measure has some similarities with the previous two measures but restricts the government's involvement to the "withdrawal of subsidies and provision of information about associated risks."[64] Private owners are left with the choice and details of retreat. However, abandonment will eventually be required as natural resources become depleted and residents are frequently flooded.

Overall, retreat allows ecological systems to reestablish on the coast over time, thus developing into a natural buffer from hazards. However, this strategy can create perceived economic, social, and cultural disadvantages for the affected area. Retreat drawbacks include: potential removal of culturally significant sites and traditional environments, abrupt changes of lifestyle to inhabitants, and limited future growth. For areas with a smaller landmass, such as island-communities, these effects are more taxing.[65]

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[63] Ibid., 23.
[64] Ibid.
[65] Ibid., 26, 30, 35.

Table 2.6 Retreat Measures

MEASURE	DESCRIPTION	BENEFITS	DRAWBACKS
Full Governmental Control	Involves land acquisition, enforcing land use restrictions and prohibiting future redevelopment in post-disaster or flood-prone areas.	• Full control of hazard mitigation. • Promotes conservation lands. • Becomes buffers zones for vulnerable settlements.	• Providing large amounts of compensation for affected settlements (largely based on the government's financial standing and current policies).
Equal Government and Private Control	Allows developers to remain on land through long-term or conditional leases. Developers are unable to initiate private constructions of protective structures. Both parties are aware retreat will required over time.	• Gives time for both parties to plan accordingly.	• Properties and individuals are still at risk of the flood hazard.
Full Private Control	Private owners decide if retreat is required. Government power is limited to providing subsidies and information about associated risks.	• Private owners have full control.	• Settlements are still at risk of hazards. • May not be able to be compensated by government due to lack of funds or change of insurance policies.

Source: Data from Charlier, and De Meyer 1998.

Precedent #1: Louisiana's Comprehensive Master Plan for a Sustainable Coast

Some of the initiatives in the *Louisiana's Comprehensive Master Plan for a Sustainable Coast* report demonstrate the application of retreat. The master plan was developed after Hurricanes Katrina and Rita in 2005. According to the master plan's executive summary report, the "Louisiana Legislature established CPRA [Coastal Protection and Restoration Authority] and set in motion the creation of a comprehensive master plan for the coast that would be updated every five years with the best available information and a fiscal annual plan that details the funding and implementation schedules for the project."[66] The first plan was approved in 2007 and further refined in 2012. Since the plan's execution, about 135 projects have either been completed or funded for construction.[67] Overall, the 2017 Coastal Master Plan aims to respond to the loss of coastal lands and threats originating from storm surge events through projects that either build or maintain land and reduce risks to communities.[68] A total of 124 projects are included in the 2017 master plan—79 restorations, 13 structural protection projects, and 32 nonstructural risk reductions—which are together expected to reduce damage by $8.3 billion annually over the next 50 years.[69]

In this case, retreat is categorized as a nonstructural risk reduction project which seeks to "elevate and flood proof buildings and help property owners prepare for flooding or move out of areas of high flood risk."[70] With properties destroyed, the government saw an opportunity to regulate development in vulnerable areas. Mapping and the analysis of land change and flood depths were critical tools for this precedent for determining flood-prone areas throughout Louisiana. Land acquisition was determined for properties prone to 100-year flood depths greater than 14 feet and approximately 2,400 voluntary acquisitions of such properties were made. Out of the three measures of retreat detailed in this section, full governmental control has been implemented in this case due to the severe risks involved in developing on flood-prone lands and the opportunity to create potential buffer areas for future redevelopment.

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[66] Coastal Protection and Restoration Authority, *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (Baton Rouge: OTS-State Printing, 2017), 2, http://coastal.la.gov/wp-content/uploads/2017/04/2017-Coastal-Master-Plan_Web-Book_CFinal-with-Effective-Date-06092017.pdf.
[67] Ibid., 14.
[68] Ibid., 2.
[69] Ibid., 15.
[70] Ibid.

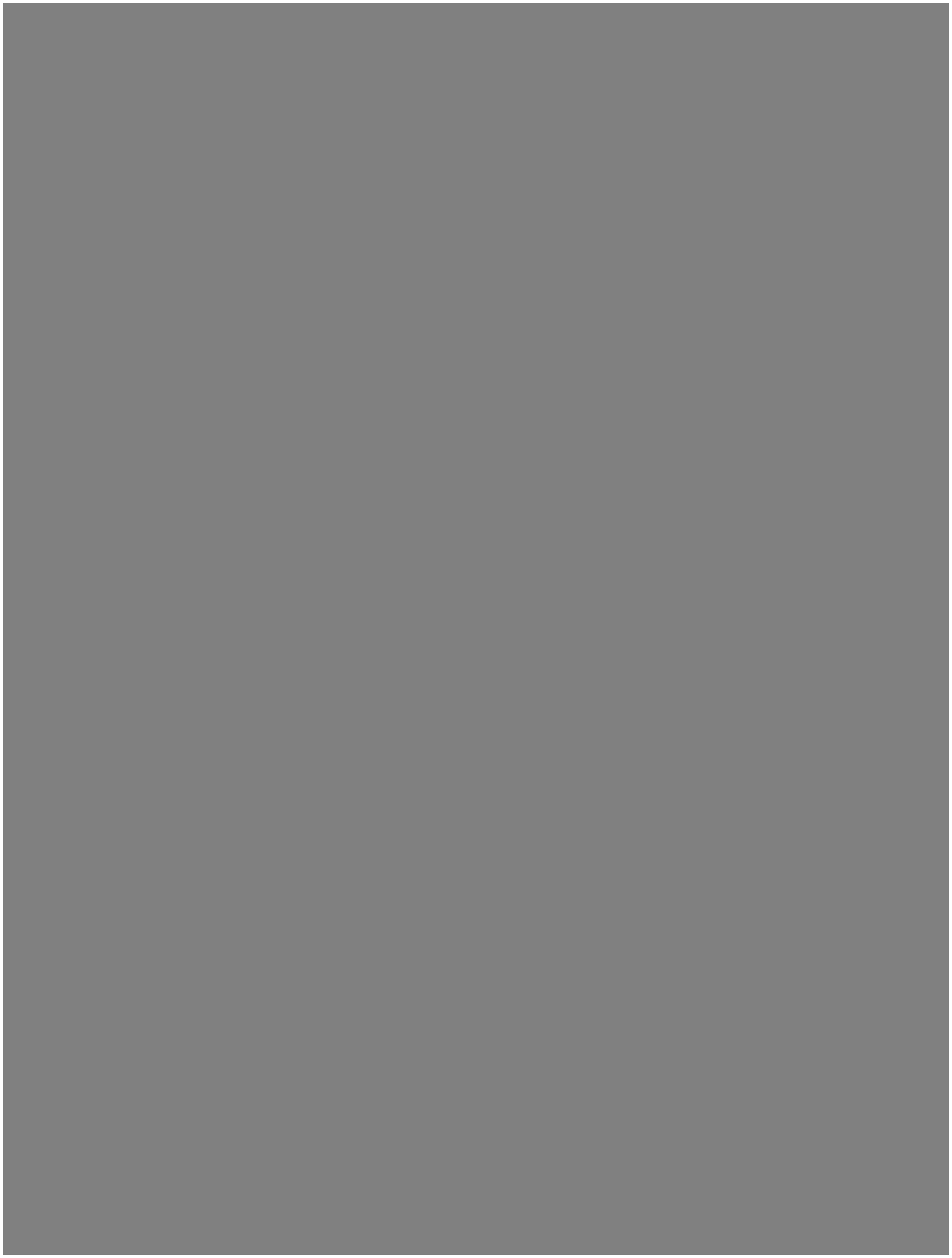

Figure 2.9: Coastal Master Plan and mapping analysis
Source: Louisiana's Comprehensive Master Plan for a Sustainable Coast

2.4.2 Protection

Protection, another mitigation and adaptive response strategy, involves the "defense of vulnerable areas, especially population centers, economic activities and natural resources."[72] This strategy primarily addresses the treatment of the threshold between the land and water. There are two types of protection structural measures, hard and soft. Charlier and De Meyer write that the benefits of protection include the prevention of "physical damage to property as a result of waves and flooding"; "loss of [economic] production and income"; "land loss through erosion"; and "loss of natural resources (environmental and recreational)."[73] When considering protection measures, it is best to remember that there is no standard solution, each site requires different approaches, and the effects of protection extend beyond the focus area and may be adverse.

Hard structural measures are human-made, engineered technologies designed to "decrease shoreline erosion or reduce coastal risks associated with wave damage and flooding."[74] Commonly used structures: dikes, levees, seawalls, revetments, groins, and nearshore breakwaters (Table 2.7).[75] While these measures can decrease the impacts of flood hazards, they are often misused. Adverse effects of incorrect implementation of hard structures can affect not only the immediate environment but also the vicinity.[76] For example, seawalls along shoreline properties have been proven to cause the deterioration of natural beaches. Waves reflecting off the wall cause the seabed to dissipate over time, thus increasing the wave and flood risk for nearby properties.[77]

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[72] Charlier and Meyer, *Coastal Erosion*, 25.
[73] Charlier and Meyer, *Coastal Erosion*.
[74] US Army Corps of Engineers, *Coastal Risk Reduction and Resilience* (Washington, DC: Directorate of Civil Works, 2013), 6.
[75] Ibid.
[76] Charlier and Meyer, *Coastal Erosion*, 27.
[77] Charles H. Fletcher, ed., Living on the Shores of Hawai'i: Natural Hazards, the Environment, and Our Communities (Honolulu: University of Hawai'i Press, 2010).

Soft structural measures replicate natural features and generally provide more benefits than hard structures (Table 2.8). USACE identifies two sub-categories of soft structural measures: natural and nature-based features.[78] Natural features are the result of natural processes over time.[79] For example, beaches are created when more sediment is deposited than swept away by waves. When the opposite occurs, the beach erodes.[80] Nature-based features have similar characteristics, but the process is engineered. Measures of this type require continuous maintenance to preserve intended use. For instance, several man-made beaches around the world are built to stimulate local economies, but they also serve as buffer zones from flooding.[81]

Between the two types of protection measures, soft structures offer the most benefits while addressing flooding and other coastal hazards. They can simultaneously enhance existing ecologies and provide public amenities. As illustrated in the example of beach formation, natural and nature-based features are dynamic systems due to the influences of external forces (e.g., storm-generated winds and waves). Those same forces can also cause permanent erosion, removing important natural environments along coastal zones. On the other hand, hard structures are just as useful, but require more preparation and studies to avoid any future costs. Overall, for both to perform effectively, regular maintenance is essential.

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[78] *Coastal Risk Reduction and Resilience*, 2.
[79] Ibid., 2-3.
[80] USGS, "Building Beaches," Geology and Geophysics, accessed December 6, 2017, https://geomaps.wr.usgs.gov/parks/sea/beach1.html.
[81] *Coastal Risk Reduction and Resilience*, 4.

Table 2.7 Protection - Hard Structural Measures

MEASURE	DESCRIPTION	BENEFITS	DRAWBACKS
Dike, levee, floodwall	Raised embankments or walls constructed for flood protection purposes. Internal drainage may be accomplished by gravity flow, tide gates, or pumping system.	• Wave and surge attenuation • Reduces flooding	• Requires regular maintenance and strengthening • Construction costs for advanced designs.
Storm Surge Barrier	Fixed installations that allow water to pass in normal conditions and have gates or bulkheads that can be closed against storm surges or spring tides to prevent flooding.	• Wave and surge attenuation • Reduced salinity intrusion • Harbor protection and associated economic risk reduction	• Construction costs • Time needed to close barriers • Technical failure • Environmental impacts
Seawall, revet-ment, bulkhead	Protects inland properties from the effects of waves and storm tides. Typically constructed along open coast areas to defend against wave attack.	• Reduces flooding • Reduces wave overtopping • Shoreline stabilization behind structure	• Wave reflectors, causing erosion to beaches.
Groin	Structures placed perpendicular to the shoreline; extends from the land into the shore zone to trap sediment moving along the shore.	• Shoreline stabilization. • Coastal erosion reduction with groin field.	• Disrupts natural processes and public access along upper beach. • Likely to cause downdrift erosion if beach is not managed.
Break water	Structures placed offshore and parallel to the shoreline.	• Shoreline stabilization behind structure • Wave attenuation • Harbor protection and associated economic risk reduction	• Environmental impacts • Construction costs

Sources: Data from “Adaptation or Improvement of Dikes and Dams — Climate-ADAPT,” accessed March 16, 2018, http://climate-adapt.eea.europa.eu/metadata/adaptation-options/adaptation-or-improvement-of-dikes-and-dams.; “Storm Surge Gates / Flood Barriers — Climate-ADAPT,” accessed March 16, 2018, http://climate-adapt.eea.europa.eu/metadata/adaptation-options/storm-surge-gates-flood-barriers.

Table 2.8 Protection - Soft Structural Measures

MEASURE	DESCRIPTION	BENEFITS	DRAWBACKS
Seagrass Bed	Flowering plants that carry out their entire lifestyles underwater. Typically found in shallow salty and brackish waters.	• Promotes habitats • Regulates water quality • Potential amenity relating to tourism, recreation and education. • Wave attenuation	• Vulnerable to waves and storms. • Vulnerable to boat anchors and propellers. • Vulnerable to increasing ocean temperatures. • Vulnerable to ocean acidification, sea level rise.
Coral Reef	Large underwater structures composed of the skeletons of coral, which are marine invertebrate animals.	• Promotes habitats • Wave attenuation • Sediment retention • Potential amenity relating to tourism, recreation and education.	• Vulnerable to increasing ocean temperatures. • Vulnerable to ocean acidification, sea level rise. • Vulnerable to boat anchors and propellers.
Oyster Reef	Common submerged habitats which typically grow near estuarine river mouths where waters are brackish and less than 10 meters deep.	• Promotes habitats • Wave attenuation • Sediment retention • Potential amenity relating to tourism, recreation and education.	• Vulnerable to waves and storms. • Vulnerable to boat anchors and propellers. • Vulnerable to increasing ocean temperatures, sea level rise. • Vulnerable to ocean acidification.

MEASURE	DESCRIPTION	BENEFITS	DRAWBACKS
Salt Marsh	Coastal wetlands that are flooded and drained by salt water brought in by the tides. They are marshy because of the soil may be composed of deep mud and peat.	• Promotes habitats • Wave attenuation • Sediment retention • Raw material provision. • Potential amenity relating to tourism, recreation and education.	• Vulnerable to waves and storms. • Vulnerable to lateral erosion, sea level rise.
Barrier Island	Long, relatively narrow islands that run along a coast parallel to the mainland.	• Promotes habitats • Wave attenuation • Sediment retention • Raw material provision • Potential amenity relating to tourism, recreation and education.	• Constantly changing and heavily influenced by urban development.
Beach	Narrow, sloping strip of land that lies along the edge of an ocean, lake or, or river. Sand, pebbles, rocks, and seashell fragments cover beaches.	• Promotes habitats • Wave attenuation • Sediment retention • Raw material provision. • Potential amenity relating to tourism, recreation and education.	• Vulnerable to erosion • Constantly changing and heavily influenced by urban development.

MEASURE	DESCRIPTION	BENEFITS	DRAWBACKS
Dune	Accumulation of sand grains shaped into a mound or ridge by the wind under the influence of gravity.	• Promotes habitats • Wave • Attenuation • Raw material provision • Storage and filtration of water through sand. • Potential amenity relating to tourism, recreation and education.	• Vulnerable to erosion without dune grasses. • Vulnerable to urban development.
Freshwater Wetland	Non-tidal systems dominated by grasses, sedges and other emergent species. Typically, are non-forested and have non-peat soils. They are periodically or continually flooded.	• Detention of surface water runoff from surrounding areas. • Infiltration of floodwater followed by percolation to aquifer. • Sediment retention • Short- and long-term storage of overbank floodwater.	• Vulnerable to urban development. • Vulnerable to sea level rise. • Vulnerable to increasing ocean temperatures. • Vulnerable to ocean acidification. • Influenced by changes in hydrology.

Sources: Data from "Barrier Islands," Hurricanes, Carleton College SERC, accessed March 16, 2018, https://serc.carleton.edu/hazards/hurricanes/barrier_islands.html;"Florida Wetlands: Freshwater Marshes," University of Florida, IFAS Extension, accessed March 16, 2018, https://soils.ifas.ufl.edu/wetlandextension/types/marsh.htm; Pamela L. Reynolds, "Seagrass and Seagrass Beds," Ocean Portal, Smithsonian, accessed February 27, 2013, http://ocean.si.edu/seagrass-and-seagrass-beds; "Beach," National Geographic Society, accessed December 7, 2012, http://www.nationalgeographic.org/encyclopedia/beach/; "What Is a Salt Marsh?," NOAA, US Department of Commerce, accessed March 16, 2018, https://oceanservice.noaa.gov/facts/saltmarsh.html; "Sand Dune," Encyclopedia Britannica, accessed March 16, 2018, https://www.britannica.com/science/sand-dune; "What Are Coral Reefs? Coral Facts," Live Science, accessed March 16, 2018, https://www.livescience.com/40276-coral-reefs.html.

Precedent #2: A Stronger More Resilient New York

New York City, along with other east coast settlements in the United States, Canada and the Bahamas, was severely damaged by Hurricane Sandy in 2012. Following the event, *A Stronger More Resilient New York*, a comprehensive plan of actionable recommendations, was released to the public. Chapter 1 begins with a list of damages incurred during the storm including "43 deaths… 6,500 patients evacuated from hospitals and nursing homes… 90,000 buildings within the inundation zone… 1.1 million New York City children unable to attend school for a week… close to 2 million people without power… 11 million travelers affected daily… $19 billion in damage."[82] The document includes numerous mitigation and adaptation strategies designed to improve the city's resilience during future disasters.

Because the storm surge was one of the most damaging features of the event, the report strongly focuses on enhancing New York City's coasts through the implementation of various protection measures. The Comprehensive Coastal Protection Plan is a city-wide master plan of full-build recommendations encompassing three of four coastal strategies laid out in *A Stronger More Resilient New York*: (1) increase coastal edge via beach nourishment, revetments, bulkheads, and tide gates and other drainage devices; (2) minimize upland wave zones with dunes, offshore breakwaters, wetlands, reefs, living shorelines, and groins;, (3) protect against storm surge through integrated flood protection systems, floodwalls, levees, local storm surge barriers, and multi-purpose levees.[83] Proposed protection measures are not only based on the site's conditions, but also related to historic protection measures that once existed along the site's coasts. For instance, natural beaches, dunes, and oyster reefs.

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[82] *A Stronger More Resilient New York*, n.d., 11, http://s-media.nyc.gov/agencies/sirr/SIRR_singles_Hi_res.pdf.
[83] Ibid., 46.

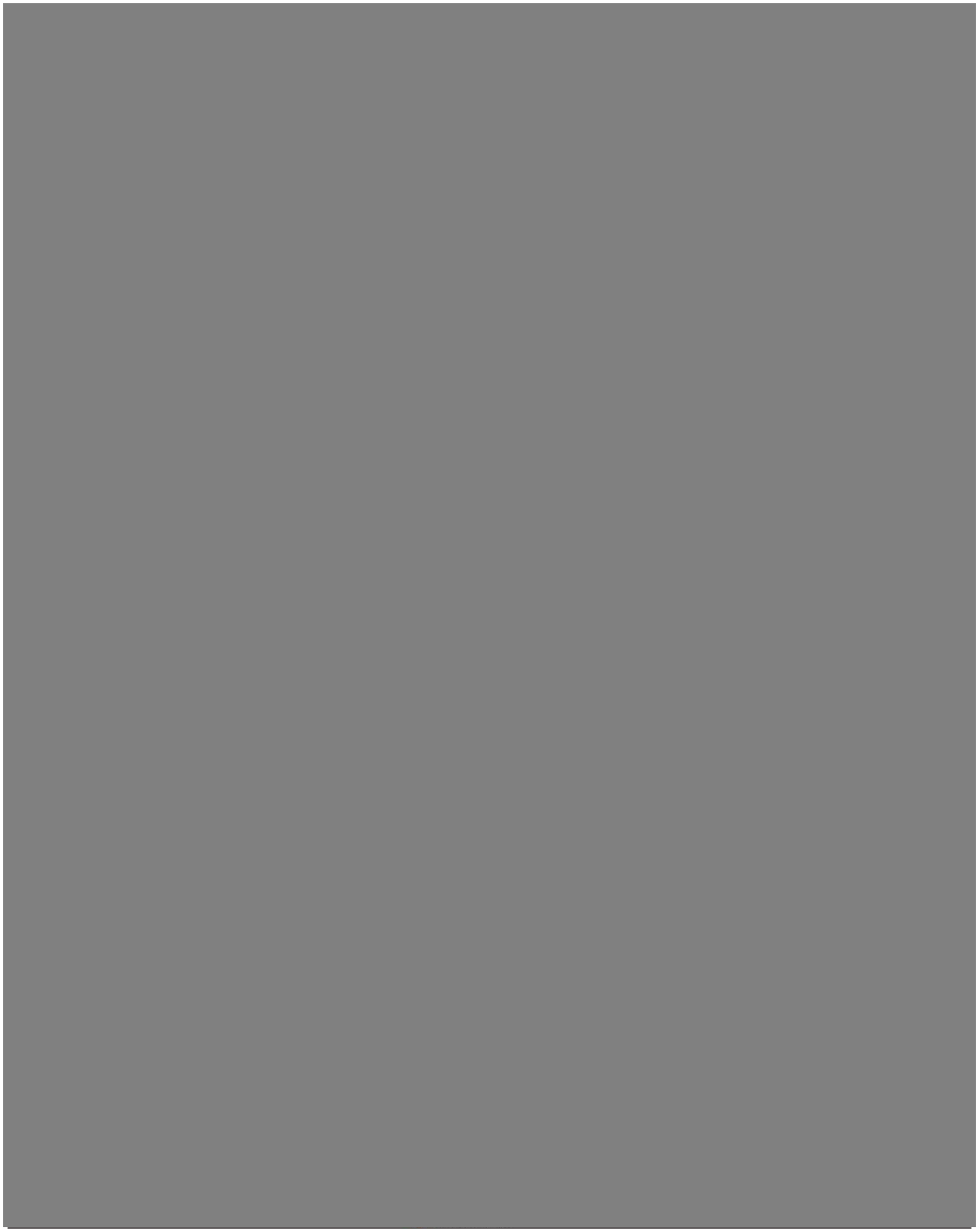

Figure 2.10: Comprehensive Coastal Protection Plan - Full-build recommendations
Source: Stronger More Resilient New York

2.4.3 Accommodation

Accommodation is the "continued occupancy and use of vulnerable areas."[85] This strategy falls somewhere between retreat and protection. Unlike the previously mentioned strategies, accommodation focuses on partial policy and structural alternatives (Table 2.9). Measures under this category are relatively feasible and allow adaptability during hazardous events.

The first couple of accommodation measures involve structural adjustments. For instance, elevating structures and infrastructures is a common practice throughout the world. By raising properties up from flood prone areas, impacts are likely to decrease, and daily activities can continue with minimal interruptions. Flood proofing is another type of structural alternative and has two methods, dry and wet. As the term implies, dry floodproofing seals sensitive areas with "waterproof coatings, impermeable membranes or supplemental layer of masonry or concrete."[86] The approach of wet floodproofing is the opposite as the structure allow uninhabited areas to become flooded; this method lessens the pressure from floodwaters, and thus decreases immediate damage.[87] The third identified measure addresses changes in land use, a partial policy adjustment. Changes in land use like the transition to freshwater and aquaculture crops promote new industries and a different lifestyle. Among the three adaptive strategies, accommodation provides the most flexibility and allowance for the built environment and inhabitants.

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[85] *Coastal Risk Reduction and Resilience*, 22.
[86] FEMA, "Selecting Appropriate Mitigation Measures for Floodprone Structures," Chapter 7 Dry Floodproofing, n.d., 1-2.
[87] FEMA, "Selecting Appropriate Mitigation Measures for Floodprone Structures," Chapter 6 Wet Floodproofing, n.d., 1-2.

Table 2.9 Accommodation Measures

MEASURE	DESCRIPTION	BENEFITS	DRAWBACKS
Elevating Structures	Involves raising the lowest floor to or above the required level of protection and relocating critical infrastructures out of hazardous areas.	• Reduces flood insurance premiums. • Techniques are well-known, and qualified contractors are often readily available.	• Initial and construction costs. • Bringing structures into compliance with current code requirements. • Appearance and accessibility.
Floodproofing (wet and dry)	Wet- allows floodwaters to enter and exit. Dry- prevents floodwaters to enter and exit (watertight).	• Less costly than other mitigation and retrofitting methods. • -Does not require land.	• Requires additional warning and protective measures. • Does not minimize potential damage from high-velocity flow and wave action. • Cleanup and maintenance required.
Changes in Land Use	Changing existing land use to adapt to future climatic conditions.	• Re-establishes pre-existing ecologies. • Generates economy • Mitigates hazards - stormsurges; inundation and erosion.	• Current land uses may be costly to modify. • May not interest a large percentage of land owners. • Land decisions influenced by economic, cultural and legal considerations.

Source: Data from FEMA (2007)

Precedent #3: Miami Beach Flood Prevention Project

Florida is known for its severe hurricanes and tropical storms, but in recent years, their primary concern has shifted toward the effects of sea level rise. Since most parts of the city, are at sea level and developed on top of limestone, sea waters have little difficulty encroaching land. Streets and properties are frequently becoming inundated during high tides, prompting city officials to conduct a city-wide approach on flood mitigation through the implementation of street pumps and elevated streets and sidewalks throughout Miami Beach. The redesigned elevated street and sidewalk is 2.5-feet higher than storefront businesses. Drains are located on each side of the tier, redirecting runoff to become filtered at the detention box. Then it pressurizes as it moves through the pump and finally separates any solids in the vortex. The filtered water is later released back into the body of water.[88] The flood prevention measures described in this precedent relate to the overall concept of accommodation, as they are geared towards maintaining settlement in flood-prone settlement through adaptable means.

In Sunset Harbour, a neighborhood west of Miami Beach, these flood prevention measures were installed and prevented floodwaters from entering during king tides. However, despite its seeming success, there are still some concerns raised by residents. For instance, the quality of water that is filtered through the pump system was put into question, as well as the overall cost of the project. According to city officials, city-wide flood prevention through the application of pumps and elevated road systems may cost around $500 million.[89]

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[88] "Miami Beach's Battle to Stem Rising Tides," miamiherald, accessed March 31, 2018, http://www.miamiherald.com/news/local/community/miami-dade/miami-beach/article41141856.html.
[89] Ibid.

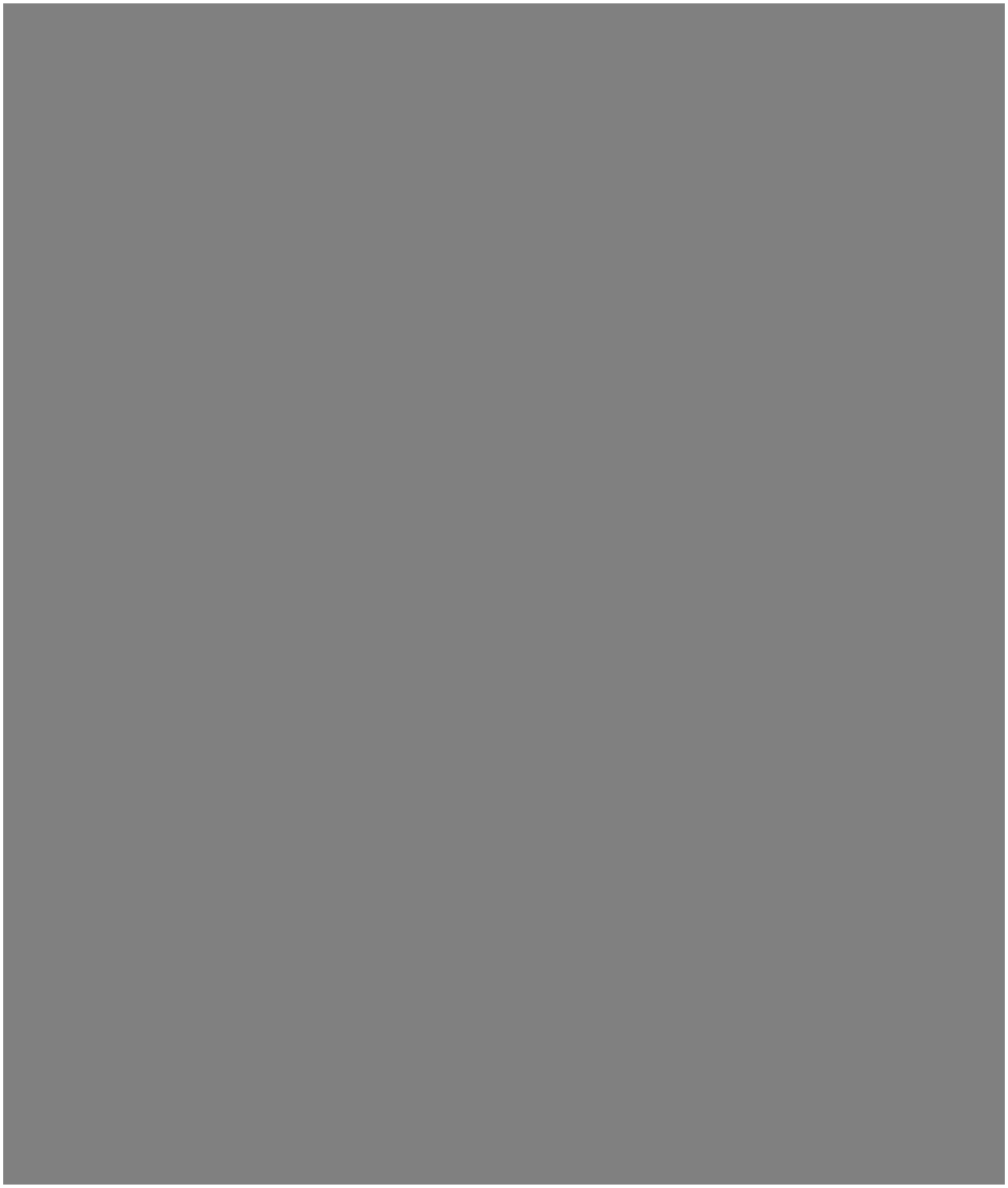

Figure 2.11: Miami’s proposed solution to mitigate flood.
Source: Miami Herald

2.4.4 Green Stormwater Infrastructure

This design dissertation identifies green stormwater infrastructure as a potential strategy for reducing the probability of flooding in highly urbanized areas. According to the EPA, green stormwater infrastructures involve systems that "rely on natural or engineered-as-natural ecosystems to specifically control and manage stormwater runoff, often with the primary goal to reduce occurrence and magnitude of combined sewer overflows (CSOs)" (Table 2.10).[91] As discussed in sections 2.2.1 and 2.2.2, water is naturally absorbed by vegetation and soils, or diverts into smaller water bodies eventually finding its way to the ocean. The infiltration of water in a natural environment is efficient and flooding in these circumstances is minimal. However, altered environments consisting of impervious surfaces, channelized streams, little vegetation, and compromised soil conditions significantly increases flooding. Implementing green stormwater infrastructures reintroduces the natural infiltration processes in developed areas. Moreover, they improve water quality and quantities, air quality, climate resiliency, habitat and wild life, and communities.[92]

Localized flooding events in the urban environment signifies poor drainage at the site, but also reflects inadequate stormwater management throughout the entire watershed. For green stormwater infrastructures to work effectively they must be executed throughout the entire watershed, especially upland where most of the precipitation is received. By utilizing green stormwater infrastructures further upstream, it addresses stormwater runoff immediately and lessens the amount of overflow downstream.

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[91] Environmental Protection Agency, "Terminology of Low Impact Development: Distinguishing LID from Other Techniques That Address Community Growth Issues," n.d., https://www.epa.gov/sites/production/files/2015-09/documents/bbfs2terms.pdf.
[92] OW US EPA, "What Is Green Infrastructure?," Overviews and Factsheets, US EPA, September 30, 2015, https://www.epa.gov/green-infrastructure/what-green-infrastructure.

Table 2.10 Green Stormwater Infrastructures

MEASURE	DESCRIPTION	BENEFITS	DRAWBACKS
Green Roofs	Roofs covered with growing media and vegetation that enables rainfall infiltration and evapotranspiration of stored water.	• Cost effective • Mitigate effects of urban heat island • Increase lifespan of roof membranes • Reduce noise and air pollution • Creates habitats • Provide space for urban agriculture • Minimize and stores stormwater runoff • Treat runoff	• Structural limitations • Maintenance and initial costs • Plant palette restrictions • Potential for leaks
Permeable Pavements	Surfaces that infiltrate, treat, and/or store rainwater where it falls.	• Cost effective • Recharge local groundwater • Minimizes and stores stormwater runoff • Treat runoff • Cool temperatures of urban runoff	• Installation costs • Maintenance requirement • Durability

Rainwater Harvesting	The collection and storage of rainfall for later use.	• Minimizes and stores stormwater runoff • Treats runoff • Provides source of usable water • Easy to maintain • Reduces demand on ground water	• Rainfall is unpredictable • Maintenance and initial costs • Certain roofs may have chemicals or animal droppings • Storage limits
Rain Gardens	Shallow, vegetated basins that collect and absorb runoff from roofs, sidewalks, and streets.	• Minimize and treat stormwater runoff • Recharge local groundwater • Create habitats • Enhance sidewalk appeal	• Impossible in areas with high groundwater tables • Can accumulate standing water
Planter Boxes	Urban rain gardens with vertical walls and either open or closed bottoms.	• Minimize and store stormwater runoff • Ideal for space-limited areas • Enhance sidewalk appeal	• Installation costs • Maintenance requirements
Bioswales	Vegetated, mulched, or xeriscape channels.	• Minimize and store stormwater runoff • Treat runoff • Ideal for space-limited areas	• Maintenance requirements • Slope requirements
Urban Tree Canopy	Increasing tree canopy in urban areas.	• Minimizes and treats stormwater runoff • Reduces air pollution	• Maintenance requirements • Maintenance costs

Source: Data from EPA 2017.

Precedent #4: Greater New Orleans Urban Water Plan

Hurricane Katrina is one of the most severe natural disasters recorded in the United States as 80% of the city was severely inundated and took a long period of time for floodwaters to drain.[93] The need for better stormwater management practices was inspired by the aftermath since it revealed critical weaknesses to the previous system comprised of conventional hard-engineered stormwater systems and standard dike design.

The proposed plan is based on forecasted flooding and rainfall conditions in 2050 and offers 41 actions to construct citywide resilience and addresses an approach of stormwater management through systems that slow, stores and drains water effectively.[94,95] Slow, in the sense of the plan, refers to minimizing pressure on existing drainage systems through the application of vegetated roofs, rainwater harvesting, rain gardens, bioswales, and pervious pavements. Storing water is achieved through the implementation of excavated basins, improved canals, leveed basins, and storage behind weirs, which is intended to be used as extra areas for storage during peak flow periods. Draining involves improving existing and modifying existing pump stations, surface, and subsurface canals. Initially, runoff was primarily diverted to Lake Pontchartrain. However, a "centralized" approach proved to be limiting in regards to the city's existing size and growing demands of drainage. Instead, water is designed to be diverted into the lake, Mississippi River, and wetlands at the east and west, thus mitigating dependence on existing pump stations. Overall, most of the measures identified in the plan demonstrate the potential opportunities and application of green stormwater infrastructures, while addressing New Orleans' relation to water from the sea, river, rain, and ground.

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93 "Hurricane Katrina."
94 C40 Cities Climate Leadership Group, "Good Practice Guide: Climate Change Adaptation in Delta Cities," February 2016, 15-16.
95 H+N+S Landschapsarchitecten, "Greater New Orleans Urban Water Plan: System Design," October 2013, 21.

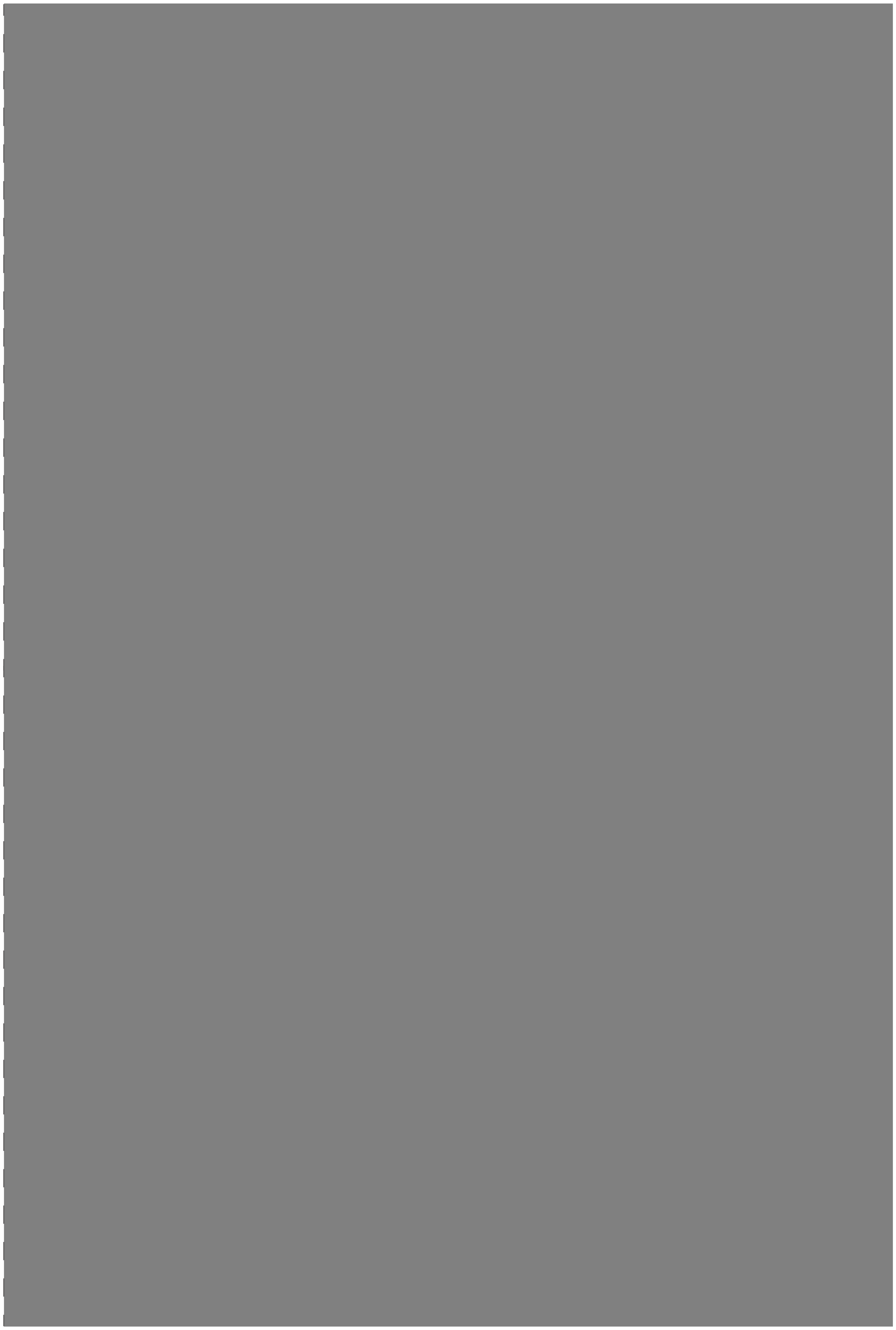

Figure 2.12: Greater New Orleans proposed water design
Source: H+N+S Landsacpe Architects

2.5 Conclusion

Floods are one of the most frequent, damaging, and complex natural hazards in the world today. In Hawai'i, as in most places around the planet, the primary cause of flooding is rainfall. Other major factors that contribute to flooding in Hawai'i are sea level rise and the effects of urban development. Sea level rise extends the reach of coastal flooding and elevates groundwater tables, eventually causing permanent inundation to lower coastal regions. Urban development encourages mass modifications to the landscape that exacerbate flood conditions such as altering streams and rivers, introducing impervious surfaces, and encouraging properties to encroach on vulnerable areas. As floods continue to escalate in scale and frequency, so does the need to update city infrastructures that are equipped to mitigate flood impacts.

Flood impacts relate to one another. When properties are damaged by floodwaters, an area's land value also decreases. Lost lives and sick individuals mean fewer human resources to rehabilitate the city and go to work. Prolonged and frequent inundation may discourage residents and visitors from returning, thus resulting in a decrease in the local economy. Standing water is likely polluted from sewage overflows and poses a potential health hazard, especially in urban areas. Essentially, all implications of the affected area—physical, environmental, and socioeconomic—are related to one another as one implication category influences another (Figure 2.13).

Traditional usages of mitigation and adaptation approaches are mono-dimensional—they only address the issue of flooding. However, as most coastal cities expect continued population growth, there is a greater need to develop flood-resilient urban infrastructures that address multiple implications in a cohesive matter. These measures must accommodate water flow, community needs, and restore natural features of the landscape. These three facets of flooding are referenced throughout the dissertation and are the primary guiding principles of the proposed design strategies (chapter 5). The following chapter provides insight on the flooding types in Hawai'i and existing mitigation and adaptation strategies.

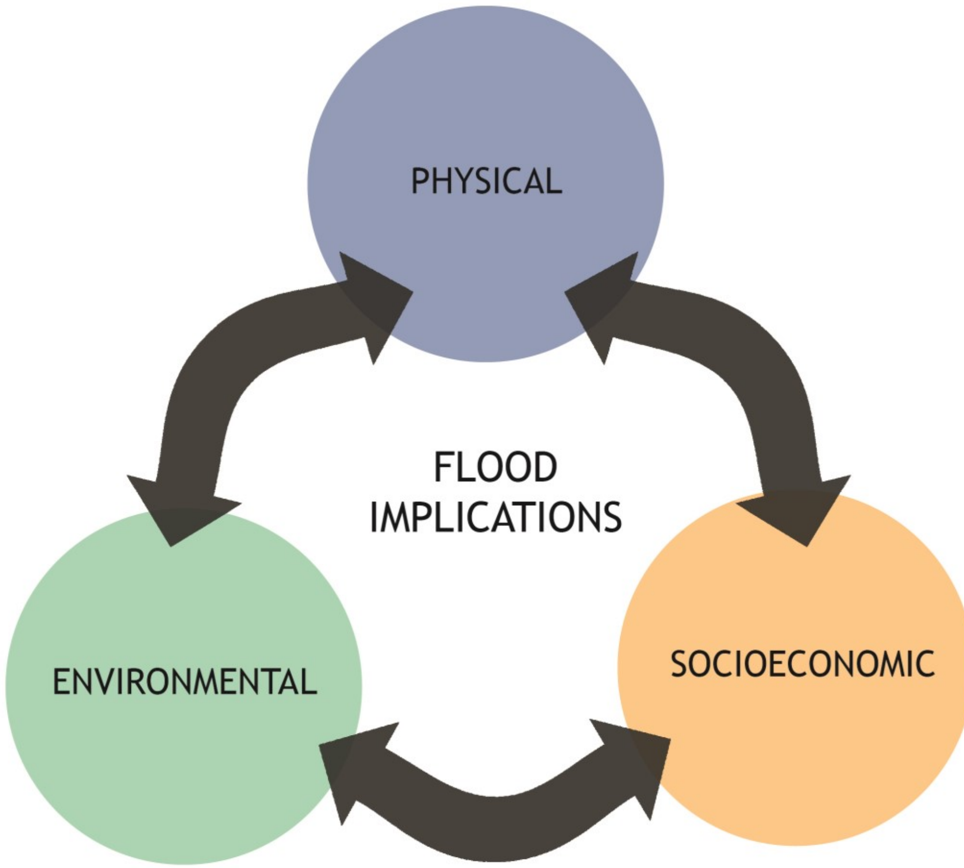

Figure 2.13 Relationships between identified flood implications

Source: Author

CHAPTER 3: FLOODING IN HAWAI‘I

The Hawaiian Islands have dynamic landscapes that transition from steep mountains to coastal plains within a short distance. For instance, the average distance from the mountain to the sea in O‘ahu ranges from 5 to 8 miles. Steep slopes allow copious amounts of water to flow rapidly to the lower regions of the watershed. Due to the alteration of many of the islands' streams and the high concentration of impervious surfaces throughout urban areas, flash floods occur more frequently and are more destructive. Additionally, settlements in lower, coastal regions are susceptible to inundation from hurricanes, tropical storms, tsunamis, and the effects of sea level rise.

Overall, floods in Hawai‘i can originate from many different sources and directions such as precipitation from passing rain clouds, storm surges and tsunamis from the sea, and rising groundwater tables influenced by sea level rise. This chapter discusses the types of floods most common to the islands—flash floods, storm surges, tsunamis, and sea level rise—and expands on leading circumstances and existing local mitigation and adaptation efforts. Understanding Hawai‘i's flooding conditions provides a perspective on the region's strength and weaknesses regarding mitigation and adaptation strategies.

3.1 Flash Floods

Flash floods are "a rapid and extreme flow of high water into a normally dry area, or a rapid water level rise in a stream or creek above a predetermined flood level, beginning within six hours of a causative event (Figure 3.1)."[97] These events are common in Hawai'i, especially during the wet season where rainfall periods are longer and more intense. Steep mountain slopes, impervious surfaces, and channelized streams allow rain to travel at a rapid pace, thus overwhelming stormwater systems and damaging properties further downstream. Flash floods can also trigger mud and landslides, structural bridge failures, and carry large amounts of debris downstream.

Figure 3.1 Circumstances leading to flash floods.

Source: BBC News[98]

[97] "Glossary - F."

[98] "Flash Flooding a 'Freak Event,'" August 17, 2004, http://news.bbc.co.uk/2/hi/uk_news/3572360.stm.

An example of an extreme flash flood event is the Manoa Valley flood in 2004. During this period, thunderstorm activity, concentrating in Oahu's southeast region, caused Manoa stream to overflow its banks. From 2 PM (October 30, 2004) to 2 AM (October 31, 2004), the highest recorded rainfall total was 10.07 inches at the Manoa Lyon Arboretum gauge. Areas throughout the valley suffered significant damage; many homes adjacent to the stream became inundated, a local footbridge was destroyed (Figure 3.2), and several cars were swept along the stream's banks (Figure 3.3).[99] Fortunately, there were no deaths or injuries reported. Out of the documented damages, the University of Hawai'i at Manoa's campus suffered the most, resulting in an estimated $80 million worth of damages to 32 buildings (Figure 3.4).[100]

Figure 3.2 Small footbridge over Manoa Stream damaged.

Source: National Weather Service[101]

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[99] "Manoa Valley Flood Oct 30, 2004," National Weather Service Weather Forecast Office, accessed December 3, 2017, http://www.prh.noaa.gov/hnl/pages/events/ManoaFlood20041030/.

[100] "Hamilton Library Thrives 10 Years after Devastating Flood," University of Hawai' i System News, October 28, 2014, http://www.hawaii.edu/news/2014/10/27/hamilton-library-thrives-10-years-after-devastating-flood/.

[101] NWS, *Small Footbridge over Manoa Stream Damaged.*, digital image, accessed December 6, 2017, http://www.prh.noaa.gov/hnl/pages/events/ManoaFlood20041030/Manoa_Stm9.JPG.

Figure 3.3 Waters from Manoa Stream pushes cars to the side.

Source: National Weather Service[102]

Figure 3.4 Flooding in Hamilton Library at the University of Hawaii at Manoa

Source: Honolulu Advertiser[103]

[102] NWS, *Manoa Stream Waters Push Cars to the Side.*, digital image, accessed December 6, 2017, http://www.prh.noaa.gov/hnl/pages/events/ManoaFlood20041030/Manoa_Stm2.JPG.
[103] "UH Salvages What's Left after Halloween Eve Flood | The Honolulu Advertiser | Hawaii's Newspaper," accessed April 2, 2018, http://the.honoluluadvertiser.com/article/2004/Nov/01/ln/ln01p.html.

3.2 Storm Surge

Storm surges are the “abnormal rise in sea level accompanying a hurricane or other intense storm, whose height is the difference between the observed level of the sea surface and the level that would have occurred in the absence of the cyclone (Figure 3.5).”[104] For example, Hurricane Iniki, a Category 4 on the Saffir-Simpson Hurricane Classification Scale, was recorded to be the most destructive and one of the costliest hurricanes in Hawai’i; damages were estimated to be $1.8 billion total. Many of the losses were the result of storm surges and waves generated from the hurricane (Figure 3.6). Out of the main Hawaiian Islands, Kauai and Oahu received the most impacts on the southern and western shores, respectively.[105]

Figure 3.5 Causes of storm surges

Source: The Wall Street Journal[106]

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[104] “Glossary - S,” National Oceanic and Atmospheric Administration’s National Weather Service, accessed December 3, 2017, http://w1.weather.gov/glossary/index.php?letter=s.

[105] U.S Department of Commerce and National Weather Service, *Hurricane Iniki, September 6-13, 1992*, 1993, ix, https://www.weather.gov/media/publications/assessments/iniki1.pdf..

[106] Robert Lee Hotz, “Range of Events Feeds Surge,” *Wall Street Journal*, October 30, 2012, sec. US, https://www.wsj.com/articles/SB10001424052970204789304578087060837168592.

Figure 3.6 Storm surge flooding on beach-front hotel in Kauai

Source: National Weather Service[107]

[107] NOAA NWS, *Storm Surge Damage*, digital image, accessed December 6, 2017, https://hilo.hawaii.edu/~nat_haz/p/p/1106785203.jpg.

3.3 Tsunamis

Tsunamis are “a series of long-period waves (on the order of tens of minutes) that are usually *generated by an impulsive disturbance* that displaces massive amounts of water, such as an earthquake occurring on or near the sea floor (Figure 3.7).”[108] This occurrence is not a type of flooding, but their impacts exacerbate coastal flooding conditions tremendously. Tsunamis traveling in open waters are unperceivable due to the depths of the ocean, but as it reaches shallower waters, waves begin to increase in height and their speed accelerates. This development allows sea waters to inundate vast areas within minutes.

Figure 3.7 Causes of tsunamis

Source: Geography from KS3 to IB[109]

[108] “Glossary - T,” National Oceanic and Atmospheric Administration’s National Weather Service, accessed December 3, 2017, http://w1.weather.gov/glossary/index.php?letter=t.
[109] “Causes of Tsunami,” Geography from KS3 to IB, accessed April 2, 2018, http://www.jkgeography.com/causes-of-tsunami.html.

Hawaiʻi is prone to tsunamis from other regions in the globe (teletsunamis)[110], and locally generated tsunamis—primarily from Hawaiʻi Island due to ongoing volcanic activity[111]. The last local tsunami originated from an earthquake off the shores of Hawaiʻi Island in 1975, and generated waves as high as 26 ft. in Halape. Teletsunamis were recorded to reach areas off the coasts of Alaska, California, Japan and Samoa. The outcome of this event resulted in 2 deaths, 19 injured, and about $4.1 million in property damage.[112] Since then, Hawaiʻi has not been directly involved with tsunami events, but rather receiving teletsunamis from other global events. For instance, waves generated from the 2011 Tohoku Earthquake in Honshu, Japan, reached Hawaiʻi's shores and inundated various parts of the state (Figure 3.8); incurred damages to private and public properties were estimated to be tens of millions of dollars.[113]

Figure 3.8 Waters overtop walls in Miyako City, Japan.

Source: Telegraph[114]

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[110]Martin & Chock, Inc., "State of Hwaii Multi-Hazard Mitigation Plan 2013 Update," August 19, 2013, 322.

[111] Ibid., 323.

[112] Ibid., 330.

[113] Dan Nakaso, "Tsunami Damage Estimate for Hawaii Now Tens of Millions," *Honolulu Star-Advertiser*, March 14, 2011, http://hsa.stablecode.ru/breaking-news/tsunami-damage-estimate-for-hawaii-now-tens-of-millions/.

[114] *Waters Overtop Walls in Miyako City, Japan.*, 2011, digital image, 2011, http://i.telegraph.co.uk/multimedia/archive/02162/20110311-tsunami-w_2162733b.jpg.

3.4 Sea Level Rise

As described in section 2.2.3, sea level rise is an effect of climate change stemming from the melting of glaciers and ice sheets and the thermal expansion of ocean water. Sea level rise is not in itself a flood hazard, but its effects have serious implications for coastal communities worldwide. Sea level rise allows tides to reach farther inland and causes groundwater tables to rise, making these areas susceptible to flooding during heavy rains. In Hawaiʻi, the effects of sea level rise are increasingly evident as coastal flooding conditions become more intense than previous years.

The *Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report* presents the first statewide evaluation of Hawaiʻi's susceptibility to sea level rise with up-to-date science on climate change and sea level rise. In order to identify the areas at risk, modeling scenarios of different sea level rise forecasts (0.5 feet, 101 feet, 2.0 feet, and 3.2 feet) and coastal hazards were conducted.[115] Three coastal hazards were analyzed: passive flooding, annual high wave flooding, and coastal erosion. The combined exposure of each island to all three of these coastal hazards was used to determine the projected areas that will be affected by chronic flooding from the impacts of sea level rise. In all of the modeled areas, chronic flooding of low-lying coastal areas will eventually result in permanent inundation or land loss as sea level rise will continue to occur beyond the 2100-year mark. The report identifies these areas as sea level rise exposure areas (SLR-XA).[116] According to models with a sea level rise increase of 3.2-feet, it is estimated by 2100 that flooding within SLR-XA areas will cost over $19 billion in land and structure damage, displace 19,800 people, and affect 25,800 acres, 65,000 structures, and 38 miles of major roads (Figure 3.9).[117] The effects of sea level rise in the Hawaiian Islands have increased the frequency of two types of flood occurrences: tidal flooding, also known as nuisance flooding, and passive flooding.

115 "Sea Level Rise Vulnerability and Adaptation Report," vii.
116 Ibid.
117 Ibid., x.

[118] “Sea Level Rise,” x.

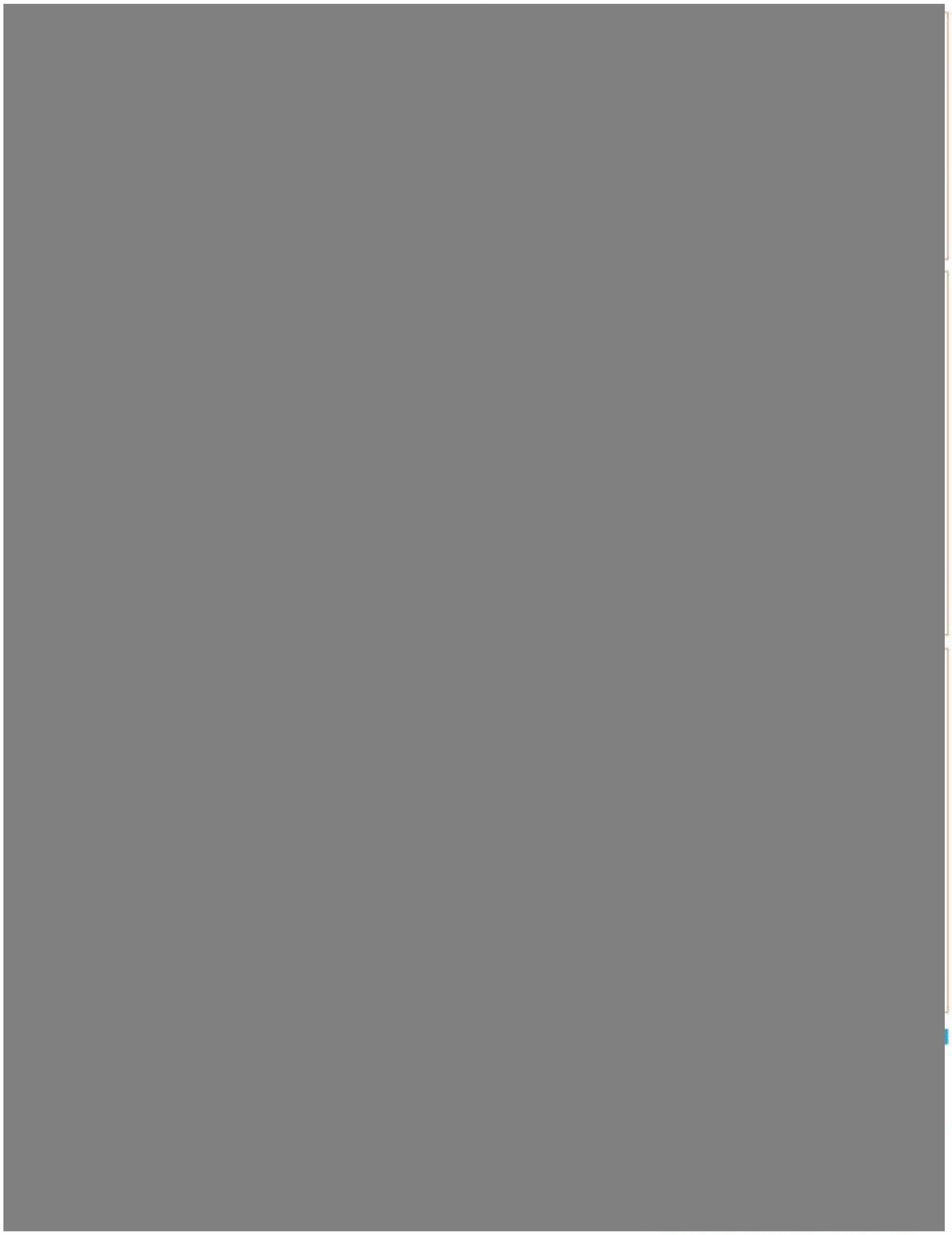

Figure 3.9 Summary of potential impacts in SLR-XA zones with 3.2 feet of sea level rise in Hawai‘i

Source: Hawai‘I Sea Level Rise Vulnerability and Adaptation Report[118]

[118] “Sea Level Rise,” x.

Figure 3.10 Sea-level, water table, and freshwater-saline water interface

Source: Rotzoll and Fletcher[119]

ldTidal Flooding (Nuisance Flooding)

Tidal flooding, also known as nuisance, blue-sky, and high tide flooding, refers to continuous flooding events with little or no property damage that cause public inconvenience (Figure 3.10).[120] Since the 1960s, nuisance flooding along U.S. coasts has increased between 300 and 925 percent, with most of the activity occurring in cities along the east coast.[121] As relative sea levels rise, the gap between the ocean and city infrastructures narrows, allowing tides to travel further inland.[122]

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119 Kolja Rotzoll and Charles H. Fletcher, "Assessment of Groundwater Inundation as a Consequence of Sea-Level Rise," *Nature Climate Change* 3, no. 5 (May 2013): 477–81, https://doi.org/10.1038/nclimate1725.

120 NOAA, "What Is High Tide Flooding?," National Ocean Service website, accessed December 3, 2017, https://oceanservice.noaa.gov/facts/nuisance-flooding.html.

121 "NOAA: 'Nuisance Flooding' an Increasing Problem as Coastal Sea Levels Rise," NOAA - National Oceanic and Atmospheric Administration, accessed December 3, 2017, http://www.noaanews.noaa.gov/stories2014/20140728_nuisanceflooding.html.

122 "What Is High Tide Flooding?"

In Hawaiʻi, lower coastal regions, at or just above sea level, are highly susceptible to tidal flooding. During high tides, storm drains become backed up and spill onto the streets. During exceptionally wet weather, these events become more damaging. The 2017 summer king tides demonstrated the affect of exceptionally high tides. In Waikiki, tides persistently reached properties next to the beaches and simultaneously caused backwash in nearby storm drains. Businesses prepared for flooding by arranging sand bags around their properties; however, such measures can only work to a certain extent. In Māpunapuna, the dissertation's project site, storm drains near Ahua Street overflowed onto the streets reaching to the top of the sidewalk (Figure 3.11).

Figure 3.11 Flooding in Māpunapuna during King Tides.

Source: Author

Passive Flooding

Passive flooding is another flood hazard greatly influenced by the effects of sea level rise. Circumstances leading to this flood type are minimal as all it takes are continuous flows over the shoreline of lands that are below sea elevation (Figure 3.10). As sea level rise continues to rise, low-lying coastal regions bescome flooded by groundwater tables being pushed up. Heavy rains can further exacerbate passive flooding as grounds become oversaturated by runoff and sea waters.

Figure 3.12 Flooding near Hilton Hawaiian Village's Duke Kahanamoku Lagoon in Waikiki.

Source: KHON 2[123]

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[123] Gina Mangieri, "Disaster Response Readied for 'king Tide' Flood Risk," KHON, May 22, 2017, 2, http://www.khon2.com/news/always-investigating/disaster-response-readied-for-king-tide-flood-risk_20180104063603325/901528391.

3.5 Conclusion

Due to Hawai‘i’s geographical location and unique topography, several types of flood hazards exist. As mentioned in the beginning of chapter 3, the combination of wet weather and steep mountains often results in flash floods in the lower parts of the larger islands; streams overrun their banks, while soils and vegetation become water logged. The impacts of flash floods are worse in highly urbanized areas of Hawai‘i due to the large concentrations of impervious surfaces and channelized streams. Past efforts to mitigate these events focused on stream channel improvements; however, over time these have caused adverse impacts to the downstream ecosystems. Areas immediately near the coast are highly susceptible to inundation from storm surges and tsunamis, yet few mitigation and adaptation strategies are enforced. Of the strategies that do exist, most fall under the category of accommodation and protection. Currently, accommodation measures center on building codes and design recommendations for all development projects that take place in Flood Insurance Rate Map (FIRM) special zones and soft protection measures center on coral reef protection around the islands’ shores. More recently, beginning in the mid-twentieth century, nuisance flooding has plagued several coastal developments. For Hawai‘i, the lower coastal regions are highly susceptible on a daily basis due to shallow groundwater tables and proximity to the shore (all influenced by high tides). Past government reports about mitigation and adaptation strategies do not efficiently address the minimization of flood impacts. However, the recent *Hawai‘i Sea Level Rise: Vulnerability and Adaptation Report* emphasizes the increased frequency of nuisance flooding and provides an outlook on probable mitigation approaches.

Overall, Hawai‘i is unceasingly vulnerable to floods from rainfall, surging seawater, and the effects of sea level rise, and although each are addressed individually, it is important to note that these flood events can occur simultaneously. Flash flooding and storm surges are likely to occur at the same time during a hurricane, while tsunamis can travel further inland with increased sea level rise. From the examination of flood characteristics in Hawai‘i, as well as the state’s current flood mitigation approaches and adaptation strategies, this dissertation provides an array of critical strategies and an analysis of potential application through design.

Chapter 4 presents a series of design precedents and summarizes possible flood mitigation approaches for highly urbanized coastal cities.

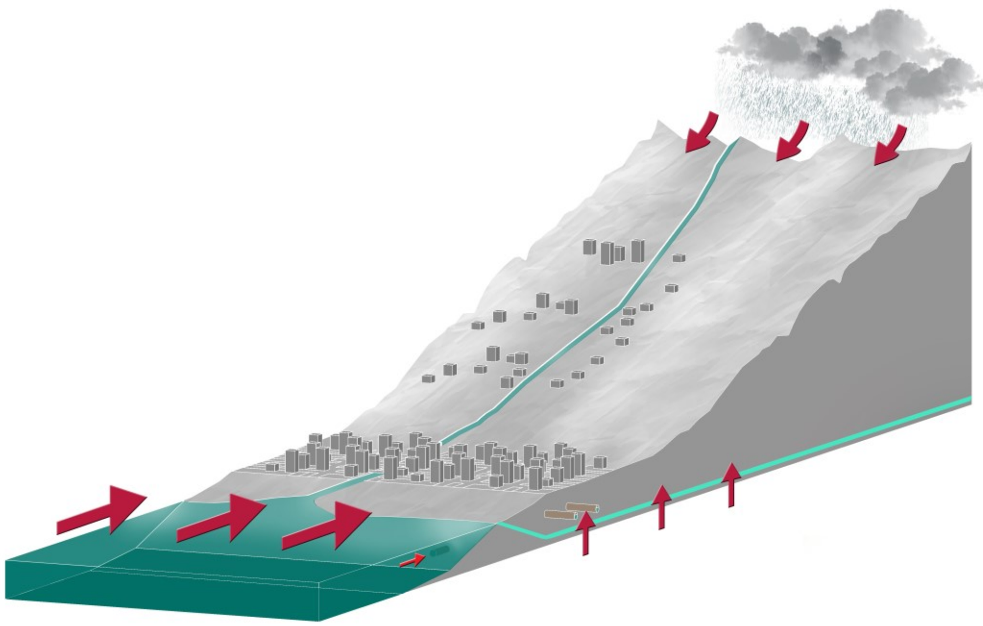

Figure 3.13 Schematic axonometric drawing of flood Hazards in Hawaii

Source: Author

CHAPTER 4: DESIGN PRECEDENTS

The balance between a flood's physical characteristics and the vulnerability of the human population determines a location's degree of flood risk. A balance between these two categories reflects safety, while an imbalance reflects potential disaster. For many coastal cities around the world, as well as in Hawai'i, flood risk is high due to dense urban development in flood zones. How do we as designers help to establish a balance between existing built and natural environments along our coasts? The analysis of precedents is a viable design tool. Precedents provide examples of solutions designed and implemented under similar conditions, revealing a project's intent, critical decision-making steps, and appropriate design measures. Overall, the consideration of key lessons from precedents adds authority and meaning to the final design.

As identified in chapter 2, this dissertation focuses on three significant areas of implication concerning flood resilience:

- Physical: Addresses problems originating from destroyed properties and infrastructures after coming into contact with flood waters.
- Ecological: Emphasizes the missing components of the natural landscape that mitigate and filter stormwater runoff efficiently.
- Socioeconomic: Underlines issues relating to the disruption of daily activities

The selected precedents were chosen based on how each addressed the physical, ecological, and socioeconomic implications of flooding in densely developed urban environments. The projects implemented the adaptation and mitigation strategies and measures detailed in section 2.5, with varying emphases. Precedents are organized according to five themes: coastal protection, ecological restoration, floodable and floating architecture, and stormwater management.

4.1 Coastal Protection

Coastal protection involves the application of protection measures (see 2.4.2), and most common forms include hard, engineered types like levees, ripraps, and seawalls. The overall strength of these measures is the ability to address inundation immediately. However, in most cases, they are misused, causing adverse effects to the immediate area and those in the vicinity. Another flaw is prohibiting future growth and providing little opportunity for other functions besides what it is intended. The following precedents in this section present bold designs which challenge the idea that hard-engineered protection measures are strictly mono-functional.

LIVING BREAKWATERS
SCAPE

Living Breakwaters is one of the winning designs from the Rebuild by Design Hurricane Sandy Design Competition in 2014; an organized effort "to help governments create research-based, collaborative processes that prepare communities and regions for future challenges." The project site includes Tottenville's shorelines and waters surrounding the areas, the southernmost part of Staten Island. in the southernmost part of Staten Island. The project is currently being put into action by the Governor's Office of Storm Recovery (GOSR) with $60 million of CDBG-DR funding and is scheduled to break ground before the end of 2018.

The project site has undergone erosion in the past 35 years, causing hurricane-generated waves to be harsher; numerous properties were damaged, and many lives were lost. In the past, the area had soft structural protections of natural oyster reefs but disappeared over time due to overharvesting. With this in mind, SCAPE developed three core values that drove the project to fruition: physical, ecological and social resilience.

In Orff's concept, physical resilience translates into reducing the risk from future natural hazards, such as the hurricane-generated waves from Sandy. The design team proposes the usage of breakwaters, about 730-1200 feet from the shore, to lessen wave impact and reverse shoreline erosion. Results from several impact modeling scenarios, in the setting of high intensity and low-frequency storms, indicated the most vulnerable areas, thus providing potential locations of the breakwaters.

The design team uses the phrase Ecological Resilience to describe the concept of providing habitats and enhancing ecosystems services throughout Raritan Bay by adjusting the traditional offshore breakwater model. Instead of a pile of rubble, the project promotes the usage of bio-enhancing concrete units, "reef streets" and "reef ridges"; this supports richer biodiversity, referring to the project title Living Breakwaters. In order to have a minimal impact on existing habitats, the structures were designed to be shorter in length, have little spacing and a steeper slope (decreasing the footprint).

Social Resilience, in Orff's sense of the term, refers to the restoration of the Tottenville community. The proposed nearshore breakwaters intend to have the seawaters turn calmer, and beaches become wider. This will promote more recreational opportunities along the shoreline. Another critical component of social resilience is the integration of programming and education; this allows "locals and residents to engage with the shoreline, learn about resiliency initiatives and ecological restoration activities, and become stewards of the harbor." The result of numerous Citizen Advisory Committees expressed the need for "continuous water access along the shoreline and increased ability to remain along and in the water."

Source: SCAPE

THE BIG U
BIG

The BIG U is another winning design from the Rebuild by Design Hurricane Design Competition in 2014. The design proposal incorporates a portion of Manhattan's coastline, from West 157th street south to The Battery, and then stopping at East 42th street. The design team, led by Bjark Ingels Group (BIG), understood the limiting qualities of commonly designed coastal barriers -the lack of aesthetic appeal, constricting waterfront access, and inhibiting future growth-, and proposed a regional barrier system that provides multiple functions for the city. Many community outreach meetings and workshops determined the desired barrier typology and amenities for each sub-region. Besides the physical protection from floodwaters and storm surges, the team also sought to foster social and environmental resilience within Manhattan.

Overall, the BIG U design team proposed "three compartments that, while linked together, function independently in terms of flood protection." Compartment 1 focuses on the areas from E. 23rd St. to Montgomery St.; protective measures include an undulating berm and levee, while amenities include pavilions, recreational areas and sports fields. Compartment 2 addresses the areas between Montgomery St. to the Brooklyn Bridge; protective measures suggests the raising of critical structures, waterproofing of buildings and the evacuation of first levels in apartments, while also providing amenities such as a system of benches, skateparks, tai-chi platforms and a pool.

Compartment 3 prioritizes the areas from the Brooklyn Bridge to the Battery; protective measures include berms and floodwalls, while amenities include an upland landscape, a maritime museum or environmental education facility, and an elevated public space and pathways.

Source: BIG

4.2 Ecological Restoration

The next category of design precedents is ecological restoration. Both projects have similar constraints, where the previous land uses caused the area to become polluted and an underutilized site within highly urbanized areas. Common mitigation and adaptation measures in these precedents is the application of soft-vegetated protection measures along the banks, thus controlling erosion, attenuating wave and controlling flood impacts on neighboring urban areas. While addressing the constraints of the site through thoughtfully designed landscapes, amenities were provided such as footpaths, bicycle routes, pavilions, and community events; over time becoming destinations for residents and visitors to enjoy.

Buffalo Bayou Promenade

SWA

Before the construction of the Buffalo Bayou Promenade, the site was as a public eyesore; a typically underutilized grayfield located below the elevated freeway infrastructure. Talks about transforming the area into a linear park dates back to the early 1900s, but were not put into action until later that century. Over time, numerous parks were implemented, but they had no physical connections. The complexities of the site inspired SWA to propose a 1.2-mile park urban and recreational zones integrated within the same area of the corridor as the elevated freeway system.

In order to restore the ecological conditions of the bayou, several native vegetation and trees were planted throughout the park; there were nearly 300,000 plants, which included 640 trees. Simultaneously, invasive species were removed. Vegetation that is suitable to the periodic inundation of the site, as well as enhancing the inherent qualities of the landscape resulted in a diverse and vibrant over time.

Due to the nature of Buffalo Bayou as a critical drainage system for the majority of Houston, extensive regrading was proposed. This approach would minimize not only the impact of erosion but also improve floodwater movements.

The selection of native and naturalized riparian species, along with the implementation of gabion sacks addressed erosion control; both strategies preserve the conditions of the sloped edges as plantings secure soils within the landscape, while the permeable structure allows water to flow freely. Floodwaters are addressed by increasing the site's storage capacity by 18.65 acre-feet through the excavation of 23,013 cubic meters of soil.

Source: SWA

Shenzhen Bay
SWA

Shenzhen has drastically changed within the past 40 years, starting out as a fishing village of 30,000 and transforming into an enormous city of with a population of over 10 million people. Compared to the city's original size in 1980, its footprint drastically increased 200 times. To accommodate the expansion of Shenzhen, "over 65 km2 of marsh and shallow bay were filled to create more land." The consequences of these alterations lead to the destruction of pre-existing native mangroves, salt marshes, and wildlife. SWA proposes a complete restoration of the bay's ecological wildlife, as well as providing amenities for the existing population.

Throughout the site, encompassing 15 kilometers (roughly 9.3 miles) of Shenzhen's coastline, pre-existing ecological systems are introduced such as brackish tributaries, mangroves, sea grasses and salt marshes; these elements are designated to enhance the wildlife conditions of the area, as well as restoring the bay's sense of place. Amenities such as "significant parks, promenades, forests, open meadows and a lengthy promenade" can be found along the coastline. Other amenities included are "entertainment and educational pavilions, an outdoor theater, an aquatic center, restaurants, teahouses, along with convenient transit stops."

Source: SWA

4.3 Floodable and Floating Architecture

The overall intent of floodable and floating architectural design is to allow waters to flow undisturbed, thus minimizing impacts on the structure itself. The application of accommodation measures such as increasing elevations and flood proofing will enable structures to be floodable while floating structures allows the building to remain on top of the water level. Rather than preventing the intrusion of flood waters, these measures allow waters to flow undisturbed, thus diminishing the impacts of flood waters. In this aspect, the precedents given are the elevation of the built environment and at the same time, allowing water to flood through the site temporarily.

Floating architecture is another example that involves the application of accommodation measures such as increasing elevations and floodproofing structures. Rather than preventing the intrusion of flood waters, these measures allow the water to flow undisturbed, thus lessening the damage of flood waters. In this aspect, the precedents involve the elevation of the built environment and at the same time, allowing water to flood through the site temporarily. The following precedents demonstrate the application of these measures in dense urban developments in flood-prone areas.

Hafencity

The area of HafenCity, located in the borough of Hamburg, Germany, is situated on the Elbe river island called Grasbrook. Since the earliest settlements, flooding has been an issue due to its proximity to the water. During the redevelopment of the district, several measures were taken into consideration. Initially, dikes were proposed, but costs of the construction and water-front views would be compromised for residents and visitors. Instead, a portion of the city was designed to become floodable. New structures and roadways built on plinths, elevated 8-9 meters above sea level, connect to raised streets and provide protection from flooding. During periods where waters inundate the streets, residents and visitors can circulate throughout the area without disruptions. The interior of these structures is dedicated to parking and sealed from intruding waters. Other public spaces remain at previous levels of 4.5-5.5 meters above sea level, preserving the historic waterfront characteristics.

In comparison to floating architecture, floodable architecture is a more reasonable approach to rising waters and inundation. As demonstrated in the images of HafenCity, it promotes a diverse urban lifestyle and seems like the ideal walkable city. Sacrificing first floors to flooding is a factor to consider, as it alleviates the impacts from surging waters. Letting the water flow accordingly, while out of harm's way, is one approach of thinking how to co-exist with water.

Source: Hafencity Hamburg

Fostering Resilient Ecological Development (F.R.E.D)
Ennead Lab and Architects

"Fostering Resilient Ecological Development, or F.R.E.D., addresses the complex Arverne East site through the implementation of a flexible kit of parts. Comprised of an integrated system of dunes, piers, and housing clusters, the design proposal creates a solution that is not only practical given the economic and physical constraints of the Rockaways, but also replicable for low-lying coastal communities up and down the Atlantic seaboard."

F.R.E.D, designed by Ennead Lab / Ennead Architects, was a submission for the FAR ROC For a Resilient Rockaway competition, held in 2013; it received the "Leading Innovation in Resilient Waterfront Design Award." There are four objectives of the project:

1. Be Efficient - minimize roads and infrastructure; maximize open space; create affordable housing; conserve resources
2. Be Adaptable - accommodate rising tides and ground water; adjust to changing coastlines; respond to economic conditions
3. Maximize Ecological Function - for coastal protection; for habitat; for site identity and character
4. Be a Good Neighbor - an economic engine for the larger community; a source-neutral consumer of carbon; a generator of social resilience; an open and welcoming neighborhood; a safe harbor in times of crisis

Source: Ennead Lab and Architects

Ennead Lab and Architects addressed the ecological conditions of the site and conditions by proposing native dune ecology. Regarding the long-term circumstances, this approach would be the most efficient and feasible. This feature could also become an amenity for residents and visitors. Given the frequent flooding conditions of the area, piers were suggested as the network interconnecting the structures and nearby amenities. "Elevated streets", as described by the team, keeps the community linked. Housing is addressed with vertical, elevated housing typologies. Following the same language and intent as the elevated streets, residents can co-exist with water at ease. The design maintains the same number of households and business, however they are organized to accommodate natural features.

Floating Houses at Ijburg
Rohmer Architects & Urbanists

Water is not like land. If you plan to build on water, you need to do so with respect for the unique nature of water. Water is pioneering, water is adventure, danger, and relaxation, water lets you elude the rules of dry land. Living on water also means views, movement, boat docked at home, romance, jetties, a sense of individuality, wind and clouds, space, contact with the elements, feeding swans from your kitchen, ice skating around your house…
-Marlies Rohmer Architects & Urbanists

As described by Marlies Rohmer Architects & Urbanists, living on water is not solely a solution to finding another form of housing; it involves adapting to another lifestyle. With discussions about the future and the effects from climate change, people are aware that significant life changes will eventually lead to this type of living, however what does it really entail? The Floating Houses IJburg, demonstrates those possibilities in a water-based housing development in Amsterdam. The interior plan of the households is similar in nature:

- Bottom level – bedrooms, bathrooms
- Entry level – kitchen, office spaces, bedrooms
- Top level – living room, verandas

Regarding the external structure, residences from dike homes, "…that are suspended on pylons above the dike on the edge of the basin," to floating structures reinforced by submerged concrete "tubs." All the homes, with the exception to the dike types, are interconnected by a system of jetties. Residents are living with water rather than away from it. Spaces in between each home becomes a privatized amenity for the community to enjoy.

Source: Marlies Rohmer Architects & Urbanists

Jellyfish Barge
Studiomobile

Jellyfish Barge, designed by Studiomobile, is a floating greenhouse module that addresses the issues of food production and sea level rise – challenges that will become more apparent in the future. Within an area of 70 square meters, this structure is capable of growing crops without using land, supplied water and energy from the grid. There are 7 solar desalination units located on the outer perimeter of JFB and is used to purify non-potable water (seawater, brackish, and polluted water) to supply water for the greenhouse's hydroponic system; about 150 liters of clean water can be made per day, and crop production can sustain 2 families. Energy is extracted from the wind, sun and tides; however, little is needed as it is only required for the pumps and fans. The construction of JFB itself is sustainable as the majority of the materials are simple and low-cost technologies were used in the process; recycled plastic drums made it possible for the structure to float. These modules have the potential to feed a community, by establishing a broader network connected by floating boardwalks in between.

Source: Studiomobile

4.5 Stormwater Management

The final category of design precedents is stormwater management. Both projects demonstrate how a limited parcel of land can address the issues of runoff, water, and soil quality in a single site design. Several of the measures used in these projects incorporate those that are green stormwater infrastructures. Like the precedents in ecological restoration, stormwater management precedents addresses the constraints of the site through insightful designed landscapes, providing amenities such as footpaths, bicycle routes, pavilions, and community events which over time becoming destinations for residents and visitors to enjoy.

Tianjin Qiaoyuan Park
Turenscape

Located in the city of Tianjin, China, the Tianjin Qiaoyuan Park, designed by Turenscape, reflects the successful balance between the execution of a regenerative design and compelling aesthetics that requires minimal maintenance. In the past, this particular site had undergone extensive alterations in use, changing from a shooting range, into a garbage dump, and later an urban drainage sink. These changes presented several environmental issues, such as pollution and undesirable soil conditions. The extent of the conditions led to a public outcry for action and as a response, the Tianjin municipal government "set out for a park that served the surrounding residents, as well as improve environmental conditions with little maintenance." In order to meet the client's criteria, Turenscape proposed a park design that,

…provide a diversity of nature's services for the city and the surrounding urban residents, including: containing and purifying urban stormwater; improving the saline-alkali soil through natural processes; recovering the regional landscape with low maintenance native vegetation; providing opportunities for environmental education about native landscapes and natural systems, stormwater management, soil improvement, and landscape sustainability; creating a cherished aesthetic experience.

The park's design was inspired by the adaptive vegetation communities that once existed in the region's landscape, thus implementing the concept of the Adaptation Palettes; a landscape regenerative design strategy involving twenty-one pond cavities. These cavities range in size and elevation "from 10 to 40 meters in diameter", "1 to meters in depth", and some "below ground level," while "some above on mounds." The transformative qualities of the design are apparent during changes of the seasons and periods of rainfall. Species throughout the landscape are distributed according to the distinctive qualities of the wet and dry palettes, as well as the PH values. Regarding the water levels, some palettes become shallow pools and wetlands, while others remain dry. Over time, wash and filtration improve the saline and alkaline soil conditions of the dry palettes while providing nutrients for deeper ponds.
A system of red-colored asphalt paths, intertwined throughout the site, allows visitors to explore the diverse landscape. Each palette has an observation platform and interpretive signs that describe the natural patterns, processes and native species.

Source: Turenscape

Gowanus Canal Sponge Park
dlandstudio

Gowanus Canal was historically a dynamic space, serving as a transportation corridor for adjacent industries. However, the combination of changes in the economy, limited public access, sewer outfall overflows and street surface runoff led the site to deteriorate over time; the canal received its nickname as 'Lavender Lake' due to the colors produced from the pollutants. The lead design firm, dlandstudio, conceived a vision of restoring Gowanus canal involves a design that "slows, absorbs and filters surface water runoff to remediate contaminated water, activate the private canal waterfront, and revitalize the neighborhood."

A variety of amenities are introduced along the edges of the 1.4-mile-long corridor to bring public access to the site. Open spaces are dedicated to recreational activities and are interconnected by esplanades or multifunctioning areas called Street-End Sponge Parks; they serve as miniature landmarks throughout the site, as well as performs as an ecological system that filters and treats surface runoff before entering the canal. The location of these features is near existing outfalls of combined sewer and storm systems, and relieves the stress of these systems during wet weather.

The Street-End Sponge Parks are the core of the design proposal and are comprised of three zones: (1) non-flooding, (2) 0-2" of standing water, (3) 0-12" of standing water.

Each zone has a plant palette complementary to its flooding characteristics and has some species that can process polychlorinated biphenyls (PCBs) and heavy metals. For instance, pond weed and duckweed are some of the suggested vegetation for zone 3 and is capable of remediating water and soil conditions over time.

Source: dlandstudio

4.6 Conclusion

Some of the precedents were established based on deteriorating soil and water qualities, while others responded to severe flooding events and sea level rise. Each addressed the physical, ecological, and socioeconomic implications of flooding in densely developed urban environments through the application of adaptation and mitigation strategies (section 2.5), with varying emphases. Key lessons will be applied in the conceptual design phase (chapter 7) to further refine the project's intent.

CHAPTER 5: DESIGN FOR FLOODING PRINCIPLES AND STRATEGIES

As ascertained in the discussions on regional precedents (section 2.4) and design precedents (chapter 4), past disasters and deteriorating soil and water conditions have prompted the development of bold and innovative design solutions. In Louisiana, in response to severe inundation caused by Hurricane Katrina's storm surge and heavy rains, master plans were assembled that endeavor to promote resilience from future flood hazards through land development strategies and enhanced stormwater management systems. New York City, in response to the destruction caused by Hurricane Sandy, developed shoreline protection build-out recommendations; projects like the Big U and Living Breakwaters are part of this larger development and mobilize multi-functional protection infrastructures. In Miami, the city's on-going struggle with sea level rise inspired the concept of elevated roadways and pump systems to manage the effects of sea level rise in the short term.

Hawai‘i has yet to experience any flood events of similar magnitude to Hurricanes Katrina or Sandy. However, despite the state's relatively stable conditions, floods are still among the most common and costly natural disasters and will worsen over time as climate change exacerbates rainfall patterns and sea level rise and populations continue grow in coastal developments. According to the *Hawai‘i Sea Level Rise Vulnerability and Adaptation Report*, a 3.2-foot sea level rise by 2100 will affect approximately 25,800 acres of land. This land will be chronically exposed to seawater. The report estimates that 6,500 structures, 39 miles of major roads, and 500 cultural sites will be flooded and 19,800 people displaced, altogether costing the State over $19 billion.[139] Existing flood mitigation and adaptation strategies in Hawai‘i are not equipped to withstand this degree of flooding in the near future. Taking immediate action to make Hawai‘i flood resilient, rather than waiting for a disaster to occur, is beneficial in the long run as it minimizes potential loss.

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[139] "Sea Level Rise Vulnerability and Adaptation Report," 65.

Hawaiʻi has made recent strides towards resilience. On June 6, 2017,

> …Govern**or David Ige signed Act 32 Session Laws of Hawaiʻi, 2017**, making Hawaiʻi the first state to enact legislation implementing parts of the Paris Climate Accord. The Paris agreement was signed by 195 nations on November 4, 2016, and is the largest, concerted global effort to combat climate change to date.[140]

Following this enactment, the Hawaiʻi Climate Change Mitigation & Adaptation Commission (Climate Commission) was established,

> The Climate Commission will work with all stakeholders to address these challenges by systematically reducing greenhouse gas emissions and improving our resiliency to its serious impacts, utilizing the principles and contributing to the goals set by the Paris agreement.
>
> It is anticipated that the new Climate Commission will provide direction, facilitation, coordination and planning among state and county agencies, federal agencies, and other partners about climate change mitigation (reduction of greenhouse gases) and climate change resiliency strategies. These include, but are not limited to, sea level rise adaptation, water and agricultural security, and natural resource stewardship.[141] (Emphases mine)

This is a grand step for Hawaiʻi's government and crucial in promoting the research, funding, and implementation of resilient design strategies in the future. The design strategies developed for this dissertation represent objectives similar to those of the Climate Commission and will serve to complement Hawaiʻi's progression towards resilience in the future. Hawaiʻi has published a handful of reports that address adaptation and mitigation, but

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[140] "Department of Land and Natural Resources | 10/03/17 – State Holds First Hawaiʻi Climate Change Mitigation and Adaptation Commission Meeting," Department of Land and Natural Resources, October 3, 2014, https://dlnr.hawaii.gov/blog/2017/10/03/nr17_0155/. .

[141] Ibid.

a majority of these are at the policy level and specifically focus on climate change and sea level rise rather than flood resiliency and design and spatial strategies. This dissertation intends to fill this gap by introducing design strategies geared toward resilience in the face of future flood hazards.Resilience is the ability to recuperate efficiently from difficulties, a trait that many coastal cities lack. Initially, the proposed design strategies were intended to solely address the physical impacts of flooding. However, the research for this project, encompassing the context of flooding in a broad setting, in specific locations and events, and as it relates to Hawaiʻi, revealed that flooding involves much more than the immediate, tangible destruction caused by the event itself. Flooding also takes a toll on the community, on the lifestyles of those affected, and on the natural environment. Thus, the three identified implications of floods—physical, environmental, and social—have inspired the three design principles of flood resilience that are the focus of this project: risk reduction, green networks, and placemaking (Figure 5.1).

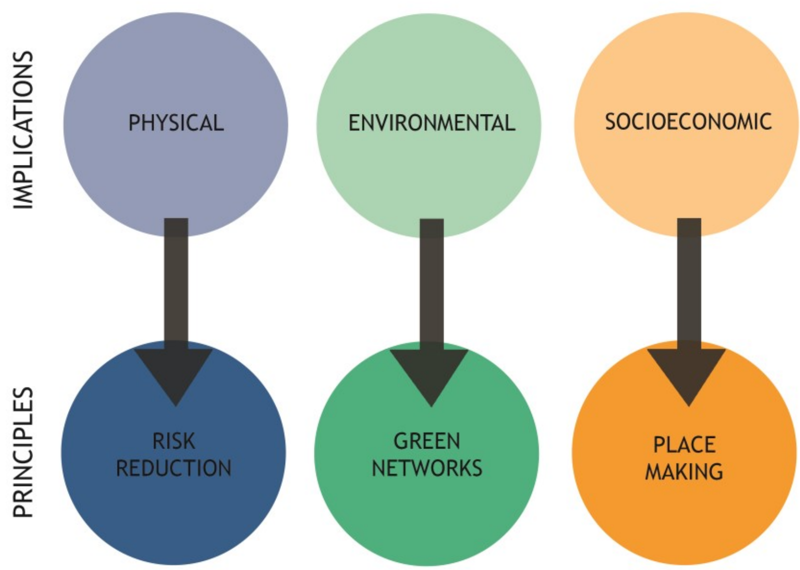

Figure 5.1 Flood implications to flood design principles

Source: Author

5.1 Risk Reduction

Risk reduction is a concept that focuses on decreasing the degree of flood damage in the built environment. Discussions from the research portion of this dissertation emphasize the damaging impacts of floods in coastal and floodplain areas mostly due to urban development. Coastal areas often become densely developed because of the variety of amenities the water bodies provide. With growing numbers of inhabitants and properties concentrated in flood prone areas, exposure to flood risk increases over time.

This is the case for Hawai‘i, which currently has a significant number of private and public properties situated in coastal areas. However, most of these properties have minimal or no protection and are not equipped to withstand additional floodwaters from severe events. The properties include prominent hotel corporations, shipyards, airports, residences, beach parks, schools, and military bases. Most are located on low, flat lands vulnerable to the effects of sea level rise, such as elevated groundwater tables and exacerbated event-based coastal flooding. Overall, damage to or destruction of these facilities will significantly affect the state, from displacing populations to disrupting local economies and trade, and thus change the living conditions of the overall population.

Design Strategies for Risk Reduction

A holistic approach is required in order to minimize the degree of flood risk in Hawai‘i’s urban settings while maintaining its relationship with the natural environment. This can be done through the adaptation and mitigation strategies of retreat, accommodation, and protection (Figure 5.2). Each strategy is broken down into a series of design measures.

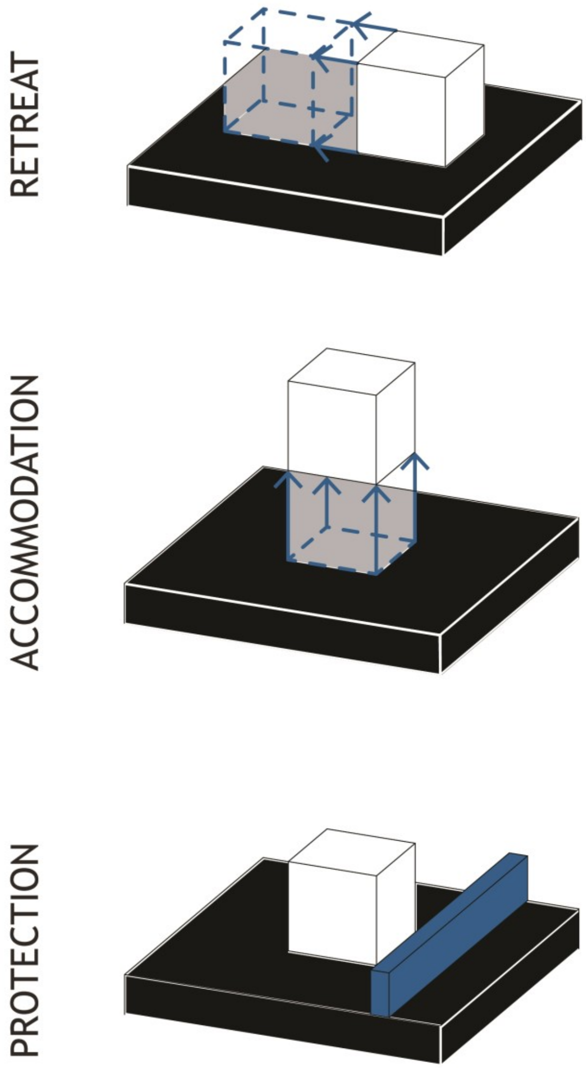

Figure 5.2 Risk reduction strategies and measures.

Source: Author

Retreat involves the removal of properties from flood prone areas and, of the three strategies, requires the most land. The evacuation of specified areas greatly reduces risk of potential flood loss while creating a designated buffer zone for adjacent developments. In the Louisiana Comprehensive Master Plan for a Sustainable Coast, land acquisition was determined for areas projected to flooding depths of 14 feet in order to prevent future damages.

Accommodation, which requires the least amount of land, focuses on the application of floodproofing and increasing the elevations of buildings and pathways. Using accommodation, buildings and infrastructures can remain onsite and allow people to move through the area unaffected during a flood event. This is the case with HafenCity, a quarter of the city of Hamburg in Germany; a majority of its blocks are elevated, placing the street level one story up and connecting buildings using elevated pedestrian pathways.[142] Similarly, Miami raised part of its road and sidewalk systems and installed a sophisticated mechanical pump system in order to better manage chronic flooding conditions.[143]

Protection provides hard or soft defense systems along shoreline edges, primarily to mitigate the impacts of surging waters. The amount of required land varies greatly and depends on the type of measure selected. For instance, in the urbanized coastal development arena, New York City's Living Breakwaters propose a hard-engineered defense system—near-shore breakwaters—to attenuate storm surges while also promoting ecological habitats and fostering amenities for the neighboring community.[144] This design defies the belief that hard-engineered structural measures are exclusively mono-functional. Similarly, the designs of Hong Kong's Shenzhen Bay demonstrate how mangrove habitats can act as natural buffers to wave

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142 Hafencity
143 "Miami Beach's Battle to Stem Rising Tides."
144 "Living Breakwaters Design and Implementation."

impact and erosion.[145] Designed natural environments not only restore lost ecologies but also provide valuable amenities for neighboring areas.

In Hawai'i, land is a limited resource and most designated urban lands near the coast are highly developed. Thus, proposed measures should not only effectively address flood hazards, but also provide additional functions that will enhance the community and environment, as demonstrated in the examples above. Multifunctional flood mitigation and adaptation measures integrated in the urban fabric add greater value to both the system itself and the community. The overall goal, then, is to allow water to flow undisturbed, causing less damage to the built environment while also providing new amenities to the community.

5.2 Green Networks

Green networks include strategies that improve the drainage quality and natural land cover of urban areas through green stormwater infrastructure systems like rain gardens and bioswales. Undeveloped natural landscapes are capable of regulating water effectively. Vegetation and soils receive rainfall; runoff then travels throughout the watershed through streams and rivers. Some water may end up in smaller, permanent water bodies like ponds and lakes, while the rest returns to the ocean or, through evapotranspiration, the atmosphere.[146] Throughout this entire course, runoff undergoes a natural treatment process. Conventional stormwater infrastructure uses storm drains to receive the rainfall and conveyance networks to transport the excess water to water bodies in the vicinity, such as the ocean. However, because many of the natural filtering components are altered or completely removed from the manmade systems, runoff often becomes polluted. Some of this polluted runoff flows to the ocean; some remains in the urban environments, collected in pools of standing water, which

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[145] "SWA Group Honored with Rare National First Prize, China's Highest Design Award, for Shenzhen Bay Urban Design, and Additional Award for OCT Bay | Business Wire."

[146] "The Water Cycle, U.S. Geological Survey (USGS) Water Science School," accessed March 30, 2018, https://water.usgs.gov/edu/watercycle.html.

introduces unsanitary conditions to communities and, over time, pollutes the soils that are present.

In Hawai‘i, periodic flooding in urbanized watersheds indicates an impaired water cycle. Impervious surfaces combined with steep elevation changes allow great volumes of water to travel at a fast rate to low-lying, developed coastal areas. Stormwater infrastructures become overwhelmed and water overflows onto the streets. Urbanized streams and canals, significantly small in size, overtop their banks and flood adjacent properties. At lower regions of the watershed, water is likely to be polluted and engrossed with sediment, becoming health hazards. Stormwater infrastructures in Hawai‘i are gradually aging and if rainfall trends become more severe in the future (see discussion in 2.2.1), they will be unable to regulate large quantities of water during prolonged and intense showers. Moreover, the networks close to sea level will be affected by the impacts of sea level rise in the near future. Continuous repairs and maintenance to conventional stormwater infrastructures are costlier than the application of green stormwater management systems in the long run. Depending on the selected system, green stormwater infrastructures may cost more in the beginning, but regular maintenance is more cost-effective over time.

Design Strategies for Green Networks

In order to address the conditions of Hawai‘i's existing stormwater infrastructures—periodic overflows and flooding, non-treatment capabilities—landscape features must be reintegrated into the urban settings. This can be achieved with the implementation of green stormwater management. As previously mentioned (section 2.4.4), these systems are engineered to mimic the process of water filtration and regulation of an unaltered landscape (below).

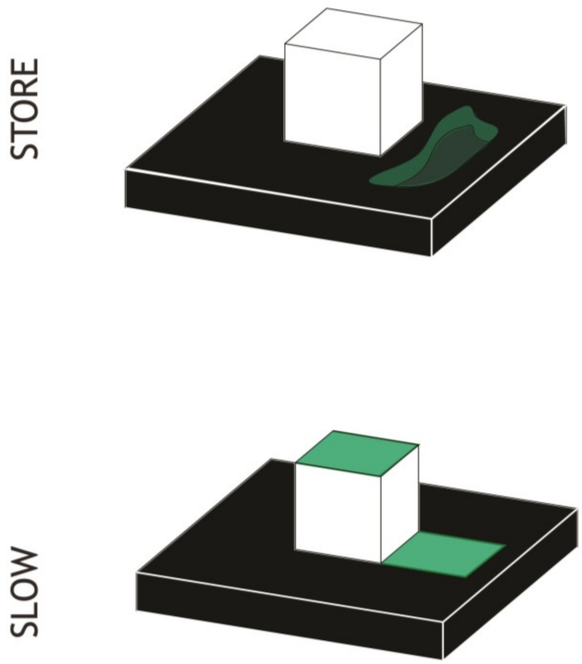

Figure 5.3 Green Networks strategies

Source: Author

Slowing water the moment it falls is one of the primary features of green stormwater management systems. Common measures used to achieve this include green roofs, rainwater harvesting, rain gardens, pervious paving, and bioswales. Water traveling through these systems is naturally filtered. These measures are ideal for highly urbanized areas as they can be placed in underutilized spaces like rooftops, portions of a sidewalks, medians, and parking lots. Pervious paving can be allocated to parking lots of any size. Essentially, these measures are multi-functional; they prevent flooding, filter water, improve the aesthetics of an area, enhance urban ecologies, and more. As discussed in chapter 4, the design of New York City's Sponge Park, at Gowanus Canal, is an example of the capabilities of a green stormwater management system in a limited area. Infiltration swales and remediation wetland basins are strategically located at the ends of the streets, collecting and filtering surface runoff before entering Gowanus Canal. These systems also become an amenity for the neighborhood, reactivating the underutilized public spaces.[147]

Another approach that is complementary to slowing water is the temporary storing of redirected runoff in basins. Basins can accommodate larger quantities of water during peak flows. However, unlike the measures that slow water, basins require more space. They can be incorporated into features that become public amenities for adjacent properties. In Tianjin City's Tianjin Qiaoyuan Park, a series of retention and detention basins regulates and treats stormwater runoff collected from the neighboring apartment complexes; they are also a frequently visited destination and educational tool for locals and visitors.[148]

As previously mentioned, space in Hawai'i is limited but given the flexibility of green stormwater infrastructures and the considerable amount of impervious surface area in the state, there is great opportunity for the strategic implementation of these systems. Measures that focus on slowing waters are primarily addressed at the lot and street scale, while

147

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measures that focus on storing water are typically addressed at the lot and block scale. In order to work effectively, these measures should be allocated across a greater area. Given the unique character of the islands' landscapes, green stormwater infrastructures should be applied intensely throughout the upper tier of the watershed to prevent additional waters downstream.

As previously mentioned, space in Hawai'i is limited but given the flexibility of green stormwater infrastructures and the considerable amount of impervious surface area in the state, there is great opportunity for the strategic implementation of these systems. Measures that focus on slowing waters are primarily addressed at the lot and street scale, while measures that focus on storing water are typically addressed at the lot and block scale. In order to work effectively, these measures should be allocated across a greater area. Given the unique character of the islands' landscapes, green stormwater infrastructures should be applied intensely throughout the upper tier of the watershed to prevent additional waters downstream.

5.3 Placemaking

One of the conclusions in chapter 2 is that floods can have serious impacts on the social aspects of affected communities. Some impacts are direct, such as death, injury, and illness, while others are indirect, occurring over time, such as population displacement, forced changes in lifestyle, and losses to local economies. It is important for flood mitigation strategies to not only address the physical but also the social impacts. Placemaking is a concept whose purpose is to strengthen the relationship between a community and its physical environment. In connection with flooding, placemaking can be used to develop risk reduction and green network strategies into additional amenities that attract people to enjoy and interact safely within flood-prone areas, encouraging ownership of the spaces, and thereby alleviating some of the social impacts.

Design Strategies for Placemaking

Within the precedents detailed in chapter 4, the social conditions of each of the project's constraints are approached in creative ways informing the chosen strategies for placemaking. These strategies include accessibility, density and mixed-use, and recreational and green spaces (below).

Schematic axonometric drawing of flood Hazards in Hawaii

Accessibility pertains to providing multiple layers of transportation at various heights to provide multiple routes of circulation Schematic axonometric drawing of flood Hazards in Hawaii within a flood prone area. The proposed designs of Fostering Resilient Ecological Development (F.R.E.D.), for New York's FARROC (For a Resilient Rockaway) competition, has pathways scattered throughout the site at two levels, ground level and at least two to three stories high. The ground level is designated for vehicles, pedestrians, and bicycles; the second level is for pedestrians only and provides an alternate route during floods and future events related to sea level rise. The second level is also connected to a rail station, thus providing another means of transportation to and from the neighborhood.

Another placemaking strategy is density and mixed-use. Density refers to the concentration of properties within a specified area, while mixed-use pertains to the area's variety of programming. The design precedents F.R.E.D. and HafenCity both reflect the necessity of designing solutions for densely developed floodprone areas. For both projects, the design developments needed to mitigate flooding impacts onsite in order to retain the populations and businesses, with building typologies of medium- to high-density structures. As projects have begun to elevate street levels, different types of zoning— retail, commercial, residences, and industrial— were created throughout the urban developments. Rather than the traditional approach of zoning, mixed-use zoning instills a vibrant and diverse urban environment. Thus, when space is limited but the desire to remain in the area is strong, a good option for minimizing flood loss is to build up.

The final placemaking strategy is recreational and green spaces. This strategy can be used in conjunction with green networks approaches. In the example of Houston's Buffalo Bayou Promenade, the entire urban waterfront area was designated as a recreational and green space for the adjacent neighborhoods. Initially, the space was a polluted and underutilized drainage area for the city. However, it was redesigned to become a linear park, connecting the neighborhoods on each side of Buffalo Bayou. Houston now holds many events throughout the year along the Promenade and it has become a popular spot for visitors and locals alike.

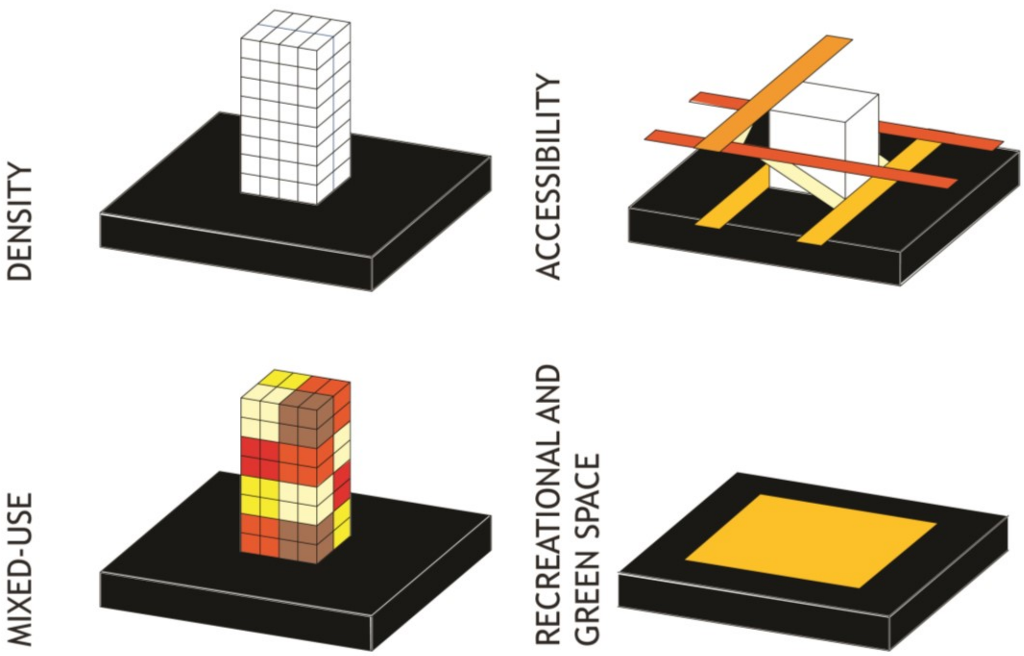

Figure 5.4 Placemaking strategies

Source: Author

5.5 Conclusion

The body of research on the consequences of floods (section 2.3) provided the foundation for the three design principles chosen to address flood resilience in Hawaiʻi—risk reduction, green networks, and placemaking. Designing for flood resilience must address not only the immediate, physical impacts, but also the drainage qualities of the landscape and the social conditions of the affected community. Information on existing mitigation and adaptation strategies (section 2.4) and key lessons gleaned from the design precedents (chapter 4) assisted with establishing relative strategies that fulfill and support the concepts of the developed design principles.

The first principle, risk reduction, addresses the physical implications of floods. It strives to improve the built environment's resilience from the impacts of floodwater through the strategies of retreat, accommodation, and protection. The second principle, green networks, addresses the environmental implications of floods. The overall goal of green networks is to enhance the drainage and ecological qualities of the urban area through the application of green stormwater infrastructures that slow and store runoff more effectively. The final principle, placemaking, pertains to the socio-economic implications of floods. It focuses on redeveloping built environments into flood-resilient, desirable neighborhoods that promote ideal live, work, and play conditions. By executing risk reduction, green networks, and placemaking strategies, the area becomes more resilient to flooding in the future.

The principles, strategies, and measures identified in this chapter guide the final, conceptual design in chapter 7. In order to apply these effectively, an understanding of the site is necessary. A site inventory was conducted to establish the area's constraints and opportunities. Chapter 6 details the information collected from the inventory of Māpunapuna, and discusses the strategies and measures of the three flood resilience design principles in relation to the findings.

CHAPTER 6: MĀPUNAPUNA

Understanding the site is fundamental to the development of a design solution. The information gathered provides details on the site's opportunities and limitations that inform the designer's decision-making. Section 2.5 presents existing flood mitigation and adaptation strategies and measures, emphasizing the importance of implementing them based on site conditions. Inappropriate application of these strategies not only reflects poor decision-making but also a lack of regard for potential future conditions and the surrounding environments. The conceptual and built precedents detailed in chapter 4 provide examples of the execution of these design strategies and measures. In each project, the design problems were addressed based on past, present, and future conditions. In the case of Living Breakwaters, design solutions reflected the possibility of future storm surges; in HafenCity, solutions involved anticipated overflows from the neighboring river.

Māpunapuna was selected for this design dissertation due to frequent flooding conditions, the effects of sea level rise, and its surrounding context. The 192-acre site is located within the Moanalua watershed (Figure 6.1). It is part of an industrial and business district surrounded by residential neighborhoods, military lands, and other industrial districts. Before choosing flood mitigation and adaptation strategies for the site, a site inventory of its conditions, including land use and ownership patterns, physical environment, flooding hazards, transportation, and sewage and stormwater infrastructure, was conducted in order to comprehend potential design opportunities and constraints.

6.1 Land Use and Ownership Patterns

The information in this section is adapted from Cultural Surveys Hawai'i's *Addendum to an Archaeological Inventory Survey Plan for the Airport (Phase 3) Construction of the Honolulu High-Capacity Transit Corridor Project Halawa and Moanalua Ahupuaa, Ewa and Honolulu Districts*.

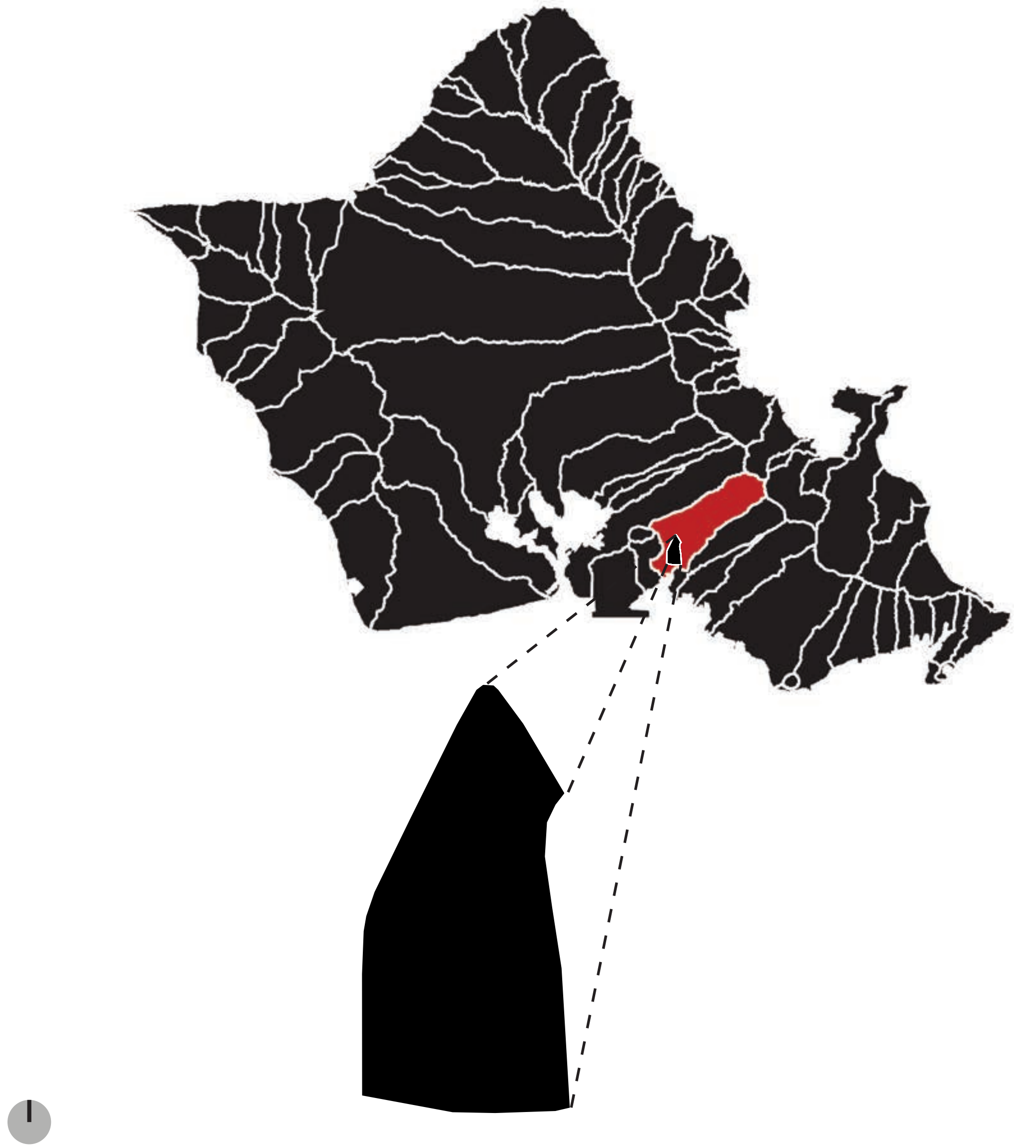

Figure 6.1: Site location on Oahu
Source: Hawaii GIS Statewide, Graphic: author

Like many of the ancient ahupuaʻa, or Hawaiian land divisions, much of Moanalua's landscape is dramatically different today than it was. Currently an urbanized neighborhood, Moanalua was once a self-sustaining land maintained by the Native Hawaiians. According to various foreigners' depictions, Moanalua was an abundant landscape, encompassing most of the physical components of the ideal ahupuaʻa; it had forested uplands, low-lying coastal plains imprinted with village structures and a variety of crops (e.g., banana trees, sugar cane, taro), and shores lined with fishponds.[149] Figure 6.2 shows a sketch of land uses throughout the ahupuaʻa assembled from the records of Otto von Kotzebue, a Russian sailor, during his visit in 1816. During this period, irrigated fields (lo'i) and huts (hale) were situated around Moanalua Stream, slowly tapering off upstream. Numerous fishponds (loko-kua) were located along the shore near Moanalua Stream's natural mouth, which is much more inland compared to the existing location.

Overall, the ancient ahupuaʻa throughout the Hawaiian Islands were consistently plentiful due to the communal stewardship of the land. Dr. Carlos Andrade, former professor of Hawaiian Studies at the University of Hawaiʻi at Mānoa, describes the Native Hawaiian's land management system as follows:

> In ancient Hawaiʻi, ʻaina (land) was the most revered natural resource. As Hawaiians used the abundant natural resources within their ahupuaʻa (ancient land division), they practiced aloha (respect), laulima (cooperation), and malama (stewardship) which resulted in a desirable pono (balance). This is the sound resource management where the interconnectedness of the clouds, the forests, the streams, the fishponds, the sea, and the people is clearly recognized.[150]

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[149] Cultural Surveys Hawaii, "Addendum to an Archaeological Inventory Survey Plan for the Airport (Phase 3) Construction of the Honolulu High-Capacity Transit Corridor Project Halawa and Moanalua Ahupuaa, Ewa and Honolulu Districts, Oahu Island TMK Sections [1] 1-1 and 9-9," 2013, 42.

[150] "Distinguished Fellows Program," Hawaiian Islands Land Trust, accessed March 13, 2018, http://www.hilt.org/na-koa-aina/.

Figure 6.2: Kotzebue's sketch of land use in the ancient ahupuaa of Moanalua during 1816.
Source: Cultural Surveys Hawaii, Graphic: adapted from Cultural Surveys Hawaii

In 1848, the entire Moanalua ahupuaʻa was inherited by Lot Kamehameha, eventually King Kamehameha V (Figure 6.3).[151] Around this time, the Māhele act was passed which permitted private land ownership for the first time. After Lot Kamehameha's death in 1872, the ahupuaʻa was inherited by various entities over the next twelve years—Princess Ruth Keʻelikōkalani (1872-1883), Princess Bernice Pauahi Bishop (1883-1884), and finally Samuel M. Damon, through Bishop's will. Damon's inheritance of the ahupuaʻa spurred an upset within the Native Hawaiian community as Kuleana lands, or "parcels granted to native Hawaiian tenant farmers between 1850 and 1855," were bought and used for pasture, rice, sugar, and banana crops," instead of returning the land back to the native Hawaiians. [152] Throughout the 1900s, Damon retained ownership of the land as numerous industries were developed and lands altered. After his death in 1924, the Damon Estate trust was created to manage the family's properties. In 1927, John Rogers Airport, now the Daniel K. Inouye International Airport, was built on a part of the Moanalua ahupuaʻa, an area once covered in sugar cane fields and salt works. Simultaneously, the Navy began dredging the Pearl Harbor channel to remove a sand bar and improve access for development efforts.[153] When comparing maps of Pearl Harbor in 1943 and 1953, Cultural Surveys Hawaiʻi speculates the dredged material may have been used to fill lands at the airport, Keʻehi Lagoon, and Māpunapuna (Figure 6.4, Figure 6.5).[154] By the 1970s, development within Moanalua had gradually transformed the land into a combination of residential, commercial, and industrial neighborhoods, which remains relatively the same today. At the turn of the millennium, part of the land changed hands again. In 2003, Damon Estates sold 224 acres of property to HRPT Properties Trust, a Massachusetts-based company, for $480 million. The acquired lands included properties between Honolulu Harbor and

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[151] "Addendum to an Archaeological Inventory Survey Plan for the Airport (Phase 3) Construction of the Honolulu High-Capacity Transit Corridor Project Halawa and Moanalua Ahupuaa, Ewa and Honolulu Districts, Oahu Island TMK Sections [1] 1-1 and 9-9," 44.
[152] Ibid., 50.
[153] Ibid., 52.
[154] Ibid.

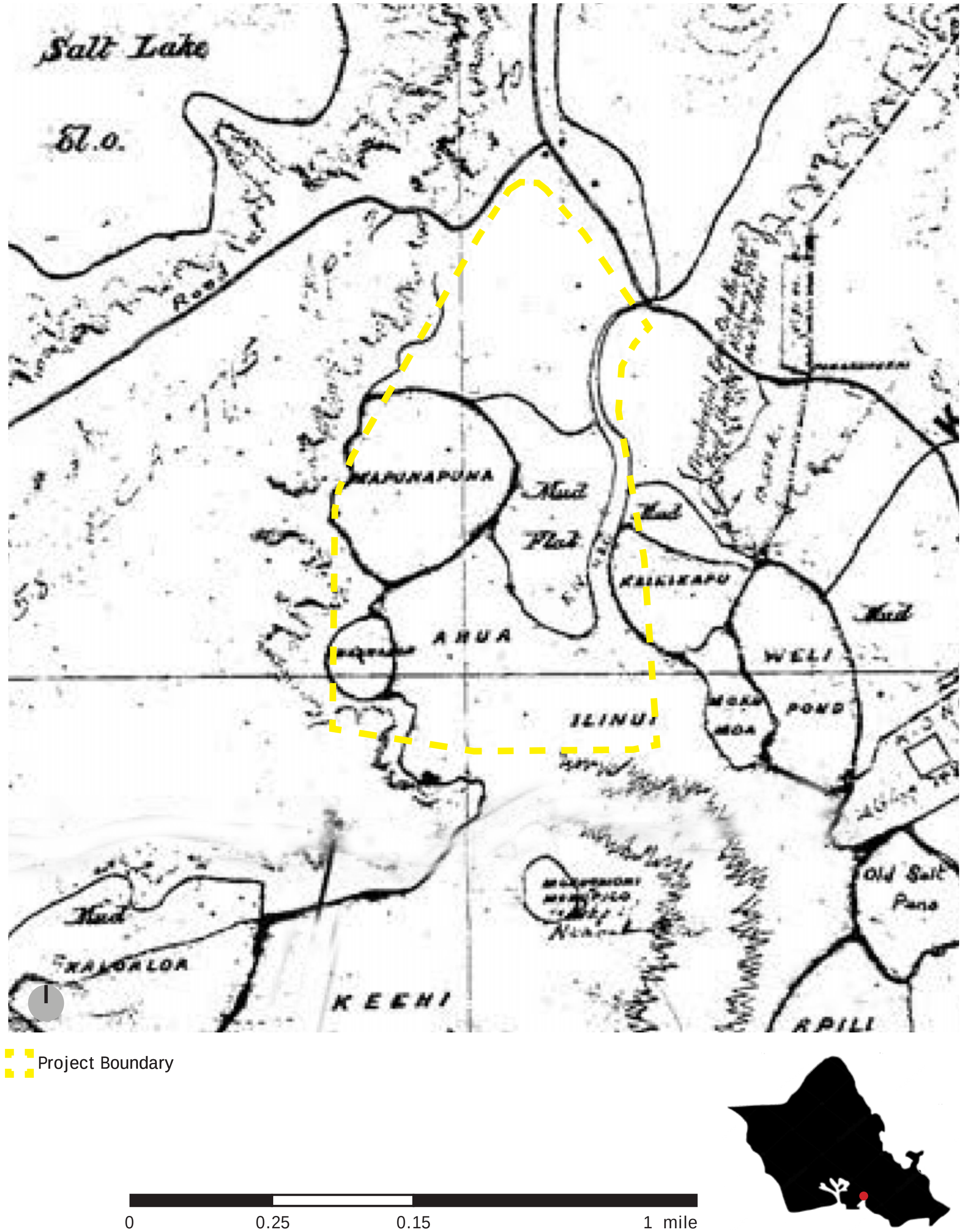

Figure 6.3: Landscape features of Māpunapuna during 1890.
Note the existence of fishponds further inland from Keehi Lagoon.
Source: Cultural Surveys Hawaii, Graphic: adapted from Cultural Surveys Hawaii

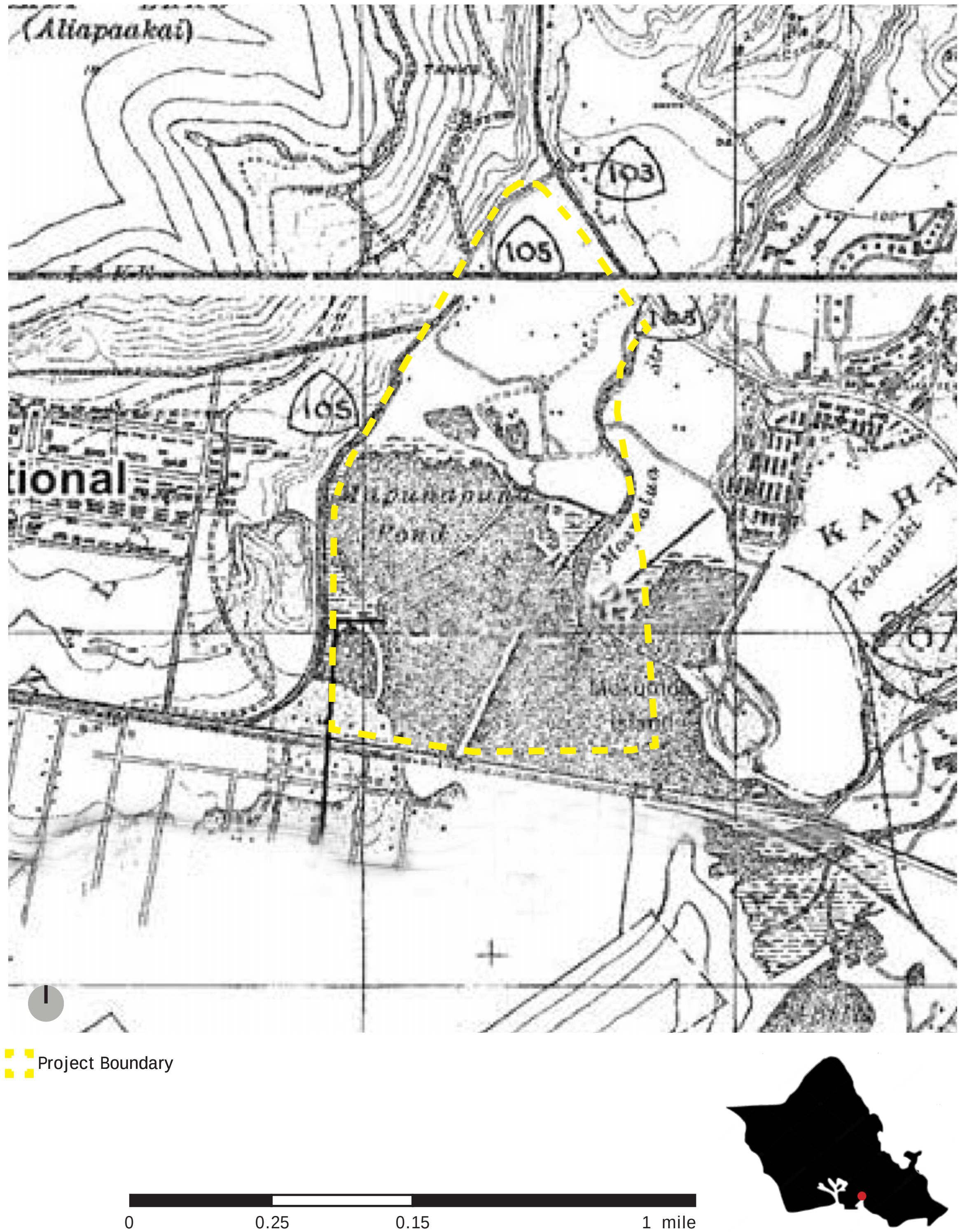

Figure 6.4: Landscape features of Māpunapuna in 1943. Fishponds remain in Māpunapuna, but areas south of the area filled in.
Source: Cultural Surveys Hawaii, Graphic: adapted from Cultural Surveys Hawaii

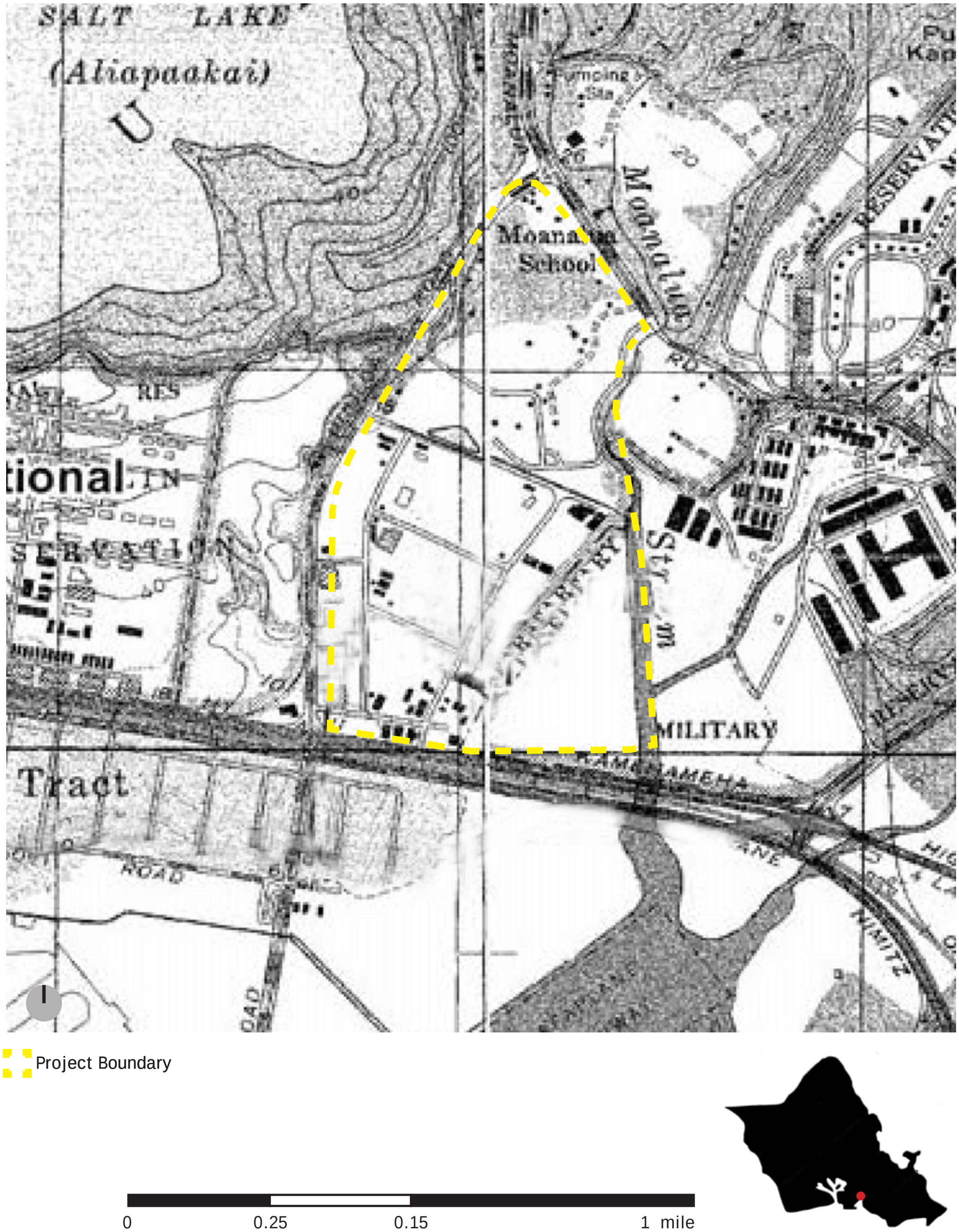

Figure 6.5: Landscape features of Māpunapuna in 1953.
Fishponds in Māpunapuna are filled in and used for development.
Source: Cultural Surveys Hawaii, Graphic: adapted from Cultural Surveys Hawaii

Honolulu International Airport representing approximately 137 tenants with 186 separate leases, each with an average remaining period of about twenty-two years. About 150 acres of this publicized deal were located in Māpunapuna.[155] As leases expire, properties developed, warehouses transformed into shopping centers, HRPT Properties Trust expects land value to increase.[156] Figure 6.6 shows major landowners in Māpunapuna, the largest portions belonging to HRPT Properties Trust, state entities, and the City and County of Honolulu. Māpunapuna's urban industrial character is influenced by zoning designations at the state, and city and county levels. At the state level, most of the lower regions of Moanalua are designated as urban, for "'city-like' concentrations of people, structures, services," while the uplands are designated conservation land, "existing forest and water reserve zones" (Figure 6.7).[157] At the city and county level, primary zoning categories include residential (north), industrial (south), commercial (central), and military (east and west) districts. The residential zones range from low to medium density districts (Moanalua Valley, Salt Lake, and Fort Shafter). Military zones consist of housing in the west and base facilities in the east. Compared to the surrounding neighborhoods in the aerial, the industrial zone of Māpunapuna is distinct' the scale of its buildings' footprints contrast greatly with adjacent residences and commercial buildings. The immediate area of Māpunapuna contains two districts (Figure 6.8). The larger of the two is classified as industrial (I-2). Industrial areas are sectioned off to protect residents and prevent unnecessary competition for other non-industrial businesses. Uses include manufacturing, refining, sorting, processing, and storage of materials and products. I-2 is specifically for a

> …full range of industrial uses necessary to support the city. It is intended for areas with necessary supporting public infrastructure, near major transportation systems and with other locational characteristics necessary to support industrial centers. It shall be

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[155] "Damon Estate Puts Commercial Land up for Sale," Pacific Business News, accessed March 19, 2018, https://www.bizjournals.com/pacific/stories/2003/06/30/daily49.html.
[156] "Damon Estate's Land Sale Completed | The Honolulu Advertiser | Hawaii's Newspaper," accessed March 19, 2018, http://the.honoluluadvertiser.com/article/2003/Dec/06/bz/bz04a.html.
[157] "Land Use Commission | State Land Use Districts," accessed March 13, 2018, http://luc.hawaii.gov/about/state-land-use-districts/.

located in areas away from residential communities where certain heavy industrial uses would be allowed.[158]

The smaller, northern parts of Māpunapuna are zoned for business (B-2). These areas are designated for activities that support the economic development of the city. B-2 is meant to

> …provide areas for community-wide business establishments, serving several neighborhoods and offering a wider range of uses than is permitted in the B-1 district. The intent is to apply this district to areas conveniently accessible by vehicular and pedestrian modes and served by adequate public facilities. Typically, this district would be applied to lots along major streets and in centrally located areas in urban and urban fringe areas.[159]

The existing businesses in this zone include restaurants, banks, car dealerships, craft material shops, office supply stores, and small office buildings. While these address the needs of adjacent industrial companies, they do not effectively accommodate nearby residential neighborhoods in the north like Moanalua and Fort Shafter.

Future development near Māpunapuna includes the Lagoon Drive station of the Airport Area Transit-Oriented Development (TOD) plan. According to the *Airport Area: Transit-Oriented Development Plan Community Workshop #3 Summary*, the overall intent of the proposed rail station is for it to be an "employment-focused TOD area providing convenient access to jobs located in the Waiwai Loop district, Airport industrial corridor and Māpunapuna industrial area."[160] To fulfill Lagoon Drive Station's intent, some adjustments were made to the area's current zoning designations (Figure 6.9). Properties abutting Lagoon Drive, Puuloa Road, and Nimitz Highway are proposed to be zoned Mixed-Use Industrial to "provide for areas of diversified business and employment opportunities by permitting a broad range of uses, without exposing nonindustrial uses to unsafe ad unhealthy

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[158] City and County of Honolulu, "Revised Ordinances of Honolulu 1990: Article 3. Establishment of Zoning Districts and Zoning District Regulations," October 17, 2017, 22.
[159] Ibid., 19-20.
[160] AECOM and City and County of Honolulu, "Airport Area Transit-Oriented Development Plan: Existing Conditions Report," August 2015.

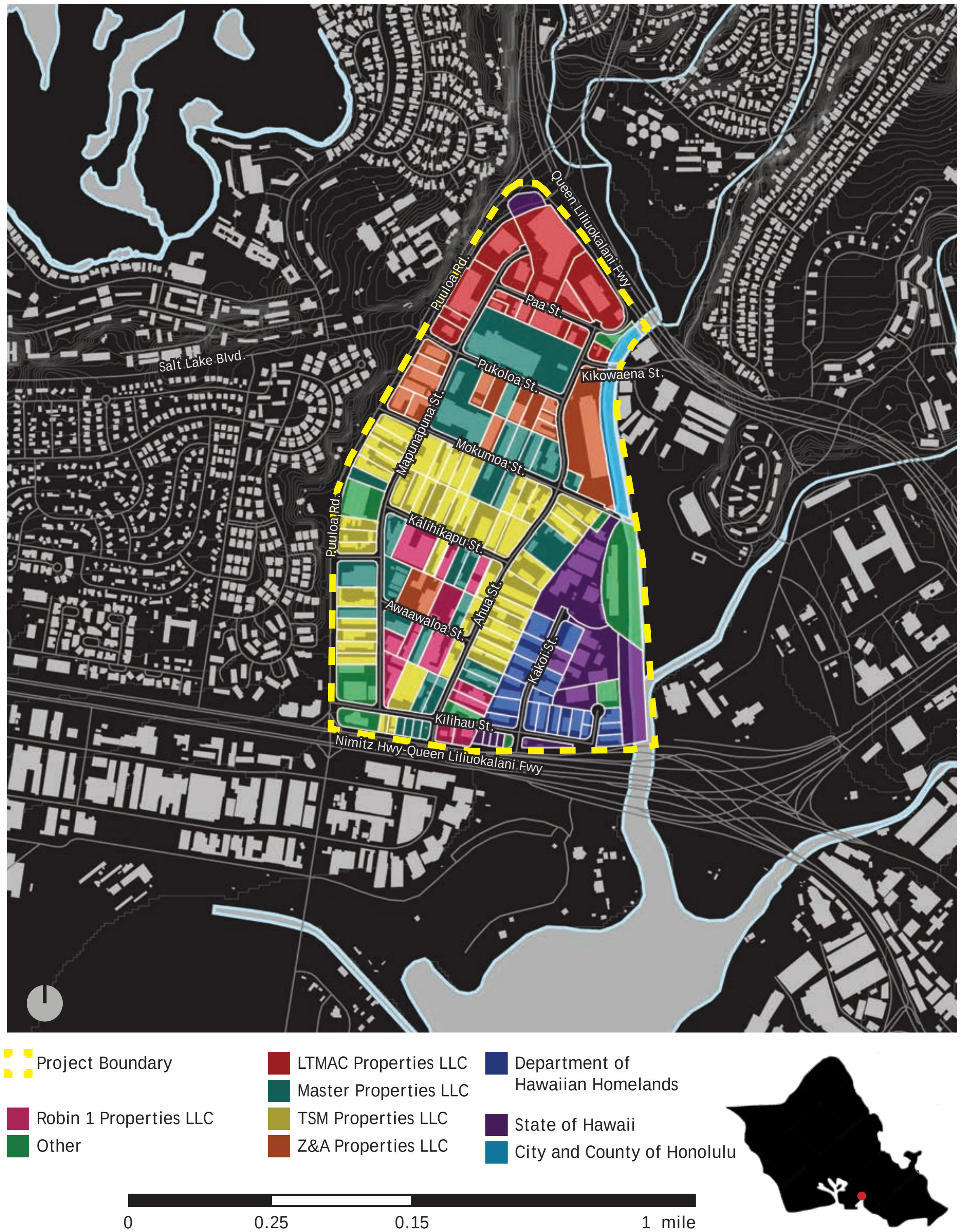

Figure 6.6: Major landowners
Source: Hawaii GIS Statewide, Graphic: author

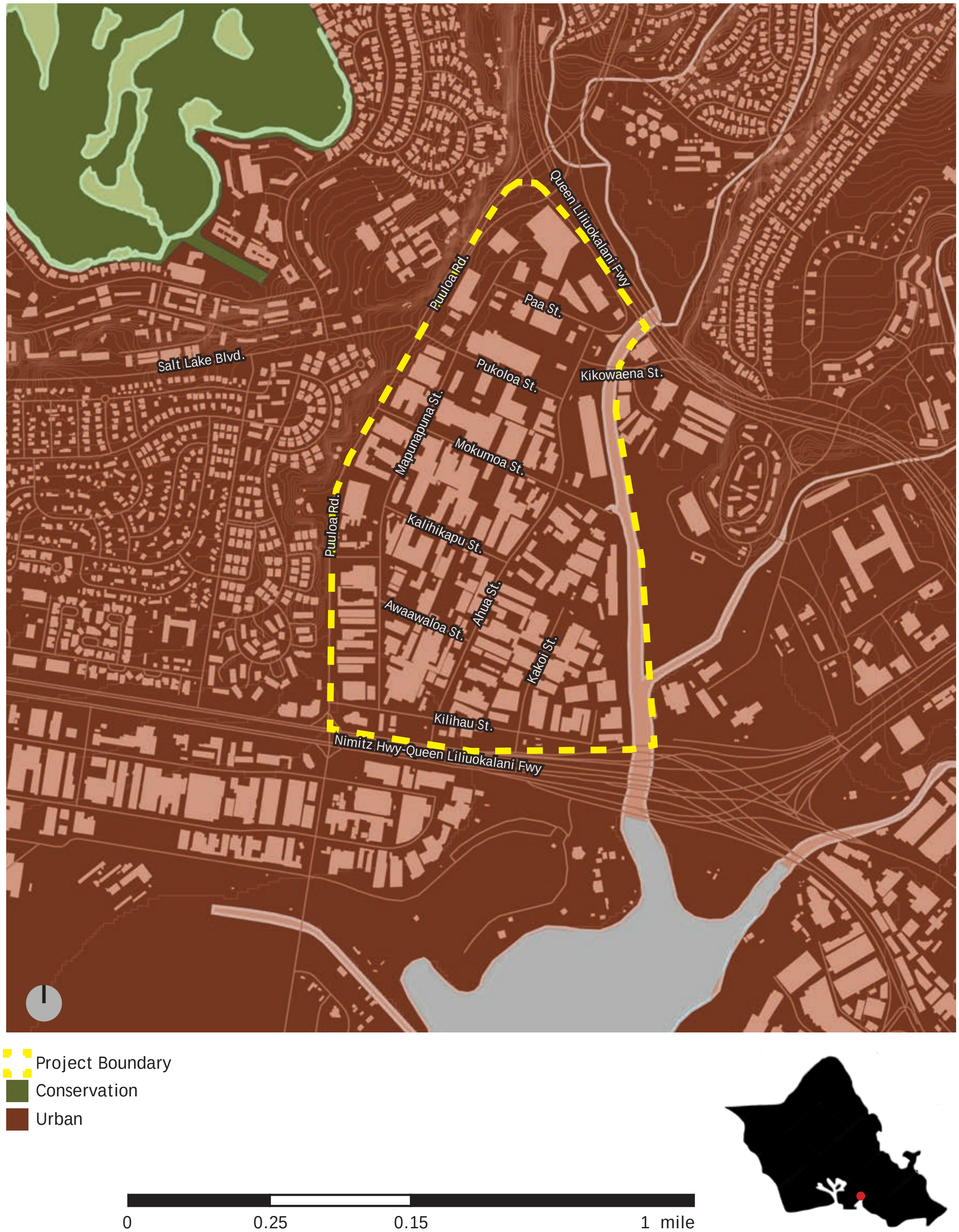

Figure 6.7: State land use districts
Source: Hawaii GIS Statewide, Graphic: author

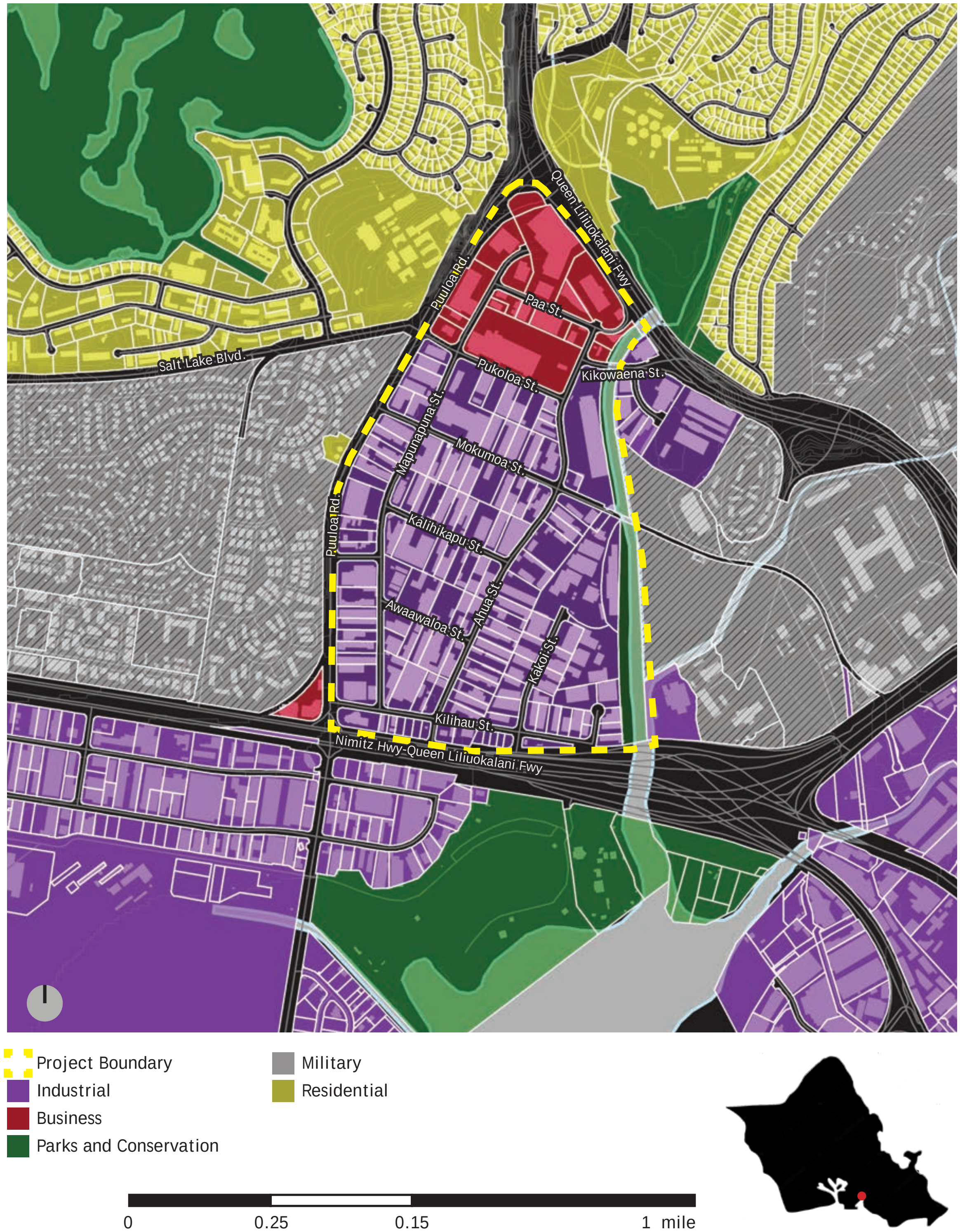

Figure 6.8: Land use zoning designations
Source: Hawaii GIS Statewide, Graphic: author

Figure 6.9: Lagoon Drive Station Area Proposed Land Use/Zoning
Source: AECOM, Graphic: adapted from AECOM

Figure 6.10: Warehouses in Mapunapuna
Source: author

environments."[161] An illustrative plan was also developed to demonstrate how the suggested zoning would affect the urban form (Figure 6.11). Most of the proposed urban forms are located along Lagoon Drive and are mixed-use commercial, mixed-use industrial, and retail and include designated parking areas, a plaza, and pathways. There are no proposed physical changes to neighboring properties. However, as previously mentioned, HRPT Properties Trust expects an increase in land value as leases begin to expire in about seven years.

Throughout its history, Māpunapuna has always been a center of lively activity. Maintaining similar trades within the vicinity allows similar industries to support one another; however, a concentration of this type may also have long-term adverse effects such as poor soil, water, and air conditions, and limited amenities for neighboring regions. Perhaps of even greater importance is the risk inherent in critical industries near the coast in exacerbating flood hazard conditions. Considerations such as deciding what should stay and what should be removed, as well as changes in land use are important for the conceptual design portion of this project.

[161] "Revised Ordinances of Honolulu 1990: Article 3. Establishment of Zoning Districts and Zoning District Regulations," 23.

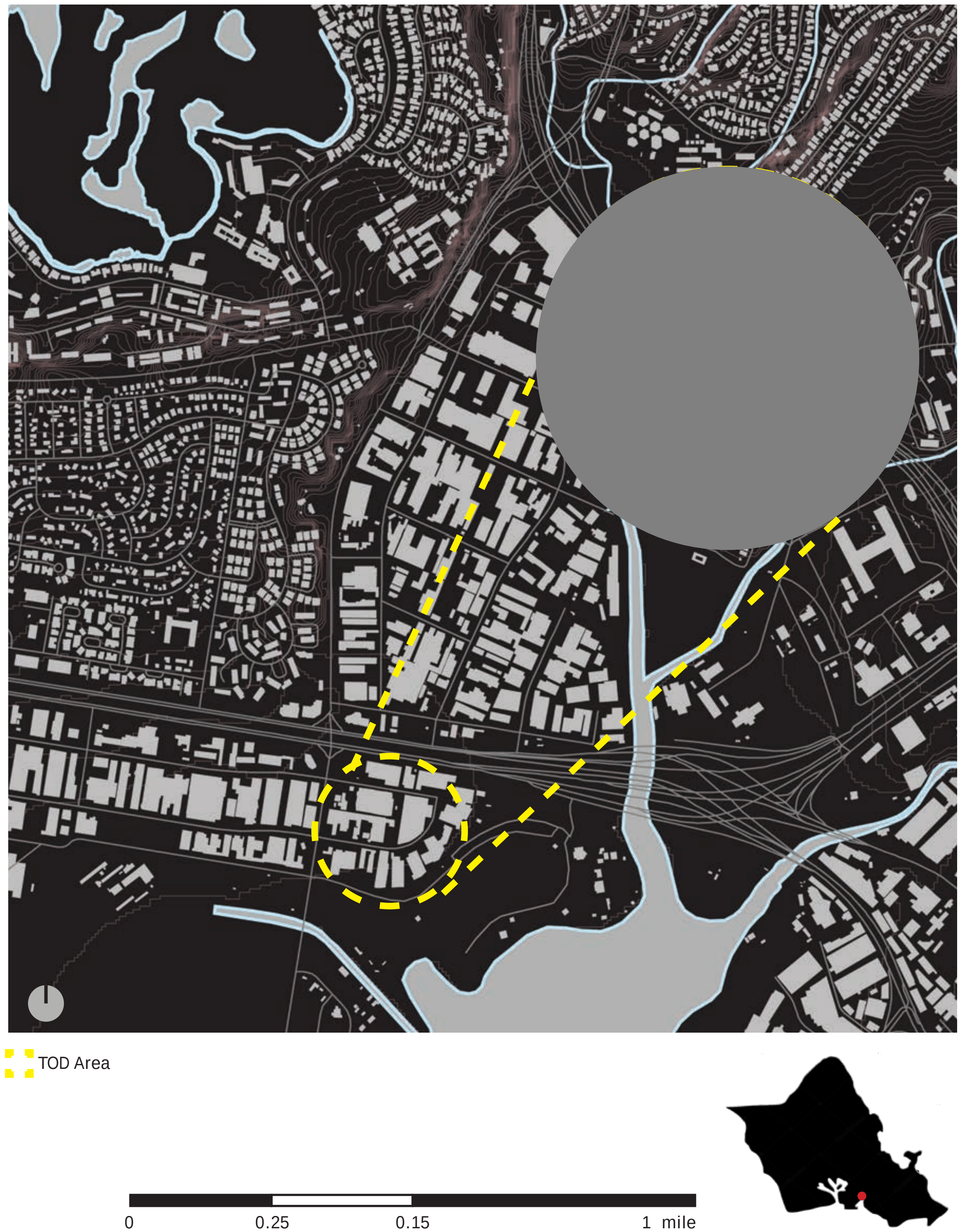

Figure 6.11: Lagoon Drive Station area illustrative plan
Source: AECOM, Graphic: adapted from AECOM

6.2 Physical Environment

Māpunapuna is relatively flat and essentially at sea level. The lowest point of the site is Moanalua Stream's bed, slightly below sea level, and the highest elevation is roughly thirteen feet along Puuloa Road (Figure 6.12). The area receives a moderate amount of annual rainfall. However, Māpunapuna often collects an ample volume of rain during the winter months (November-March) (Figure 6.13). As previously stated, the site's present landscape features are the result of land development from the early 1900s. Flat topographies at low elevations near the coast accrue, over time, issues with drainage and vulnerability to flooding, sea level rise, storm surges, and tsunamis (see section 6.3).

Key water features include Moanalua Stream, along Māpunapuna's eastern border, and Keehi Lagoon, south of Nimitz Highway (Figure 6.12). The stream has little grade change in the north-south direction and is relatively calm with currents influenced by local tidal levels. This portion of the stream transitions between fresh water, brackish water, and seawater. Due to the minimal grade change, the buildup of sediment often occurs near Kikowaena Street and at the confluence of Moanalua and Kahauiki Streams. The stream's edges vary throughout its entirety, ranging from an armored embankment in the north to vegetation in the south. Public access to the stream is completely blocked off by various public and private entities. According to the *Geology, Soils, Farmlands, and Natural Hazards Technical Report* prepared in 2008 for the City and County of Honolulu, "groundwater is approximately 10 feet below the ground surface" throughout the general area of Māpunapuna.[162]

As previously indicated, Māpunapuna's existing landscape is in part the result of landfill development from the first half of the twentieth century. Cultural Surveys Hawai'i notes the lack of documentation on the origin and composition of the fill, but speculates it derived from

[162] City and County of Honolulu, "Geology, Soils, Farmlands, and Natural Hazards Technical Report: Honolulu High-Capacity Transit Corridor Project," October 16, 2008.

the development of Pearl Harbor.[163] According to the technical report, “the geology consists generally of artificial fills placed over thick marine deposits. Below 80 to 150 or more feet of soft material lie sand, coral, and silty clays.”[164] Table 6.1 provides a summary of Māpunapuna’s soil characteristics based on information from Hawaiʻi Soil Atlas; Figure 6.14 illustrates the location of each soil classification.

Several site visits and studies of aerial imagery confirm that Māpunapuna is mostly covered with impervious surfaces, and vegetation is scarce (Figure 6.15). Existing vegetation is limited to ornamental landscape designs (e.g., lawns and shrubs) and weeds and trees (e.g., monkeypod and plumeria). There are patches of tidal marsh species along the eastern edge of the site, influenced by the brackish water environment. Relatively low vegetated land cover contributes to many environmental issues such as increased temperatures, insufficient drainage, poor air and water quality, and flooding. Some speculate that there are low vegetation concentrations at Māpunapuna due to existing land use impacts and soil quality; most of the classified soil types have reduced fertility and high permeability qualities. This could also be affected by the site’s increased exposure to seawater and raised groundwater tables from sea level rise. The introduction of more green spaces in Māpunapuna can be a useful design opportunity, but the site’s limiting factors—reduced soil fertility, high permeability, exposure to seawater, and raised groundwater levels—must be taken into consideration.

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[163] “Addendum to an Archaeological Inventory Survey Plan for the Airport (Phase 3) Construction of the Honolulu High-Capacity Transit Corridor Project Halawa and Moanalua Ahupuaa, Ewa and Honolulu Districts, Oahu Island TMK Sections [1] 1-1 and 9-9,” 52.
[164] “Addendum to an Archaeological Inventory Survey Plan for the Airport (Phase 3) Construction of the Honolulu High-Capacity Transit Corridor Project Halawa and Moanalua Ahupuaa, Ewa and Honolulu Districts, Oahu Island TMK Sections [1] 1-1 and 9-9.”

Figure 6.12: Topography and water features
Source: Hawaii GIS Statewide, Graphic: author

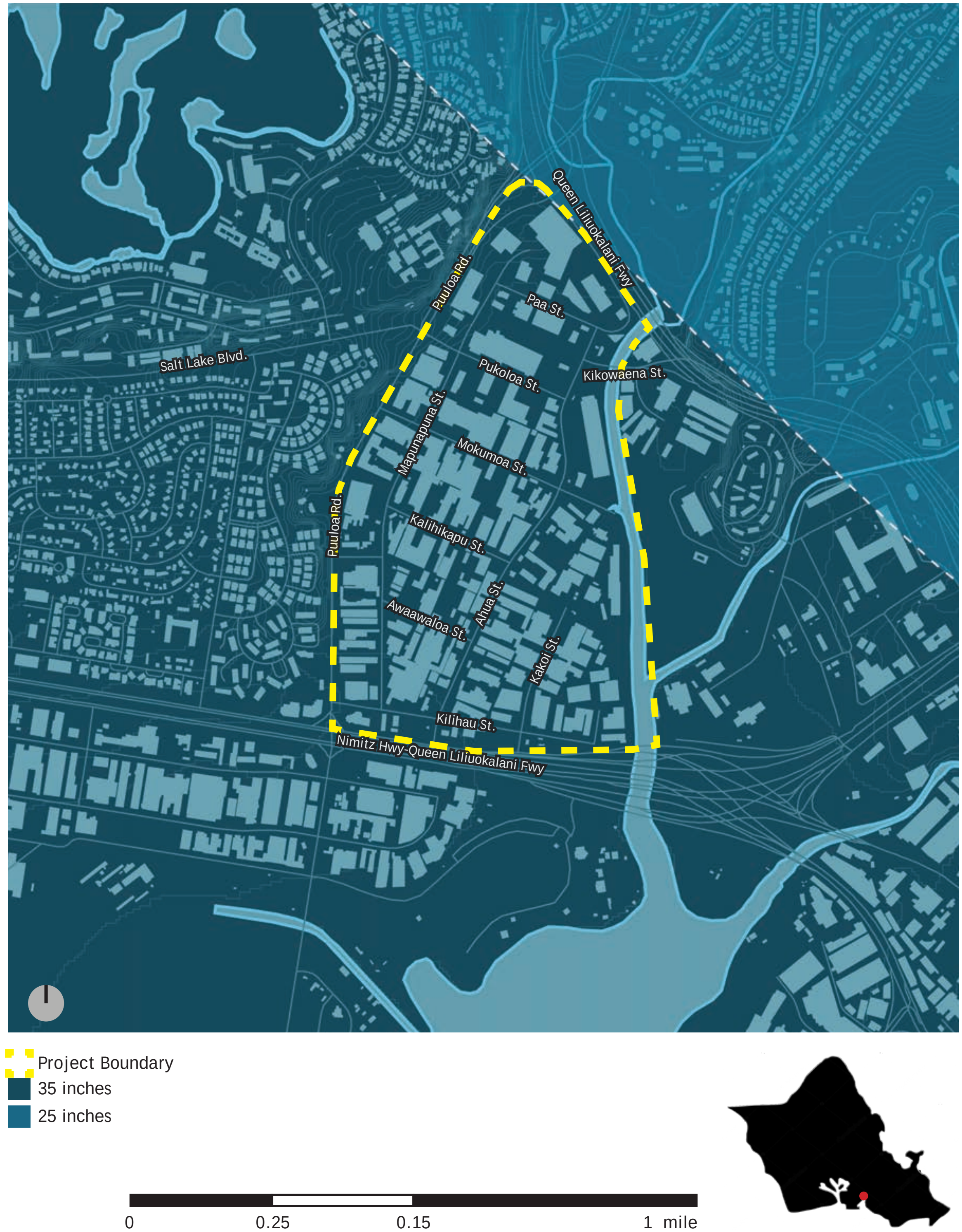

Figure 6.13: Mean annual rainfall patterns
Source: Rainfall Atlas of Hawaii, Graphic: author

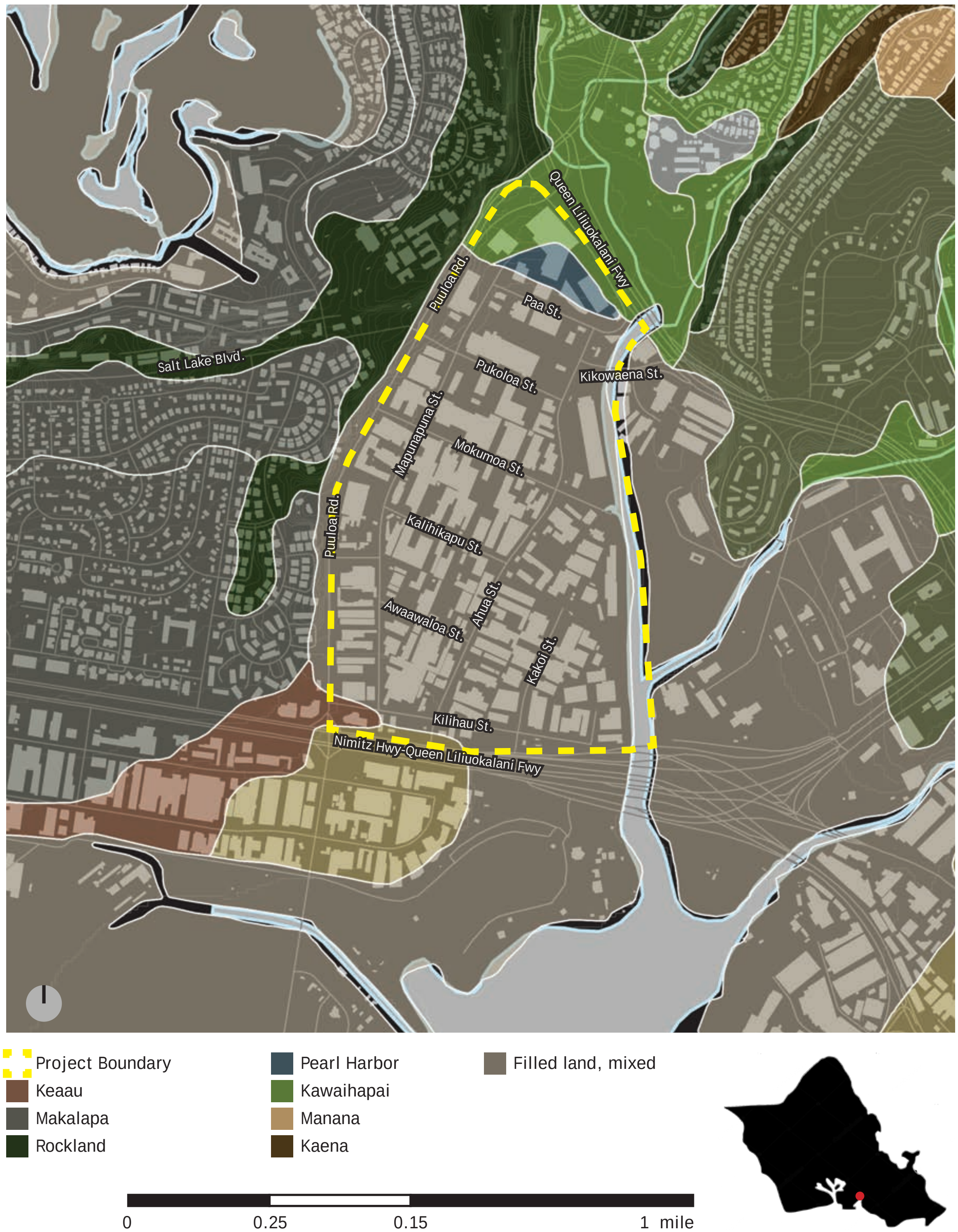

Figure 6.14: Soil types
Source: Hawaii Soil Atlas, Graphic: author

Table 6.1 Soil description in Māpunapuna

	FILLED LAND	PEARL HARBOR	KAWAIHAPAI
Location	These lands are generally found on coastal, low-lying areas on Kaua'i, O'ahu, and Maui, and were once used for disposal of dredging, garbage, and old sugar mill waste. They are now urban.	This very poorly-drained soil is found on coastal flats around O'ahu. This soil is well-suited and still cultivated for wetland taro production on the windward side of O'ahu, but it has been urbanized on the south and north coasts.	This productive soil is found along coastal plains and stream banks on O'ahu and Moloka'i. This soil is well-suited and used for diversified farming, flooded agriculture, and pasture on both islands.
Water	Moderate water holding capacity. Extremely fast permeability.	Moderate water holding capacity. Soil saturated with water for part of the year. Very slow permeability, thus prone to flooding. Brackish water table and peat layer reached at less than 1 meter deep.	High water holding capacity. Moderate permeability. Dry conditions in some areas require irrigation.
Fertility	Naturally infertile (Fertility Class= Other). Moderate nutrient holding capacity	Fertile (Fertility Class= Fertile). High nutrient holding capacity. Well-supplied in calcium, magnesium, and potassium.	Very fertile (Fertility Class= Fertile). High nutrient holding capacity. Well-supplied in calcium, magnesium, and potassium.
Structure	Moderate physical structure. These lands are suitable and often used for urban development.	Swells when wetted and shrinks when dried, which creates cracks and unstable conditions for construction over time. Additions of organic matter can improve soil tilth. Flooded conditions make engineering and cultivation difficult.	Swells slightly when wetted and shrinks when dried, which creates cracks and unstable conditions for construction over time. Sticky nature upon wetting makes cultivation difficult. Additions of organic matter can improve soil tilth.
Taxonomy	Ustorthents	Fine, halloysitic, isohyperthermic Thapto-Histic Endoaquolls	Fine-loamy, mixed, superactive, isohyperthermic Cumulic Haplustolls

Sources: Data from Hawai'i Soil Atlas.

Figure 6.15: Land cover
Source: NOAA, Graphic: author

Figure 6.16: Vegetation in Mapunapuna
Source: author

6.3 Flooding Hazards

According to the Federal Emergency Management Agency (FEMA), a majority of Māpunapuna falls into different Special Flood Hazard Area (SFHA) zones (Figure 6.17). An SFHA is an "area that will be inundated by the flood event having a 1-percent change of being equaled or exceeded in any given year. The 1-percent annual chance flood is also referred to as the base flood or 100-year flood."[165] Table 6.2 briefly describes each zone in Māpunapuna. Other flood zones that are more moderate than SFHAs are Zone B or Zone X (shaded). These are "the areas between the limits of the base flood and the 0.2-percent-annual-chance (or 500-year) flood."[166] Overall, the immense coverage of SFHAs is indicative of Māpunapuna's vulnerability to various types of floods. Simulation models from NOAA's Sea Level Rise Viewer and the Pacific Islands Ocean Observing System (PacIOOS) Voyager support this conclusion; the models show the site's susceptibility to floods from tsunamis, storm surges, and the onset of sea level rise.

As discussed in chapters 2 and 3, a site's level of vulnerability to floods can be influenced by a number of factors. The first and primary factor for Māpunapuna is the density of urban development near the shore. Encroachment in densely urbanized flood-prone areas is likely to cause devastating impacts on the built environment and to the local populations. Another factor is the site's position in the lower region of the watershed. These regions have significantly higher water tables, often with poor drainage quality. Highly urbanized areas with large concentrations of impervious surfaces also worsen drainage conditions. During heavy and prolonged rainfall events, it is likely that the rainfall will overwhelm stormwater management systems, especially if they are not well-maintained or are outdated. Figure 6.18 illustrates the current tsunami evacuation and safe zones. Properties along the banks of Moanalua Stream are most susceptible to the effects of a tsunami when the

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165 "Flood Zones | FEMA.Gov," accessed March 13, 2018, https://www.fema.gov/flood-zones.
166 Ibid.

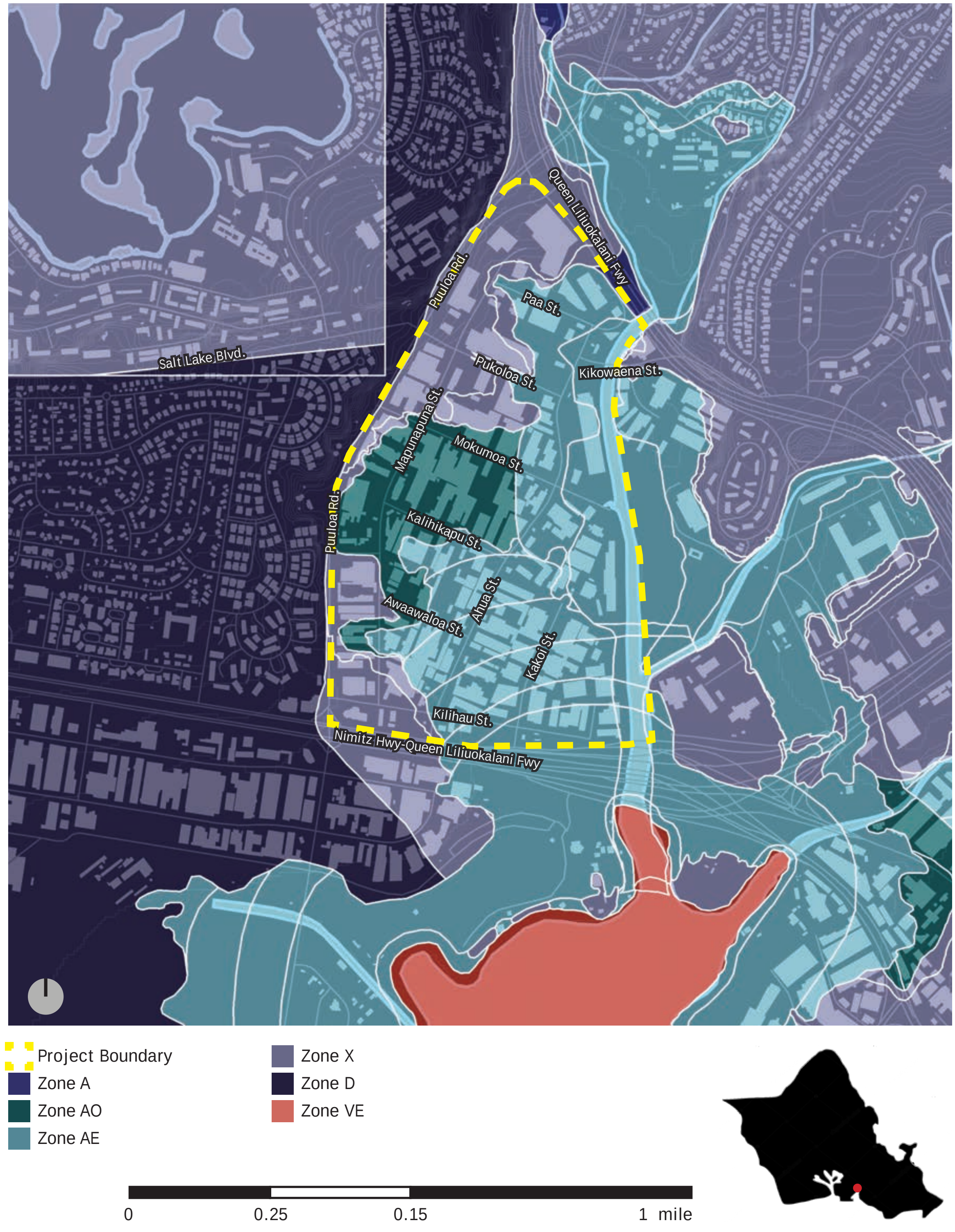

Figure 6.17: Flood hazard areas
Source: Hawaii GIS Statewide, Graphic: author

Table 6.2 FEMA's Flood Insurance Rate Map (FIRM) Flood Zones

FIRM ZONE	DESCRIPTION	LOCATION
Zone A	No Base Flood Elevation (BFE) determined.	• NE area of Māpunapuna.
Zone AE	BFE determined.	• E and SE areas of Māpunapuna • all of Keehi Lagoon • areas near the start of Lagoon Drive.
Zone AO	Flood depths of 1 to 3 feet (usually sheet flow on sloping terrain); average depths determined.	• Mid-W area of Māpunapuna.
Zone VE	Coastal flood zone with velocity hazard (wave action); BFE determined.	• Shoreline edge of Keehi Lagoon, Lagoon Drive and Moanalua Stream (south of Nimitz Freeway).
Zone AEF	Floodway areas in Zone AE. The floodway is the channel of stream plus any adjacent floodplain areas that must be kept free of encroachment so that the 1% annual chance flood can be carried out without increasing the BFE.	• Edges of Moanalua Stream; there is larger coverage on the northern parts.
Zone XS (X shaded)	Areas of 0.2% annual chance flood; areas of 1% annual chance flood with average depths of less than 1 foot or with drainage areas less than 1 square mile; and areas protected by levees from 1% annual chance flood.	• Mid-W and NW of Māpunapuna.
Zone X	Coastal flood zone with velocity hazard (wave action); BFE determined.	• SW and NW of Māpunapuna.

Source: DLNR - Flood Hazard Assessment Tool

Figure 6.18: Tsunami safe and evacuation zones
Source: Hawaii GIS Statewide, Graphic: author

stream's tidal levels are higher than normal. During extreme cases, most of the site requires evacuation. Nevertheless, because Māpunapuna is located slightly inland, records show that much of a tsunami's energy dissipates by the time it reaches the site. Māpunapuna is also protected by several other wave-attenuating mediums such as the small islands and coral reefs in Keehi Lagoon, beach areas at Keehi Lagoon Beach Park, and structures along the Nimitz Highway and Queen Liliuokalani Freeway. Designated safe zones are located north of Interstate H-1 and west of Puuloa Road.

Chapter 3 discusses how sea level rise can influence floods in the lower coastal regions of Hawaiʻi, causing permanent inundation in time. Current sea level rise data from NOAA's Sea Level Rise Viewer shows a rise of six feet with mean high-high waters. However, existing sea level rise literature indicates that it is plausible for the rise to be as high as eight feet by the end of the century.[167] It is important to note that the effects of sea level rise will continue and grow if no climate change adaptation actions are taken and no mitigating efforts made.[168]

Projected inundation influenced by a(n) one to two feet increase of sea level rise begins at the intersection of Ahua Street and Kilihau Street (Figure 6.19, Figure 6.20). During three feet increase, the affected area expands to neighboring blocks (Figure 6.21). By the time sea level rise increases by four to six feet, areas bordered by Mokumoa Street and Māpunapuna Street become permanently inundated (Figure 6.22, Figure 6.23, Figure 6.24). At the moment, some businesses in the southern parts of the district are threatened by flooding during high tides.

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[167] Sweet et al., "Global and Regional Sea Level Rise Scenarios for the United States."
[168] "Sea Level Rise Vulnerability and Adaptation Report."

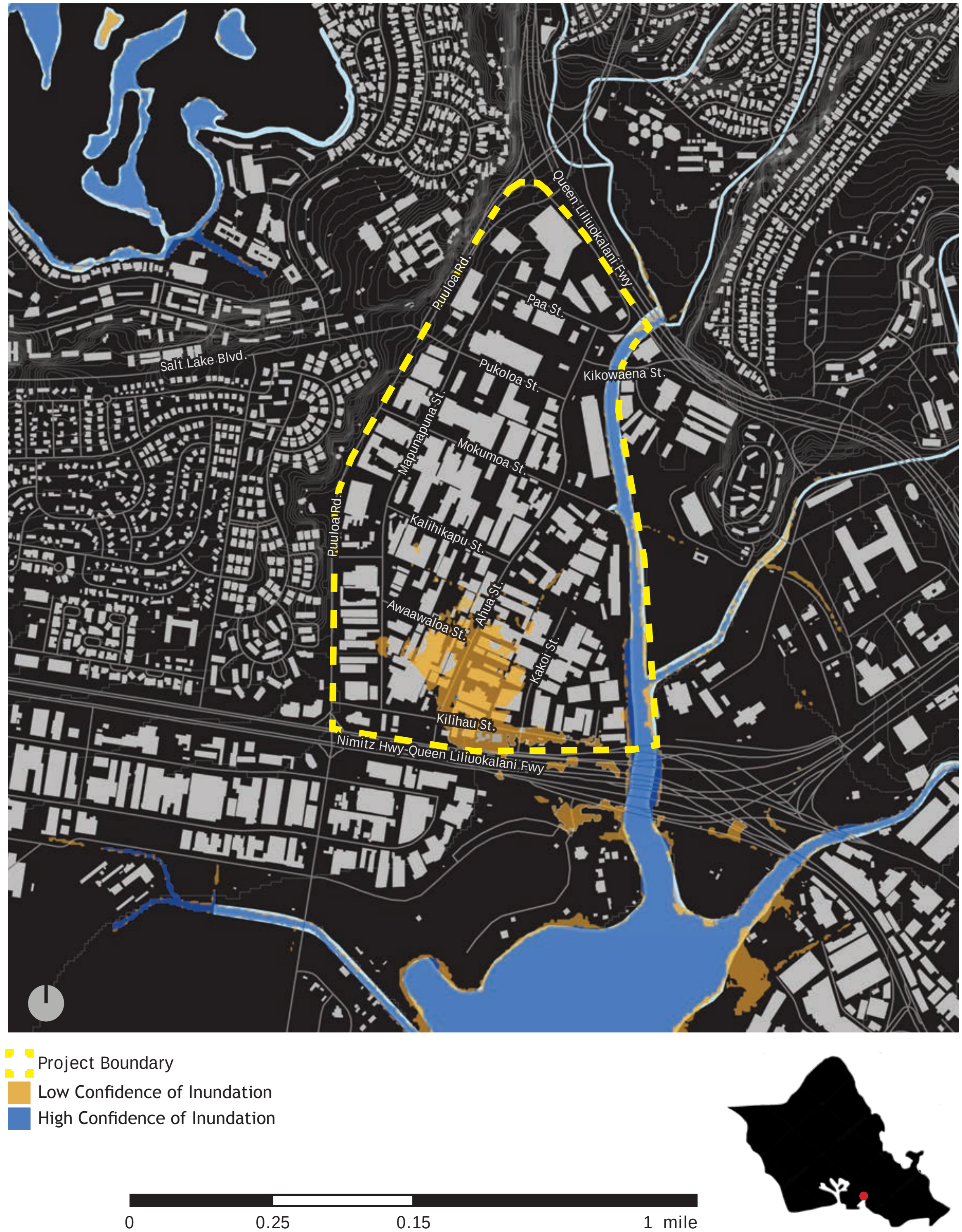

Figure 6.19: 1 ft. sea level rise + MHHW
Source: NOAA, Graphic: author

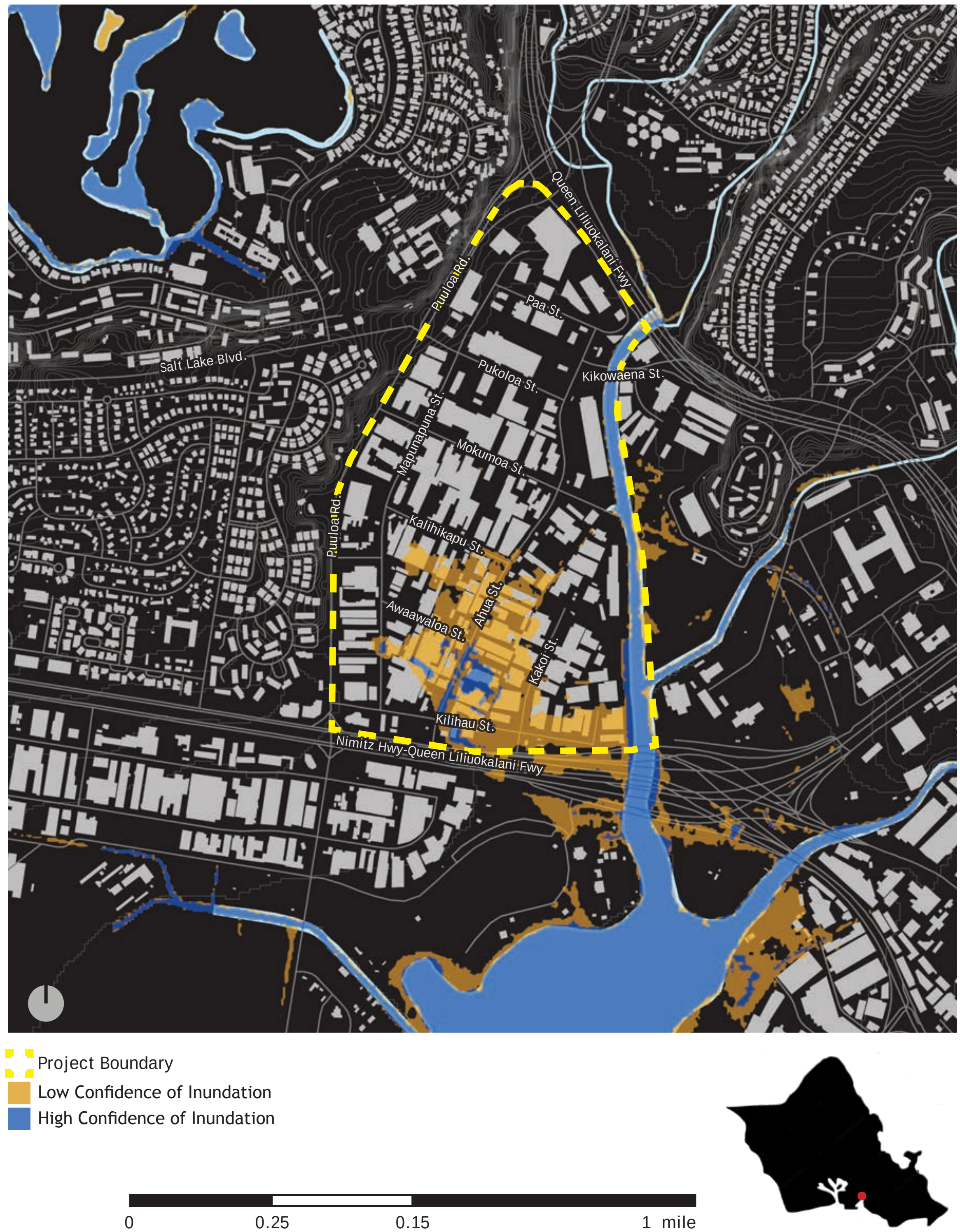

Figure 6.20: 2 ft. sea level rise + MHHW
Source: NOAA, Graphic: author

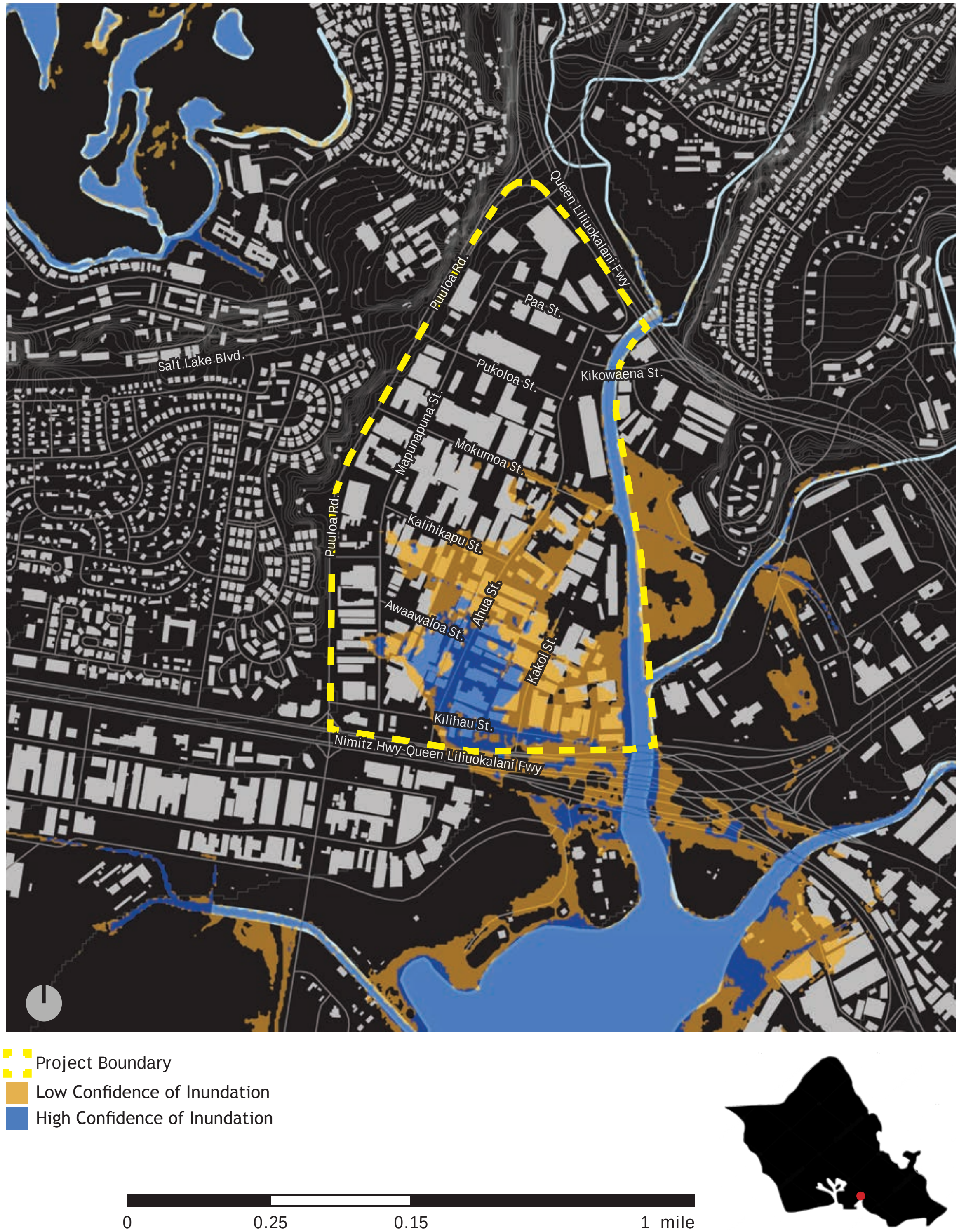

Figure 6.21: 3 ft. sea level rise + MHHW
Source: NOAA, Graphic: author

Figure 6.22: 4 ft. sea level rise + MHHW
Source: NOAA, Graphic: author

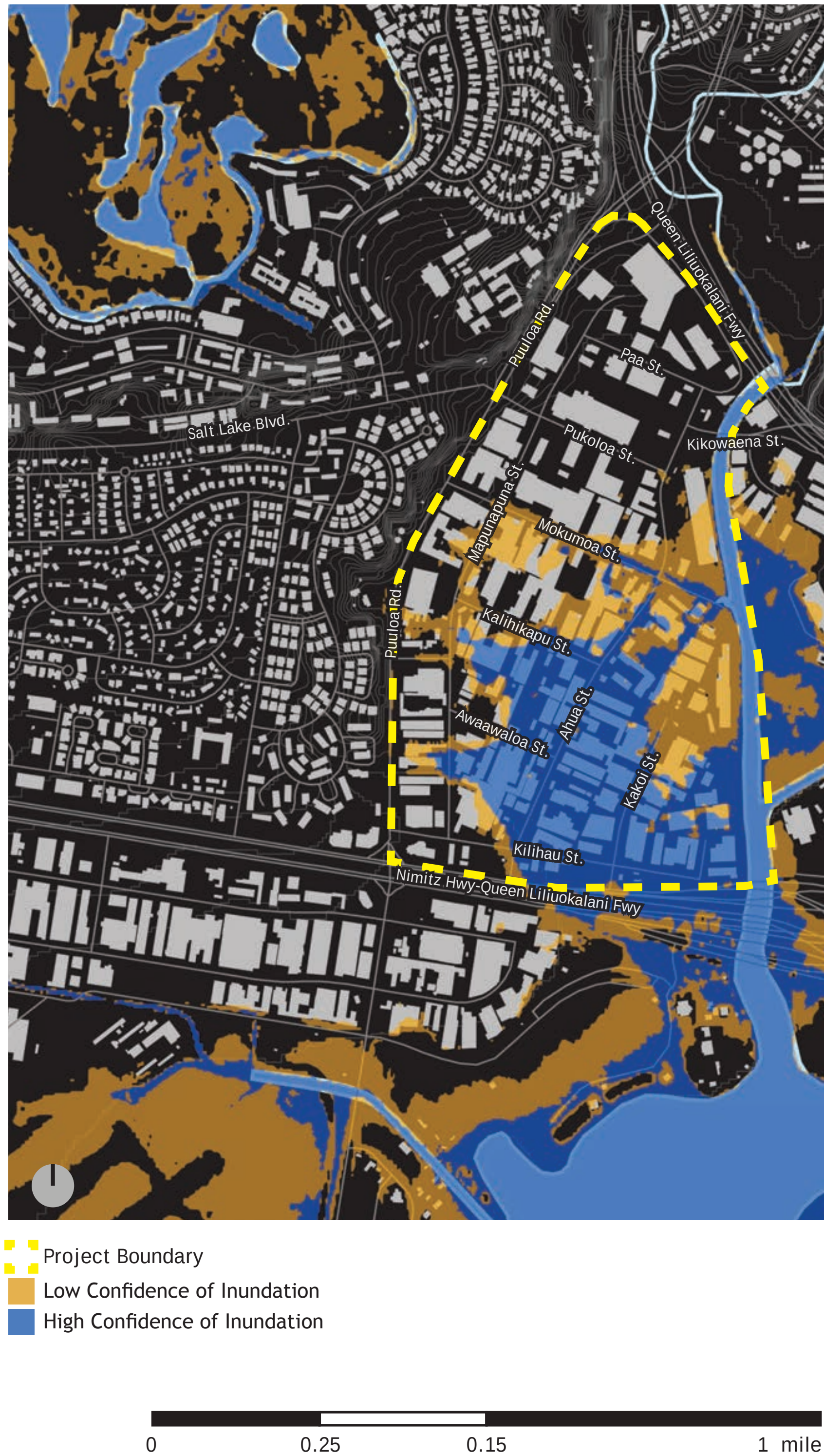

Figure 6.23: 5 ft. sea level rise + MHHW
Source: NOAA, Graphic: author

Figure 6.24: 6 ft. sea level rise + MHHW
Source: NOAA, Graphic: author

6.4 Transportation

Māpunapuna is accessible from most directions due to the existing transportation systems, which include roadways, bike facilities, and bus routes (Figure 6.25). The Interstate H-1 and Kikowaena Street/Kaua Street overpass is located north of the site. Puuloa Road is set along the western boundary of the site, and Nimitz Highway and Queen Liliuokalani Freeway is set along the southern boundary. Many of the roads throughout the site are significant as they connect to other industrial neighborhoods and serve as alternative routes during morning and afternoon rush hours. Out of the listed transportation systems in Figure 6.26, vehicles can travel throughout Māpunapuna with the most ease.

The Bus is the only public transportation service currently available within the City and County of Honolulu.[169] In general, Māpunapuna currently has an adequate number of routes throughout the site (Table 6.3). However, there are no stops along Ahua Street, possibly due to the road's heavy traffic conditions, number of industrial vehicles, and narrow lanes. Depending on the location from which bus riders arrive, walks can average between ten minutes from Puuloa Road and 20 minutes from Pukoloa Street and Nimitz Highway (Figure 6.26). Walks are reasonable at this length, but sidewalk conditions throughout Māpunapuna are unfavorable (e.g., poor shading, lack of street amenities, and narrow widths). Overall, the site has ample pedestrian access, but some areas, especially along the edge at the site, are underutilized for potential waterfront pathway amenities. As described in section 6.2, Māpunapuna is entirely landlocked by various private and public entities.

Bicycle access is sufficient throughout the general area of Māpunapuna, but the conditions are also lacking. The presence of illegally parked cars and industrial equipment cause blind spots making the area arguably dangerous for bicyclists. Separate bike paths exist near Nimitz Highway and Puuloa Road has marked bike lanes. The Airport Area Transit-

[169] "TheBus," accessed March 19, 2018, http://www.thebus.org/default.asp?f=y&m=main.

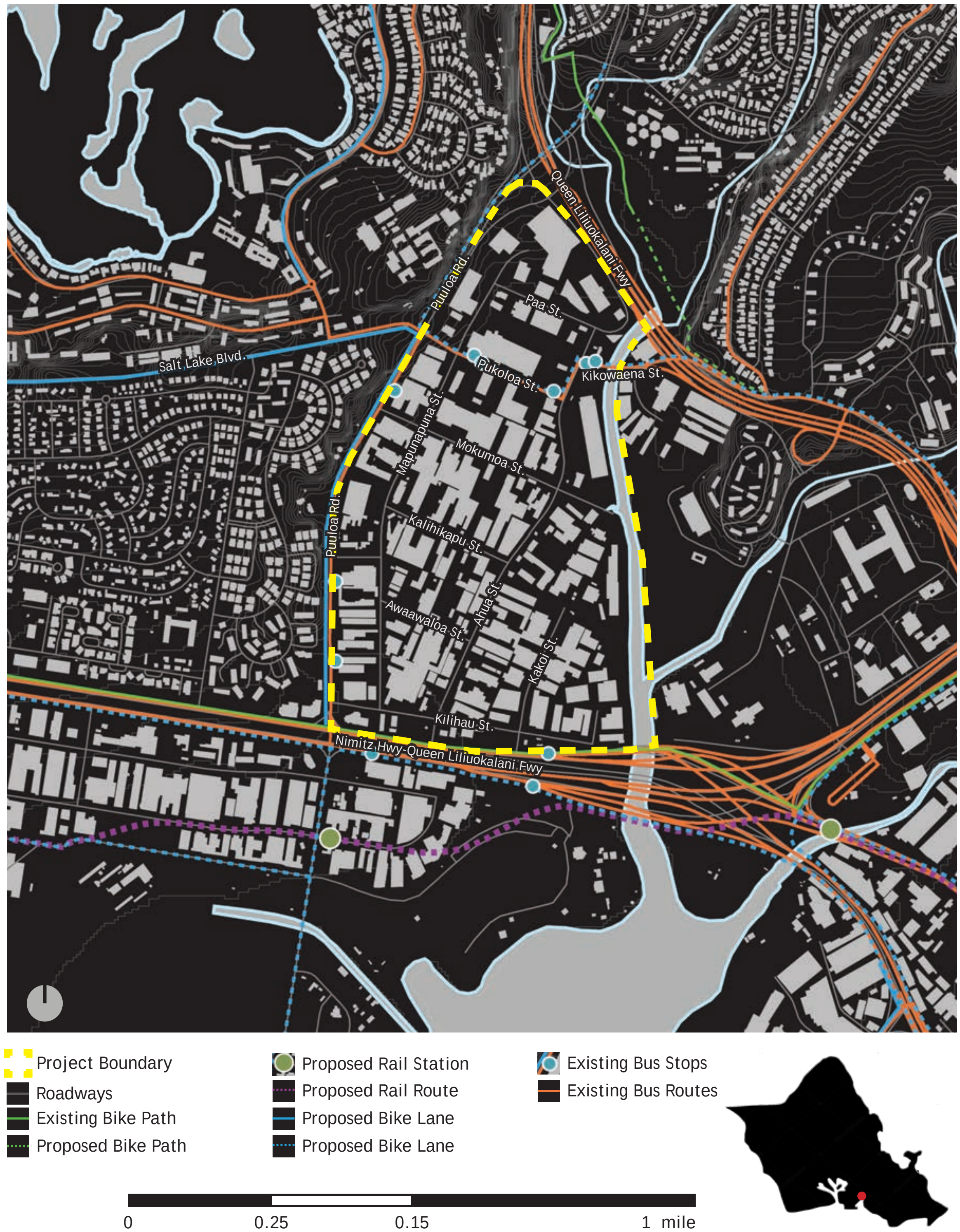

Figure 6.25: Existing and proposed transportation systems
Source: Hawaii GIS Statewide, Honolulu Authority Rail Transportation, AECOM,
Graphic: author

Figure 6.26: Average walking times from bus stops to Puuloa Road, Pukoloa Street, and Nimitz Highway
Source: Google, Hawaii GIS Statewide, Graphic: author

Oriented Development proposes new bike lanes and paths connecting existing routes south of Nimitz Highway and north of Māpunapuna (Puuloa Road, Pukoloa Street, Kikowaena Street/Kaau Street overpass, and Moanalua Gardens).[170] This proposal promotes more efficient routes in the east-west direction, providing users safer routes to and from town.

Māpunapuna has the potential to become a significant transportation center along the south shores of O'ahu because of its convenient proximity to major roadways, the international airport, and future rail stations. The design portion of this dissertation will take into consideration the maintaining of the east-west access of all types of transportation, as well as the enhancement of the north-south corridor for bicyclists and pedestrians.

Table 6.3 Existing Bus Routes

ROADWAY SYSTEM	ROUTE
Pukoloa Street	
Stop ID: 2816	3
Stop ID: 2817	3
Stop ID: 2818	3
Stop ID: 2849	3; 31; 32
Stop ID: 2850	3; 31; 32
Puuloa Road	
Stop ID: 2861	31; 32
Stop ID: 2862	31; 32
Stop ID: 2863	31; 32
Nimitz Freeway	
Stop ID: 465	9; 19; 20; 31; 32; 40; 42; 62

Source: Data from TheBus[171]

[170] "Airport Area Transit-Oriented Development Plan: Existing Conditions Report."
[171] "TheBus."

6.5 Sewage and Stormwater Infrastructures

Assessing the current conditions of onsite sewage and stormwater infrastructures is significant due to the site's sensitivity to flooding.

Māpunapuna has two types of sewage systems: 1) gravity and 2) low-pressure force (Figure 6.27). Gravity mains are used in the northern and southeastern areas of Māpunapuna. As the term implies, gravity is used to transport stormwater and wastewater from homes and businesses to the water treatment plant. For areas that cannot rely on gravity, such as the southwestern areas of the site, low-pressure force systems are used. Typically, each property has a pump connected to the city's network. Sewage systems are directed to the Sand Island Treatment Plant (approximately four miles southeast of the site).

Stormwater systems are separate from the sewers in Hawaiʻi. The City and County's stormwater system viewer displays existing catch basins and inlets in Māpunapuna (Figure 6.28). Collected stormwater eventually drains through the outfalls along Moanalua Stream and Keehi Lagoon. For decades, however, drainage has been a problem in Māpunapuna, in 2013, the City and County addressed this by installing one-way duckbill valves (Figure 6.29).[172] The rubber valve allows storm water to flow out and remains closed to high tide water flowing in, preventing seawater from entering the system. However, when wet weather and high tide coincide, this solution fails as the systems become backed up causing an overflow onto the streets. Once the tide decreases, the valves work again and the water is able to drain.

The extremely high tide levels in the summer of 2017 caused problems in the area as seawater overflowed inlets into properties near sea level.[173] At Māpunapuna, the entire intersection of Ahua Street and Kilihau Street was temporarily inundated; waters reached as high as the top surface of the sidewalks.

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[172] Nakagawa, "Flood Prevention Project Resumes," 06/29/20111, https://www.pressreader.com/usa/honolulu-star-advertiser/20110729/282235187327685.
[173] "What Is High Tide Flooding?"

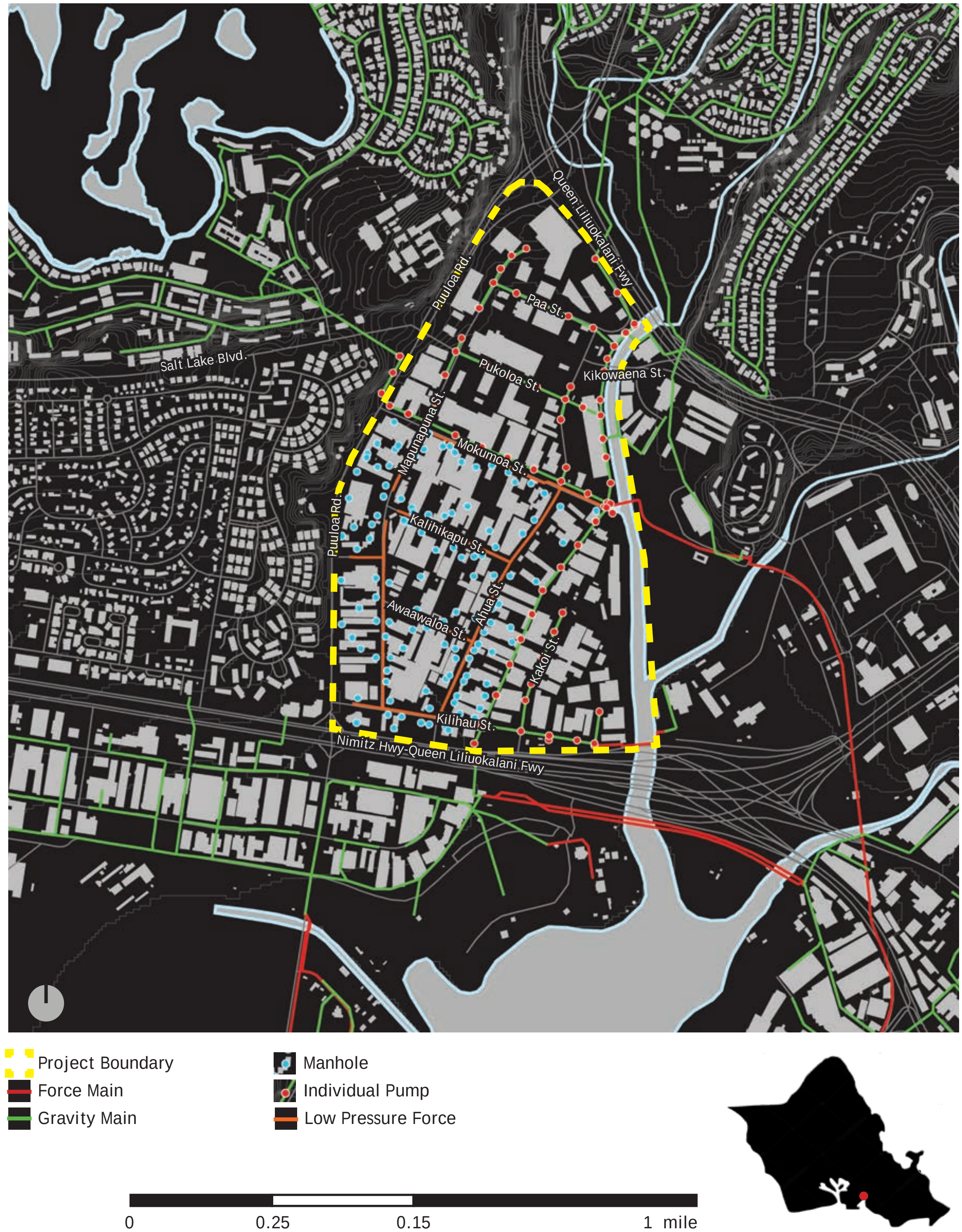

Figure 6.27: Sewer utilities
Source: Hawaii GIS Statewide, Graphic: author

Figure 6.28: Stormwater system
Source: Hawaii GIS Statewide, Graphic: author

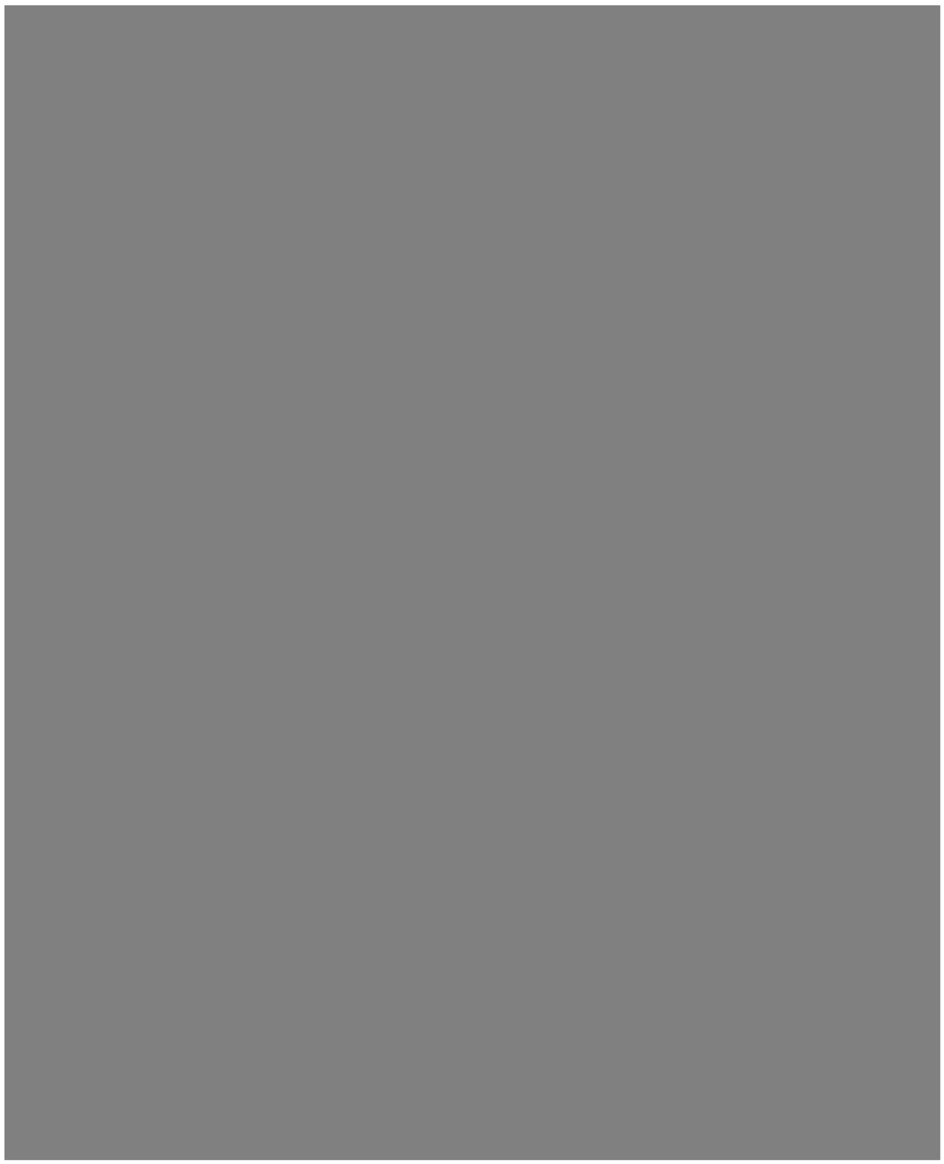

Figure 6.29: One-way duckbill valves
Source: Eckhard Brandes Inc.

In an interview conducted by KHON 2, Panos Prevedourous, chair of the University of Hawai‘i at Mānoa Department of Civil and Environmental Engineering, mentions that other solutions, such as pumps, would be costly and obtaining funding would be challenging due to current real estate that is affected.[174] The scenario would likely be addressed differently if hotels and higher-tier commercial businesses were vulnerable.

6.6 Conclusion

Māpunapuna has undergone many changes throughout its history. Initially, the site was a lagoon environment and a critical component of the Moanalua ahupua‘a. Western contact influenced a shift away from communal stewardship to privatized property ownership. After the lagoon was filled, businesses and inhabitants began to populate the area and, over time, it has become the active urban environment it is today.

The progression of these events physically altered Māpunapuna’s landscapes and consequently indirectly generated existing constraints such as chronic flooding, vulnerability to sea level rise and tsunamis, and poor drainage. Retreat for the entire district would be an effective solution as it would decrease the degree of risk significantly, but would come at the expense of the existence of several well-established businesses. On the other hand, conservative and limited measures, such as hard infrastructures, do not address the long-term problem of flooding. In fact, such measures could worsen future flood events in time. After reviewing various conditions of Māpunapuna, a series of conceptual master plans will be devised to demonstrate the application of appropriate flood mitigation and adaptation strategies. The designs intend to minimize the physical impacts of water, improving the urban environment’s ecological conditions, and most importantly, enhancing the amenities of the redeveloped urban environment.

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[174] “Can Anything Be Done about the Flooding in Mapunapuna? | Hawaii,” accessed April 2, 2018, http://www.khon2.com/news/local-news/can-anything-be-done-about-the-flooding-in-mapunapuna_20180104062657601/901396301.

CHAPTER 7: CONCEPTUAL DESIGN

The body of information in Part I provides insight into the broad context of flooding—conditions, causes, consequences, and mitigation and adaptation strategies—that created the basis for the formulation of three design principles of flood resilience in Hawai‘i. Risk reduction addresses the physical implications of flooding, green networks address environmental constraints, and placemaking, which ties everything together, addresses the socioeconomic aspects of the affected community. The beginning of Part 2 presents an investigation of Māpunapuna's past, present, and future conditions conducted in order to determine the most appropriate flood mitigation and adaptation strategies and measures based on the principles of resilience for the Māpunapuna conceptual design.

Over time, Māpunapuna has undergone many land-use transformations reflecting the needs of its populations. Before Western contact and in its early days, near-shore areas like Māpunapuna teemed with fishponds and wet-agriculture fields. As foreign influence strengthened, landscapes were manipulated more dramatically; Māpunapuna was changed from a lagoon environment to an artificial landscape occupied by commercial and industrial businesses. Nevertheless, Māpunapuna has always been an area of important activity.

Māpunapuna's existing problematic flooding conditions stem from the shift from wetlands to reclaimed land. These changes to the natural environment together with the users' continued desire to be close to the shore is at the root of the site's flooding conditions. Current poor drainage qualities and inadequate stormwater systems cause the site to be vulnerable to heavy and extended rainstorms, infrequent tsunamis and storm surges, and chronic flooding. As discussed in chapters 2 and 3, frequent flooding will eventually lead to permanent inundation and land loss as sea level rise continues to increase rapidly in the second half of the century. Together, these hazards offer ample reason to evacuate to safer grounds, but because Māpunapuna has become such a well-established industrial-commercial neighborhood on O‘ahu's south shore and a prime location for future development, and because available lands are a finite resource on the islands, desire to stay remains strong.

Using the design principles for flood resilience, this dissertation offers a speculative design solution that is sensitive to the community and natural environment while effectively addressing short- and long-term flooding conditions. Because sea level rise is central to the project site's flooding conditions, the conceptual design will be divided into three phases that follow the timeline of sea level rise in the CSSR's High scenario (Table 7.1). As discussed in section 2.2.3, this scenario was chosen based on the highest parameters (six feet) available in NOAA's Sea Level Rise Coastal Viewer.

Table 7.1 GMSL rise High scenario in meters (feet) relative to 2000.

SCENARIO	2020	2030	2050	2100
High	0.11 (0.4)	0.21 (0.7)	0.54 (1.8)	2.0 (6.6)

Source: Data from Doken, Fahey, Hibbard, Horton, Kopp. LeGrande, Maycock, Romanou, Stewart, Sweet, Wuebbles 2017.

The redesigned Māpunapuna will be used to convey potential alternatives for coastal development in Hawaiʻi; it will demonstrate flood mitigation and adaptation strategies that enforce functional qualities and provide public amenities to the growing population, enhancing the site's resilience to flooding. Although the dissertation focuses on Māpunapuna, the design interventions and processes can be translated for and reproduced in other coastal areas of Hawaiʻi and potentially worldwide. Although chosen strategies and measures may differ based on location, culture, or community, flood design based on critical understanding and site-appropriateness highlights the potential perspective of floods as a motivating vision rather than a limiting threat.

7.2 Phase 1

Table 7.2 Brief summary of Phase 1's design.

Sea level rise scenario:	Approximately 2030; 1-ft. increase
Location:	Lower Ahua Street
Risk Reduction	Retreat- Property lots exposed to chronic flooding, influenced by sea level rise, will be subjected to land acquisition. Accommodation- Changes in land use
Green Networks	Green roofs, street planter boxes, detention basins, urban tree canopy, rain gardens, pervious pavement
Placemaking	Detention basin park, foot pathways, rain gardens, elevated pathways

The first phase of the conceptual design addresses conditions forecast for the 2030s where sea level rise is expected to be about one foot. The light blue shaded area on the mapped projection generated by NOAA's Sea Level Rise Coastal Viewer indicates that lower Ahua Street will likely experience chronic flooding by this time. This area currently experiences flooding, largely due to outdated and overburdened stormwater systems combined with high tides. During high tides, runoff still in the system is elevated and overflows onto the streets. Neighboring properties are subject to damage from extended exposure to runoff and seawater, while cars passing regularly through the street may incur corrosion over time. Moreover, runoff that remains on the street for prolonged periods is subject to pollution from neighboring lots. Only when tidal levels decrease can the one-way duckbill valves release backed-up runoff and allow this portion of Ahua Street to properly drain. These conditions will only be exacerbated by 2030. Phase 1 of the conceptual design proposes the application of retreat and green stormwater infrastructure measures to regulate potential losses and manage regular runoff as well as excess volumes of water present during high tides and extreme weather events. The following sections provide details on the measures proposed for Phase 1.

Risk Reduction

As established in section 6.1, a large portion of business owners in Māpunapuna are facing the expiration of their lease terms, creating an opportunity for chronically flooded businesses to relocate to safer lots.[175] The land values of properties subject to chronic flooding will eventually decrease, discouraging businesses from developing on these lots. Phase 1 includes a proposal to remove and compensate existing businesses bordering the western perimeter of Ahua Street. This method of retreat was chosen not only because of the existing hazards of frequent flooding from the neighboring stormwater inlet drains but also to provide space for the implementation of large retention ponds. By removing businesses subject to increased flooding, the degree of flood loss will also be reduced.

Green Networks

Most lots in Māpunapuna house large warehouses or impervious lots designed for parking commercial and construction vehicles. There is little land available for new use. Nevertheless green stormwater infrastructure measures make it possible to effectively maximize small or unusual spaces. Phase 1 proposes the installation of vegetated roofs that redirect rainfall into barrels on certain large warehouses. Also, in order to slow runoff, planter boxes will be strategically placed along existing stormwater infrastructures. As noted, some businesses will be required to relocate due to chronic flooding near stormwater drain inlets. The lots acquired will then be retrofitted with detention basins, rain gardens, and bioswales in order to accommodate excess runoff during heavy and extended rainfall and high tides. Infrastructure that allows water to collect and flow through more efficiently will lower the chances of overflow onto the streets and adjacent properties.

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175 "Damon Estate's Land Sale Completed | The Honolulu Advertiser | Hawaii's Newspaper."

Hawai‘i is moving toward a more rigorous environmental policy, thus encouraging the statewide application of green stormwater infrastructures. Although many of the green stormwater infrastructure measures specified in Phase 1 are lot-specific, in order to address the underlying issue of drainage and runoff, they must be dispersed throughout the entire watershed, especially at higher elevations. This will decrease the amount of runoff traveling offsite and minimize the load on the conventional stormwater management systems, reducing their rates of failure. Other benefits provided by green stormwater management measures include lowered atmospheric temperatures, the promotion of urban biodiversity, enhanced aesthetics, and improved air, soil, and water quality. The proposed measures in this section will be continued throughout the course of Phase 2 and 3.

Placemaking

Māpunapuna is in dire need of both vegetation spaces and improved public amenities for its users. In order to address the social aspects of both risk reduction and green networks, Phase 1 includes the integration of a park-like space on the site. As mentioned, detention basins, rain gardens, and bioswales will be integrated on the acquired lots. Pathways shaded by planted trees will be built along the perimeter of the site, providing users a place of refuge despite the neighborhood’s industrial tone. Because the detention basin will be periodically filled with water, elevated boardwalks will be erected to allow users to observe the vegetation and current flooding conditions. Several trees will be planted around the retention pond, providing ample shade along the pathways. Due to the site’s proximity to the coast, salt-tolerance tree species will be selected for this purpose. In essence, this humble, retrofitted park-lot will become a tool promoting public awareness of the inevitable permanent inundation in many coastal communities in Hawai‘i’s near future.

Figure 7.1: 1 foot sea level rise + MHHW and affected areas
Graphic: author

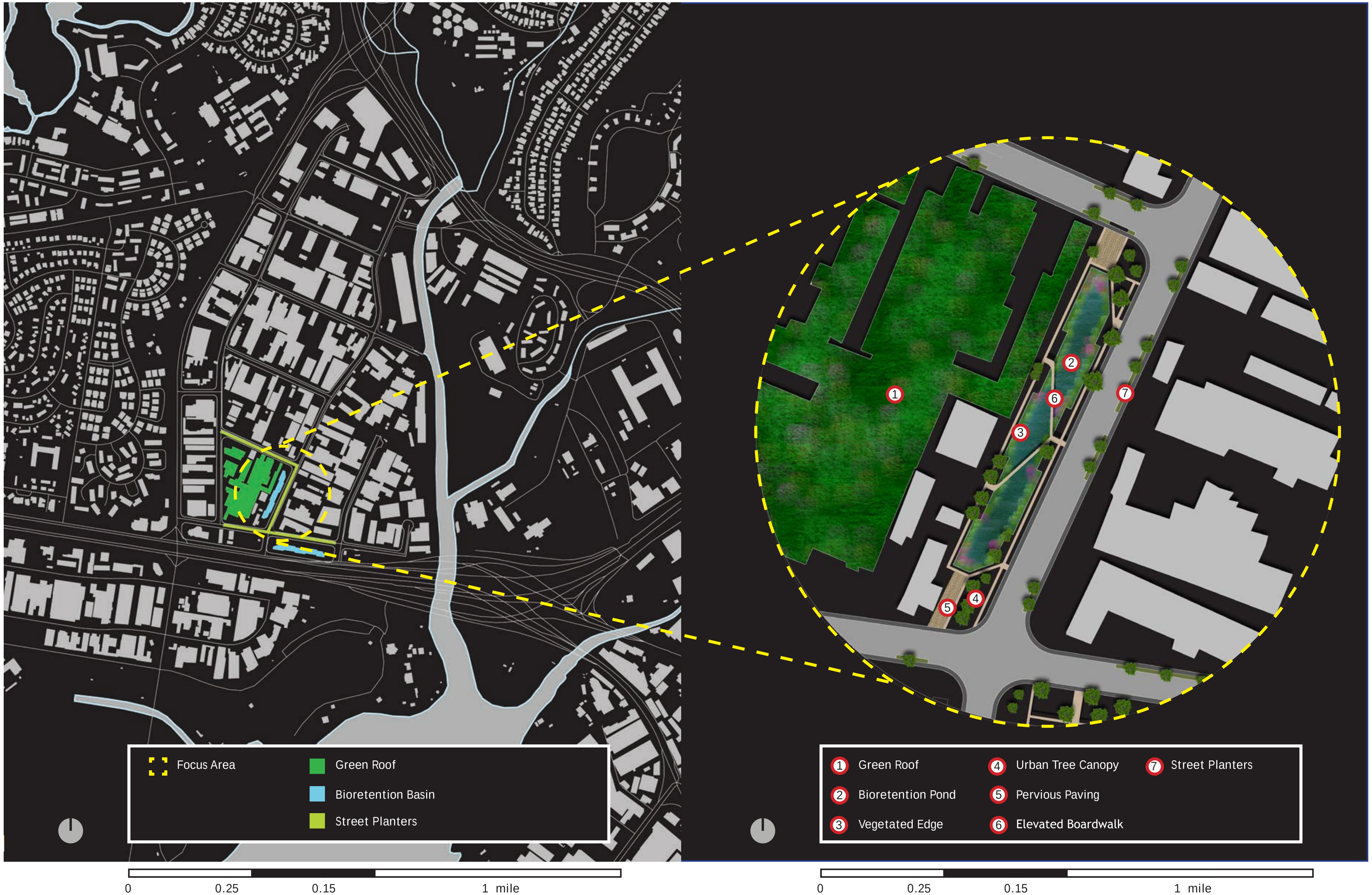

Figure 7.2 Phase 1 key design features and focus area, Graphic: author

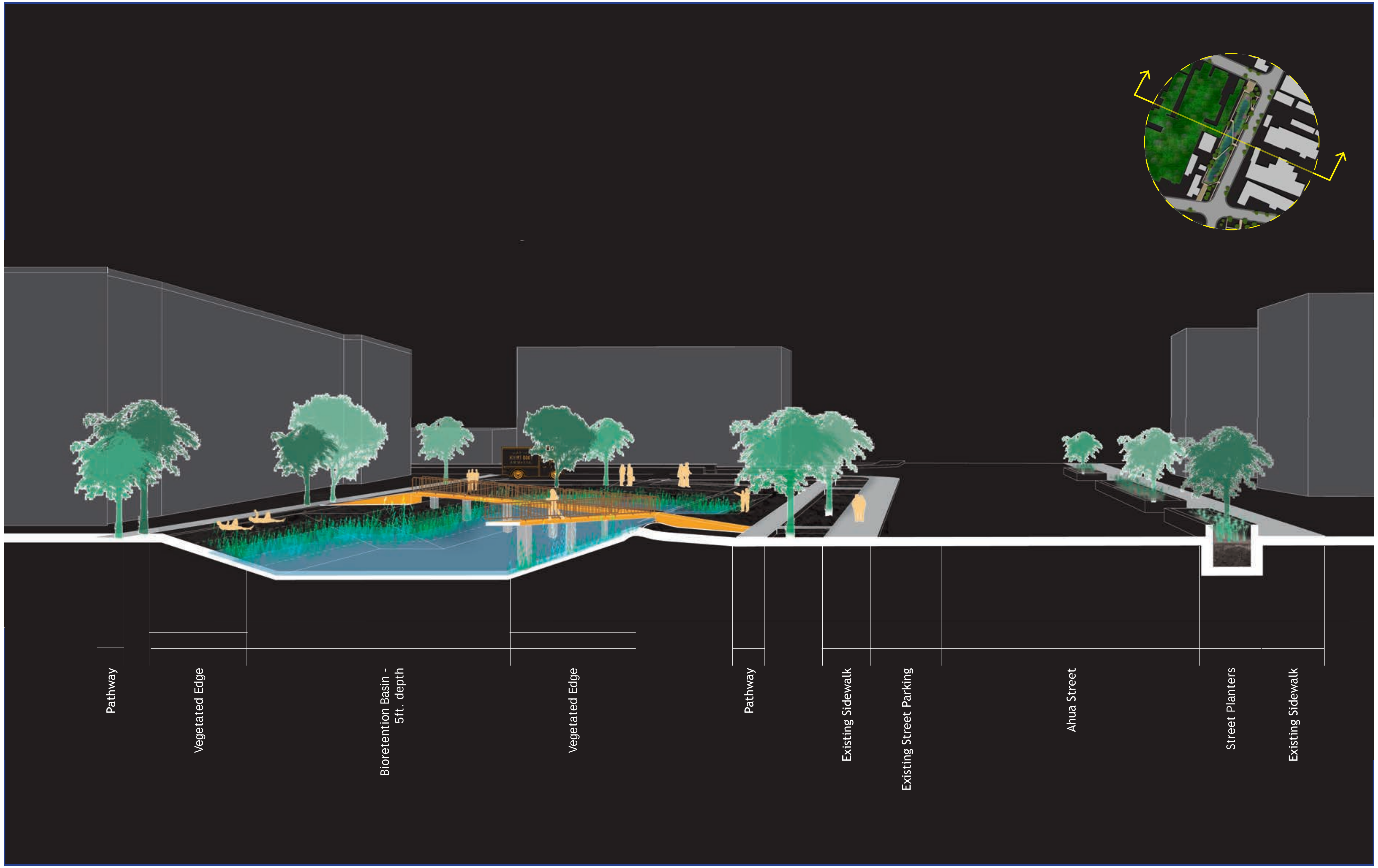

Figure 7.3 Section perspective of bioretention ponds , Graphic: author

7.3 Phase 2

Table 7.3 Brief summary of Phase 2's design.

Sea level rise scenario:	Approximately 2050; 2-ft. increase
Location:	Lower Māpunapuna
Risk Reduction:	Retreat- Property lots exposed to chronic flooding, influenced by sea level rise, will be subjected to land acquisition. Protection- Super levee; marshes Accommodation- Elevate structures, changes in land use
Green Networks:	Green roofs, street planter boxes, detention basins, urban tree canopy, rain gardens, pervious pavement
Placemaking:	Elevated pathways over marshes and on super levee's tiers, rain gardens, food truck parking, dock development

Phase 2 addresses the conditions forecast for the 2050s, with a projected sea level rise of two feet. On the map in Figure 7.5, the darker shade of blue indicates a higher chance of chronic flooding (80%) and the lighter blue, a lower chance (40%). The area of impact will spread out from Ahua street and be mostly contained between Mapunapuna Street to the west, Kalihikapu Street to the north, Moanalua Stream to the east, and Kilihau Street to the south. As discussed at the beginning of the chapter, it is important to remember that mapping tools provide educated predictions that have inherent room for error such as, in this case, the "natural evolution of the coastal landforms, as well as the data used to predict the changes."[176] However, if the forecasted conditions hold steady, lower Ahua Street will become permanently inundated by the end of the century and adjacent lots subject to chronic flooding conditions.

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[176] Sea Level Rise Coastal Viewer

As indicated in section 2.2.3 and chapter 3, sea level rise not only influences high tides, which become progressively worse allowing seawater to encroach farther inland and spill out through stormwater systems more frequently, but also raises groundwater tables further hindering already deficient drainage in low-lying coastal areas. Phase 2 of the conceptual design is the first stage in the development of large-scale retreat and protection measures. These measures are complemented by proposed accommodation measures. The application of green stormwater infrastructure measures from Phase 1 will continued to be applied throughout the site to maintain and regulate run off. The following sections provides details on the measures proposed for Phase 2.

Risk Reduction

A growing number of businesses and infrastructures will be at stake during the 2050s when most of the southeast portion of Māpunapuna is expected to experience intensified flooding conditions. Roadways are a critical component of the industrial structure and the frequent inundation of eastern Kilihau Street, Kakaoi Street, Ahua Street, and half of Awaaloa Street are projected to frequently inundated, it becomes a serious problem for local businesses cause corrosion to vehicles that frequent the area. One potential solution is installing elevated roadways and pumps, as in the example of Miami Beach. However, this solution is not ideal; connecting property lots to the new infrastructure will be complex and costly, and the hard structures could have adverse impacts on the natural environment.[177] It is also only temporary; as sea levels continue to rise, pumps that have limited lifespans will become increasingly costly to repair and water will eventually overtop elevated roadways, especially if they are only a few feet off the ground.

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[177] "Miami Beach's Battle to Stem Rising Tides."

Therefore, Phase 2 continues to focus on the removal, relocation, and compensation of endangered businesses within the southeast portion of the site. Over time, these businesses will become burdened with the task of preventing floodwaters from destroying their properties and eventually, the cost of damage and self-mitigation will be too high. The goal of this approach is to decision to continue this approach is based on the livelihood and impacts on local businesses, and to control the scale of flood loss. Once evacuations are complete, the lots will be excavated to appropriate depths to transform the landscape into a wetland. Wetlands offer more drainage space for the water and act as a buffer during extreme flooding events like storm surges and tsunamis. The marsh will also become the last tier of filtration for runoff before it enters the ocean and provide more ecological habitats.

In order to encourage Māpunapuna's remaining businesses to stay in place and to ensure their safety, Phase 2 proposes the first phase of the construction of a levee, a hard protection measure, running from Mokumoa Street to Kilihau Street and changing the topography of the properties adjacent to Mapunapuna Street. However, rather than the conventional, mono-functional approach, the levees will be designed similar to the super levees in Tokyo's metropolitan area. This part of Tokyo is densely developed and in order to accommodate existing conditions while providing a means of protection, super levees were employed along the Ara and Sumida Rivers.[178] This approach successfully deters flooding while maintaining existing populations, assets, and core functions of social and economic activities in the area. The structure's foundation is secure; the tiered levels on the landward side of the levee promote rigidity and thus enhance resilience from earthquakes and flooding (Figure 7.4).[179]

Because Māpunapuna is also a relatively developed and dense area with limited available lands, super levees are an ideal option that support multiple functions throughout the

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[178] Rutger de Graaf and Fransje Hooimeijer, eds., *Urban Water in Japan*, Urban Water Series, v. 11 (London ; New York: Taylor & Francis, 2008), 138-1393.
[179] Ibid., 137-38.

large protection system. The design of Māpunapuna's super levees is two-tiered. The first tier is 12-feet high and 25-feet wide and is designated for service vehicles and pedestrians. During extreme events, this tier can be flooded. The second tier is 24-feet high and 50-feet wide; its height was chosen based on recorded storm surge elevations during Hurricane Iniki, one of the worst hurricanes to make landfall in Hawai'i (see discussion in chapter 3).[180] The landscape between the levee and Puuloa road will not be flat, the peak of the levee will reach the existing levels of Puuloa Road. Material and landfill from acquired properties will be used to provide fill for the proposed levee system. Marsh landscapes will extend to the banks of the levee, softening the edge of the hard-engineered system. Buildings on the landward side of the levee will be retrofitted to the sloped landscape using elevation construction methods.

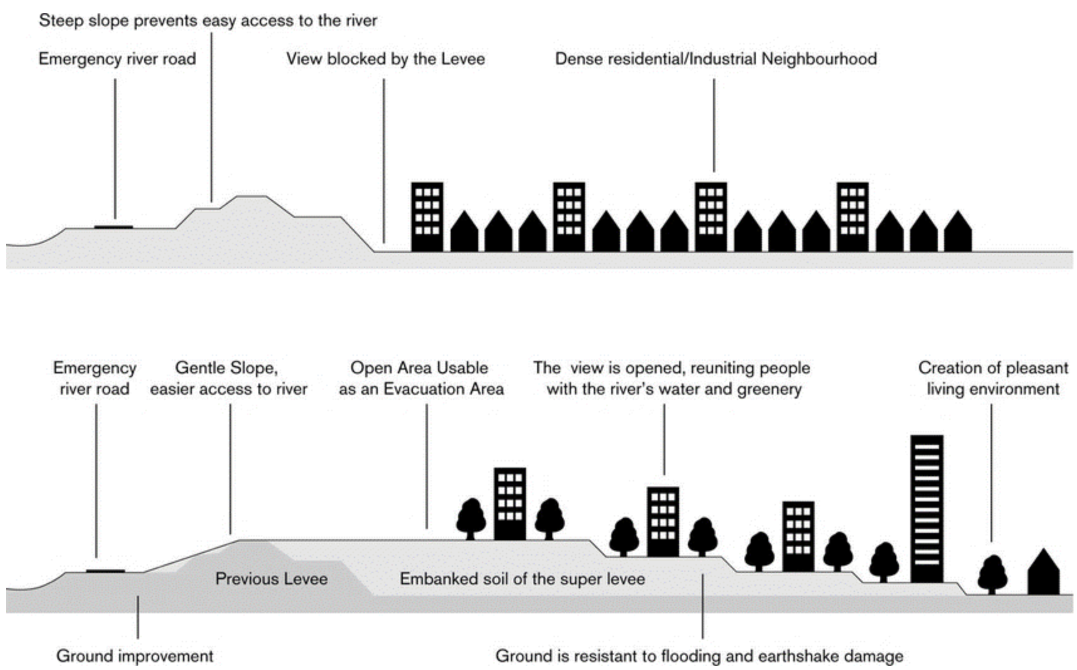

Figure 7.4 Conventional dikes and super levees.

Source: Graaf and Hooimeijer[181]

[180] *Hurricane Iniki, September 6-13, 1992*.

[181] Graaf and Hooimeijer, *Urban Water in Japan*, 137.

In terms of accommodation, properties at the intersection of Mokumoa and Ahua Streets will be elevated on docks, despite not yet being in range of chronic flooding. The intent is to provide temporary lots for existing and future businesses in a pier-like environment, profiting from the new waterfront marsh landscape. In order to maintain the north-south connection within Māpunapuna, Ahua Street will be converted into a bridge.

Rather than employing a conventional approach to flood mitigation and adaptation, measures to reduce risk were taken to the next level in anticipation of unprecedented future events. Also, the measures of Phase 2 prepare the area for the final stage of development, Phase 3.

Green Networks

Some of the proposed green stormwater infrastructure measures from Phase 1 will be continued throughout Phase 2. Building roofs will be retrofitted to accommodate vegetation and store water and Mapunapuna and Pukoloa Streets will be embedded with planter boxes. Some lots on the landward side of the levee will be partially retrofitted to accommodate retention basins. The north parts of Māpunapuna will be left alone during Phase 2; the construction of the super levee on these lots will continue during Phase 3.

Placemaking

In order to address the social aspects of risk reduction and green networks, Phase 2 includes the addition of a large, linear park-like space on the proposed levee system. The tiers will provide walkways at two levels. The first level is designated for service and maintenance, but includes walkways for users. This level is close to the marsh; however, smaller pathways leading farther down the levee will deliver a more intimate experience along its banks. The second level will offer expansive views of the marsh and the landward side of the levee. Trees will be scattered throughout the top tier and landward areas of the super levee, providing shade for park users

Phase 2 proposes the installation of docks along Mokumoa Street intended to house commercial businesses and eateries. The goal is to generate income for the maintenance and additional construction of the super levee that will take place in Phase 3. The docks will become an active waterfront development with varied amenities for users and visitors to enjoy. New types of amenities will also promote new types of industries such as eco-tourism and light industries.

Figure 7.5: 2 foot sea level rise + MHHW and affected areas
Graphic: author

Figure 7.6: Phase 2 illustrative master plan
Graphic: author

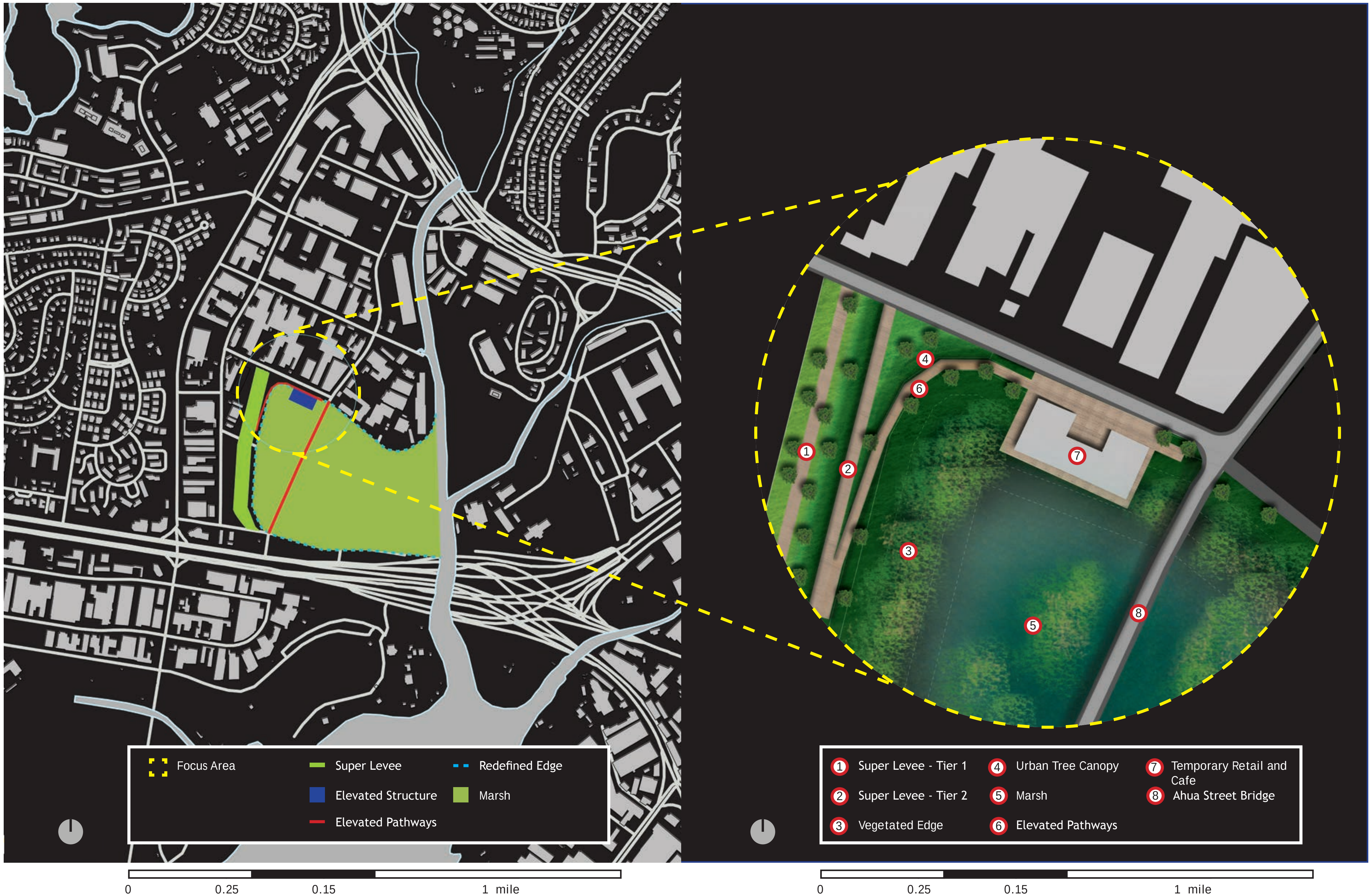

Figure 7.7 Phase 2 key design features and focus area, Graphic: author

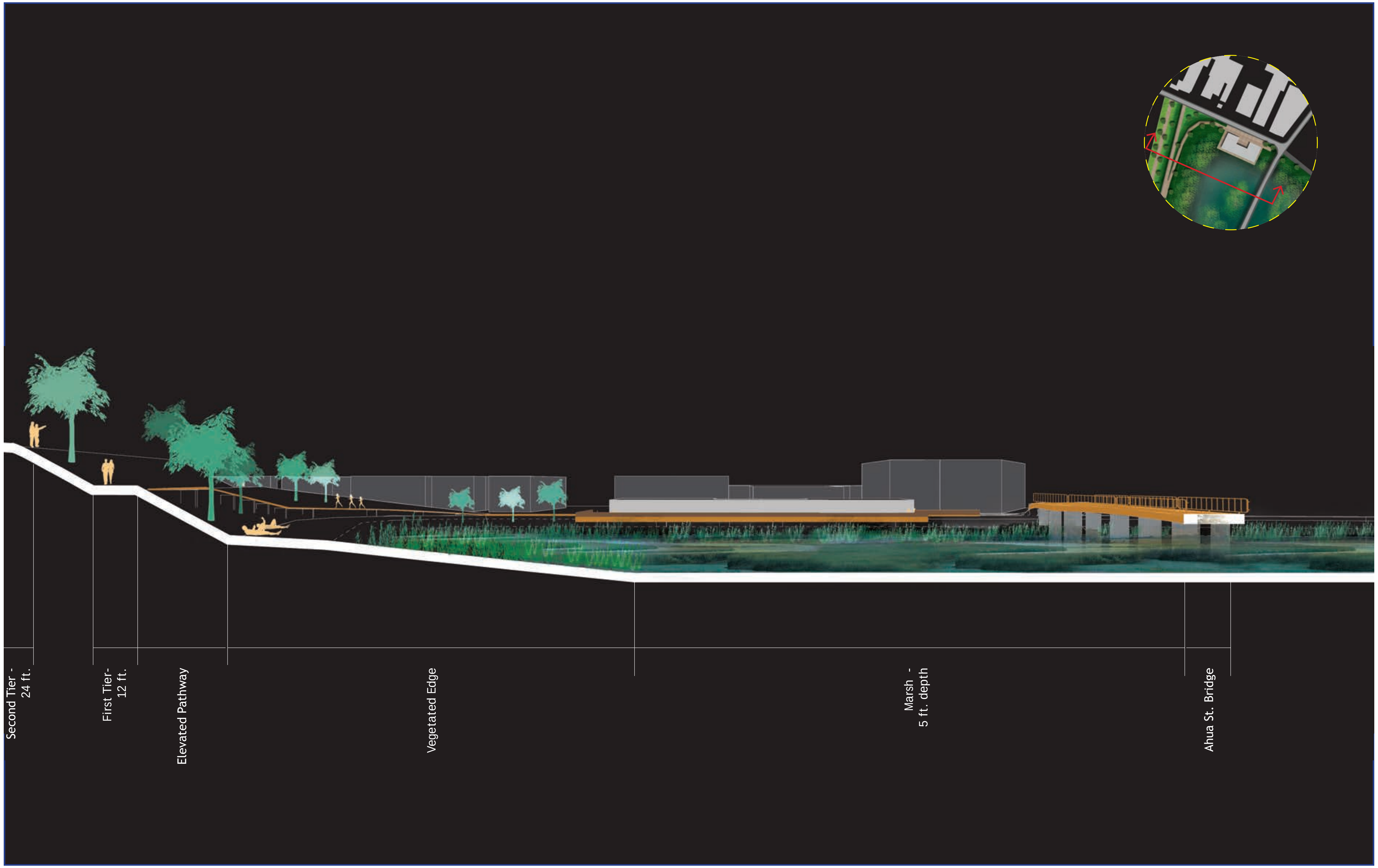

Figure 7.8 Section perspective of super levee and marsh, Graphic: author

7.4 Phase 3

Table 7.4 Brief summary of Phase 3's design.

Sea level rise scenario:	Approximately 2100; 6-ft. increase
Location:	Māpunapuna, Keehi Lagoon, and parts of the airport
Risk Reduction:	Retreat- Property lots exposed to chronic flooding, influenced by sea level rise, will be subjected to land acquisition. Protection- Super levee; marshes Accommodation- Elevate structures
Green Networks:	Green roofs, street planter boxes, detention basins, urban tree canopy, rain gardens, pervious pavement
Placemaking:	Elevated pathways over marshes and on super levee's tiers, rain gardens, food truck parking, dock development

Phase 3 of the conceptual design is the final phase of the redeveloped master plan of Māpunapuna and responds to projected flooding conditions influenced by an approximate 6.6-foot sea level rise by 2100. The affected area is significantly greater than the projections for the 2050s, corresponding to findings indicating that sea level rise will increase more rapidly during the second half of the century.[182] By this time, flooding influenced by sea level rise will encompass most of the lower half of Māpunapuna. Floodwaters are projected to reach past Mokumoa Street in the north, Māpunapuna Street in the west, and overtake Nimitz Highway—Queen Liliuokalani Freeway in the south. Over the course of this period, it is anticipated that a substantial amount of land in Māpunapuna will be lost to permanent inundation.

Phase 3 completes the large-scale retreat and protection measures begun in Phase 2, again complemented by proposed accommodation measures. As the landward side of the super

182

levee is finalized, the application of green stormwater infrastructure measures begun in Phase 1 will continue. The following sections provide details on the measures proposed for Phase 3.

Risk Reduction

Few applications of retreat are required in Phase 3 as properties in southeast Māpunapuna were already evacuated in Phase 2 in preparation for the forecasted flooding conditions. The applications of retreat that will take place involve several lots north of Mokumoa Street to accommodate the super levee's northern extension, and Keehi Lagoon Memorial, south of the primary project site, which will be turned into wetlands. As anticipated, as the area is subject to higher chances of inundation caused by sea level rise, the wetlands created from the evacuated lots in Phase 2 are an essential buffer from the impacts of flooding. Marshes will be continued south of the Nimitz Highway—Queen Liliuokalani Freeway where Keehi Lagoon Beach Park used to be. These marshlands become the first line of defense in the Māpunapuna and Lagoon Drive areas, and supply more ecological habitats.

The super levee is the second line of defense. The strengths of levee systems are maximized when applied over long distances, thus the proposal extends the super levee beyond Māpunapuna to the north and the south. The northern extension of the super levee will follow Mokumoa Street and run along the existing contour of Moanalua Stream. Eventually its slope will taper off to existing elevations north of Queen Liliuokalani Freeway. In the southern parts of Māpunapuna, the super levee will cross the intersection of Kilihau and Ahua Streets and encompasses a portion Keehi Lagoon as some parts of this city park will either be exposed to chronic flooding or permanent inundation by this time. Finally, the levee will follow the contour of Aoilele Street and continue into the airport area.

The implementation of the super levee involves adjustments to major roadway systems. To accommodate the super levee extension to the north and Queen Liliuokalani Freeway, parts of the freeway will be retrofitted to make room for the levee underneath, thus creating a gradual slope to both east and west bound directions. To the south, the super levee will intersect with the existing Nimitz Highway—Queen Liliuokalani Freeway. The freeway's existing height is capable of housing the levee underneath its overpass structure, but this would prevent vital access to Honolulu. In order to accommodate both the super levee southern extension and Honolulu's transportation needs, the intersecting segment will be reduced to one tier (12 feet). Roadways will be sloped up in the east- and westbound directions, permitting access on both sides of the levee. Increasing the slope on both ends will likely help mitigate flooding along this section of road as flooding is expected to reach this far. The segment of Nimitz Highway—Queen Liliuokalani Freeway specifically projected to be affected will be retrofitted into an elevated bridge.

Phase 3's third and final tier of protection is the application of deployable floodwalls, similar to those demonstrated in the design proposal of the BIG U. These floodwalls will be located along the north and south faces of the Nimitz Highway—Queen Liliuokalani Freeway. During extreme natural disasters, like hurricanes, storms and tsunamis, the floodwalls can be launched to enclose this entire stretch of the transportation system. These will provide a means of protection for Māpunapuna as well as other developments to the west, including the military housing and golf course.

Because Māpunapuna is close to the ocean, it will be exposed to increasingly severe coastal conditions and thus drastic changes in the built environment will be required. Proposed buildings will be medium- and high-density, meaning their development will be primarily vertical, elevating habitable spaces one story up from ground level. Spaces at the ground level will be wet or dry floodproofed, depending on intended use. Wet floodproofing can be applied to amenities that are temporary and require little furnishings, while dry floodproofing can be used in spaces that are more permanent like cafes, shops, and parking garages.

Green Networks

As the development of Māpunapuna is being completed, northern parts will receive green stormwater infrastructure measures including green roofs, street planter boxes, detention basins, urban tree canopy, rain gardens, and pervious pavement. Similar to Phase 1 and 2, new and old buildings will be required to install vegetated roofs. Streets connecting in the north to Mapunapuna and Pukoloa Streets will be adjusted to make room for planter boxes. Some lots on the landward side of the levee will accommodate retention basins.

At this point in the century, it is speculated that rainwater harvesting and filtration and treatment technologies will be sophisticated enough to be easily integrated into buildings. If rainfall forecasts hold true, rains in Māpunapuna will be infrequent but more massive (see discussion in 2.2.1). Torrential downpours will dump large amounts of water that can be stored for later use. Lots will be able to maintain private water supplies, reducing their dependence on O'ahu's freshwater reserves.

The widespread green stormwater infrastructures in conjunction with marsh landscapes will efficiently filter runoff. Soils will be able to be saturated and local groundwater tables replenished. With the continued implementation of stringent practices throughout all three phases and beyond, existing groundwater tables are expected to recharge thus mitigating land subsidence and the effects of sea level rise, and passive flooding in particular, in Māpunapuna.

Placemaking

According to Panos Prevedourous (chapter 6), in order for sophisticated adaptation and mitigation strategies to be implemented in an area, there must be some level of value or incentive for protecting the area. Prevedourous suggests that existing land uses and zoning designations in Māpunapuna do not generate enough means to protect the area from severe and chronic flooding. As a significant number of leases expire, proposing zoning changes will be less problematic. Phase 3 recommends a change to several land use designations in order to enhance value in the area and provide incentive for protecting the area. The conceptual design divides the project site into two neighborhoods that will be named after historic fishponds and a third neighborhood, outside the site, named after the proposed HART rail station for the area.

The first neighborhood retains the name Māpunapuna and is situated between the Queen Liliuokalani Freeway and Pukoloa Street. The historic fishpond named Māpunapuna was the largest in the area and was originally located near the intersection of Mapunapuna and Kalihikapu Streets. The new Māpunapuna is proposed to be a medium- and high-density mixed-use residential and commercial development. This type of zoning will create a residential atmosphere connecting it with adjacent neighborhoods to the east, west, and north. Residents traveling to and from the area will have access to existing bus lines running to Downtown, Ala Moana, and Waikiki in the east and Pearl Ridge in the west. Residents will also have access to Lagoon Drive Waterfront, the third created neighborhood; roads that are not affected by sea level rise will remain, and a pedestrian and bicycle pathway will be placed along the length of the two-tiered super levee. The top tier, designated as a buffer space and public park, will be wide. Linear parks along the super levee will provide neighborhood amenities and will activate the area. A residential waterfront is proposed near the original location of Mokumoa Street. Similar to the measures applied in Phase 1, retention ponds are proposed for the landward side of the super levee to store excess peak flows and to function as parks for the building complexes.

The second neighborhood will be named ʻAwaʻawaloa, after the fishpond that once existed in the area. It will be located between Mokumoa Street and the Nimitz Highway—Queen Liliuokalani Freeway. Unlike the new Māpunapuna, ʻAwaʻawaloa will be primarily zoned for commercial and industrial uses, but will include a limited number of residences as the proposed building structures and densities are vertical medium to high. The zoning decision is based on HART's proposed land use for the area.

ʻAwaʻawaloa will act as the transition between Māpunapuna and the third neighborhood, Lagoon Drive Waterfront. Properties near Puuloa Road are designated for mixed-industrial use. Light industries will be promoted in the area. Light industries are consumer-oriented businesses that have smaller impacts on the environment.[183] Some examples of light industries that may be introduced to the neighborhood include the production of food, drinks, clothing, furniture, and art. Māpunapuna's current industrial businesses are considered heavy industries, which have more adverse impacts on the environment over time. Most of this development will lie along Puuloa Road; existing bus routes along the road will support these properties and walk times for users will be short.

The third and final neighborhood is Lagoon Drive Waterfront, named for the proposed HART rail station that will be located in the vicinity. This area was not a part of the dissertation's original project site; however, because the proposed super levee extends along this site, the conceptual design proposes measures to activate certain areas the super levee will protect. By 2100, the planned Lagoon Drive Rail Station should be complete along with other proposed amenities that are part of AECOM's transit-oriented development plan. According to AECOM's plans, the area will be primarily mixed-use commercial and industrial waterfront, set up for businesses to have convenient access to the rail station. Residents that live in ʻAwaʻawaloa and Māpunapuna will be able to travel to Lagoon Drive Waterfront using the proposed two-tiered levee. As described in the preceding passages, the proposed hard protection measure will provide additional functions such as alternative routes of circulation and a public park and waterfront development in each neighborhood. Despite the distance of the pier walk between the first two neighborhoods and Lagoon Drive Waterfront, the pathways' proximity to the water and marshes and ample shade trees will make the stroll a pleasant experience.

Because the area is projected to serve an array of users from workers to residents to tourists traveling to and from the airport, a water taxi station will be set along the super levee near the intersection of Aolele Street and Lagoon Drive. It will serve as an additional form of transportation along the south shores of Oʻahu. One more station will be located onsite, east

183

of the new Māpunapuna. Māpunapuna residents will be able to access the taxi and ride it to the station at Lagoon Drive Waterfront and others that will be constructed along the south shore. Providing alternate routes and means of travel will promote more foot traffic and visitors, thus activating the area even more. Amenities including retail and commercial shops located on the top tier of the super levee are proposed for the water taxi station sites.

Figure 7.9: 6 feet sea level rise + MHHW and affected areas
Graphic: author

Figure 7.10: Phase 3 illustrative master plan
Graphic: author

Figure 7.11: Phase 3 neighborhood and zoning
Graphic: author

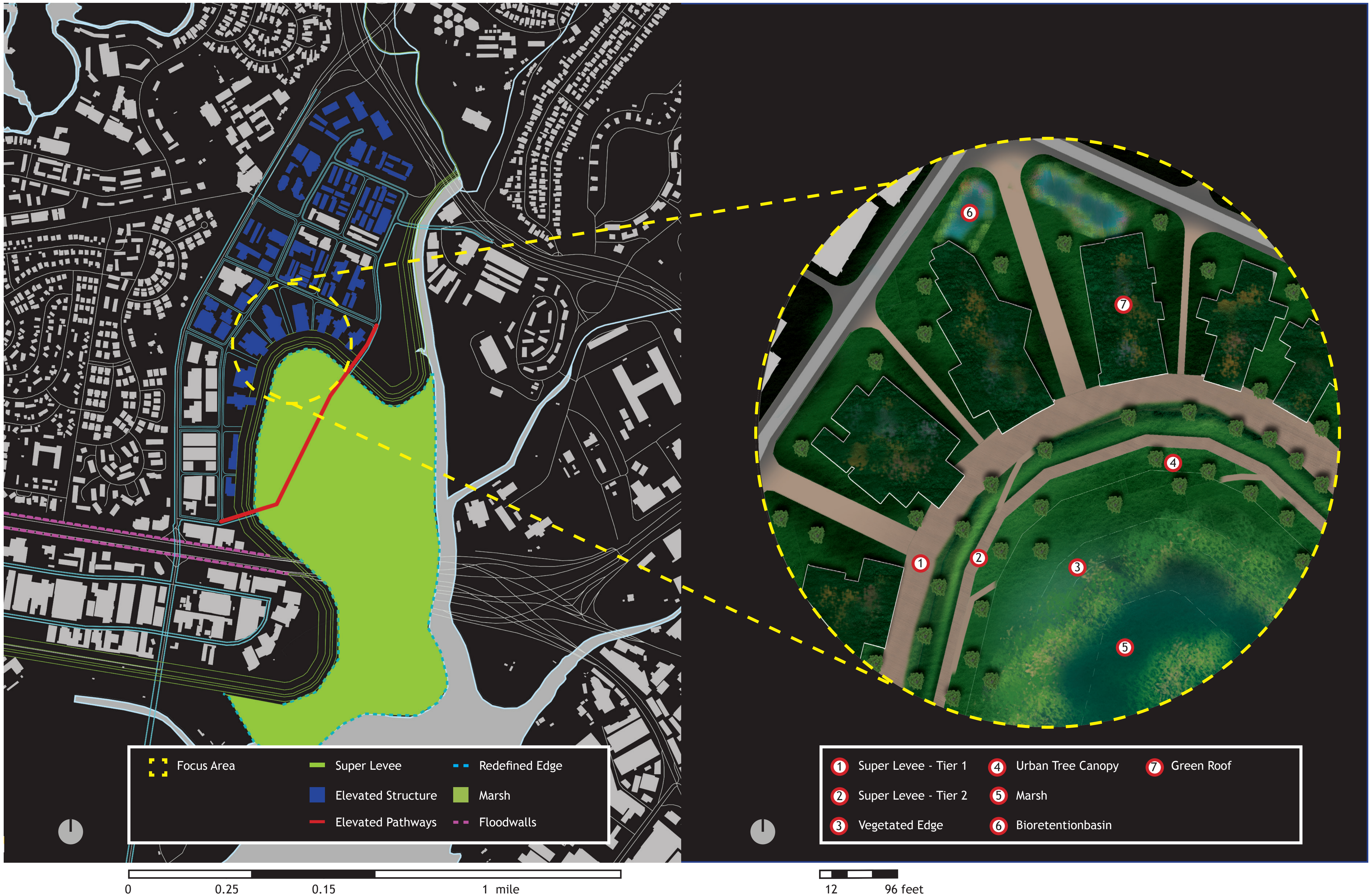

Figure 7.12 Phase 3 key design features and focus area, Graphic: author

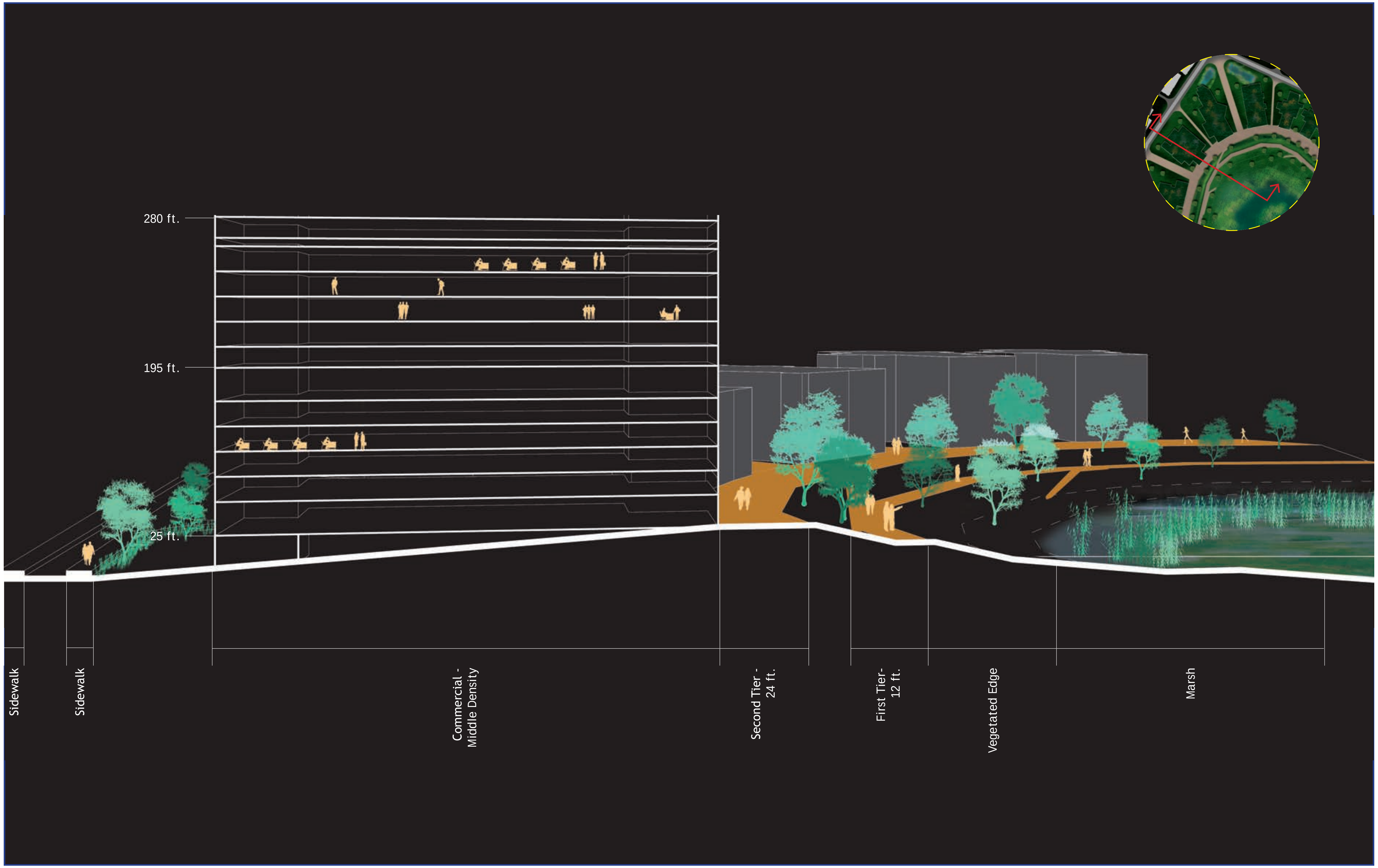

Figure 7.13 Section perspective of activated commercial waterfront in ʻAwaʻawaloa, Graphic: author

CHAPTER 8: CONCLUSION

Floods primarily originate from excessive rainfall. In most cases, natural undeveloped landscapes can successfully regulate the runoff. However, as humans have gradually altered natural environments and settled in flood prone areas for the benefits coastlines offer, the severity of floods has begun to grow. It is not the flood itself that is the root of the problem, but rather the level of exposure to the built environment. As sea level rise continues to escalate and exacerbate coastal flooding conditions, many places will eventually become permanently submerged. Some of the general outcomes of floods in urban environments include property damage, loss of life, stalled livelihoods, a decline in economies, and the spread of hazardous pollution. Are these consequences and others worth the risks inherent in living and working near the water? Floods have been addressed since the earliest documented settlements and today remain an impending problem that takes a toll on all aspects of urban life—physical, environmental, and socioeconomic.

In Hawai‘i, flooding conditions reflect this imbalance between the built and natural environments. Local populations are densely concentrated in coastal regions which are also the last tier of the watersheds. These conditions literally leave residents surrounded by different types of flood hazards—surging waters from the ocean, rainfall from the sky, runoff from the mountains, and rising groundwater from below. Existing efforts to mitigate and adapt to flooding are inadequate and perform at the bare minimum. Hawai‘i is not alone in facing this problem; examples from other parts of the world provide a look at pioneering solutions designed for recurrent, unresolved problems. Precedents were chosen for their ingenuity of designs as well as their similarity in conditions and constraints to those in Hawai‘i. These examples demonstrate that flood mitigation and adaptation designs can be taken to new levels and present opportunity for use in Hawai‘i.

Through the application of design principles formulated from research on flood mitigation and adaptation, strategies and measures were compiled into a conceptual master plan for Māpunapuna. This master plan aims to create a flood resilient development that functions as a holistic design with components working together as a system, creating ideal live, work, and play conditions, while accommodating floodwaters and reintroducing natural environments into urbanized areas.

By its final phase, the master plan will result in the creation of three new neighborhoods—the new Māpunapuna, ʻAwaʻawaloa, and Lagoon Drive Waterfront. It illustrates a progressive response to coastal flooding conditions in Hawaiʻi, transforming the negative aspects of floods into favorable circumstances. The immediate goal is to provide flood mitigation and adaptation design strategies for Māpunapuna. However, it is important to note that the process, concepts, and solutions presented in this dissertation were designed to be duplicated, expanded on, or used as inspiration for new projects along coastlines in Hawaiʻi and around the world.

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