University of Hawai‘i Sea Grant College Program

WAIKĪKĪ RESILIENCE & SLR ADAPTATION PROJECT

NATURAL HAZARDS AND CLIMATE IMPACTS ASSESSMENT

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Acknowledgments

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Table of Contents

Content and Framework

The University of Hawai‘i Sea Grant College Program (Hawai‘i Sea Grant) prepared this Waikīkī Natural Hazards and Climate Impacts Assessment focusing on the Waikīkī Special District. This assessment examines the current landscape of natural hazards, climate change and sea level rise, highlighting their risk implications for land use in the long-term timeframe (year 2050 to 2100^{+}). While not exhaustive, this natural hazard overview aims to illuminate the primary hazards and climate change impacts with a focus on long-range adaptation planning, policy and implementation as a basis for future state-level adaptation planning for the Waikīkī watershed and special district.

The Natural Hazard Assessment provided here is a complementary effort to the Climate Risk Profiles that have been developed as part of the City and County of Honolulu's (City) *Adapt Waikīkī 2050* project which strives to develop a shorter-term (30 year) climate adaptation plan for the Waikīkī Special District with a focus on City infrastructure.[1] The *Adapt Waikīkī 2050* project is being led by the City Department of Planning and Permitting in partnership with a technical consultant team and the City One Water panel. Together, these efforts form a shared level of understanding for risks in Waikīkī and provide a foundational component of the Waikīkī Resilience and Adaptation Project (WRAP), spearheaded by the University of Hawaiʻi Community Design Center (CDC) and supported by the State Office of Planning and Sustainable Development.

[1] Courtney, C., G. Orozco and N. Cole. 2024. Adapt Waikīkī 2050: Climate Risk Profile for the Waikīkī Special District. Prepared by Tetra Tech, Inc. and the City and County of Honolulu Department of Planning and Permitting under Contract No. CT-DPP-2300252. https://ssfm.konveio.com/adapt-Waikīkī-factsheet

Executive Summary

The Waikīkī Natural Hazards and Climate Impacts Assessment (Natural Hazards) report provided here is a component section report to the Waikīkī Resilience and Sea Level Rise Adaptation Project (WRAP). The goal of the WRAP is to develop a framework and lay the groundwork for a future Waikīkī adaptation and resilience plan that addresses the projected impacts of climate change and sea level rise in the Waikīkī Special District and beyond. The intent of this Natural Hazards section is to provide a broad summary of key trends, natural hazards, vulnerabilities and long-term (50-100^{+} years) planning considerations related to sea level rise and climate change in the Waikīkī Special District. The WRAP identifies long-term adaptation planning considerations using established sea level rise benchmarks as a planning rationale and establishes the framework for subsequent adaptation plans emphasizing a phased implementation approach for selected adaptation pathways.

This section of the WRAP provides key takeaways related to natural hazards, projected climate change impacts and policy and planning implications and opportunities relevant to the Waikīkī Special District. The Natural Hazards section provides a summary of natural hazards, climate change trends and projections of potential impacts for Waikīkī with a focus on hazards and vulnerabilities specific to sea level rise. The Natural Hazards Assessment is complemented by Section 7.1.a *Resilience and Adaptation Planning Precedents, Policies and Work Products* with an overview of adaptation planning and policy precedents from other municipalities. The *Preliminary Adaptation Implementation Roadmap* section highlights opportunities for climate change adaptation implementation initiatives relevant for Waikīkī. The Roadmap section provides a foundation for the next steps by exploring potential implementation strategies, adaptation pathways and planning options.

This Natural Hazard section references the guidelines and benchmarks for sea level rise (SLR) adaptation planning from the State of Hawaiʻi and the City and County of Honolulu.

The Hawaiʻi Climate Change Adaptation Initiative (Act 83) in 2014 and in a follow-up through Act 32 in 2017, created a State Climate Change Mitigation and Adaptation Commission and mandated the development of the Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report. The report, completed and adopted by the commission in 2017, focused on the best-available sea level rise projections at the time from the IPCC 5th Assessment Report pointing to 3.2 feet of sea level rise as a planning target in this century. The 2017 report and companion Hawaiʻi Sea Level Rise Viewer online mapping tool provide a Sea Level Rise Exposure Area (SLR-XA) depicting potential flooding and erosion hazards up to 3.2 feet of sea level rise, which remains a primary benchmark for sea level rise adaptation planning in Hawaiʻi.

A 2022 update to the State Sea Level Rise report included updated global and local sea level rise projections based on the latest science from a NOAA-led interagency report released that year that points to 3.9 and 5.9 feet of sea level rise by 2100 for the Intermediate and Intermediate-high NOAA-Interagency SLR scenarios for Hawaiʻi. In 2022, the City & County of Honolulu Climate Change Commission transmitted updated sea level rise guidance to the mayor, city council and executive departments that recommends 3.8 feet by 2100 as a minimum scenario for all planning and design and 5.8 feet by 2100 as the SLR scenario for planning and design of public infrastructure and recommends that the City continue to utilize the 3.2 ft SLR-XA until updated map data is available. These planning benchmarks were included in Climate Ready Oʻahu: The City's Climate Adaptation Strategy adopted by the mayor and city council in February, 2024.

Key Takeaways: Climate Science

Sea Level Rise Impacts

- *Hawai'i, including Waikīkī, is vulnerable to impacts associated with climate change and sea level rise due to our coastal-focused society and economy, concentrated shoreline development and remote location in the Central Pacific.*
- *It is increasingly likely that we will experience 3 to 4 feet of sea level rise by the end of this century under an Intermediate (mid-range) sea level rise scenario. Six feet or more of sea level rise by 2100 is plausible under Intermediate High and High scenarios.*[2]
- *There is a pronounced flooding threshold between 3 and 4 feet of sea level rise in which passive (high tide) flooding and groundwater inundation in Waikīkī becomes significantly more widespread. Using the U.S. Interagency Intermediate-High Sea level rose scenario, this threshold would occur around the year 2080.*[3] *This elevation threshold is not unique to Waikīkī, in fact, most of the Primary Urban Center in Honolulu is subject to a similar phenomenon.*
- *Flooding from extreme tides, impaired drainage and rising groundwater will affect low-lying coastal areas in Waikīkī decades before sea level reaches projected benchmarks permanently.*[4]
- *Using data from the Hawai'i Sea Level Rise Vulnerability and Adaptation Report,*[5]*we find that 3.2 feet of sea level rise would cause the following impacts in*

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[2] U.S. Interagency Sea Level Rise Scenario Tool. https://sealevel.nasa.gov/task-force-scenario-tool?psmsl_id=155

[3] Sweet, W.V., et al., 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nostechrpt01-global-regional-SLR-scenarios-US.pdf

[4] (PUC, 2018). Sea Level Rise & Climate Change. Final White Paper. Honolulu Primary Urban Center Development Plan. University of Hawaii Sea Grant College for the City and County of Honolulu. December, 2018. https://www.honolulu.gov/rep/site/dpptod/dpptod_docs2/Sea_Level_Rise_Final_White_Paper.pdf

[5] Hawai'i Climate Change Mitigation and Adaptation Commission. 2017. Hawai'i Sea Level Rise Vulnerability and Adaptation Report. Prepared by Tetra Tech, Inc. and the State of Hawai'i Department of Land and Natural Resources, Office of Conservation and Coastal Lands, under the State of Hawai'i

Waikīkī (assuming no adaptation measures are employed): chronic flooding in 174 acres of land potentially impacting 302 buildings, displacing 1870 residents and flooding 5.5 miles of road.[6]

- *The economic impacts of 3.2 feet of sea level rise will be disproportionately high in Waikīkī due to dense development on low-lying coastal lands, potentially threatening $4.9 billion in private resort and hotel buildings and property or 26% of Oʻahu's total property value.*[7] *The monetary impacts to roads, utilities and other critical infrastructure and municipal property are unknown but may be an order of magnitude greater than potential loss of privately-owned structures and property.*

Climate Change Impacts

- *Global mean air temperatures have increased by 2.1° F in this century.*[8] *Honolulu is experiencing a significant increase in the number of days with temperatures above 90° F. Temperatures in Hawaiʻi are expected to increase between 2° F and 5° F by 2100 depending on future greenhouse gas emission trends.*[9]
- *Public health risks associated with rising temperatures and extreme heat events include increased respiratory illnesses, heatstroke and cardiovascular and kidney disease.*[10]
- *Hawaiʻi has experienced a statewide decline in average annual rainfall in recent decades.*[11] *Precipitation extremes are also becoming more common in the Pacific*

Department of Land and Natural Resources Contract No: 64064. https://climateadaptation.hawaii.gov/wp-content/uploads/2017/12/SLR-Report_Dec2017.pdf

[6] Data from the Hawaiʻi Sea Level Rise Viewer and 2017 Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report, subsetted using the boundary of the Waikīkī Special Improvement District.

[7] Calculations provided by the University of Hawaiʻi Institute for Sustainability (unpublished for the City & County of Honolulu Office of Climate Change, Sustainability and Resilience). Property values in 2023 dollars and includes private lands and structures in the hotel and resort category, only.

[8] NASA Goddard Institute for Space Studies. Surface Temperature Analysis (GISTEMP v4): https://data.giss.nasa.gov/gistemp/ (baseline 1950-1980, its 2.45 F above pre-industrial 1850-1900)

[9] Zhang, C., Y. Wang, K. Hamilton and A. Lauer, 2016: Dynamical Downscaling of the Climate for the Hawaiian Islands. Part II: Projection for the Late Twenty-First Century. J. Climate, 29, 8333–8354, https://doi.org/10.1175/JCLI-D-16-0038.1.

[10] City & County of Honolulu Climate Change Commission (HCCC, 2024). Urban Heat - Guidance Document. https://www.resilientoahu.org/climate-change-commission/#guidance

[11] Frazier, A.G. and Giambelluca, T.W. (2017) Spatial trend analysis of HI rainfall from 1920 to 2012. Int. J. Climatol, 37: 2522-2531, DOI: 10.1002/joc.4862.

Basin with both more frequent heavy rainfall events and more periods of sustained drought.[12] *Climate models predict these extremes to become more pronounced with climate change.*

- *Projections for future climate change impacts on local precipitation patterns remain uncertain. However, rising sea levels and groundwater inundation will reduce drainage capacity during heavy rainfall events and contribute to the risk of environmental impacts from contaminated groundwater and compromised wastewater and utility systems.*
- *Models of future climate conditions indicate that Hawaiʻi will be impacted by tropical cyclones more frequently as storm tracks shift northward. Because a significant portion of Hawaii's population, economic assets and critical infrastructure are concentrated within the PUC, a tropical cyclone hitting the area would have major statewide impacts.*

[12] Kruk, M. C., et al. (2015) On the state of the knowledge of rainfall extremes in the western and northern Pacific basin, Int. J. Climate., 35(3), 321–336.

Key Takeaways:

SLR Adaptation Planning Considerations

- *The WRAP is utilizing a long-range planning perspective (~year 2050-2100⁺).*
- *For long-term conceptual visualization purposes, a 4-foot planning benchmark is utilized as a minimum for most development and a 6-foot planning benchmark for critical infrastructure with long expected life spans and/or low risk tolerance. This adaptation planning benchmark is consistent with the recommendations of the City and County of Honolulu Climate Change Commission's (HCCC) updated (2022) sea level rise guidance and recommendations.*[13]
- *The HCCC's sea level rise guidance recommends using a 3.8 ft sea level rise estimate by the year 2100 as a planning benchmark using the Interagency Report's Intermediate sea level rise scenario for all planning and design (for (WRAP purposes we are rounding this up to 4 ft) (*Sweet, W.V., et al., 2022)*.*
- *For planning and policy, the HCCC's guidance recommends using the interagency Intermediate High (5.8 ft by 2100) sea level rise scenario for all planning and design of public infrastructure projects and other projects with low tolerance for risk (for WRAP purposes we are rounding this up to 6 feet).*
- *The HCCC recommends utilizing the state's 3.2 ft SLR-XA and the 6 ft passive flooding map layer from NOAA until updated SLR-XA map data is available. As of 2024, this sea level rise map data is now currently available, in 1 ft increments up to 10 ft from the University of Hawai'i Coastal Resilience Collaborative SOEST Climate Viewer.*[14]
- *HCCC's SLR guidance aligns with Mayoral Directive No. 18-2 which requires city departments and agencies to use the Hawai'i Sea Level Rise Vulnerability and*

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[13] City & County of Honolulu Climate Change Commission (HCCC, 2022). Updated Sea Level Rise Guidance (July, 2022). https://static1.squarespace.com/static/5e3885654a153a6ef84e6c9c/t/62f46b3fff589f651af14410/1660185409937/HonoluluClimateChangeCommission-SeaLevelRiseGuidance_Updated-July2022.pdf

[14] Note: This updated modeling data, while publicly available, has not been formally adopted by state or City agencies for official planning use as of May, 2024. https://www.soest.hawaii.edu/crc/slr-viewer/

Adaptation Report and the City and County of Honolulu Climate Change Commission Sea Level Rise Guidance in planning, programing and capital improvement decisions.

- *Adaptation planning and resilience efforts should prioritize resilience actions that provide multiple benefits and strategically incorporate adaptation measures into ongoing projects and planning efforts. Some of these include design flood elevations, accommodating flood water and raised critical infrastructure which will mitigate shorter-term hazard risks in addition to longer-term climate impacts.*
- *Adaptation plans that incorporate flexible, trigger-based pathway scenarios will serve Waikīkī well in developing plans that are actionable, clear and implementable into existing land use codes and rules. Refer to Section 9 Adaptation Implementation Roadmap for more details.*
- *Climate change adaptation and mitigation strategies can be integrated into overarching Waikīkī planning and zoning frameworks, as Oʻahu prepares for predicted SLR impacts while also cutting greenhouse gas emissions driving climate change.*

Environmental Setting

Waikīkī- Ala Wai Watershed and Environmental Setting

O‘ahu is the most populous of the Hawaiian Islands and Waikīkī lies within the Primary Urban Center (PUC) which serves as the business and government center of the State. Much of the PUC including Waikīkī, is built on a low-lying coastal plain composed of reef and marine deposits from periods of higher sea levels 125,000 years ago. Much of Waikīkī is below 6 feet in elevation. The Waikīkī shoreline is highly engineered and bears little resemblance to its former natural condition with the entire shoreline armored with seawalls and other shore protection and stabilization structures. Much of the Waikīkī backshore area consists of fill material dredged from the creation of the Ala Wai Canal to raise natural and man-made wetlands that once were prolific in the area. The Waikīkī coastal plain is backed by steep valleys leading to the headwalls of the Ko‘olau Mountains including the Palolo, Manoa and Makiki valleys. This steep topography adds to flood risks within the Ala Wai Watershed (PUC, 2018).

Waikīkī, situated on the southern shore of Oahu, Hawaii's most populous island, is a bustling district known for its picturesque beaches, urban landscape and economic vitality. Waikīkī is located in the moku of Kona and lies within the ahupua‘a, or traditional land division of Waikīkī. The ahupua‘a boundaries extend from the mountains to the ocean and typically encompass all of the environmental zones to support communities and are often centered on the flow of water. The Waikīkī district is characterized by dense urban resort and commercial development, heavily visited urban beaches and the iconic image of Diamond Head crater (Le’ahi) in the background. Waikīkī's urban environment is defined by a mix of high-rise hotels and commercial-residential buildings.

Waikīkī and the associated Special District, is most often defined as the area bounded on the north and west by the Ala Wai canal (including the Ala Wai Boat Harbor), on the east by Kapahulu Avenue and on the south by the ocean shoreline of Māmala Bay (Figure

1).[15] Waikīkī in 'Ōlelo Hawai'i means "spouting waters." The name refers to the many rivers and springs that once made up the land along the coast, in an area that was formerly wetland and taro loi. The entire southern shoreline of Oahu has been reshaped over the last century with nearshore reefs dredged and low elevation ponds filled to allow the development that we see today. The term Waikīkī is an important historic reminder to the geographic and environmental background for this highly altered location as sea level rise will eventually inundate this area over the next century. Waikīkī also lies within the Ala Wai watershed, an important urban watershed extending from the top of the Koolaupoko mountains to the edge of the reefs.

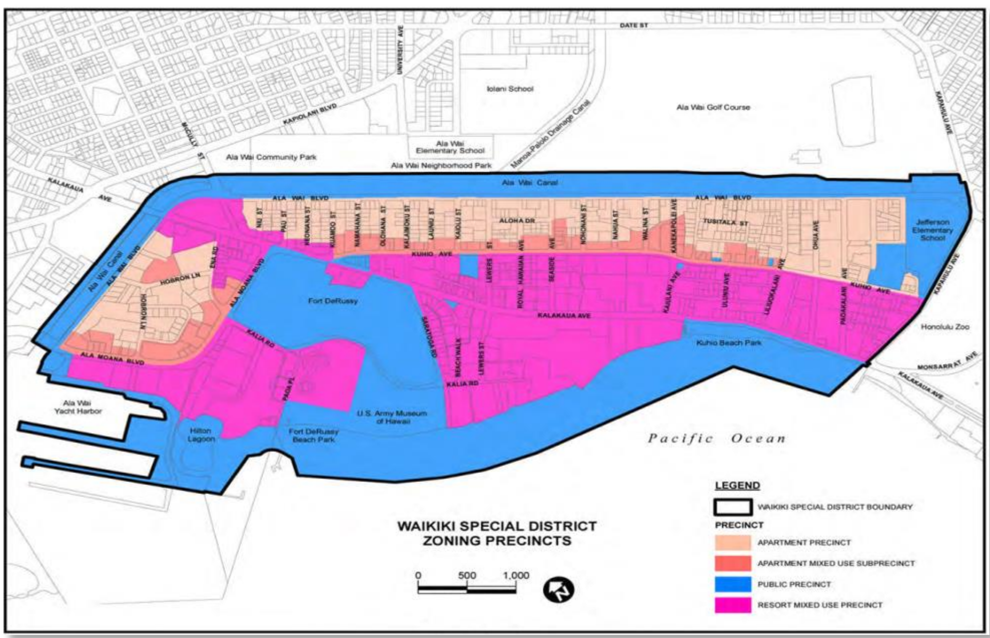

Figure 1. Waikīkī Special District Precincts (Image Credit: WSD, 2021).

The adjacent Ala Wai Watershed includes Waikīkī and spans parts of the ahupua'a of Waikīkī and Honolulu. The watershed encompasses 19 square miles (12,064 acres) and extends from the ridge of the Ko'olau Mountains to the near-shore waters of Māmala

[15] Design Guidelines Waikīkī Special District (WSD, 2021). City and County of Honolulu, Department of Planning and Permitting. August, 2021. https://www.honolulu.gov/rep/site/dpp/dpp_docs/Waikīkī-special-district-guidebook.pdf

Bay.[16] The watershed includes several streams, which flow to the Ala Wai Canal, a 2-mile-long, man-made waterway constructed during the 1920's to drain extensive coastal wetlands. This construction and subsequent draining allowed the development of the Waikīkī District as we know it today. The canal was constructed to drain the Waikīkī marshlands to allow development and was not designed for major flood control.

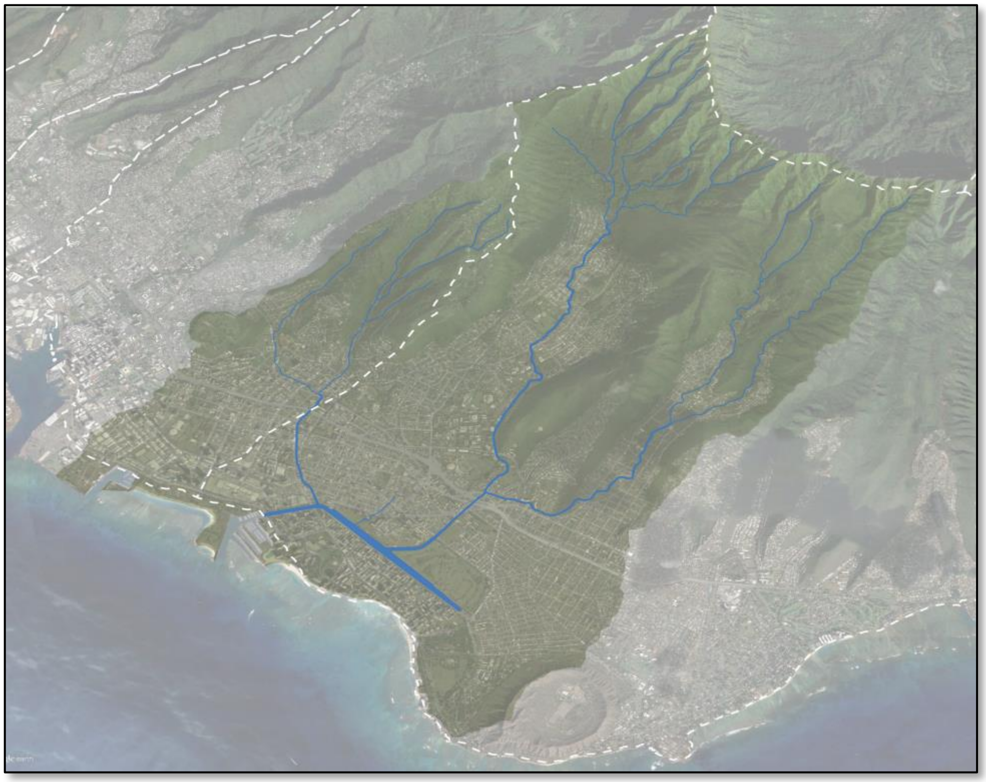

Figure 2. Ala Wai Watershed (color-highlighted) showing the Waikīkī ahupuaʻa (dashed lines), primary streams and the location of the Ala Wai Canal in Waikīkī.

The Ala Wai watershed is defined by the three Koʻolau Mountain Range streams (made up of smaller streams) that flow into the Ala Wai Canal and ultimately into Māmala Bay at Ala Wai Harbor: Makīkī Stream, Mānoa Stream and Pālolo Stream (Figure 2). Within the watershed are also man-made canals and ditches. The watershed is home to multiple

[16] Ala Wai Study. Flood Risk Management. City and County of Honolulu. https://www.honolulu.gov/AlaWai

neighborhoods including Waikīkī, institutions such as the University of Hawaiʻi, hospitals, several private and public schools, business and a mix of both residential and commercial development. It is the most densely populated watershed in Hawaiʻi (~200,000 people) and makes up 7% of the state's gross domestic product, 7% of civilian jobs and 9% of state and county tax revenue.[17]

Economic Background

The Waikīkī economy is centered on tourism, drawing 5.6 million visitors in 2023. For 2023, total visitor spending was $9.01 billion, up from $8.69 billion in 2022 and $8.14 billion in 2019.[18] Waikīkī generates approximately 42% of the state's visitor industry revenue and is responsible for 8% ($5 billion) of the Gross State Product.[19] Statistics on development in Waikīkī underscore its status as a bustling urban center. The area encompasses approximately 1.5 square miles (3.9 square kilometers) and is home to over 20,000 residents. Waikīkī serves as a primary hub for hospitality and service industries, providing employment opportunities and contributing significantly to the island's economy. Waikīkī is recognized as Hawaii's primary visitor destination and is home to more than 30,000 visitor accommodation units (contrasted to the 20,000 residents of Waikīkī) including resorts, hotels and condominiums, which accounts for 90% of all units on Oʻahu and nearly half of all units in the State of Hawaiʻi. In addition, 10% of all State and County tax revenues and 8% of all civilian jobs statewide can be credited to Waikīkī's attraction of visitors. Despite its dense urbanization, efforts are underway to balance development with environmental conservation and sustainability. Initiatives aimed at preserving natural resources and mitigating the impacts of climate change reflect Waikīkī's commitment to maintaining its unique blend of urban character, Hawaiian culture, history and natural beauty.

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[17] The Economic Contribution of Waikīkī Department of Business, Economic Development & Tourism May 2003. https://files.Hawaiʻihawaii.gov/dbedt/economic/data_reports/e-reports/econ_Waikīkī.pdf
[18] State of Hawaii Department of Business, State of Hawaii Economic Development & Tourism (January, 2024). https://dbedt.hawaii.gov/blog/24-05/
[19] State of Hawaii, 2022. In: State of Hawaii Data Book. Department of Business, Economic Development and Tourism (DBEDT).https://files.hawaii.gov/dbedt/economic/databook/db2022/section07.pdf

Ala Wai Flood Risk Management Study (Army Corps of Engineers)

The objective of the Ala Wai Canal Flood Risk Management Project is to reduce riverine flood risks in the Ala Wai Watershed. Flooding associated with a 1% Annual Exceedance Probability (AEP) 24-hour rainfall event would affect approximately 1,358 acres within the Ala Wai Watershed, including over 3,000 properties with an estimated $1.14 billion in structural damages at 2016 price levels.[20] In December 2017, the US Army Corps of Engineers completed the Feasibility Study for The Ala Wai Canal Flood Risk Management Project with an authorized cost of $345 million (D-SEIS, 2023).

Updated analysis conducted during a subsequent Engineering Documentation Report included a 2023 Draft Supplemental Environmental Impact Statement Analyses conducted in support of this study show that the 1% AEP flood event—an event with a 1% chance of being equaled or exceeded in any given year—affects approximately 3,111 structures with an estimated $905,327,000 in structural damages alone (2023 price levels), not accounting for loss in business income or other similar economic losses (D-SEIS, 2023). As part of this study, an updated cost of the tentatively selected plan was estimated at $1.075 billion (D-SEIS, 2023). Since its construction, the drainages have been highly urbanized causing urban pollutants and runoff to increase to the Canal. The canal is owned and maintained by the state of Hawaii. The canal has been dredged at least four times, in 1967, 1978, 2002 and 2021.[21]

Waikīkī Beach, Marine and Coastal Area

The historical context of Waikīkī reveals a significantly altered landscape. What was once wetland and loʻi kalo (a submerged water-based kalo or taro farming technique similar to rice paddies) were drained through the construction of the Ala Wai Canal in the early

[20] Draft Supplemental Environmental Impact Statement (D-SEIS) for the proposed U.S. Army Corps of Engineers Ala Wai Canal Flood Risk Management Project https://files.hawaii.gov/dbedt/erp/Doc_Library/2023-11-23-OA-DSEIS-Ala-Wai-Canal-Flood-Risk-Management-Project.pdf

[21] Ala Wai Flood Risk Management Project. U.S. Army Corps of Engineers. https://www.poh.usace.army.mil/Missions/Civil-Works/Civil-Works-Projects/Ala-Wai-Flood-Risk-Management-Project/

1920's. This wetland drainage, along with massive coral reef and sand dredging throughout Waikīkī was followed by rapid coastal development. This had a dramatic impact on the Waikīkī environment, forever changing these unique coastal ecosystems. As a result of the nearshore reef dredging, coastal erosion accelerated resulting in a proliferation of shoreline structures around the turn of the century and into the 1950s, some of these structures are still there today and serve as a stark reminder of the consequences of unplanned or poorly coordinated projects.

Waikīkī Beach has undergone significant changes since the turn of the century. Waikīkī is a highly developed urban beach with a long history of coastal engineering projects including beach nourishment and shoreline structures such as groins and seawalls. Hardened shoreline structures dominate Waikīkī's beach dynamics by altering sediment transport dynamics, thereby influencing beach location and width. Historical sand hauling from the beach and dredging/mining of the reef in Waikīkī during the early 20th century also significantly altered coastal dynamics in the region.

Waikīkī and the associated beach areas are part of the widely recognized economic hub for the State of Hawaii. Although Waikīkī is predominantly a visitor and hotel industry economic sector, the shoreline area is heavily utilized by visitors and locals alike, serving as a critical lateral access corridor along the shore that has a demonstrated vulnerability to the impacts of sea-level rise, coastal storms, wave attack and coastal erosion. Much of the public space and recreation is centered on the beach areas of Waikīkī and is complemented by a series or "lei" of public parks that surround Waikīkī. In the last couple of years, several of the properties in the Waikīkī area have experienced increasingly severe beach loss and damage to the backshore infrastructure including the seawalls, public lateral walkways and land loss. The State of Hawai'i, Department of Land and Natural Resources (DLNR), in partnership with the Waikīkī Beach Special Improvement District Association (WBSIDA)[22] is currently conducting a State Final Environmental

[22] https://www.wbsida.org/

Impact Statement that proposes shoreline stabilizing, mitigation actions to renourish and reinforce the area through structural engineering and beach fill.[23]

Waikīkī is renowned for the image of white sand beaches, sunsets and the backdrop of Diamond Head. Waikīkī Beach is a globally recognized icon of Hawaiʻi and is the state's largest tourist destination. Beaches are a primary attraction for visitors to Waikīkī. It has been estimated that Waikīkī Beach accounts for over $2 billion in annual income for the local economy[24]. However, a 2008 survey found that 12% of visitors would not return to Waikīkī due, in part, to limited beach area and resulting overcrowding.[25] An update to the 2008 report was completed in 2016 which estimated the economic value of Waikīkī Beach to the local economy at just over $2 billion using updated 2016 economic and visitor arrival data.[26] Waikīkī Beach also has tremendous cultural significance as a former playground of Hawaiian royalty and the birthplace of the sport and culture of surfing. For over 100 years, there have been repeated efforts to stabilize the beaches in Waikīkī with shoreline structures and beach restoration sourced with sand outside of Waikīkī with varying degrees of success.[27] The beaches and myriad of world-renowned surf breaks and reef ecosystems located offshore are valuable natural resources that support the culture and lifestyle of Hawaiʻi and the idyllic image of Waikīkī.

Waikīkī Beach is largely defined by historic shoreline structures that create district littoral beach cells. Nearly all of the beaches in Waikīkī are inherently unstable and have

[23]Hawaii Department of Land and Natural Resources. OCCL. Draft Programmatic Environmental Impact Statement (DPEIS) for the Waikīkī Beach Improvement and Maintenance Program (2021). https://files.hawaii.gov/dbedt/erp/Doc_Library/2021-06-08-OA-DEIS-Waikīkī-Beach-Improvement-and-Maintenance-Program.pdf.
[24] Tarui, N., Peng, M., Eversole, D. Economic Impact Analysis of the Potential Erosion of Waikīkī Beach. April, 2018. University of Hawaiʻi Sea Grant College Program. https://seagrant.soest.hawaii.edu/wp-content/uploads/2018/08/Economic-Impact-Analysis-Waikīkī-Beach-1016-web.pdf
[25] Hospitality Advisors, LLC. (2008). Economic Impact Analysis of the Potential Erosion of Waikīkī Beach. Final Report prepared for Waikīkī Improvement Association. https://static1.squarespace.com/static/58eec8afc534a5631767d450/t/58f5314f37c581de8a8c3117/1492463952799/2008-economic-HospitalityAdvisorsReport-web.pdf
[26] Tarui, N., Peng, M., Eversole, D. Economic Impact Analysis of the Potential Erosion of Waikīkī Beach. April, 2018. University of Hawaiʻi Sea Grant College Program.
[27] Waikīkī Beach Special Improvement District Association (2024). https://www.wbsida.org/storymap

experienced chronic erosion since it was first enhanced in the early 1900s, in part due to the history of repeated human interventions to alter the shoreline, primarily through sediment placement, shoreline armoring and shoreline stabilizing structures. Beach restoration and maintenance is currently limited to utilizing offshore sand sources rather than importing sediment from outside the Waikīkī nearshore, but these offshore sources have limited volume for widespread renourishment. Despite the lack of ready access to large quantities of beach quality sand, it is an invaluable resource for risk reduction and community resilience, especially so in a beach-oriented recreational district like Waikīkī with high density urban development in close proximity to the shoreline.

The nearshore marine ecosystem of Waikīkī is degraded by direct human impacts (historical and present day) and impaired water quality from storm water run-off, which will be compounded by the effects of climate change including sea-level rise and ocean warming and acidification. The U.S. Geological Survey (USGS) conducted a study in 2019 and estimated that the coral reefs surrounding the Hawaiian Islands provide between $80-$300 billion dollars in risk reduction to communities.[28] Healthy coral reefs are some of the most biologically diverse and economically valuable ecosystems on earth, providing food, jobs, recreational opportunities, coastal protection and other important services to billions of people world-wide. Coral reefs are in decline in the U.S. and around the world. Many scientists now believe the very existence of coral reefs may be in jeopardy unless we intensify our efforts to protect them.[29] Unfortunately, many of Waikīkī's coral reefs (including the associated nearshore coral-algal habitats) have been damaged or destroyed due to climate change and other human impacts.

Ongoing beach improvements in Waikīkī serve as vital components for the community's well-being and the economy's sustainability. The looming threats associated with climate

[28] Storlazzi, C.D., et al., 2019, Rigorously valuing the role of U.S. coral reefs in coastal hazard risk reduction: U.S. Geological Survey Open-File Report 2019–1027, 42 p., https://doi.org/10.3133/ofr20191027.
[29] Frieler, K., Meinshausen, M., Golly, A. et al. Limiting global warming to 2 °C is unlikely to save most coral reefs. Nature Clim Change **3**, 165–170 (2013). https://doi.org/10.1038/nclimate1674.

change require innovative and proactive measures to adapt Waikīkī to rising sea level, forcing a reevaluation of traditional and historic coastal hazard mitigation techniques. A new adaptive planning approach may involve future plans and policies to accommodate water, rather than fight it. These adaptation initiatives not only preserve, restore and enhance the natural beauty of the beach but also reinforce its resilience against environmental threats such as coastal erosion and sea-level rise. By preserving Waikīkī's iconic shoreline, at least in the short to mid-term time frames, these projects ensure continued access to safe and enjoyable recreational opportunities for residents and visitors alike. Moreover, they play a crucial role in supporting Waikīkī's tourism industry, which serves as a cornerstone of the local economy.

Comprehensive adaptation plans and community resilience projects can serve as models of adaptation, environmental stewardship and economic prosperity and underscore the collective efforts to sustain Waikīkī's legacy as a resilient and sustainable community. Through collaborative efforts between government agencies, universities, professional engineers, local communities and environmental organizations, these endeavors serve as examples of public-private partnerships with a shared vision for adaptation of Waikīkī and contribute to the long-term prosperity and cultural significance of Waikīkī community, preserving its legacy for generations to come.

Natural Hazard Assessment[30]

USGS Atlas of Natural Hazards

Located in the Central North Pacific, Hawaiʻi is uniquely exposed to a range of natural hazards ranging in time scales from episodic and relatively short-lived inundation events such as storm surge, coastal flooding and tsunami which are exacerbated by long-term chronic exposure hazards to sea level rise and groundwater inundation. Dense

[30] Detailed natural hazard risk profiles have been conducted as part of the *Adapt Waikīkī 2050* and are summarized in various sections of this report (Courtney, et al, 2024).

development concentrated at the shoreline and in low-lying backshore areas increases vulnerability to natural hazards in Waikīkī (PUC, 2018). Information on existing natural hazards including coastal erosion studies for Waikīkī is available from a variety of sources including The University of Hawaii Coastal Resilience Collaborative, the Federal Emergency Management Agency (FEMA) Flood Insurance Rate Maps (FIRMS), maps of tsunami evacuation zones, storm surge models and reports such as the U.S. Geological Survey's Atlas of Natural Hazards in the Hawaiian Coastal Zone.[31]

The heavily developed coastal metropolis of Honolulu and Waikīkī is built on a low-lying coastal plain, which was submerged by a higher relative sea level approximately 125,000 years ago and again as recently as 1,500 to 4,000 years ago (PUC, 2018). Throughout Waikīkī and the encompassing primary urban center of Honolulu, an extensive complex of shoreline structures including groins, seawalls and revetments have been built over the last 100 years or so to stabilize beaches and protect the densely developed Waikīkī urban district in response to erosion and other coastal hazards. A nearly continuous fringing reef parallels the coast at Diamond Head and widens to the west along the southern shoreline of Oahu. In the early decades of the 1900's, the reefs throughout Waikīkī were dredged to form a series of swim areas nearshore in addition to navigation channels at the outflow of the Ala Wai Canal and the Kaiser's channel fronting the Hilton Hawaiian Village. This dredging is thought to be partially responsible for the accelerated beach erosion soon after the dredging occurred. Other natural paleo-stream channels exist in the reef complex throughout Waikīkī that form natural breaks in the reef and offer a variety of benefits for navigation and ocean recreation.

The USGS (2002) study finds that the Honolulu region has a moderate to high (5 out of 7) Overall Hazard Assessment (Figure 3). The ranking is principally dictated by the low

[31] Atlas of Natural Hazards in the Hawaiian Coastal Zone. (USGS, 2002). Charles H. Fletcher III, Eric E. Grossman, Bruce M. Richmond and Ann E. Gibbs Prepared in cooperation with University of Hawaii, State of Hawaii Office of Planning and National Oceanic and Atmospheric Administration. U.S. Department of the Interior. U.S. Geological Survey Geologic Investigations Series I-276. 2002. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://pubs.usgs.gov/imap/i2761/sections/3_Oahu.pdf

coastal slope which is especially susceptible to damage resulting from tsunami, stream flooding, hurricane storm surge and seasonal high-wave flooding. Tsunami and storms are ranked high while stream flooding and high seasonal waves are moderately high for the Honolulu area. These rankings are supported by a history in Honolulu of severe flooding from both storm surge and stream runoff from the steep surrounding hillsides of the Koolau Range and low-lying coastal development in the flood zone. Climate change and sea level rise will increase the severity of impacts from these natural hazards on our coasts.

Although Honolulu has yet to experience a direct hit from a major hurricane or tsunami in recorded history, the exposure risk is high and a complacency may exist among its inhabitants that hurricanes and tsunamis are not major threats to this coast. Facing southwest, Waikīkī is extremely vulnerable to strong winds and waves generated by tropical storms and hurricanes that most frequently pass the Hawaiian Islands to south and west of Oahu. While observations of tsunami flooding have not exceeded 13 ft in Honolulu (USGS, 2002), most of Waikīkī is in the Tsunami Evacuation Zone and the remainder is within the Extreme Tsunami Evacuation Zone.[32] It is important to assess current and predicted future hazard risks and the associated statistical probabilities as a baseline and within context while evaluating future scenarios with climate change. Conversely, proactive hazard planning and adaptation measures addressing climate change and sea level risks will simultaneously ensure Waikīkī is more resilient to present-day hazards such as storm flooding and tsunami, thus an example of a “no-regrets” approach to adaptation.

[32] https://dod.hawaii.gov/hiema/public-resources/tsunami-evacuation-zone/

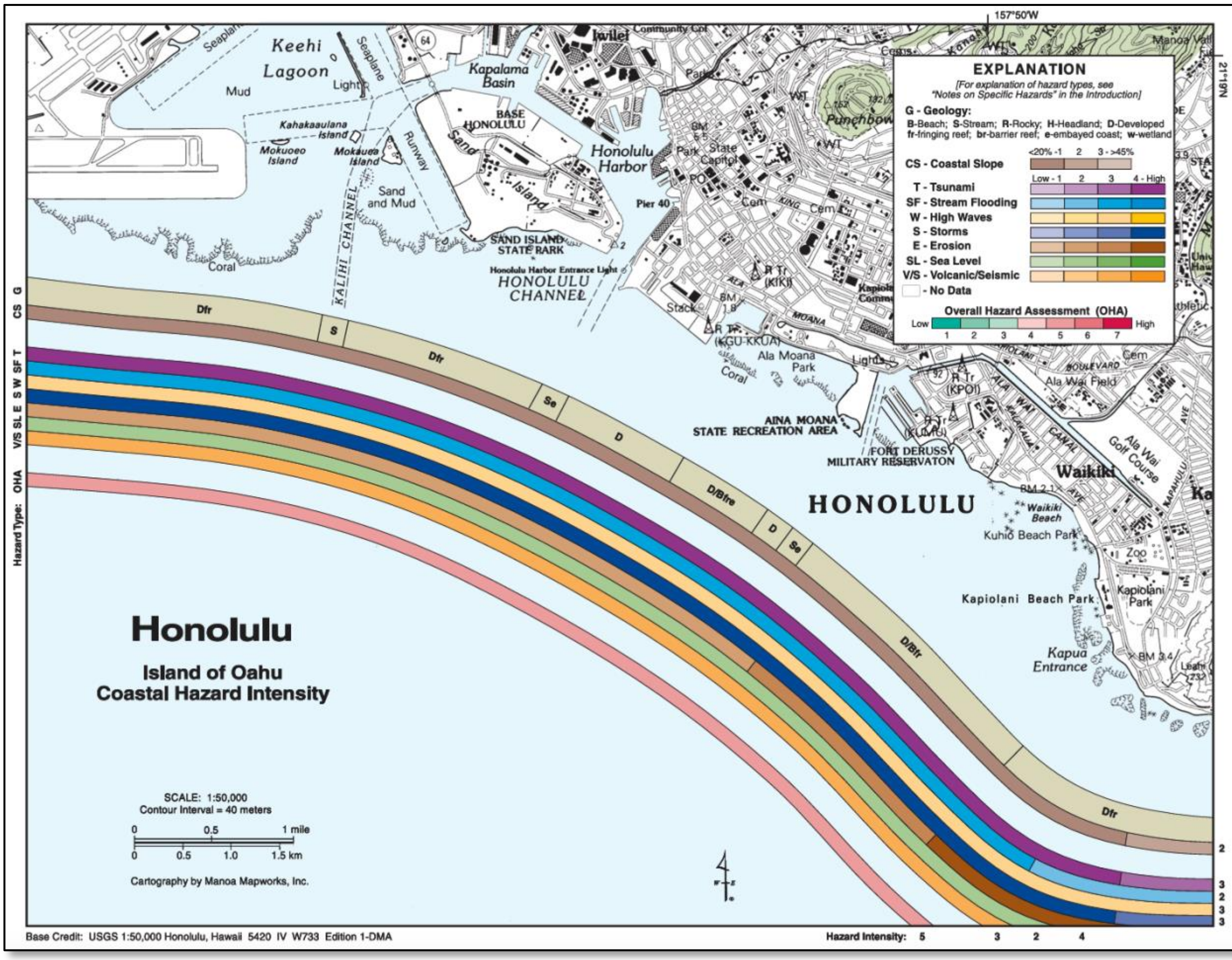

Figure 3. Coastal Hazard Intensity for Honolulu. The Overall Hazard Assessment ranking is the bottom contour. (Credit USGS. Atlas of Natural Hazards in the Hawaiian Islands, 2002.)

Sea Level Rise and Groundwater Inundation

Hawai`i Sea Level Rise Vulnerability and Adaptation Report 2022

The Hawai‘i Sea Level Rise Vulnerability and Adaptation Report (Hawai‘i SLR Report), completed and adopted by the State Climate Change Commission in December 2017 and updated in 2022, provides a statewide assessment of Hawaii's vulnerability to sea level rise and recommendations to improve resilience and begin to adapt to related impacts. The 2017 Hawaiʻi SLR Report provided a detailed overview of climate science and sea level rise observations and predictions based on the best-available science at that time including the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) and the U.S. Global Change Research Program 4th National Climate Assessment.

Sea Level Rise Outlook: Updated Global and Local Projections

As expected, climate and sea level rise science has continued to advance since the 2017 Report, with landmark intergovernmental reports including the IPCC AR6 in August 2020 and NOAA-led interagency Sea Level Rise Technical Reports in 2017 and 2022. Updated sea level rise outlook including global and local projections were provided in the 2022 update to the State SLR Report. In July 2022, the City and County of Honolulu Climate Change Commission provided an updated guidance document on the latest sea level rise science and projections with recommendations for adaptation planning. This section provides an overview of the latest climate science and sea level rise projections published in those documents with specific regional and local projections and likely impacts with application to Waikīkī.

Interagency Sea Level Rise Scenario Tool

The U.S. Interagency Sea Level Rise Scenario Tool provides a range of sea level rise scenarios for Honolulu out to the year 2150 (Figure 4).[33] Five different sea level rise scenarios have been developed under a multi-agency federal task force including NOAA, USGS, the Army and NASA that provide both global mean and local relative SLR scenarios to 2150.[34] Depicted in Figure 4, are sea level rise projections for five sea level scenarios: Low, Intermediate-low, Intermediate, Intermediate-high and High and showing the relative sea level heights for the years 2050 and 2100 (relative to the baseline year 2000). The most recent sea level rise scenarios and supporting information from the 2022 SLR Task Force report are provided in this online tool which can be selected for most U.S. tide gauges. These scenarios reflect various projections of future global sea level rise with a specific predicted amount of SLR at a date in the future. These scenarios provide planners sea level rise estimates in decadal increments and provide a critical source of high-resolution data that can help to inform policy and land use decisions.

Groundwater Inundation

Sea-level rise is influencing coastal groundwater by both elevating the water table and shifting salinity profiles landward, making the subsurface increasingly corrosive.[35] Sea-level rise is influencing Waikīkī's coastal groundwater, which is already intersecting some of Waikīkī 's subsurface utilities. Sea-level rise of about 3 feet generates groundwater inundation across 23% of the Waikīkī area in Honolulu, threatening $5 billion in taxable real estate and 30 miles of roadway, and potentially contaminating coastal environments and public health.[36]

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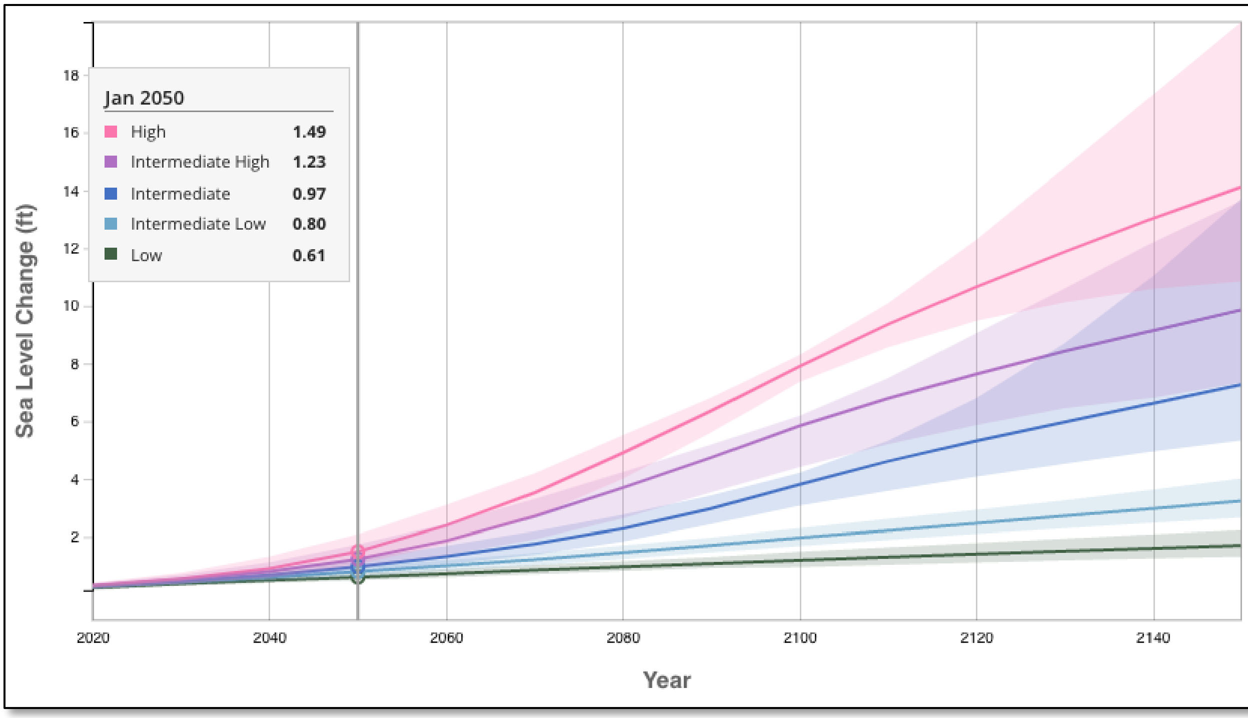
[33] Interagency Sea Level Rise Scenario Tool, https://sealevel.nasa.gov/data_tools/18
[34] Interagency Sea Level Rise Scenario Tool, https://sealevel.nasa.gov/task-force-scenario-tool
[35] Habel, S., Fletcher, C., Barbee, M., & Fornace, K. (2023). *Hidden Threat: The Influence of Sea-Level Rise on Coastal Groundwater and the Convergence of Impacts on Municipal Infrastructure*. Annual Review of Marine Science. https://doi.org/10.1146/annurev-marine-020923-120737.
[36] Habel, S., Fletcher, C., Rotzoll, K., & El-Kadi, A. (2017). Development of a model to simulate groundwater inundation induced by sea-level rise and high tides in Honolulu, Hawaii. Water Research. 114, 122-134 . https://doi.org/10.1016/j.watres.2017.02.035.



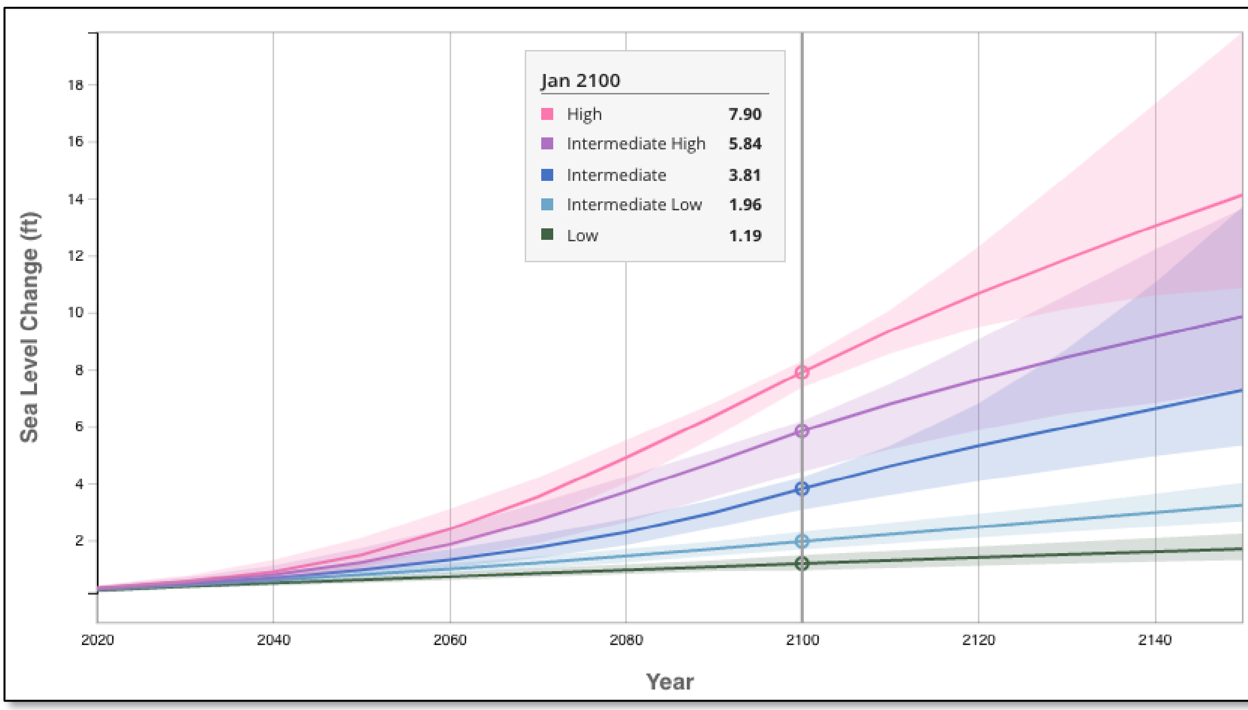


Figure 4. Sea level rise projections for the year 2050 (top) and 2100 (bottom) for Honolulu, Hawai'i. (Interagency Sea Level Rise Scenario Tool, 2022)

The recommended sea level rise planning benchmarks in the City and County of Honolulu Climate Change Commission's (HCCC, 2022) updated sea level rise guidance are supported by the NOAA Technical Report.[37] The HCCC's 2022 sea level rise guidance recommends the following as planning guidelines for the City (Table 1):

- The Low and Intermediate-Low SLR scenarios are inappropriate to use for planning because sea level rise is expected to exceed these water levels by 2100.
- The Intermediate (1.16 m, 3.8 ft by 2100) sea level rise scenario should be set as the minimum scenario for all planning and design.
- The Intermediate High (1.78 m, 5.8ft by 2100) sea level rise scenario should be set as a benchmark for all planning and design of public infrastructure projects and other projects with low tolerance for risk.

SLR Benchmark	Source	Planning Horizon
3.2 ft Sea Level Rise Exposure	Hawaiʻi Climate Mitigation and Adaptation Commission (2022)[38]	~2070-2100
3.8 ft Intermediate	Honolulu Climate Commission (2022)	~2080-2100
5.8 ft Intermediate-High	Honolulu Climate Commission (2022)	~2100

Table 1. Summary of Sea Level Rise Planning Benchmarks for Honolulu, Hawaiʻi.

[37] Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M.Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White and C. Zuzak, 2022: *Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines.* NOAA Technical Report NOS 01., National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nostechrpt01-global-regional-SLR-scenarios-US.pdf

[38] *Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report* (2022) Hawaiʻi State Climate Change Mitigation and Adaptation Commission, prepared by the State of Hawaiʻi Department of Land and Natural Resources, Office of Conservation and Coastal Lands. https://climate.hawaii.gov/wp-content/uploads/2023/01/OCCL23-Sea-Level-Rise-Report-FY22-1.pdf

Incorporating Sea Level Rise Projections into Planning

Using the 3.2 ft Sea Level Rise Exposure Area as a hazard overlay is an important first step in preparing for and adapting to sea level rise impacts. For planning decisions related to critical infrastructure with long expected life spans or low risk tolerance, 6 feet of sea level rise should be considered as a *minimum* planning benchmark (HCCC, 2022; PUC, 2018). This is consistent with the sea level rise planning recommendations from the Honolulu Climate Commission which recommends a 3.8 ft and 5.8 ft sea level rise planning benchmark for Honolulu (Table 1). This also aligns with Mayoral Directive No. 18-2 which requires city departments and agencies to use the Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report and the City and County of Honolulu Climate Change Commission Sea Level Rise Guidance in planning, programing and capital improvement decisions. After approval by the City Climate Change Commission, the 2022 Updated Sea Level Rise Guidance was transmitted to the mayor, city council and executive offices.

In February 2024, the city council and mayor adopted “Climate Ready Oʻahu”- the City’s Climate Adaptation Strategy, which describes the sea level rise benchmarks of 3.8 (Intermediate) and 5.8 feet (Intermediate-high) following the Climate Change Commission’s guidance.[39] For the purposes of the WRAP, the conceptual designs and long-range planning framework utilize rounded up SLR planning guidelines of 4 feet (instead of 3.8 feet) and 6 feet (instead of 3.8 feet) for clarity and simplicity (Figure 5).

[39] https://www.climatereadyoahu.org/

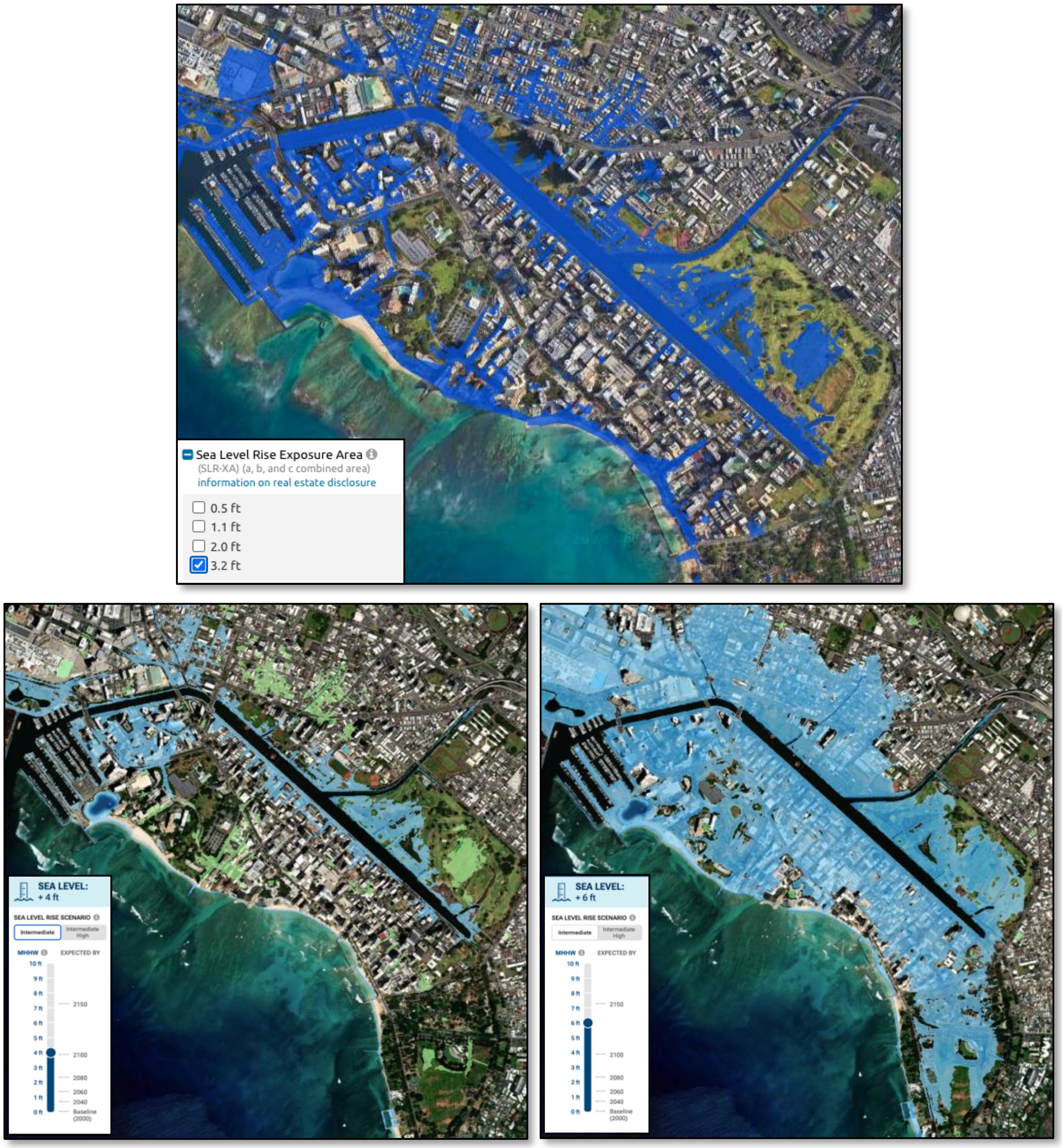


Figure 5. Sea Level Rise Projections for Waikīkī. Top (3.2 ft SLR Exposure Area); Bottom (4 foot and 6 foot passive flooding). Source: Hawaii Sea Level Viewer and UH SOEST-Climate Viewer.

Sea Level Rise Economic Impacts

Using a subset of data from the Hawai‘i Sea Level Rise Vulnerability and Adaptation Report (2022), we estimate that 3.2 feet of sea level rise would cause the following impacts in the Waikīkī Special District (assuming no adaptation measures are employed): chronic flooding in 174 acres of land[40] potentially impacting 302 buildings, displacing 1870 residents and flooding 5.5 miles of road (Table 2). The economic impacts of 3.2 feet of sea level rise will be disproportionately high in Waikīkī due to dense development on low-lying coastal lands, potentially threatening $4.9 billion in hotel and resort buildings and property, which is a disproportionately high at 26% of O‘ahu’s total risk for private land and buildings.[41] The monetary impact to roads, utilities and other critical infrastructure is unknown but may be an order of magnitude greater than potential loss of structures and property. Due to Waikīkī’s relatively low topographic elevation around 4 to 5 feet above sea level, it is anticipated that a 4-6-foot sea level rise will have a dramatically larger inundation footprint than the 3.2 foot SLR Exposure Area and will thus have an economic impact much larger than the 3.2 foot sea level rise area (Figure 5).

Table 2. Summary of Sea Level Rise Impacts for Waikīkī, Hawaii.

[40] This area calculation for flooding includes already submerged portions of the Ala Wai, Hilton Lagoon and beaches so is an overestimate. This is not a factor for the other calculations in this section.
[41] Preliminary calculation provided by the University of Hawaii Institute for Sustainability and Resilience for the City & County Office of Climate Change, Sustainability and Resilience (unpublished). This is in 2023 dollars for hotel and resort properties within the Primary Urban Center so includes some resort properties outside of Waikīkī (e.g., Ala Moana, Kapiolani Park). This estimate does not include residential properties.

FEMA Flood Insurance Rate Maps

Maps from the Federal Emergency Management Agency (FEMA) depict the 1%-annual-chance-flood zones ("100-year flood") (Figure 6). In Waikīkī, Zone VE, areas associated with 1% probability flood and coastal wave event hazards, are generally at the seaward edge of beachfront development and within the Ala Wai harbor. Zone AE, is the 1% probability coastal floodplain where base elevations have been determined. The AO Zones are areas subject to inundation by the 1% annual chance of shallow flooding where the average depths are 1-3 feet. The A-Zone areas are subject to inundation by the 1% annual chance flood where the base flood elevation (BFE) is not determined. The USGS (2002) study found that the Honolulu area has a moderately-high risk (3 out of 4) of stream flooding due to the history of severe flooding from the steep watersheds of the Koʻolau Mountains and low-lying coastal topography. The FEMA Flood zones in Waikīkī are based on historical flood events and do not account for future inundation exposure changes due to sea level rise and therefore should be considered a minimum level of safety for planning purposes.

Figure 6. FEMA Flood Zones for Waikīkī. (Source: Hawaii Sea Level Viewer).

Storm Surge (Hurricane and Tropical Storms)

Hurricane strikes in the Hawaiian Islands are infrequent compared to the south and southeast coasts of the continental U.S. However, a direct strike from a hurricane or tropical storm in Waikīkī is certainly possible and perhaps inevitable depending on the time frame considered. Hurricanes approaching Hawaii are expected to increase in both frequency and intensity with the predicted warming of the ocean in the Pacific region. The increased threat from the impacts associated with hurricanes such as wind damage, storm surge and coastal inundation are widely recognized and are a significant present-day and future risk to Waikīkī. Global climate models predict that 2°C (3.6°F) of additional warming results in a 10-15% increase in the average precipitation rate within 100 km of a tropical storm.[42] Global models forecast a 1-10% increase in tropical cyclone intensity for warming of 2°C (3.6°F), implying increasing destructive potential, assuming no reduction in storm size.[43] While there is still large model uncertainty, more frequent tropical cyclones are anticipated near Hawai'i, due to model trend predictions that storms will follow more northerly tracks that bring them into the vicinity of Hawaiʻi more often.[44] An increase in average cyclone intensity and in the number and occurrence days of very intense category 4 and 5 storms is projected for most ocean basins.[45] These model predictions provide a cautionary insight to the potentially dramatic increase in exposure to hurricane storm risks in Waikīkī.

Natural climatic cycles such as the El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation play a large role in seasonal weather trends in Hawaii. These two phenomena are strong drivers of weather and storm variability in the Pacific Basin that

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[42] Global Warming and Hurricanes, an Overview of Research Results (2020) Geophysical Fluid Dynamics Laboratory, Princeton University, NOAA: https://www.gfdl.noaa.gov/global-warming-and-hurricanes/

[43] Marra, J.J., Gooley, G., Johnson, M-V.V., Keener, V.W., Kruk, M.K., McGree, S., Potemra, J.T. and Warrick, O. [Eds.] (2022). Pacific Climate Change Monitor: 2021. The Pacific Islands-Regional Climate Centre (PI-RCC) Network Report to the Pacific Islands Climate Service (PICS) Panel and Pacific Meteorological Council (PMC). DOI: 10.5281/zenodo.6965143

[44] Murakami, H., Wang, B., Li, T. et al. (2013) Projected increase in tropical cyclones near Hawaii. Nature Climate Change 3, 749754. https://doi.org/10.1038/nclimate1890

[45] Knutson, T., et al. (2020) Tropical Cyclones and Climate Change Assessment: Part II: Projected Response to Human-made Warming, Bull. Amer. Meteor. Soc. (2020) 101 (3): E303–E322: https://doi.org/10.1175/BAMS-D-18-0194.1

influence rainfall, air and ocean temperature, sea surface height and trade winds in the Pacific Islands, including Hawaii.[46] Increased tropical storm occurrence in Hawaii's region of the Central North Pacific is closely correlated with El Niño events. Tropical Pacific Islands, including Hawai'i, will likely experience a larger number of tropical cyclones during future El Niño events and reduced occurrences during La Niña events.[47] ENSO and other sources of climate variability interact with longer-term climate change to reduce or amplify trends. Over the longer-term, these cycles can greatly compound the chronic impacts of sea level rise, such as coastal erosion and flooding (Figure 7).

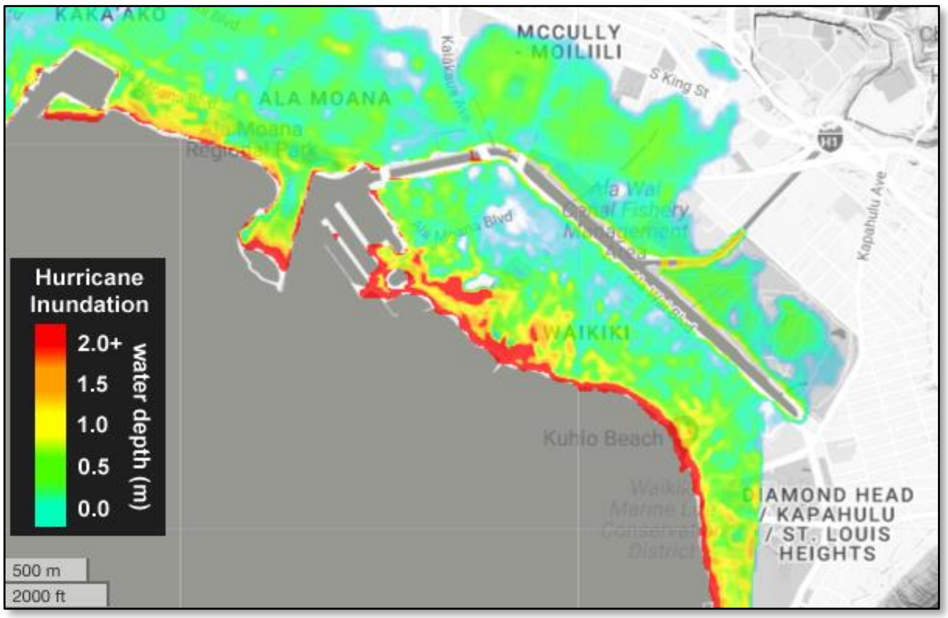

Figure 7. Category 4 Hurricane Storm Surge model. (Hawaii Sea Level Viewer).

Figure 7 depicts modeled storm surge inundation, color-coded to show storm surge flooding depth in meters, from a direct strike of a Category 4 hurricane to Waikīkī. The scenario is based on a storm similar to Hurricane Iniki, which struck Kaua'i in September 1992 and does not include additional flooding from rainfall. A storm of this magnitude

[46] Keener, V., D. Helweg, S. Asam, S. Balwani, M. Burkett, C. Fletcher, T. Giambelluca, Z. Grecni, M. Nobrega-Olivera, J. Polovina and G. Tribble, 2018: Box 27.1 in Ch. 27. Hawai'i and U.S.-affiliated Pacific Islands. In: *Impacts, Risks and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1242–1308. https://doi.org/10.7930/nca4.2018.ch27

[47] Cai, W., Santoso, A., Collins, M. et al. Changing El Niño–Southern Oscillation in a warming climate. Nat Rev Earth Environ 2, 628–644 (2021). https://doi.org/10.1038/s43017-021-00199-z

would cause severe storm surge flooding throughout the primary urban center including Waikīkī. Less severe tropical storms and southerly “Kona” frontal storms can also have a damaging impact on Waikīkī contributing to wave runup and erosion on the shoreline as well as upland flooding from heavy rain.

Compound Flooding

Compound flooding refers to the occurrence of two or more flood hazards driven by a single weather event, or the occurrence of two or more independent events that produce flood hazards jointly in space and/or time.[48] Compound flooding can also be worsened by other processes such as wave set up, tide level, stormwater runoff and sea level rise. Low-gradient coastal watersheds like Waikīkī are vulnerable to flooding hazards from both intense rainfall and coastal storm surge, which are produced from landward-blowing winds and low atmospheric pressure of the largest storms (e.g., tropical and mid-latitude cyclones).[49] In Hawaii, compound flooding events typically occur from a combination of high tide and heavy rainfall but can be greatly enhanced by storm surge. Impacts of compound flooding is an area of active research, especially in the context of sea level rise as an accelerator of the compound flooding incidence and severity.

Waikīkī was directly impacted by a Kona low event on December 4th to 6th, 2021 which resulted in significant compound flooding during the peak high tide. This event produced widespread flooding due to the compounding effects of heavy rainfall, exceptionally high tides ('King Tide') and a storm surge of up to 8 inches higher than the predicted astronomical tide (Courtney, et al, 2024). The rainfall total for the 3-day period (72 hours) at the Honolulu Airport was 9.28 inches.[50] This event did not result in any reported

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[48] Félix L. Santiago-Collazo, Matthew V. Bilskie, Scott C. Hagen. A comprehensive review of compound inundation models in low-gradient coastal watersheds, Environmental Modelling & Software, Volume 119, 2019, Pages 166-181. ISSN 1364-8152. https://doi.org/10.1016/j.envsoft.2019.06.002. (https://www.sciencedirect.com/science/article/pii/S1364815219302853)
[49] Bilskie, M. V., Hagen, S.C., 2018. Defining Flood Zone Transitions in Low-Gradient Coastal Regions. Geophys. Res. Lett. 45, 2761–2770. https://doi.org/10.1002/2018GL077524
[50] NOAA, National Weather Service. Kona Low Event Summary - December 2021. https://www.weather.gov/hfo/konaLowEventSummaryDec2021

damage in Waikīkī but did produce minor flooding to several properties and temporarily closed down major roadways including Kalākaua Avenue for several hours causing traffic delays and. The University of Hawaii, SOEST Climate Resilience Collaborative modeled this 2021 Kona Low, compound flooding event with sea level rise as an example of compound flooding with sea level rise (Figure 8).

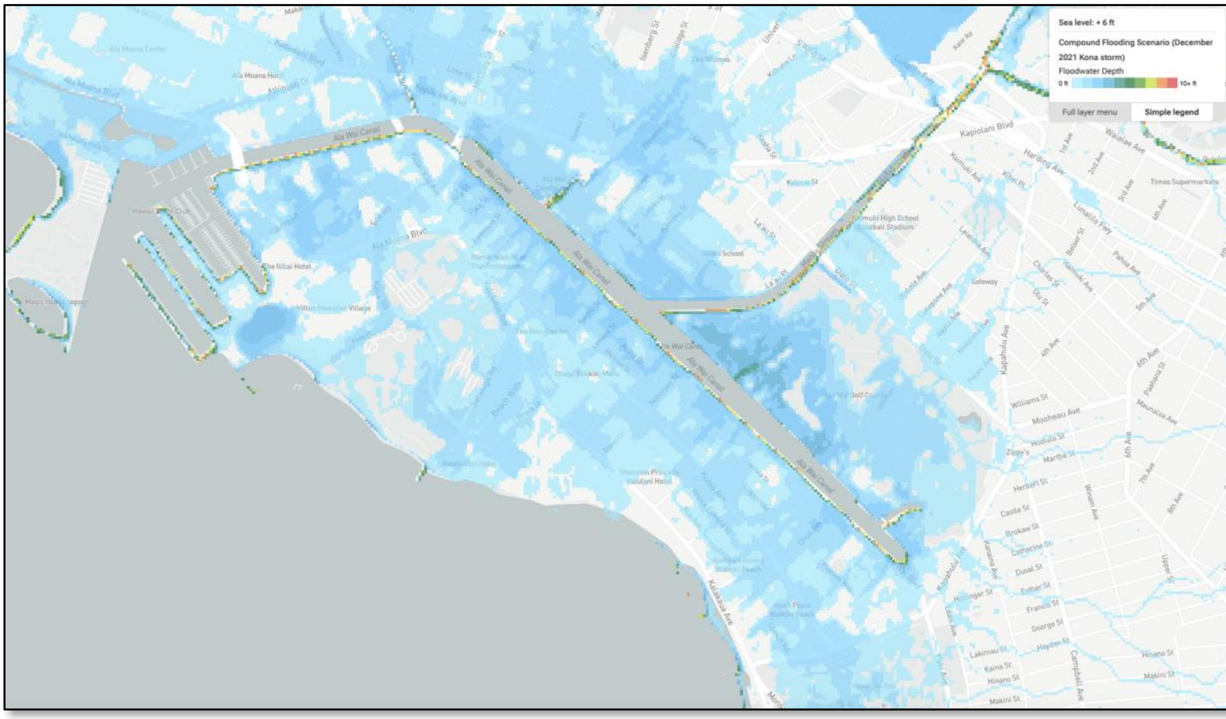


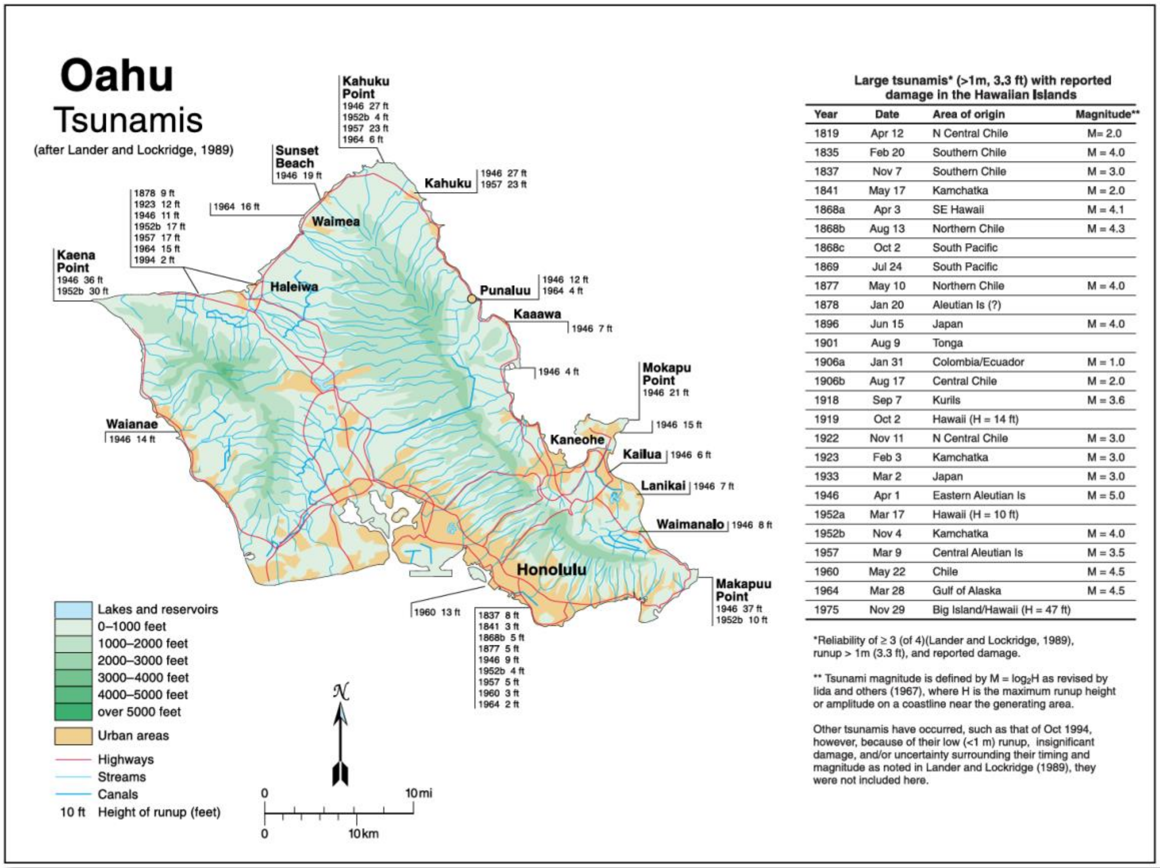
Figure 8. Modeled compound flooding extent and flood depth with sea level rise based on the 2021 Kona Low in the Waikīkī Special District (UH SOEST Climate Viewer, 2024).

Tsunami

Tsunami are waves generated by distant or localized geologic events, most often by large earthquakes that cause rapid movement of the seafloor. Hawai‘i is encircled by the “ring of fire,” a band of major subduction faults and volcanic zones surrounding the Pacific Ocean. According to USGS (2002), the Honolulu area was affected by nine damaging tsunamis since 1837 and has an overall high hazard rating for tsunamis due to the low-lying coastal topography. The highest tsunami runup recorded in the Honolulu area was 13 feet in the vicinity of Honolulu Harbor from the 1960 Chile earthquake and tsunami (USGS, 2002) (Figure 9). Twenty-six tsunamis with flood elevations greater than 3.3 ft (1 m) have made landfall in the Hawai‘ian Islands during recorded history and 10 of these had significant damaging effects on Oahu, (USGS, 2002). This translates into a recurrence interval of one large tsunami reaching Hawai‘ian shores every 7 years and one damaging tsunami reaching Oahu every 19 years. Other notable tsunami run up for Honolulu include 1946 (9 ft) and 1947 (5ft). Since the tsunami of 1946, 6 large tsunamis have been recorded in the Hawaiian Islands and 4 have caused damage on Oahu. The three highest tsunami wave run up recorded on Oahu occurred during the last 53 yr.

The 2011 Tohoku, Japan tsunami caused no severe damage on land in Waikīkī but did cause some damage in marinas around Honolulu Harbor. In general, runups with major tsunami have been less in the vicinity of Waikīkī than in other areas on O‘ahu such as Ka‘ena Point, Hale‘iwa and Kahuku; however, that should not be reason for complacency. In March 2017, the City and County of Honolulu released maps of Extreme Tsunami Evacuation Zones (XTEZ) based on a newly recognized risk of tsunami from a very large Aleutian [Alaska, Magnitude 9+] earthquake.[51] The new XTEZ zones include all of Waikīkī and extend up to and beyond the H1 freeway in some areas (Figure 10).

[51] City and County of Honolulu, Department of Emergency Management. Extreme Tsunami Evacuation Zones. Available at: https://www.honolulu.gov/dem/tsunami.html Last viewed 4/05/2024



Year	Date	Area of origin	Magnitude**
1819	Apr 12	N Central Chile	M= 2.0
1835	Feb 20	Southern Chile	M = 4.0
1837	Nov 7	Southern Chile	M = 3.0
1841	May 17	Kamchatka	M = 2.0
1868a	Apr 3	SE Hawaii	M = 4.1
1868b	Aug 13	Northern Chile	M = 4.3
1868c	Oct 2	South Pacific	
1869	Jul 24	South Pacific	
1877	May 10	Northern Chile	M = 4.0
1878	Jan 20	Aleutian Is (?)	
1896	Jun 15	Japan	M = 4.0
1901	Aug 9	Tonga	
1906a	Jan 31	Colombia/Ecuador	M = 1.0
1906b	Aug 17	Central Chile	M = 2.0
1918	Sep 7	Kurils	M = 3.6
1919	Oct 2	Hawaii (H = 14 ft)	
1922	Nov 11	N Central Chile	M = 3.0
1923	Feb 3	Kamchatka	M = 3.0
1933	Mar 2	Japan	M = 3.0
1946	Apr 1	Eastern Aleutian Is	M = 5.0
1952a	Mar 17	Hawaii (H = 10 ft)	
1952b	Nov 4	Kamchatka	M = 4.0
1957	Mar 9	Central Aleutian Is	M = 3.5
1960	May 22	Chile	M = 4.5
1964	Mar 28	Gulf of Alaska	M = 4.5
1975	Nov 29	Big Island/Hawaii (H = 47 ft)	

*Reliability of ≥ 3 (of 4)(Lander and Lockridge, 1989), runup > 1m (3.3 ft), and reported damage.

** Tsunami magnitude is defined by $M = \log_2 H$ as revised by Iida and others (1967), where H is the maximum runup height or amplitude on a coastline near the generating area.

Other tsunamis have occurred, such as that of Oct 1994, however, because of their low (<1 m) runup, insignificant damage, and/or uncertainty surrounding their timing and magnitude as noted in Lander and Lockridge (1989), they were not included here.

Figure 9. Tsunami run up on Oahu. (Credit USGS. Atlas of Natural Hazards in the Hawaiian Islands, 2002.)

Figure 10. Tsunami Evacuation Zones. Hawaii Emergency Management Agency.

Coastal Erosion

Seasonal and chronic beach erosion is a problem throughout Hawai‘i and beaches in Waikīkī are no exception. The University of Hawai‘i Coastal Resilience Collaborative used historical aerial photographs and survey charts going back as far as 1911 to map and quantify historical changes in shoreline location on Kaua‘i, O‘ahu and Maui.[52] In this mapping, the low water mark, or toe of the beach, is digitized from the corresponding historical orthophoto mosaic. It is used as a proxy of the seaward, or makai, extent of beach area in beach width calculations in the historical shoreline change analysis of the island (CGG, 2021). The shoreline change maps provide detailed historical average erosion rate data (feet/year) along shore every 60 feet.

Long-term trends of historical shoreline changes in Waikīkī range from +2 ft/year (accretion) and can reach -3-4 ft/year (erosion) which are closely related to past efforts to engineer the shoreline with seawalls, groins, break walls and other structures, as well as sand nourishment projects, which have localized effects on sediment transport. Beach erosion hotspots in Waikīkī tend to be down-drift from groins or adjacent to exposed seawalls and include sections of Ft DeRussy Beach, Queen’s Beach and Kapiolani Beach (Figure 11). The shoreline change data reveals a long-term trend of alternating erosion and accretion in Waikīkī largely driven by the shoreline structures that define each beach cell.

From about 1930 until the late 1970s, it is estimated that over 400,000 cubic yards of sand was placed on Waikīkī Beach, from a variety of sources including other beaches on O‘ahu and Moloka‘i, backshore dune deposits and crushed coralline limestone.[53] Between 1925 and 2001, the Waikīkī shoreline moved about 40 ft seaward, reflecting the

[52] Coastal Geology Group in the School of Ocean and Earth Science and Technology (CGG, 2021). University of Hawai‘i. 2021. Hawai‘i Shoreline Study. https://www.soest.hawaii.edu/crc/index.php/hawaii-shoreline-study-web-map

[53] Waikīkī Beach Improvement and Maintenance Program. Draft environmental impact statement (DEIS). Hawai‘i Department of Land and Natural Resources. June, 2021. https://files.hawaii.gov/dbedt/erp/Doc_Library/2021-06-08-OA-DEIS-Waikīkī-Beach-Improvement-and-Maintenance-Program.pdf

extensive human alteration of the shoreline. Despite past beach nourishment efforts, it is estimated that, between 1951 and 2001, at least 100,000 cy of sand has been lost to erosion.[54] The historical shoreline change data suggests the Royal Hawaiian beach and sections of the Hilton, Kapiolani and Kaimana beaches are accreting (growing seaward) over time but this data is an artifact of past beach fill projects that have artificially introduced large volumes of sand into the system rather than natural accretion of the beach. This history of intervention with shoreline stabilization structures and beach fill provides an explanation as to why the majority of Waikīkī beaches are inherently unstable and eroding.

Figure 11. Historical Shoreline Change Maps. The transects alongshore represent historical erosion rates (ave feet/year) red is erosion, blue is accretion.

(Hawai‘i Shoreline Study- https://www.soest.hawaii.edu/crc/index.php/hawaii-shoreline-study-web-map)

[54] Miller, T. L., Fletcher, C.H. (2003). Waikīkī: Historical Analysis of an Engineered Shoreline. Journal of Coastal Research, 19, 4, 1026-1043.

Summary Conclusions

This assessment examines natural hazards, sea level rise, and climate change hazard exposure for Waikīkī, Oʻahu. This effort centers on land use in the long-term timeframe (year 2050 to 2100^{+}) with a focus on long-range adaptation planning, policy and implementation as a basis for future state-level adaptation planning for the Waikīkī watershed and special district. The Natural Hazard Assessment provided here is a complementary effort to the Climate Risk Profiles that have been developed as part of the City and County of Honolulu's (City) *Adapt Waikīkī 2050* project which strives to develop a shorter-term (30 year) climate adaptation plan for the Waikīkī Special District with a focus on City infrastructure (Courtney, et al, 2024). For the WRAP, we utilize SLR datums which are rounded up to 4 feet (instead of 3.8 feet) and 6 feet (instead of 5.8 feet) for clarity and simplicity. This adaptation planning benchmark is consistent with the sea level rise planning recommendations from the Honolulu Climate Change Commission (HCCC, 2022) which recommends a 3.8 ft and 5.8 ft sea level rise minimum planning benchmark for Honolulu. Climate adaptation strategies for Waikīkī should seek to minimize the impacts of coastal hazards and climate change such as flooding and sea-level rise to the built environment.

Adaptation is sometimes described in terms of pathways and can be broadly categorized based on approach with many variations and phases for each of these. Accommodation is centered on the concept of adapting infrastructure and the built environment to changing environmental conditions in-place. More broadly, adaptation is based on the precautionary principle which when applied to land use decisions, emphasizes caution and takes an empirical, risk-based approach to long-term land use decisions. The principle can be especially helpful for climate adaptation planning and policy decisions in situations where there is the possibility of increased exposure to risk and conclusive evidence is not yet available.

While the precautionary principle emphasizes taking proactive measures to mitigate potential harm, even in the absence of full scientific certainty. Adaptation planning also provides benefits to a multi-hazard, risk-based approach for existing hazards, i.e., preparing for climate change also makes us more resilient to present day risks from hurricanes, etc. This "no regrets" concept for climate adaptation planning refers to strategies and measures to promote sustainable development and offer benefits regardless of future climate conditions. No regrets approaches encourage prioritizing plans, policies and interventions that yield immediate benefits while also building adaptive capacity and reducing long-term risks associated with climate change. The accommodation strategies presented below and in section 7.1.a are examples of no regrets actions that will provide immediate protection from coastal hazards in addition to longer-term climate adaptation benefits.

Site-specific design interventions such as flood resistance and other accommodation strategies enhance resilience by addressing the key components of vulnerability and strive to ensure resilience and longevity of coastal communities. Redesigning vulnerable urban areas by retrofitting and upgrading vulnerable areas along with proactive and community-engaged planning of urban infrastructure can provide an opportunity to build an inclusive process that utilizes local knowledge on social policy, nature-based solutions and other physical adaptation strategies.[55] Local government and landowners can take advantage of making climate and resilient designs when major renovations and upgrades are planned as they reach their expected design lifetimes. Developing a risk-based adaptation approach for Waikīkī will serve to provide more effective and efficient adaptation plans and policies. Adaptation strategies are very site specific and can be broadly categorized into protection, restoration, accommodation and retreat approaches. Each strategy has site-specific advantages and can be part of a holistic phased implementation of adaptation. Adaptation strategies are not mutually exclusive and

[55] IPCC, (2022). Pörtner, H., et al. IPCC Sixth Assessment Report. Working Group II –Impacts, Adaptation and Vulnerability. Summary for Policymakers. *Cambridge University Press*, Cambridge, UK and New York, NY, USA, pp. 20–27, DOI:10.1017/9781009325844.001. Accessed: 6/10/23 https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_SummaryForPolicymakers.pdf

instead can be considered as a spectrum of options that are available and can be implemented by specific triggers and thresholds for action.[56] See Section 9, *Adaptation Implementation Roadmap* for more information on this.

Coastal accommodation strategies are, by design, proactive, founded in hazard risk management and strive to increase the overall community resilience and sustainability to known or predicted hazard events. Accommodation strategies are based in a no regrets approach and commonly include building-scale design interventions such as; flood control, hazard zoning overlays, building codes related to hazards resistant/resilient designs, elevated structural design, base/design flood elevations and rebuilding requirements.[57,58] Similarly, avoidance techniques intended to avoid or relocate vulnerable development in hazard-prone areas may include; coastal construction setbacks, zoning, building codes restrictions, managed retreat through transferable development rights, leasebacks, land swaps and rebuilding or relocation.[4,59] (PUC, 2018). Within the design intervention field, design flood elevations and associated elevated foundation design are an increasingly common forms of accommodation and can often be administered through existing regulatory authorities for FEMA flood standards often without initiating major new adaptation policies or rules at the municipal scale.[60] This relative ease of implementation makes design flood elevations and building codes the most common early-stage form of accommodation and may be particularly useful for mid

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[56] For more details, see Section 7.1.a- *Sea Level Rise Adaptation Planning Precedents, Policy and Work Products.*

[57] City & County of Honolulu (C&C). (2020). Climate Adaptation Design Principles for Urban Development. SSFM International and Arup for the City Department of Planning and Permitting Transit-Oriented Development Division and the City Office of Climate Change, Sustainability and Resiliency.

[58] Coastal Flood Resilience Design Guidelines (CFRDG). (2019). Boston Planning and Development Agency. Accessed 9-10-21. http://www.bostonplans.org/getattachment/d1114318-1b95-487c-bc36-682f8594e8b2

[59] ORS. (2019). O'ahu Resilience Strategy City and County of Honolulu, Office of Climate Change Sustainability and Resiliency. Accessed May, 4, 2024. https://www.honolulu.gov/rep/site/ccsr/Ola_Oahu_Resilience_Strategy.pdf

[60] FEMA. (2011). Federal Emergency Management Agency Coastal Construction Manual, Fourth Edition. FEMA P-55 / Volume I / August 2011. Accessed: May 3, 2020. https://www.fema.gov/media-library-data/20130726-1510-20490-2899/fema55_voli_combined.pdf

to longer-term adaptation for dense urban areas like Waikīkī that are increased risk of sea level rise and flooding

Risk-Based Planning Approach

The National Oceanic and Atmospheric Administration (NOAA) recommends utilizing a risk-tolerance approach for sea level rise adaptation planning based on a range of potential future scenarios.[61] This risk-based approach acknowledges the uncertainty inherent in projections of sea level rise and adopts a flexible framework that considers various levels of risk tolerance for new development and (re)development. A risk-based planning approach typically involves (Sweet, 2017):

1. **Risk Assessment:** Conducting a thorough assessment of the potential impacts of sea level rise on coastal areas, infrastructure and communities. This includes evaluating vulnerabilities, exposure and potential consequences under different sea level rise scenarios.
2. **Scenario Planning:** Developing a range of sea level rise scenarios based on scientific projections and uncertainty analysis. These scenarios represent different levels of risk, from conservative estimates to more extreme projections, allowing decision-makers to explore a range of possible futures.
3. **Risk Tolerance Analysis:** Establishing risk tolerance thresholds that reflect the acceptable level of risk exposure for different stakeholders, communities and assets. This involves considering assets at risk, design lifetime, the potential consequences of sea level rise impacts and societal values and priorities.
4. **Adaptive Management:** Implementing adaptive management strategies that can accommodate changing conditions and uncertainties over time. This may include flexible planning approaches, phased implementation of adaptation measures at

[61] Sweet, W.V., et al. (2017). Global and regional sea level rise scenarios for the United States, NOAA Technical Report NOS COOPS 083. Accessed May 4, 2024. https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf

decadal scales and regular monitoring and reassessment of risks and vulnerabilities.

5. **Stakeholder Engagement:** Engaging stakeholders, including local communities, government agencies, businesses and other relevant parties, throughout the risk-tolerance approach process. Collaboration and communication are essential for building consensus, fostering resilience and ensuring that adaptation strategies are equitable and effective.

The Waikīkī Special District Climate Risk Profile report (Courtney, et al. 2024) provides a detailed parcel-level assessment of climate risk and flood risk in the near-term (25 years). The project developed risk tolerance thresholds for the Waikīkī Special District which are consistent with the NOAA risk-tolerance approach described above. The climate risk thresholds are presented as summary recommendations for both near-term (2050) and long-term (2100). These climate and flood risk profiles and associated planning timeframes are broadly aligned with existing and planned infrastructure and new or redeveloped infrastructure. The climate risk thresholds developed for Waikīkī identify decades of relative stability and lower risk and the predicted decadal shift to increased risk from climate-hazards with a notable increase in climate risk beyond the year 2070. These climate risk thresholds can be used to differentiate near and long-term climate risks for Waikīkī. Courtney, et al, (2024) found that groundwater inundation poses the greatest risk in terms of flood extent and flood depth compounded by all other flood risks with 30% of Waikīkī inundated under a 4 ft sea level rise projection and 70% inundated under a 6 ft sea level rise projection. The pronounced increase in flooded area between the 4 ft and 6 ft SLR projections highlight the significant risk threshold between these elevations. This flood risk threshold increase is due to the current ground elevation in Waikīkī which is typically between 4 ft and 6 ft above mean sea level.

Adaptation planning efforts in Waikīkī are benefiting from the precedents from other coastal communities that have implemented innovative and effective adaptation strategies.[62] Additionally, a host of tools and guidance documents have been developed by experts to identify and summarize best practices for adaptation. Adaptation of the built environment through accommodation and design intervention is centered on adapting infrastructure and the built environment to changing environmental conditions. Regional and site-specific design interventions such as elevation of critical features, flood resistance and floodwater management are signature examples. Utilizing elevation-based approaches are foundational as part of a comprehensive adaptation and accommodation plan for the built environment. A wide variety of research related to cost to benefit analysis reveals a significant socio-economic and environmental benefit from increased elevation of urban design. Utilizing adaptive designs such as design flood elevations that factor in sea-level rise projections, result in a more resilient and sustainable community that is able to resist and ultimately recover quicker after a major natural hazard as well as be better prepared for long-term impacts related to climate change. While coastal flooding and sea-level rise are the main drivers for these adaptation guidelines there are a number of overlapping co-benefits and opportunities to implement adaptation for resilience and sustainability.

[62] For more information See Section 7.1.a- *Sea Level Rise Adaptation Planning Precedents, Policy and Work Products.*