CLIMATE RISK PROFILE FOR THE WAIKĪKĪ SPECIAL DISTRICT: REPORT FOR THE ADAPT WAIKĪKĪ 2050 SPECIAL AREA PLAN
JULY 2024

Prepared by Tetra Tech, Inc. for the Honolulu Department of Planning and Permitting

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Key Takeaways

This Waikīkī Special District Climate Risk Profile (WSD Risk Profile) provides an overview of Waikīkī 's development trajectory and the current and projected future risks of climate change induced hazards to support the development of the Adapt Waikīkī 2050 (AW2050) Special Area Plan. The AW2050 Special Area Plan will provide near-term recommendations for existing structures and public infrastructure in the WSD that should be planned and implemented within the next 25 years, while furthering the conversation, information collection, and analysis needed for ongoing and future planning. The WSD Risk Profile, along with best practices research and input from public agencies and community stakeholders, will inform recommendations included in AW2050 Special Area Plan.

CLIMATE HAZARDS AND COMPOUNDING AND CASCADING EFFECTS

- Rising air and sea surface temperatures caused by unabated human-caused sources of greenhouse gases are resulting in sea level rise, heat extremes, changes in rainfall patterns (extreme rainfall as well as drought), and other climate hazards across the planet.
- The Waikīkī Special District (WSD), a primary economic engine for the island of Oʻahu, and more broadly the State of Hawai'i, is highly vulnerable to multiple climate change hazards. These hazards can occur simultaneously and consecutively.
- In Honolulu, sea level is projected to rise ~1 foot by 2040, ~2 feet by 2060, ~4 feet by 2080, and ~6 feet by 2100 under the “intermediate high” scenario from the U.S. Interagency Sea Level Rise Task Force. The City and County of Honolulu Climate Change Commission recommends that the intermediate high sea level rise scenario (~6 ft by 2100) be used for all planning and design of public infrastructure projects and other projects with low tolerance for risk.
- Projections for the decades between 2070 and 2090 represent a steep escalation in groundwater inundation in the WSD at 3’ and 5’ of SLR rise, respectively. High groundwater can be disruptive to in-ground infrastructure and structures.
- According to the Intergovernmental Panel on Climate Change’s Sixth Assessment Report (2023) *Sea level is committed to rise for centuries to millennia due to continuing deep-ocean warming and ice-sheet melt and will remain elevated for thousands of years (high confidence).* Scientists have high confidence that glaciers will continue to melt and oceans will continue to thermally expand for hundreds to thousands of years because of the global warming (1.5ºC; 2.7ºF) that has already occurred. This means that while it is still crucial to curb fossil fuel emissions to prevent even more extreme future impacts, we can assume that current sea level rise trends will hold and accelerate under current conditions and projections. Applying this locally to present and future decades, means that on a practical level, sea level rise is a permanent condition on the Hawaiian shoreline that will worsen with every year.
- A Kona Low rainfall event in December 2021 and again in May 2024 provided a glimpse of what future conditions in the WSD and the Honolulu urban core could look like under a changing climate:
  - Cascading and compounding effects were experienced from extreme rainfall, high tides, storm surge, sea level rise, and dense urban development.
  - Impacts included downed trees and power lines, damaged roofs, power outages, damaged underground cables, and roadway flooding in Waikīkī and urban Honolulu.
  - City and State disaster declarations were issued.

NEAR-TERM CLIMATE RISK OUTLOOK (~2025 – 2050)

Over the near-term, defined here as approximately to the year 2050, the following impacts are projected to affect the global climate, and specific circumstances in the WSD:

- High tide flooding is expected to increase from 2 days per year to 63 days per year before 2050. Episodic sunny day flooding of roads, properties, and stormwater drainage systems, increase disruption to businesses and transportation, and nuisance flooding to residents.
- Critically shallow groundwater (<5 feet below the land surface), currently covers over 50 percent of the WSD. With sea level rise, shallow groundwater expands coverage throughout the WSD. Critically shallow groundwater is currently a significant maintenance challenge for all subsurface infrastructure, including water and wastewater systems. With 1 ft of sea level rise (~2040), approximately 68% of the WSD is estimated to have critically shallow groundwater.
- Extreme rainfall events (days with precipitation of 3 inches or more) are rare and variable—on average occurring less often than once per year. Climate change projections suggest that while the frequency of these events may not change, the intensity may worsen, causing extensive flooding, power outages, and disruption to emergency services, transportation, and businesses, when they do occur.
- Increasing heat extremes and drought is a threat to health, power capacity, and the environment.

LONG-TERM CLIMATE RISK OUTLOOK (~2050 – 2100)

Over the long-term, defined here as approximately from the year 2050 to the year 2100, the following impacts are projected to affect the global climate, and specific circumstances in the WSD:

- Critically shallow groundwater continues to become more severe in the WSD, eventually emerging above the land surface as groundwater inundation. Areas at highest risk from groundwater inundation are the West Waikīkī area (Hobron) and along the Ala Wai canal (Ala Wai Boulevard).
- The extents of groundwater inundation and high-wave-driven flooding in the WSD are projected to increase dramatically over a 20-year period from approximately 2 percent of the WSD with 2 feet of sea level rise (~2060) to approximately 30 percent of the WSD with 4 feet of sea level rise (~2080).
- At 6 feet of sea level rise (~2100), groundwater inundation is projected to cover approximately 70 percent of the WSD, and annual high-wave-driven flooding affecting approximately 50 percent of the WSD.
- Areas at highest risk from high-wave-driven flooding are the West Waikīkī area, and along the shoreline. The costs and sustainability of beach nourishment/retention efforts in the long-term are still unknown.
- Increasing heat extremes and drought is a threat to health, power capacity, and the environment.

RECOMMENDATIONS FRAMEWORK

- Given the long lifespan of buildings and projected impacts to the end of the century, infrastructure level of service decisions and other standards for the WSD must be a topic for public discussion in the immediate near-term.
- Near-term and long-term flood mitigation and climate adaptation strategies and plans, engineering studies, cost estimates, and policies for the WSD must be developed within the next 25 years.
- Infrastructure level of service determinations for the WSD, such as road abandonment, must be made within the next 25 years.
- Level of service determinations for the WSD need to consider similar impacts that are projected for Honolulu's urban core.
- Maintaining a shoreline sandy beach in Waikīkī is an ongoing and increasingly difficult prospect in the face of rising sea levels. Coastal protection alone, nature based or artificial, will not protect against rising groundwater in the WSD.
- In the long-term, the WSD will require a hybrid of adaptation strategies that may include a combination of managed retreat, protection, accommodation, and nature-based solutions.

A Changing Climate

Greenhouse gas emissions caused by human activities are the key drivers of human-induced climate change. The atmospheric concentration of carbon dioxide, a key greenhouse gas, has increased by about 50% since the industrial revolution. [1] Current concentrations are the highest in millions of years based on measurements retrieved from bubbles trapped in cores taken from polar ice sheets. As a result, global-average atmospheric temperature has increased by about 2.7°F (1.5°C) over the past century, closely following increases in carbon dioxide and other greenhouse gases. [2] Due to thermal expansion of warming waters and melting of land-based glaciers and ice sheets, global mean sea level is rising at an accelerating rate.

The risks of climate change to people, property, and the environment from climate change in Hawaiʻi are increasingly well documented. The 5th National Climate Assessment (NCA5) [3], released in November 2023, states that *climate change—especially sea level rise, altered rainfall patterns, and rising ocean and air temperatures—impairs access to clean water and healthy food, undermines human health, threatens cultural resources and the built environment, exacerbates inequities, and disrupts economic activity and diverse ecosystems in Hawaiʻi and the US-Affiliated Pacific Islands.*

The Waikīkī Special District (WSD), a primary economic engine of Oʻahu and the State of Hawai'i, is highly vulnerable to multiple climate hazards that can occur simultaneously and consecutively. Sea level rise is a driving force in the WSD increasing the extent and frequency of coastal flooding and, especially, groundwater inundation in low-lying areas. Extreme rainfall events have swept through the state resulting in structure damage, landslides, road closures, and power outages. Winds and storm surge have caused destruction from passing tropical cyclones.

This climate risk profile provides an overview of Waikīkī 's development trajectory and the current and projected future risks of climate change induced hazards. The primary focus of the Adapt Waikīkī 2050 project (AW2050) is to identify near-term recommendations for existing structures and public infrastructure in the WSD, while furthering the conversation, information collection, and analysis needed for ongoing and future planning.

Development Trajectory in Waikīkī

In the Hawaiian language, Waikīkī comes from wai (freshwater) and kīkī (shooting up from the ground). Waikīkī was formerly a place of springs and predominant wetlands. Now, Waikīkī's watery origins are returning within a highly developed urban environment. Climate change, in particular flooding exacerbated by sea level rise, is challenging the sustainability of Waikīkī as the State of Hawaiʻi's most popular visitor destination. Key development milestones over more than a century have transformed a place of great cultural significance and a natural marsh system used in places for agriculture, into a tourism destination with a mixed population of residents and visitors. The existing surface and

[1] NOAA. https://www.noaa.gov/news-release/carbon-dioxide-now-more-than-50-higher-than-pre-industrial-levels
[2] BBC. https://www.bbc.com/news/science-environment-68110310
[3] Frazier, A.G., M.-V.V. Johnson, L. Berio Fortini, C.P. Giardina, Z.N. Grecni, H.H. Kane, V.W. Keener, R. King, R.A. MacKenzie, M. Nobrega-Olivera, K.L.L. Oleson, C.K. Shuler, A.K. Singeo, C.D. Storlazzi, R.J. Wallsgrove, and P.A. Woodworth-Jefcoats, 2023: Ch. 30. Hawaiʻi and US-Affiliated Pacific Islands. In: Fifth National Climate Assessment (NCA5). Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH30

subsurface features of the WSD such as buildings, roads, and infrastructure that support this population are subject to the compounding effects of climate hazards.

WAIKĪKĪ AHUPUAʻA

For the Hawaiian people, Waikīkī is a place of great cultural significance once serving as the center of government and wetland agricultural systems for taro and fishponds.[4] The Waikīkī ahupuaʻa extended around Diamond Head and well beyond the current boundaries of the Ala Wai watershed (**Figure 1**).

Waikīkī was referred to as Waikolu or "three waters" crossed by three major streams, the Piʻinaio, ʻĀpuakēhau, and Kuekaunahi draining from the Makīkī, Mānoa, and Pālolo valleys.[5] The Piʻinaio drained into what is now Fort DeRussy. Before the Ala Wai Canal, these streams emptied into the ocean.[6]

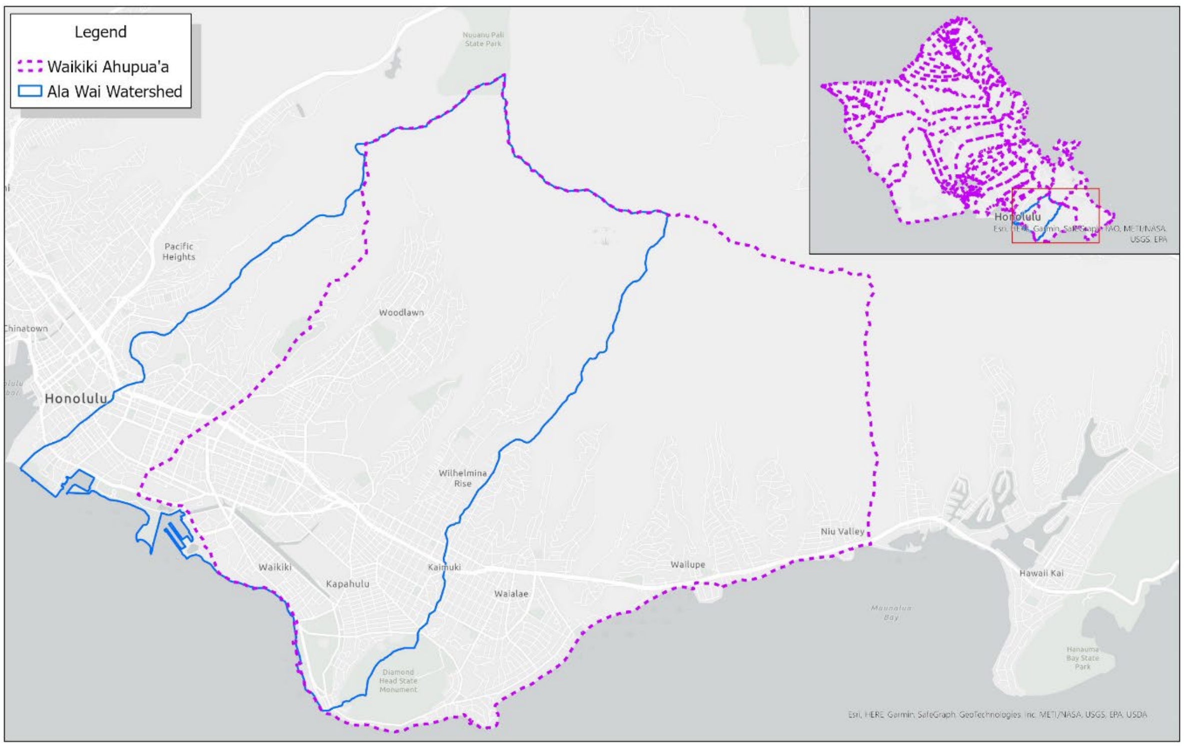

Figure 1. Waikīkī ahupuaʻa and Ala Wai watershed boundaries

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

[5] City & County of Honolulu (1992) Waikīkī Master Plan, 102 pp.

[6] Images of Old Hawai'i https://imagesofoldhawaii.com/waikiki-streams/#jp-carousel-36010

ALA WAI CANAL

Between 1904 and 1910, the U.S War Department purchased 73 acres and converted the extensive wetland agricultural systems to land. [7] Lucius Pinkham, then President of the Territorial Board of Health and later Governor, considered the wetlands "unsanitary" and promoted draining the wetlands by constructing a drainage canal. [8]

The construction of the Ala Wai Canal was a key milestone serving as a development trigger for the area we now know as the Waikīkī Special District. The Ala Wai canal was constructed between 1921 and 1924 draining and filling the existing wetlands. [9] By 1924, the Ala Wai Canal stopped the flows of the Pi'inaio, 'Āpuakēhau and Kuekaunahi streams running from the Makīkī, Mānoa, and Pālolo valleys to and through Waikīkī. [10]

WAIKĪKĪ SHORELINE

Most, if not all the beaches in Waikīkī are highly altered and have been repeatedly filled using various sand sources for beach restoration projects over the last 100 years. Historically, the Waikīkī shoreline consisted of a narrow sandy beach that separated wetlands, mudflats, duck ponds, and fishponds from a fringing reef. [11] The first shoreline structures were built in the 1880s and 1890s, some built partly on piles. These included homes, hotels, seawalls, groins, and several piers. The Natatorium, a walled oceanwater swimming pool, was built in 1927. As early as the 1910s, seawalls being used to protect properties from coastal erosion were causing beach loss. [12] Today, Waikīkī's shoreline remains dominated by highly engineered beaches and dense development (**Figure 2)**.

The Waikīkī shoreline region extends from Hilton Hawaiian Village east to Kaimana Beach, spanning 10,250 feet of shoreline. [13] The existing region includes eight littoral cells (**Figure 2**). Littoral cells are coastal compartments that contain a complete cycle of sedimentation, including sources, transport paths, and sinks. [14] Each cell is bound by man-made structures (e.g., groins, drainage outfalls) and subject to littoral processes that are unique to that cell; therefore, proposed adaptation and beach management measures are tailored to each specific cell. The primary shoreline issues affecting Waikīkī's established littoral cells are erosion, beach narrowing, structural damage, and loss of shoreline access.

Waikīkī shoreline management approaches include beach improvements and beach maintenance. Past projects have consisted of beach nourishment (e.g., Kūhiō Beach Nourishment (2006), Waikīkī Beach Maintenance (2012 and 2021), Kūhiō Sandbag Groin (2019), and Royal Hawaiian Groin Replacement

[7] City & County of Honolulu (1992) Waikīkī Master Plan, 102 pp.

[8] Young, P. (2023). Images of Old Hawai'i, Ala Wai Canal. https://imagesofoldhawaii.com/ala-wai-canal/#:~:text=In%20the%20early%2D1900s%2C%20Lucius,canal%20to%20reclaim%20the%20marshland.

[9] Wiegel, R.L. (2008) Waikīkī Beach, Oahu, Hawaii: History of its transformation from a natural to an urban shore. Shore & Beach: 76 (2) 1 -30

[10] Young, P. (2023). Images of Old Hawai'i, Ala Wai Canal. https://imagesofoldhawaii.com/ala-wai-canal/#:~:text=In%20the%20early%2D1900s%2C%20Lucius,canal%20to%20reclaim%20the%20marshland.

[11] Wiegel, R.L. (2008) Waikīkī Beach, Oahu, Hawaii: History of its transformation from a natural to an urban shore. Shore & Beach: 76 (2) 1 - 30.

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

[13] Tetra Tech, Inc.; Sea Engineering, Inc.; and Coastal Planners, LLC (2023) Regional Shoreline Management Scoping Study, prepared for the State of Hawai'i Department of Business, Economic Development, and Tourism, Office of Planning, Coastal Zone Management Program, https://storymaps.arcgis.com/stories/e76bd1de3cfb45ccbc7f1eaab196cdeb

[14] Scripps Institute of Oceanography, 2021, Living with Coastal Change, Coastal Basics, Coastal Morphological Group, URL: http://coastalchange.ucsd.edu/st3_basics/littoralcell.html. Accessed: 2 July 2023.

(2020). A draft Programmatic Environmental Impact Statement was released in 2021 by the Hawai`i Department of Land and Natural Resources in partnership with the Waikīkī Special Improvement District Association to evaluate alternatives for continued beach improvement and maintenance. [15] Beach maintenance options include beach nourishment, sand backpassing, sand pushing, and sand pumping. Beach improvement options include beach nourishment with stabilizing groins, segmented breakwaters, and modifications to existing structures. The Royal Hawaiian groin was specifically designed for 1.5' of sea level rise with the ability to add height to the crest cap as needed in the future as a form of adaptive engineering design.

Beach maintenance actions are currently proposed in three beach cells of Waikīkī:

- Fort DeRussy Beach Sector – Sand backpassing
- Royal Hawaiian Beach Sector – Ongoing maintenance using offshore sands
- Kūhiō Beach Sector: Diamond Head (east) Basin – Sand pumping

Beach improvement actions are currently proposed in two beach cells of Waikīkī:

- Halekūlani Beach Sector – Beach nourishment with stabilizing groins
- Kūhiō Beach Sector: ‘Ewa (west) Basin – Beach nourishment with a segmented breakwater

It should be noted that beach nourishment requires periodic replenishment and is not a permanent solution to erosion. Maintaining a shoreline sandy beach in Waikīkī is therefore an ongoing and increasingly difficult prospect in the face of rising sea levels. Nature based solutions or “living shoreline” practices that incorporate natural processes and materials for coastal protection and ecological benefit could provide an alternative approach to Waikīkī's coastal edge. However, such interventions would necessitate a hybrid of adaptation strategies combining managed retreat and accommodation to support a radical reshaping of the coastline. Any coastal protection alone, nature based or artificial, will not protect against rising groundwater in the WSD.

[15] Sea Engineering, Inc.(2021) Draft Programmatic Environmental Impact Statement for Waikīkī Beach Improvement and Maintenance, https://files.hawaii.gov/dbedt/erp/Doc_Library/2021-06-08-OA-DEIS-Waikiki-Beach-Improvement-and-Maintenance-Program.pdf

Figure 2. Waikīkī Beach littoral cells and examples of engineered shoreline (Sea Engineering, Inc. 2021)

ALA WAI WATERSHED

The Ala Wai Watershed includes the Pālolo, Mānoa and Makīkī valleys. [16] The watershed includes many cultural sites, initiatives, stories, and moʻolelo of place that hold extraordinary cultural value and significance. Urbanization and development have dramatically altered the landscape of the Ala Wai watershed increasing exposure to natural hazards and degrading natural areas.

The Ala Wai watershed (see **Figure 1**) is at high risk for widespread flooding across the basin and the wider community within it, including the Ala Wai Canal and Waikīkī.[17] A twenty-year plus history of efforts have been initiated, conducted, and restarted by public agencies with the assistance of the U.S. Army Corps of Engineers (USACE) to address both flood risks to people and the ecosystem as part of an Ala Wai Flood Risk Management Study.

Pursuant to a June 2021 Feasibility Cost Sharing Agreement between the USACE and the City and County of Honolulu, a General Re-evaluation Study for the project commenced, building upon prior rounds of work including a 2020 Engineering Documentation Report, now deemed to be cost ineffective. A Draft General Re-evaluation Report and Integrated Supplemental Environmental Impact Statement (SEIS) were published in November of 2023. According to the SEIS, the tentatively selected plan would include *floodwalls at Woodlawn Bridge along the Mānoa Stream, at the confluence of the Mānoa and Pālolo Streams, along the Mānoa-Pālolo Canal, and along the Ala Wai Canal, as well as a detention basin at the Ala Wai Golf Course.* [18]

The primary objective of the Ala Wai Watershed Flood Risk Management Project is to reduce risks to life and safety from direct inundation of structures and transportation infrastructure due to riverine flood risks associated with a 1% annual chance flood 24-hour rainfall event.[12] A flood wall is proposed to mitigate flood risks in the watershed and along the Ala Wai canal (Figure 3). From an economic perspective, such an event would affect approximately 3,000 structures with an estimated $905,327,000 in structural damages alone at 2023 price levels. If completed, the Ala Wai Flood Risk Management Project would reduce riverine flooding along the Makīkī, Mānoa, and Pālolo streams and associated storm surge flooding along the Ala Wai Canal for the period of analysis (50 years).

[16] UH Sea Grant College Program, Improving Water Quality in the Ala Wai Watershed https://seagrant.soest.hawaii.edu/alawaiwaterquality/#1704315373626-15e9cd39-6d9d

[17] City & County of Honolulu (2023) Ala Wai Flood Study https://www.honolulu.gov/alawai

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

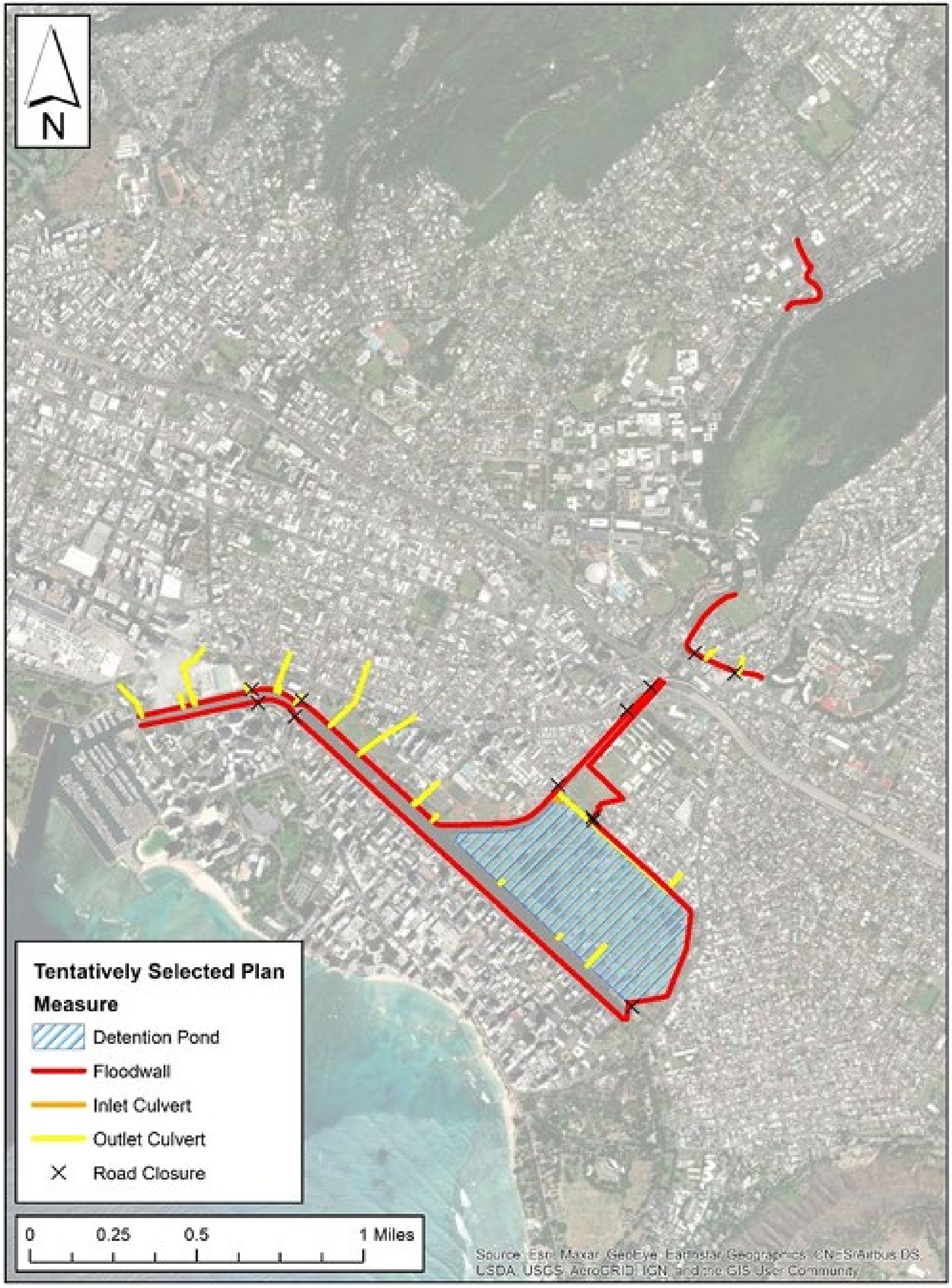

Figure 3. Conceptual diagram of proposed floodwall from Ala Wai Flood Risk Management Project (Alternative 5.1; US Army Corps of Engineers, 2023)

WAIKĪKĪ SPECIAL DISTRICT

The WSD is bounded by water features, the Ala Wai Canal, and nearshore coastal waters. Established by the City and County of Honolulu in 1976, the WSD was created in response to the rapid development of Waikīkī in the preceding decades, and the changes in character produced by that development.[19] The risks of climate change and natural hazards were understandably absent in the original objectives for the WSD's creation at that time. The 2021 update to the WSD Design Guidelines includes sea level rise, along with storm and flood resiliency, as a topic. However, given the scope and severity of the projections, any future updates to the WSD provisions themselves, will need to address substantially the anticipated impacts of climate change and sea level rise.

The WSD is organized by various precincts, which help to generate a variety of complementary pedestrian-oriented activities along major streets. Within the WSD there are three types of zoning precincts and one type of zoning sub-precinct, which are separate and different from regular zoning districts (**Figure 4**).

The population of the WSD is about 18,936 people[20] or about 14,907 people per square mile. Statistics for infrastructure to support this population are provided in **Table 1**.

Most of the land is privately owned; however, it is notable that the federal and state government owns large parcels within and adjacent to the WSD (**Figure 5**). Fort DeRussy remains the largest open space in Waikīkī.

Table 1. Land and infrastructure statistics for the Waikīkī Special District

Waikīkī Special District	Total
Area (acres)	618
Parcels (#)	772
Structures (#)	779
Hotels (#)	66
Streets (ft)	86,323
Water mains (ft)	142,542
Sewer mains (ft)	107,045
Stormwater conduits (ft)	65,670
Sewer system valves (#)	19
Manholes (#)	698
Cesspools (#)	75
Stormwater Jurisdiction Connect (#)	158
Stormwater catchment basins (#)	276

[19] City & County of Honolulu, Waikīkī Special District Design Guidelines, June 2021

[20] City & County of Honolulu, Neighborhood Profile (population estimate for 2017 – 2021) https://www.honolulu.gov/rep/site/dpp/pd/pd_docs/Population_Char_NA_2021_Web.pdf

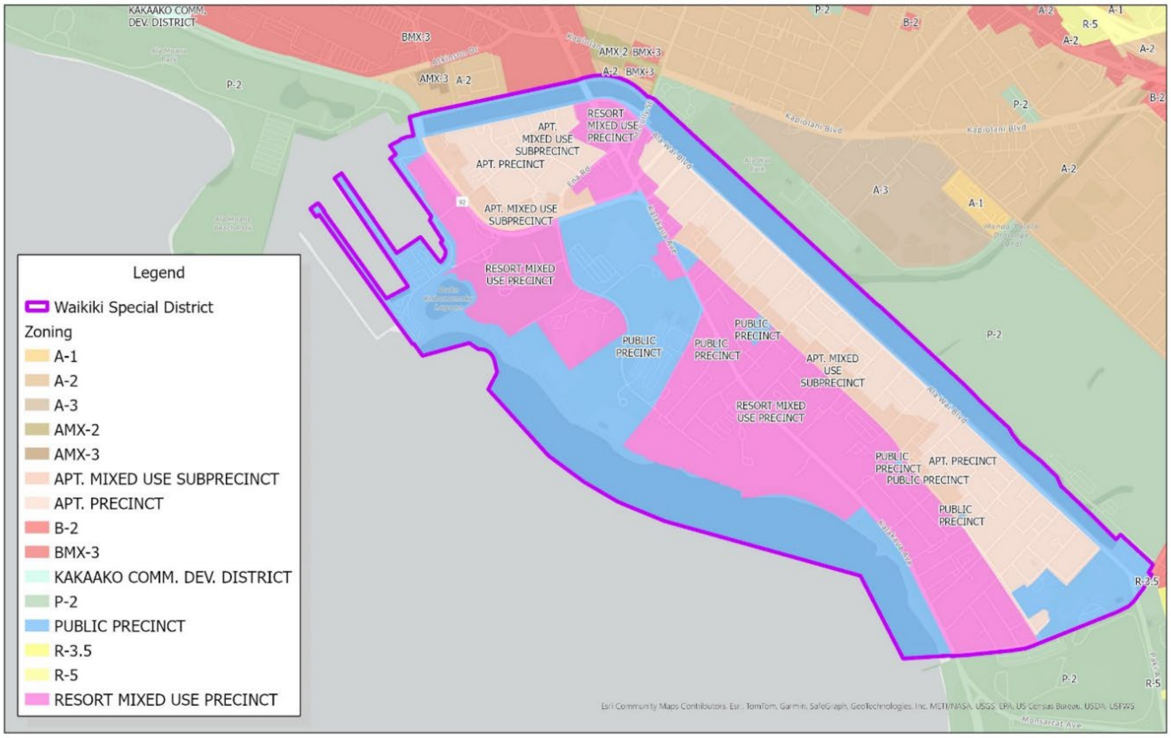

Figure 4. Waikīkī Special District Zoning Precincts

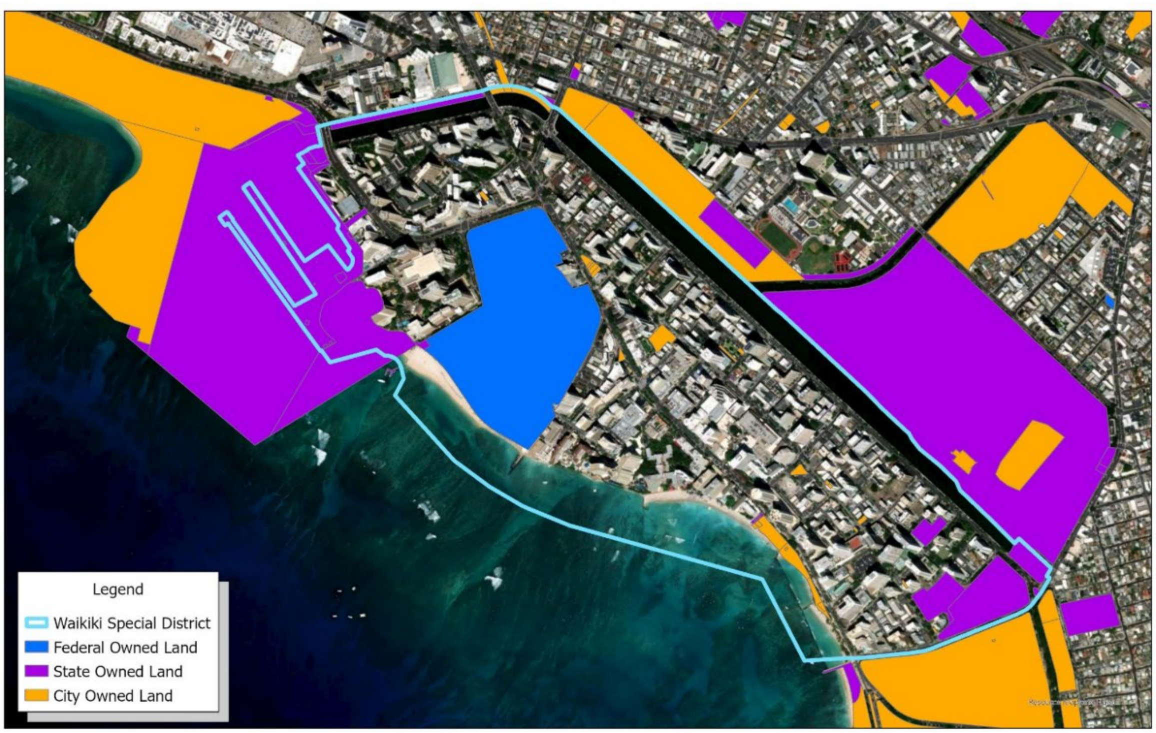

Figure 5. Government land ownership in the Waikīkī Special District

Surface Features

The WSD is a highly urbanized area with dense development and sparse tree cover. Building footprints cover approximately 27% of the WSD. Tree canopy covers approximately 13% of the WSD. Parking lots, roads, and sidewalks contribute to the overall impervious cover in the WSD. Similarly, landscaping and vegetation contribute to pervious cover in the WSD. Building footprint, structure age, and tree canopy as a percent of each parcel are shown in **Figure 6**, **Figure 7**, and **Figure 8**, respectively.

Dense urban development with limited vegetative cover or open space can compound the effects of rising temperatures, heat extremes, and flooding. Heat islands occur in urban areas where structures are highly concentrated and greenery is limited resulting in temperatures that are higher relative to outlying areas.[21] Hard, dry surfaces in urban areas such as roofs, sidewalks, roads, buildings, and parking lots provide less shade and moisture than natural landscapes and therefore contribute to higher temperatures. Other factors that contribute to the urban heat island effect include:

- Conventional pavement and roofing materials absorb and emit more of the sun's heat.
- Wind flow, altered by building dimensions, spacing of buildings, and nearby geologic features, increase heat by blocking winds that bring cooling effects.
- Vehicles, air-conditioning units, buildings, and industrial facilities all emit heat into the urban environment.
- Calm and clear weather conditions can result in more severe heat islands by maximizing heat absorption and minimizing the amount of heat that can be carried away.

Trees, vegetation, and water bodies tend to cool the air by providing shade, transpiring water from plant leaves, and evaporating surface water, respectively. Increasing temperature exacerbates drought intensity due to higher evaporation which can increase tree mortality. [22] Groundwater becomes more saline with sea level rise, another factor that can stress trees and vegetation.

Subsurface Features

The WSD subsurface infrastructure is extensive (see **Table 1**). Roads, water and wastewater systems, electrical and communication systems, and storm drains provide basic services to the WSD.

The WSD has many contaminated sites that could release chemicals in dissolved and gaseous forms into the groundwater and nearshore waters as sea level rises. Common chemical classes contaminating shoreline areas include petroleum constituents, heavy metals, solvents, pesticides, and persistent organic pollutants. These contaminants are generally the result of historical industrial and agricultural uses and releases. Some sites are managed in place to prevent exposure to contaminated materials. Some sites are old and closed. [23]

The WSD has a number of cesspools. Cesspools are essentially holes in the ground that discharge raw, untreated human waste. [24] Cesspools can contaminate groundwater, drinking water sources, streams and oceans with disease-causing pathogens, algae-causing nutrients, and other harmful substances. Untreated wastewater from cesspools contains pathogens such as bacteria, protozoa and viruses that

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[21] U.S. Environmental Protection Agency (2023) Urban Heat Islands. https://www.epa.gov/heatislands/learn-about-heat-islands

[22] Brodribb, T.J., Powers, J., Cochard, H. and Choat, B. (2020). Hanging by a thread? Forests and drought. Science, 368(6488), pp.261-266.

[23] Hawai'i Department of Health, Dr. Iris van der Zander, Hazard Evaluation & Emergency Response Office.

[24] Hawaii Department of Health (2023) Cesspools in Hawai'i. https://health.hawaii.gov/wastewater/home/cesspools/

can cause gastroenteritis, Hepatitis A, conjunctivitis, leptospirosis, salmonellosis and cholera. The Hawai'i State Department of Health, Wastewater Branch oversees (HDOH) and permits all onsite wastewater systems, including cesspools. HDOH regulations require that cesspools of any size be upgraded, converted, or closed by January 1, 2050. [25]

[25] US Environmental Protection Agency, Cesspools in Hawai'i, https://www.epa.gov/uic/cesspools-hawaii#:~:text=Property%20owners%20and%20operators%20must,closed%20by%20January%201%2C%202050.accessed January 1, 2024.

Figure 6. Percent of parcel covered with building footprint in the Waikīkī Special District

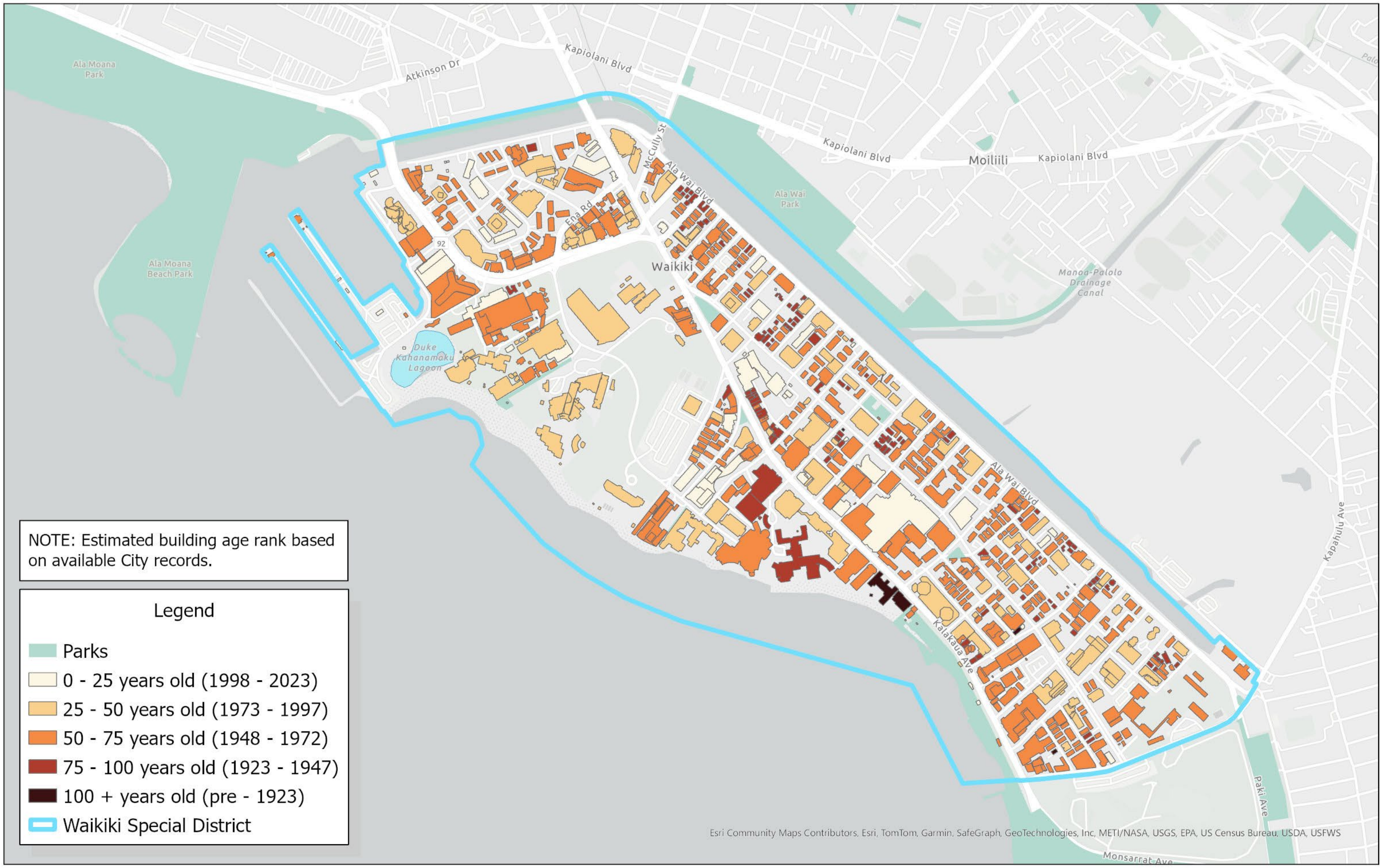

Figure 7. Age range of structures in the Waikīkī Special District

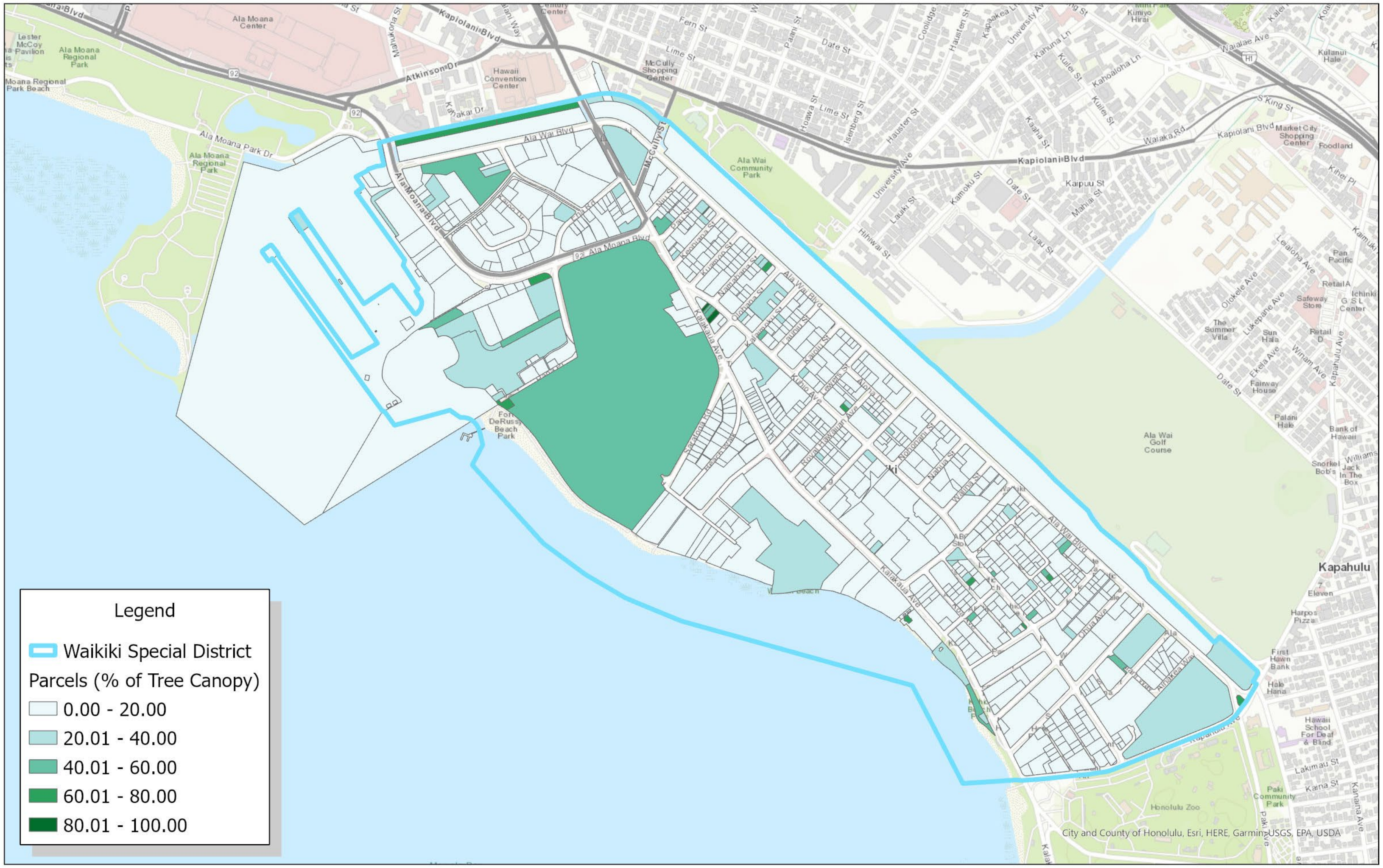

Figure 8. Percent of parcel with tree canopy in the Waikīkī Special District (City & County of Honolulu, Climate Ready O'ahu)

Climate Risk Outlook for the Waikīkī Special District

Drawing on the observations, trends, and projections of climate hazards, this section provides an outlook of climate risk for the WSD to the end of the century. Near-term and long-term outlooks are defined by thresholds of increasing climate risk. Climate change poses multiple and compounding risks to the WSD that will occur over different temporal and spatial scales and with different magnitude and direction of change. This climate risk outlook assumes that greenhouse emissions will remain largely unabated and continue to rise.

CLIMATE RISK THRESHOLDS

Climate risk thresholds for the WSD are estimated using regional and local projections for key climate hazards. **A climate risk threshold is defined herein as the decade that separates a period of relatively stable and minimal risk from one of rapidly increasing risk**. Climate risk thresholds are used to differentiate near-term and long-term climate risks for the WSD (**Table 2**).

Flood risk thresholds were based on modeling conducted by the UH SOEST Climate Resilience Collaborative. [26] For episodic and chronic flooding, the estimated threshold decade is based on the sea level rise projection in which the area flooded is about three times that of the preceding decade (**Figure 9**). For annual high wave-driven flooding and groundwater inundation, the risk threshold is 2 feet of sea level rise beginning in 2060. For passive flooding and storm drain backflow, the risk threshold is 3 feet of sea level rise beginning in 2070. The total flood extent resulting from merging annual high wave-driven flooding, passive flooding, groundwater inundation, and storm drain backflow results in a slightly higher percent of the WSD flooded but closely follows the trend of groundwater inundation with sea level rise. This higher percent of flooding, about 11 percent, with 4 feet of sea level rise, is largely due to the unique contributions of annual high wave-driven flooding and groundwater inundation.

The intermediate-high sea level rise scenario is used to assign a decade (see **Table 8**) except for high tide flooding [27] which is based on the intermediate sea level rise scenario. For other climate risk hazards, the threshold decade is based on trends and projections described in the climate risk profile (see **Figure 28**, **Figure 30**, and **Figure 36**).

In the near-term, episodic climate hazards will periodically impact the WSD; however, critically shallow groundwater depth will be a persistent hazard to the integrity of roadbeds and subsurface infrastructure. In the long-term, chronic flooding will dominate as sea level rises. **Groundwater inundation poses the greatest risk in terms of flood extent and flood depth compounded by all other flood risks.**

[26] UH SOEST Climate Resilience Collaborative. https://www.soest.hawaii.edu/crc/slr-viewer/documentation/#groundwater-info

[27] 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*. Retrieved from Silver Spring, MD:

Table 2. Climate risk thresholds for the Waikīkī Special District

CLIMATE RISK	APPROXIMATE THRESHOLD DECADE									
	NEAR-TERM					LONG-TERM				
INTERMEDIATE-HIGH SLR SCENARIO				1 FT SLR		2 FT SLR	3 FT SLR	4 FT SLR	5 FT SLR	6 FT SLR
	~2010	~2020	~2030	~2040	~2050	~2060	~2070	~2080	~2090	~2100
Air Temperature/Heat Extremes	Hawai'i Threshold 3 deg F increase over 1951 - 1980 avg				4 - 5 deg F increase over 1951 - 1980 avg					
Crtically Shallow Groundwater Depth (<5 ft below land surface)		WSD Threshold ~58% WSD at depth		69% WSD at depth						
Compound Flooding (Kona Low + High Tide Flooding)		WSD Threshold ~40% WSD flooded		~42% WSD flooded						~65% WSD floooded
High Tide-Driven Flooding			Honolulu Threshold 2 days HTF/yr	~65 days HTF/yr						
Sea Surface Temperature Extremes/Coral Bleaching					WSD Threshold Onset of severe annual coral bleaching					
Groundwater Inundation						WSD Threshold ~3% WSD inundated	~9% WSD inundated	~30% WSD inundated		~70% WSD inundated
Annual High Wave-Driven Flooding						WSD Threshold ~5% WSD flooded	~12% WSD flooded	~29% WSD flooded		~50% WSD flooded
Passive Flooding							WSD Threshold ~5% WSD flooded	~18% WSD flooded		~65% WSD flooded
Storm Drain Backflow							WSD Threshold ~3% WSD flooded	~17% WSD flooded		~65% WSD flooded

Legend	Varying Localized Impacts	Threshold to Accelerated Impacts	Widespread Impacts

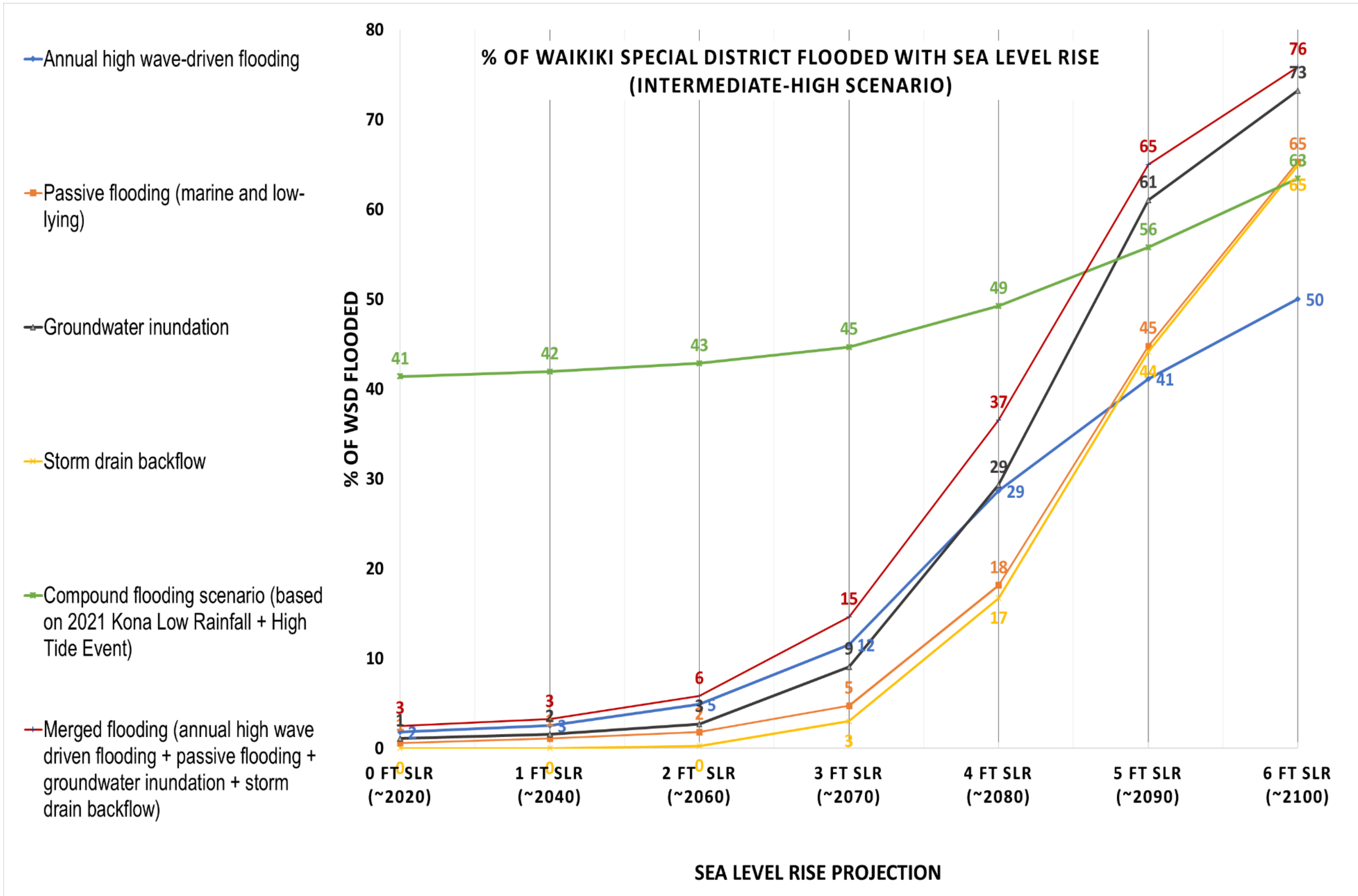

Figure 9. Flood extent based on percent of the Waikīkī Special District flooded with sea level rise

NEAR-TERM OUTLOOK (~2025 TO ~2050)

Over the next 25 years, if greenhouse gas emissions continue to increase unabated, the key drivers of climate impacts in the WSD will be extreme heat events, high tide-driven flooding, critically shallow groundwater, and compound flooding. In addition, increasing sea surface temperatures will result in annual coral bleaching, jeopardizing the coastal protection services afforded by coral reefs fronting the WSD. These near-term climate hazards can occur simultaneously and sequentially as compounding effects and serve as a backdrop to long-term impacts in the WSD. An overview of potential near-term impacts is provided in **Table 3**.

In the near-term, sea level is projected to rise by 1 foot by 2040 in Honolulu (see **Table 8**). [28] Flooding with sea level rise in the WSD will be episodic and in some cases widespread. Compound flood events that coincide with high tide flooding and extreme rainfall will result in bursts of flooding over short periods of time, serving as a preview of chronic long-term flooding with sea level rise projections of 4 and 6 feet.

Significant economic impacts and threats to human safety can result from flooded roads during episodic flood events. Modeled compound flooding, based on the 2021 Kona Low with the addition of 1 foot of sea level rise, would inundate parcels throughout the WSD (**Figure 13**). Approximately 240 acres of the WSD would be flooded at a depth of $\leq$ 2 feet (**Figure 11**). Highest flood depths would occur along the Ala Wai canal (**Figure 10)**. Roads adjacent to the Ala Wai canal would have flood depths >1 foot with compound flooding with 1 foot of sea level rise (**Figure 12**). A maximum flood depth of 30 cm (~1 ft-flood depth) was derived as a maximum threshold for safe driving above which a road is considered to be impassable. [29]

Critically shallow groundwater (5 ft or less below land surface) is and will remain a persistent hazard impacting roadbeds, subsurface infrastructure, and cesspools throughout the WSD. [30] With 1 ft of sea level rise (~2040), approximately 68% of the WSD is estimated to have critically shallow groundwater (**Figure 14**).

Groundwater fluctuates with sea level in coastal areas, rising and inundating the land surface during high tide events and discharging wastewater and contaminants when the sea level lowers and water drains back into the ocean. Submarine groundwater discharge can be a major source of excess nutrients, metals, and emerging organic contaminants (e.g., pharmaceuticals, pesticides) to coastal water bodies. [31]

Wastewater discharge to the coast and storm drains has been shown to be occurring now as a result of groundwater inundation of wastewater infrastructure in urban Honolulu, Hawai'i [32]

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[28] Interagency Sea Level Rise Scenario Tool, https://sealevel.nasa.gov/data_tools/18

[29] Pregnolato, M., Ford, A., Wilkinson, S. M. & Dawson, R. J. The impact of flooding on road transport: A depth-disruption function. Transp. Res. Part D Transp. Environ. 55, 67–81 (2017).

[30] Habel, S. Fletcher, C.H., Barbee, M.M., Fornace, K.L. (2024). Hidden Threat: The Influence of Sea-Level Rise on Coastal Groundwater and the Convergence of Impacts on Municipal Infrastructure. Annu. Rev. Mar. Sci. 16:9.1–9.23 https://doi.org/10.1146/annurev-marine-020923-120737

[31] McKenzie, T., Habel, S. and Dulai, H. (2021), Sea-level rise drives wastewater leakage to coastal waters and storm drains. Limnol Oceanogr Lett, 6: 154-163. https://doi.org/10.1002/lol2.10186

[32] McKenzie, T., Habel, S. and Dulai, H. (2021), Sea-level rise drives wastewater leakage to coastal waters and storm drains. Limnol Oceanogr Lett, 6: 154-163. https://doi.org/10.1002/lol2.10186

Table 3. Potential near-term (~2025 to ~2050) impacts from climate hazards and compounding effects in the Waikīkī Special District

Key Climate Change Hazard	Compounding Factors	Potential Near-term Impacts		
		SOCIAL/ECONOMIC	**STRUCTURES/INFRASTRUCTURE**	**ENVIRONMENTAL**
Increasing Temperature Extreme Heat Events (3-to-5-degree F increase over 1951 - 1980 average)	• Drought • Dense development and impervious surfaces (Urban Heat Island)	• Respiratory illnesses, heatstroke, and cardiovascular and kidney disease • Overwhelms to emergency services, health services, need for cooling centers • Increasing energy costs with increased demand for air conditioning	• Black outs as electrical infrastructure is unable to keep pace with sharp spikes in electricity demand for cooling • Damage to above ground infrastructure from heat	• Trees and vegetation stressed by heat extremes and drought-related water limitations
High Tide-Driven Flooding (2 days to 63 day per year before the year 2050)	• Other chronic flooding • Critically shallow groundwater depth • Annual high wave-driven flooding • Dense development/non-elevated infrastructure • Hardened shoreline protection	• Disruption to basic services • Temporary business closures • Nuisance flooding for residents and businesses • Creation of hazardous conditions from damage to coastal hardening structures	• Road closures • Reduced capacity of stormwater systems • Flooding lower levels of shoreline structures • Damage to hardened shoreline protection	• Beach loss especially when compounded with high wave events and shoreline hardening • Release of contaminants from cesspools and contaminated sites to nearshore waters
Compound Flooding	• High tide flooding • Chronic flooding • Critically shallow groundwater depth • Dense development	• Disruption to basic services • Illness from water borne pathogens and more frequent beach closings. • Nuisance flooding for residents and businesses	• Road closures restrict access to emergency vehicles • Damage to below-ground infrastructure • Reduced capacity of stormwater systems • Flooding lower levels of shoreline structures	• Impacts to coral reefs from polluted water runoff from roads and Ala Wai canal • Sewage spills to nearshore waters from pump station overflow or power loss
Critically Shallow Groundwater Depth (<5 ft below ground surface)	• Flash flooding • High tide-driven flooding • Compound flooding	• Frequent sub-surface infrastructure breaks and temporary loss of service	• Weakening of roadbed leading to sinkholes	• Landscaping loss due to saltwater intrusion

Key Climate Change Hazard	Compounding Factors	Potential Near-term Impacts		
		SOCIAL/ECONOMIC	STRUCTURES/INFRASTRUCTURE	ENVIRONMENTAL
		• Increased public exposure to lead, arsenic, and other contaminants from subsurface contaminated sites and cesspools	• Intensified corrosion of below-ground infrastructure resulting in infiltration and breakage • Corrosion and weakening of structural foundations • Cesspool failure	• Wastewater discharge to storm drains and coastal waters impacting coastal ecosystems • Potential for explosions due to methane gas accumulation especially during high tide events • Release of contaminants from cesspools and contaminated sites to nearshore waters
Sea Surface Temperature Extremes	• Tropical cyclones • Flash flooding • Extreme low tides	• Decline in tourism and fishing from loss of coral reef habitat	• Greater impacts to shoreline structures with loss of coastal protection services offered by healthy coral reef structure	• Coral bleaching and death

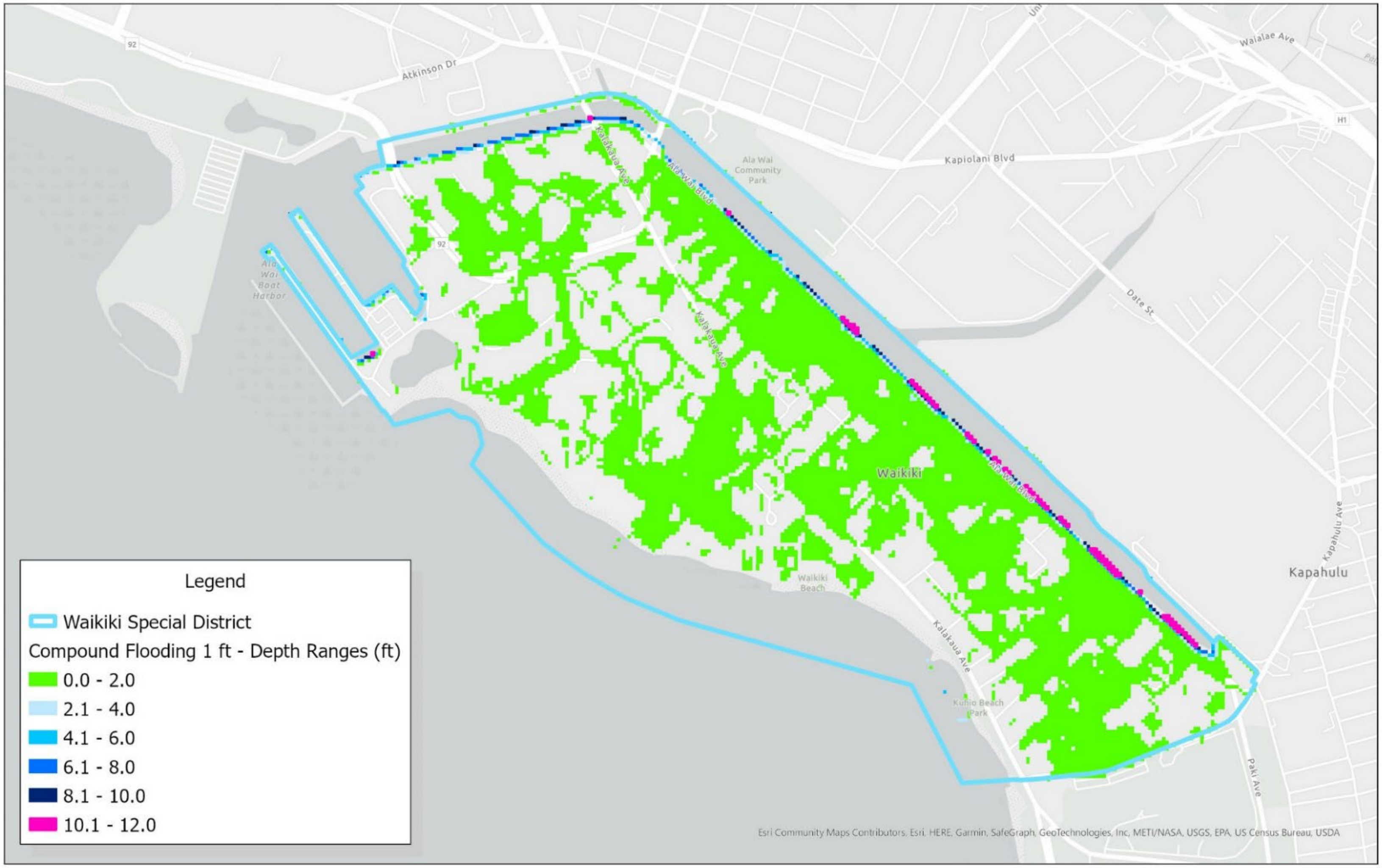

Figure 10. Extent of flooding and flood depth from compound flooding with 1 ft of sea level rise (UH SOEST Climate Resilience Collaborative 2023)

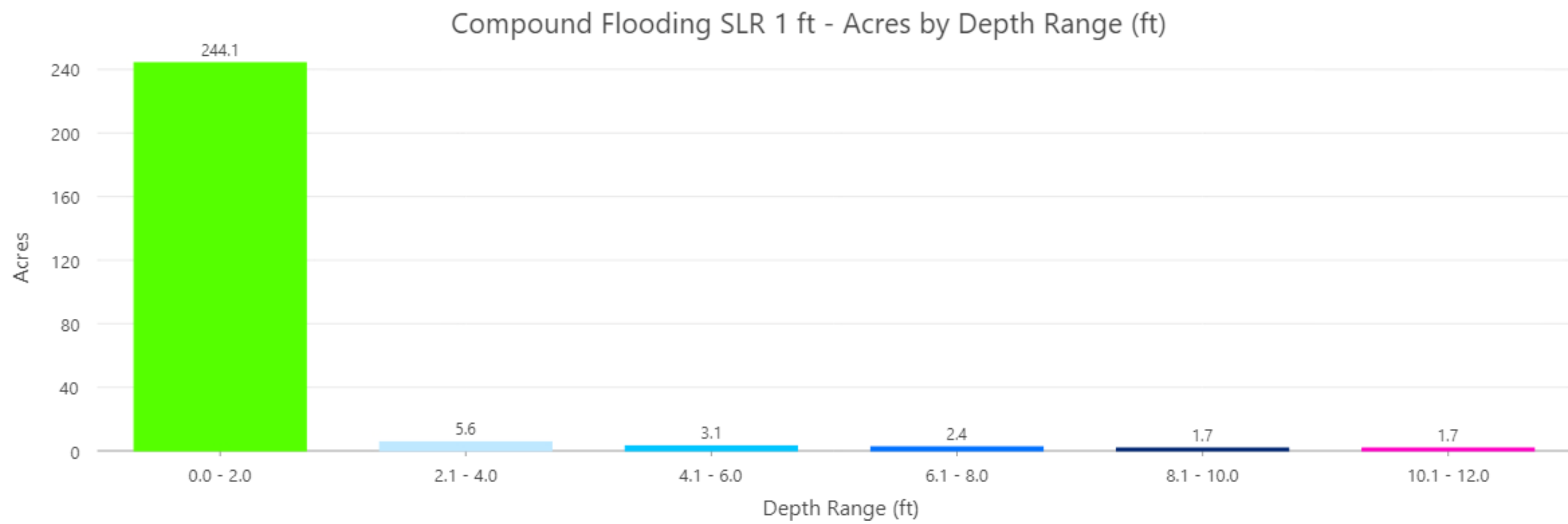

Figure 11. Acres of the Waikīkī Special District by flood depth compound flooding with 1 foot of sea level rise

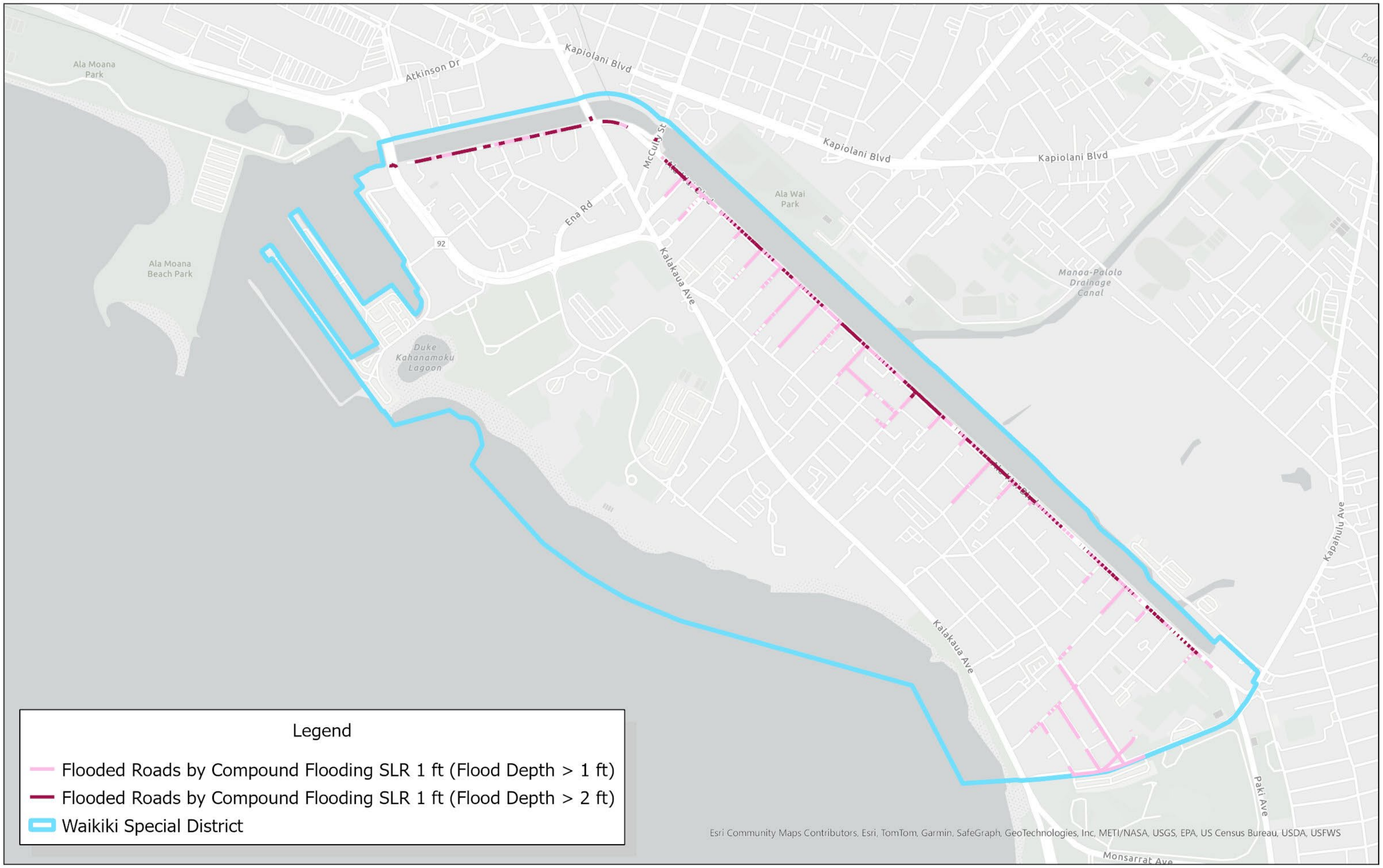

Figure 12. Roads with >1 ft and >2 ft flood depth from compound flooding with 1 foot of sea level rise in the Waikīkī Special District

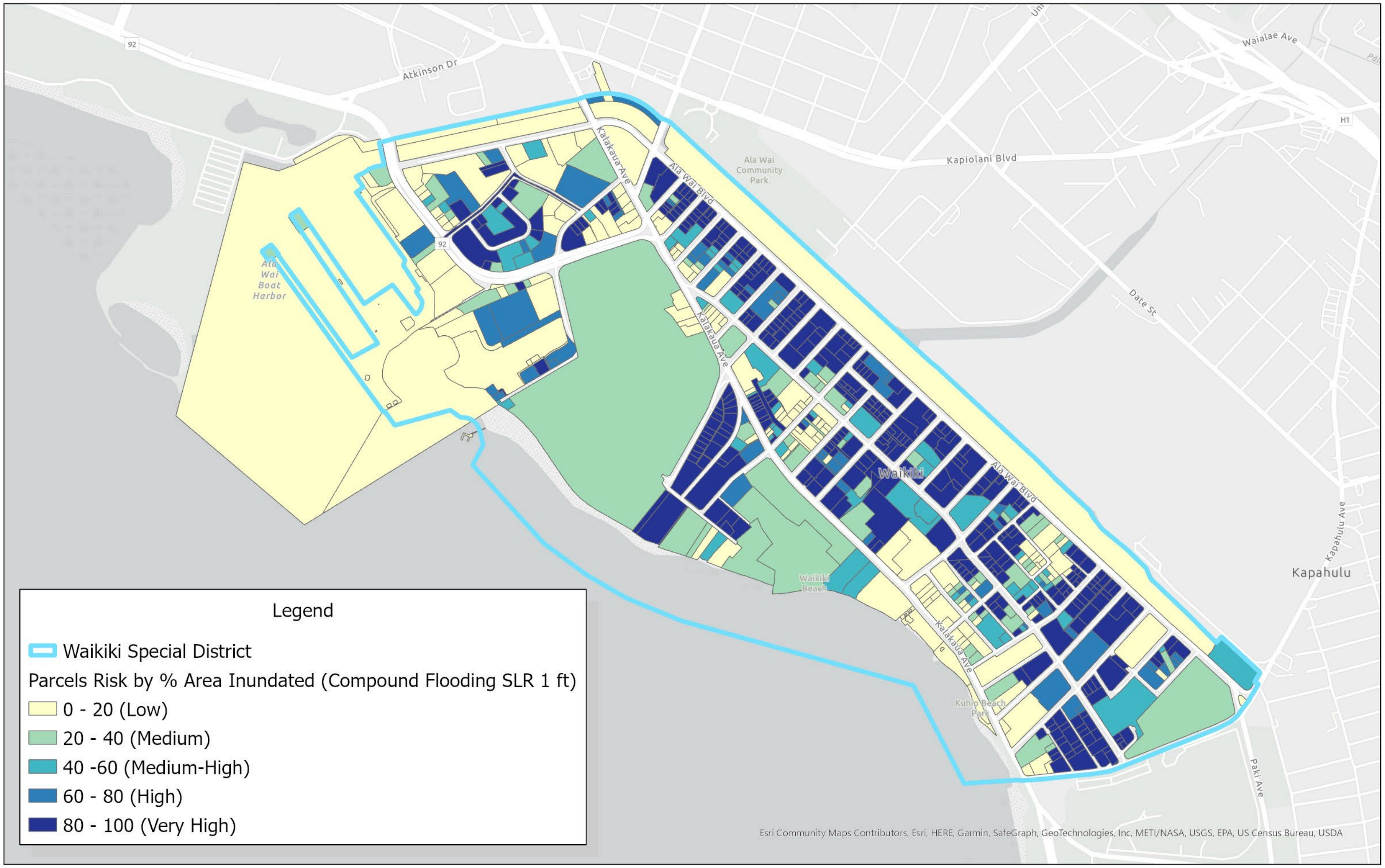

Figure 13. Percent of parcel flooded by a compound flooding with 1 ft of sea level rise in the Waikīkī Special District

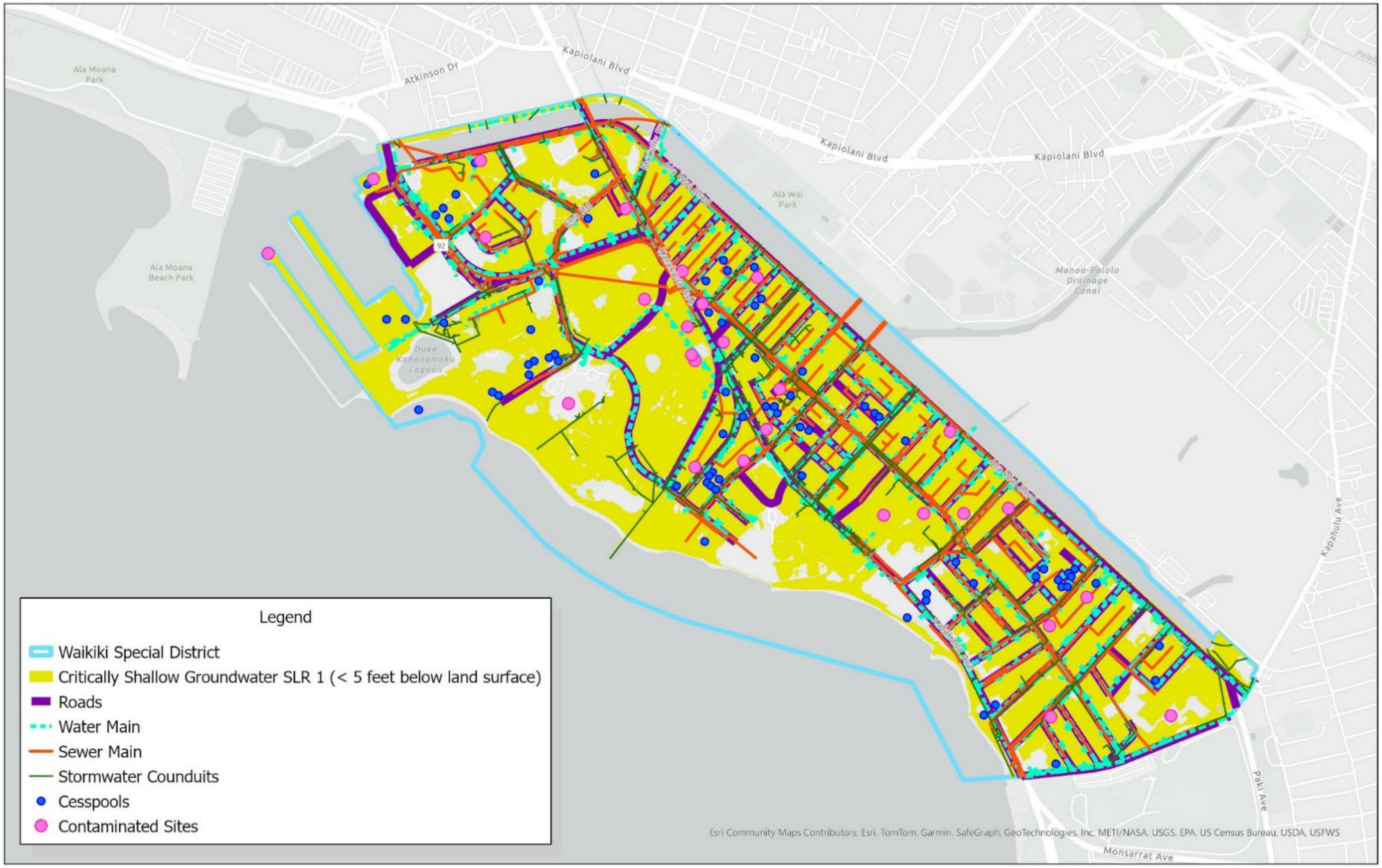

Figure 14. Extent of critically shallow groundwater (<5 ft below land surface) with 1 foot of sea level rise and infrastructure and contaminated sites in the Waikīkī Special District (UH SOEST Climate Resilience, Hawai'i Department of Health)

LONG-TERM OUTLOOK (~2050 TO ~2100)

By the end of the century, if greenhouse gas emissions continue to increase unabated, flooding in the WSD and Honolulu's urban core will be widespread. Groundwater inundation, annual high-wave flooding, passive flooding, and storm drainage failure will all contribute to chronic flooding in the WSD. All near-term climate hazards including extreme heat events, high tide-driven flooding, critically shallow groundwater depth, and flash flooding from extreme rainfall events will persist, intensify, and compound as long-term climate hazards. The coastal protection services afforded by coral reefs fronting the WSD will continue to decline from increasing sea temperature and decreasing pH resulting in bleaching and loss of carbonate structures. An overview of potential long-term impacts is provided in **Table 4**.

In the long-term, sea level is projected to rise by about 4 feet by ~2080 and 6 feet by ~2100 under the intermediate high scenario for Honolulu (see **Table 8**).[33] Groundwater inundation will lead the way in terms of timing (see **Table 2**), extent of flooding, and depth of flooding in comparison to other chronic flooding (passive, storm drain backflow, and groundwater) in the WSD (**Figure 15**).

With 4 feet of sea level rise, about 26% of the WSD will be inundated by groundwater and fully inundated with 6 feet of sea level rise (**Figure 16**). Groundwater inundation will result in flood depths ≤2 feet with 4 feet of sea level rise and ≤4 feet with 6 feet of sea level rise although higher flood depths may occur around the Ala Wai canal and shoreline **Figure 17**. Groundwater inundation with 4 feet will impact roads along the Ala Wai canal and in the West Waikīkī area (**Figure 18**).

Episodic flooding, from high tides, annual high wave-driven flooding and extreme rainfall events will exacerbate chronic flooding. A parcel-based analysis of flood impacts shows regions of the WSD with greatest impact. Parcels with highest groundwater inundation and annual high wave-driven flooding with 4 feet of sea level rise are shown in **Figure 19** and **Figure 20,** respectively. Groundwater will inundate parcels in the West Waikīkī area **Figure 19**. Annual high-wave-driven flooding will inundate parcels bordering the shoreline, the Ala Wai canal, and West Waikīkī area (**Figure 20**). The Board of Water Supply has identified the West Waikīkī area as especially vulnerable with the most feet of pipe impacted, and it is recommended as a pilot area to implement adaptation strategies.[34]

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[33] Interagency Sea Level Rise Scenario Tool, https://sealevel.nasa.gov/data_tools/18

[34] Board of Water Supply, and Brown and Caldwell. 2019. "Impacts of Climate Change on Honolulu Water Supplies and Planning Strategies for Mitigation"

Table 4. Potential long-term (~2050 to ~2100) impacts from climate hazards and compounding effects in the Waikīkī Special District

Key Climate Change Hazard	Compounding Effects	Potential Long-term Impacts		
		SOCIAL/ECONOMIC	INFRASTRUCTURE	ENVIRONMENTAL
Annual High Wave-Driven Flooding	• High tide flooding • Storm surge • Dense development/ impervious surfaces	• Loss of shoreline properties • Loss of businesses • Loss of public access to and along shoreline	• Loss of shoreline structures and infrastructure	• Beach loss especially when compounded with high wave events and storm surge
Chronic Flooding (Passive Flooding, Groundwater Inundation, Drainage Backflow)	• High tide flooding • Storm surge • Annual high wave-driving flooding events • Flash floods and riverine flooding • Dense development/ impervious surfaces	• Loss of businesses • Loss of public access to and along shoreline	• Loss/damage to roads and transportation connectivity within WSD and between WSD and Honolulu • Flooding of lower levels of structures • Road closures, overflowing storm drains, • Wastewater failures • Storm drainage failure • Damage to below-ground infrastructure	• Beach loss especially when compounded with high wave events • Sewage discharge to nearshore waters • Loss of street trees and other vegetation from saltwater intrusion • Release of contaminants from cesspools and contaminated sites to nearshore waters

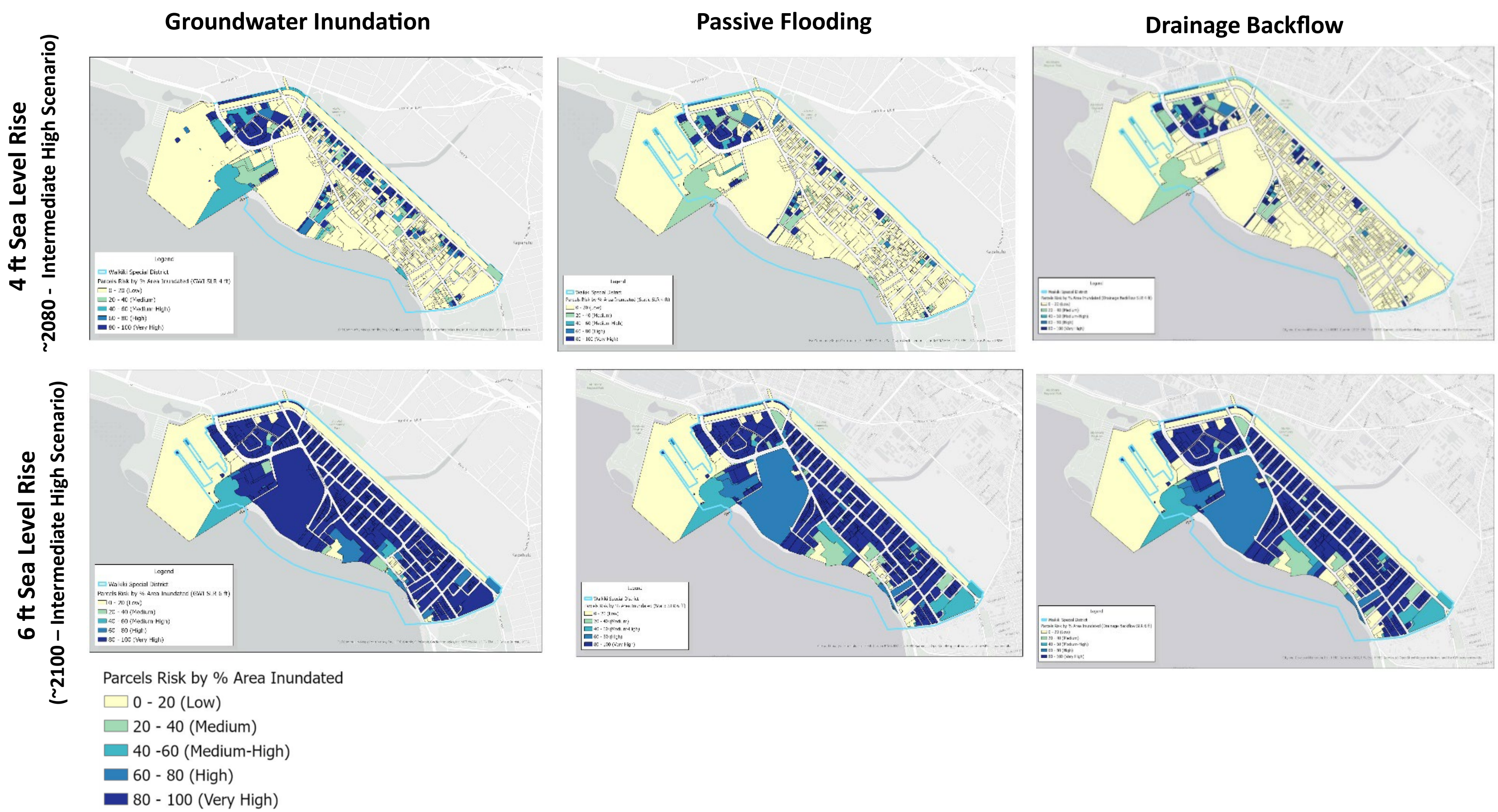


Figure 15. Comparison of percent of parcel flooded by chronic flooding with 4 ft (~2080) and 6 ft of sea level rise (~2100) in the Waikīkī Special District

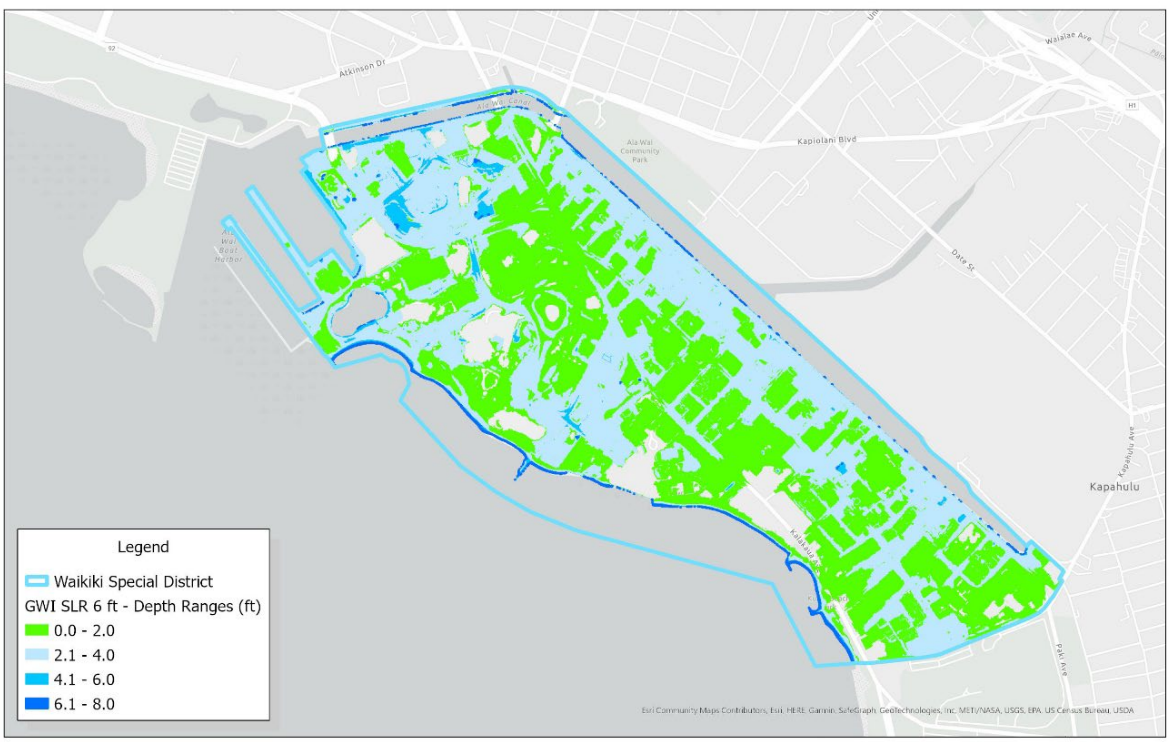


Figure 16. Extent and flood depth from groundwater inundation with 4 ft (top) and 6 ft (bottom) of sea level rise in the Waikīkī Special District

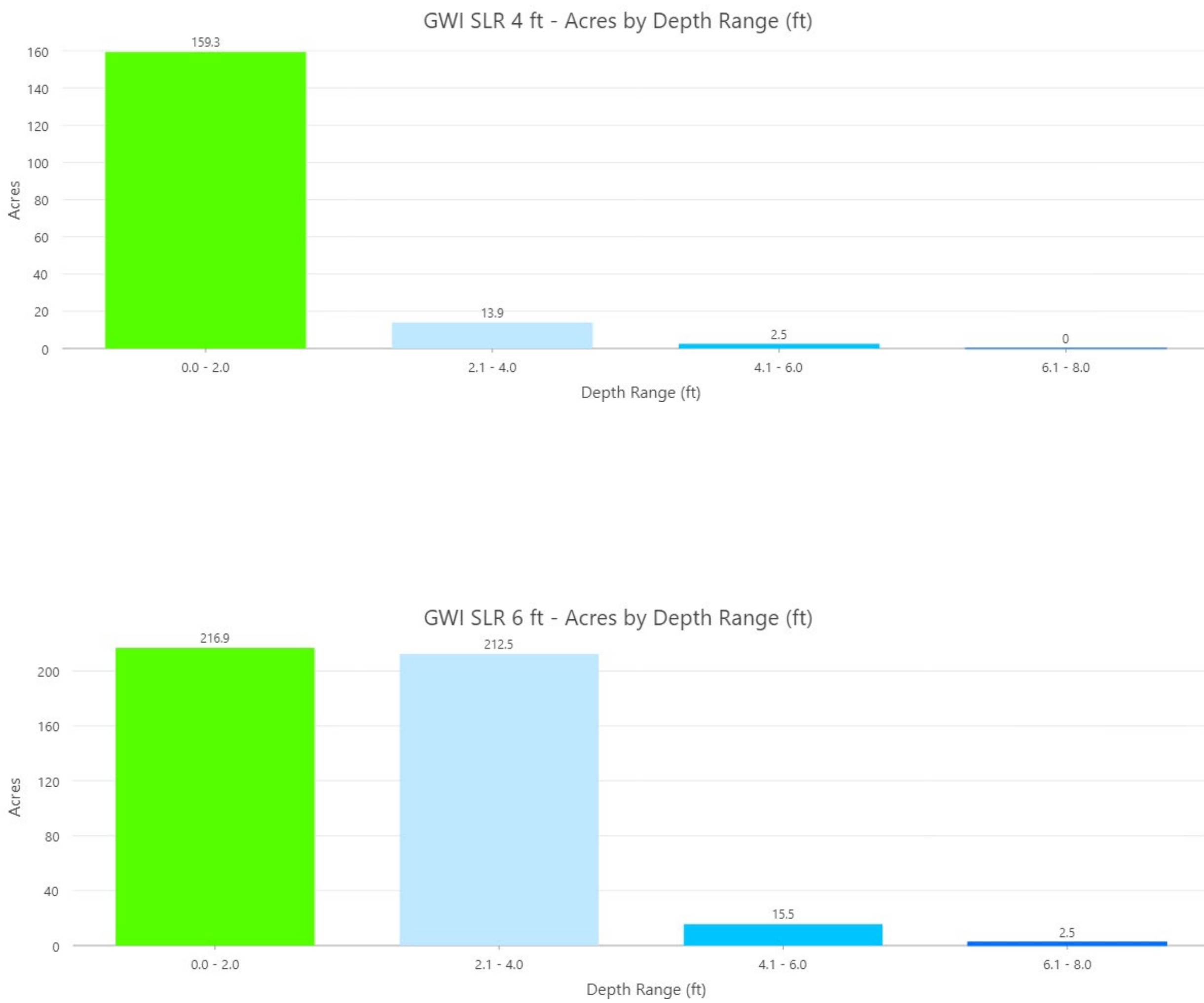
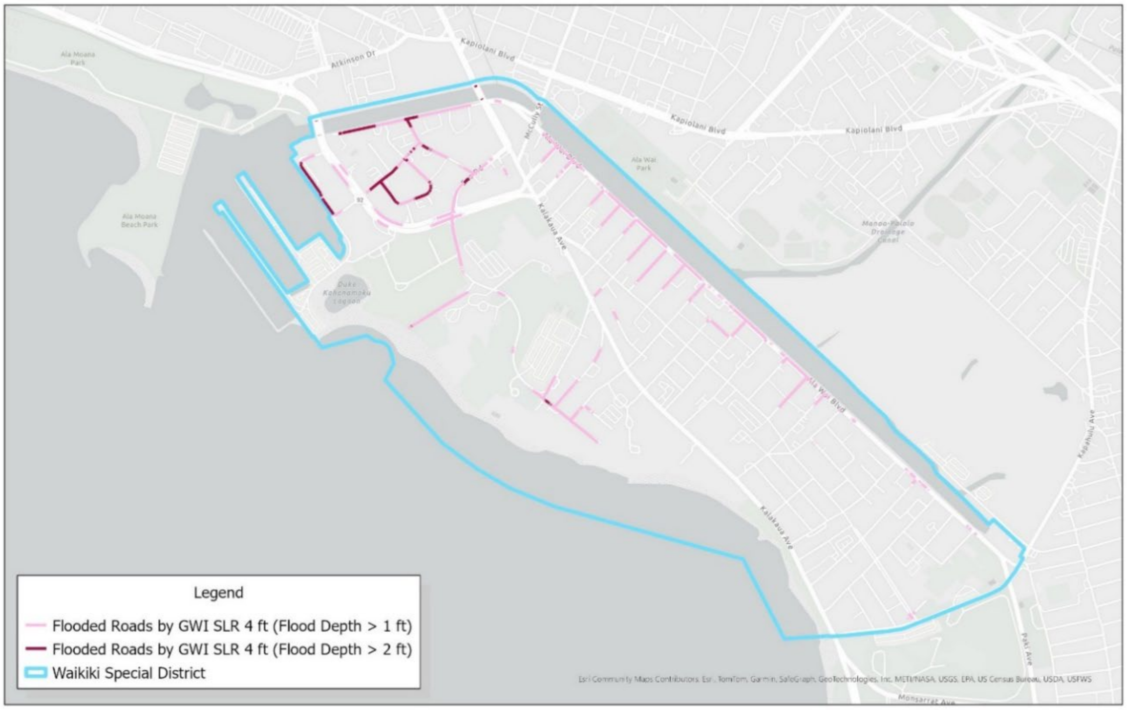


Figure 17. Acres by flood depth from groundwater inundation with 4 ft (top) and 6 ft (bottom) of sea level rise in the Waikīkī Special District



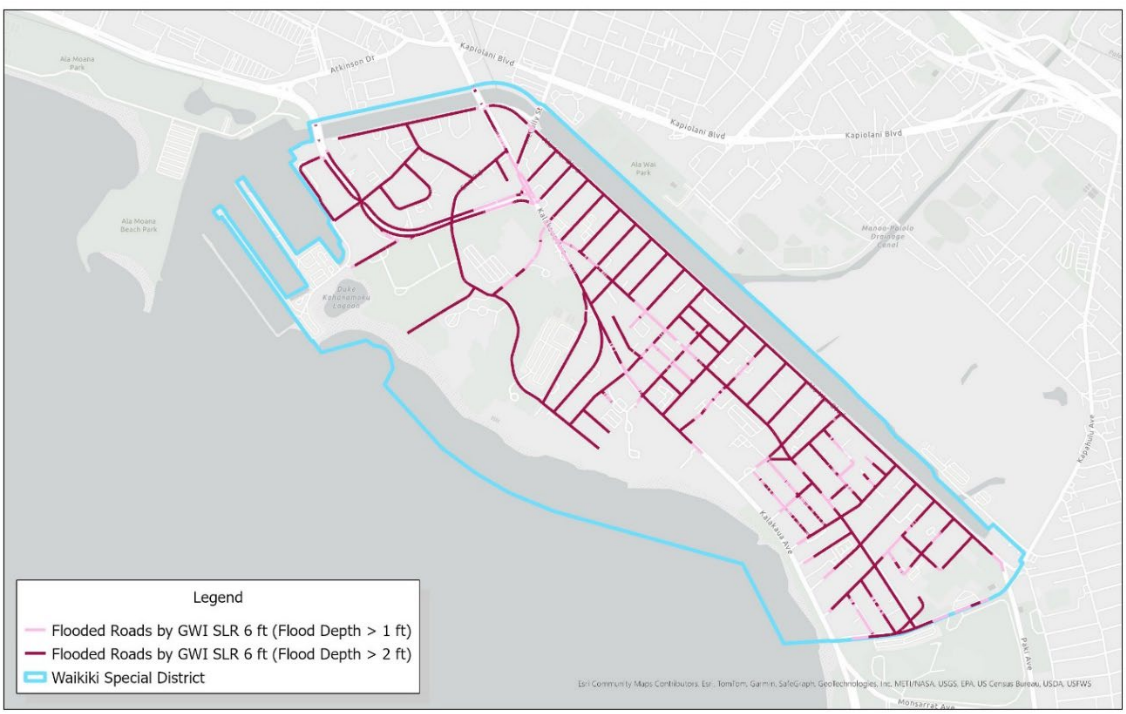


Figure 18. Roads impacted at >1ft and >2 ft flood depth from groundwater inundation with 4 ft and 6 ft of sea level rise in the Waikīkī Special District

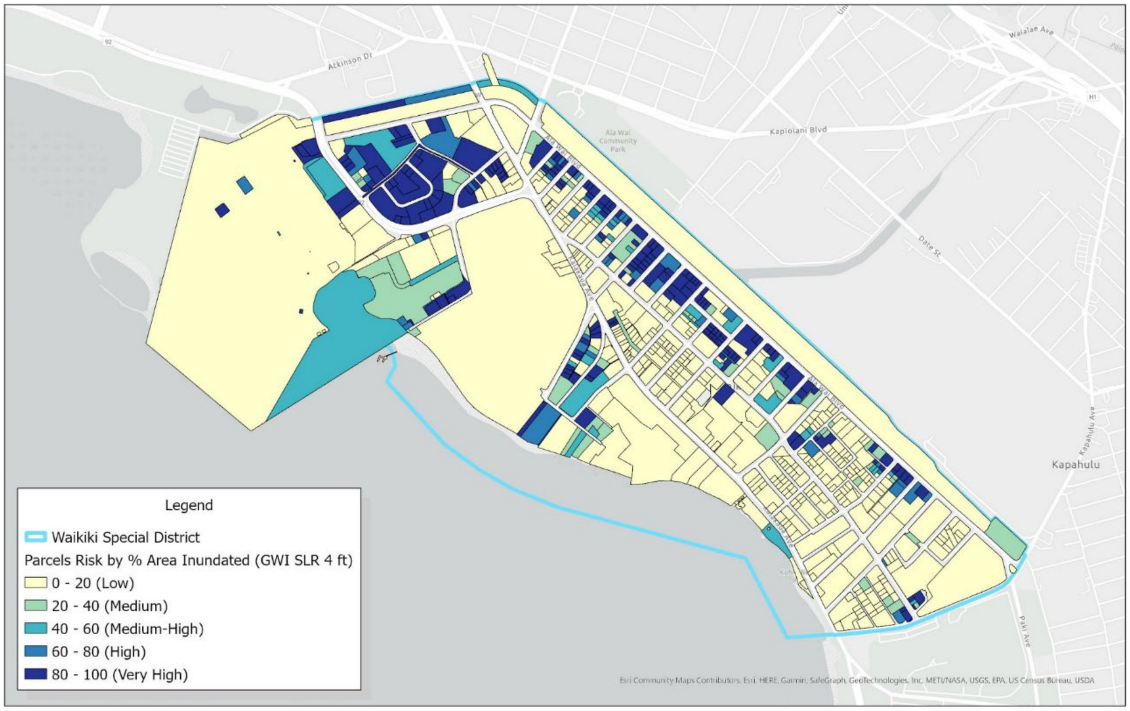


Figure 19. Percent of parcel flooded by groundwater inundation with 4 ft (~2080) in the Waikīkī Special District

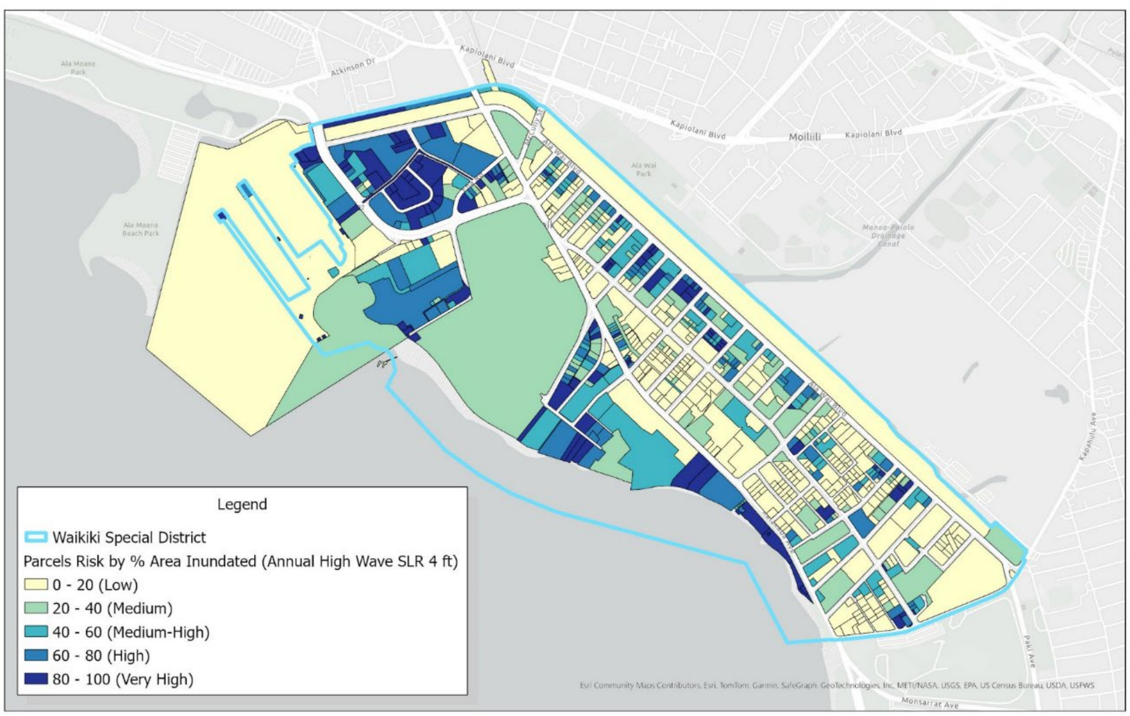


Figure 20. Percent of parcel flooded by annual high wave-driven flooding with 4 ft of sea level rise(~2080) in the Waikīkī Special District

FLOOD RISK INDEX

A flood risk index was developed to identify areas of early impact from flooding in the WSD over the next 50 years. The index characterizes the parcel-based flood risk based on three indicators for the 772 parcels in the WSD. Indicators 1, 2, and 3a were used to develop the flood risk index for groundwater inundation (**Table 5**). Indicators 1, 2, and 3b were used to develop the flood risk index for annual high wave-driven flooding (**Table 5**). Each indicator is ranked on a scale of 1 to 5. Each index is based on the sum of the ranking of the three indicators which results in a minimum rating of 3 and maximum rating of 15 for each index.

Table 5. Indicators used to develop parcel-based flood risk indices

Flood Risk Indicator*	Rationale
1. % of parcel covered by structure(s)	Indicates increased vulnerability to flooding based on the degree of impervious surface (shown in **Figure 6)**
2. Age of structure	Indicates increased vulnerability of structures to flooding based on the remaining useful life of structure (shown in **Figure 7**)
3a. % of parcel area inundated by groundwater with 4 feet of sea level rise	Indicates the extent of flooding from groundwater on the parcel by ~2080 (shown in **Figure 19**)
3b. % of parcel area minus area of structure footprint flooded by annual high wave-driven flooding with 4 feet of sea level rise	Indicates the extent of flooding from high waves on the parcel not covered by a structure by ~2080 (shown in **Figure 20)**

*Each indicator is ranked on a scale of 1 to 5.

Of the 772 parcels, 293 parcels fall in the high and very high risk rating for groundwater inundation (**Figure 21**) compared to 167 parcels for annual high wave-driven flooding (**Figure 22**). Groundwater inundation has a greater risk based on the percent of parcels in the WSD in the high and very high categories compared to annual high wave-driven flooding (**Figure 23**).

Areas at greatest flood risk for groundwater inundation are parcels concentrated in the West Waikīkī (Hobron) area and along the Ala Wai Canal (**Figure 24)**.

Areas of great flood risk for annual high wave flooding are parcels concentrated, as expected along the shoreline (**Figure 25**). Parcels in the West Waikīkī area are at greater flood risk from both groundwater inundation and annual high wave-driven flooding.

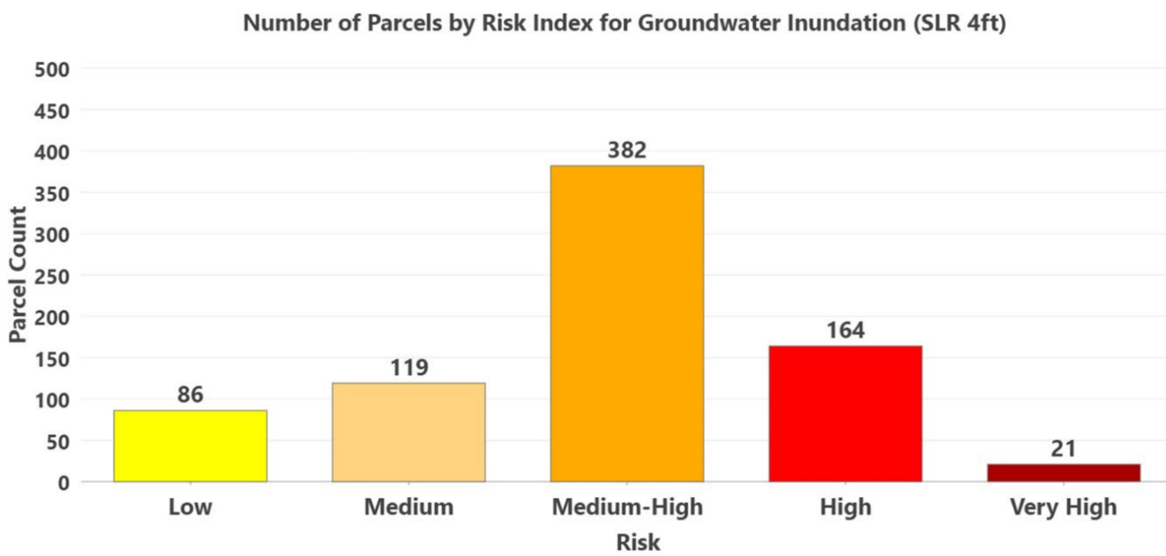


Figure 21. Number of parcels by risk rating for groundwater inundation with 4 ft of sea level rise

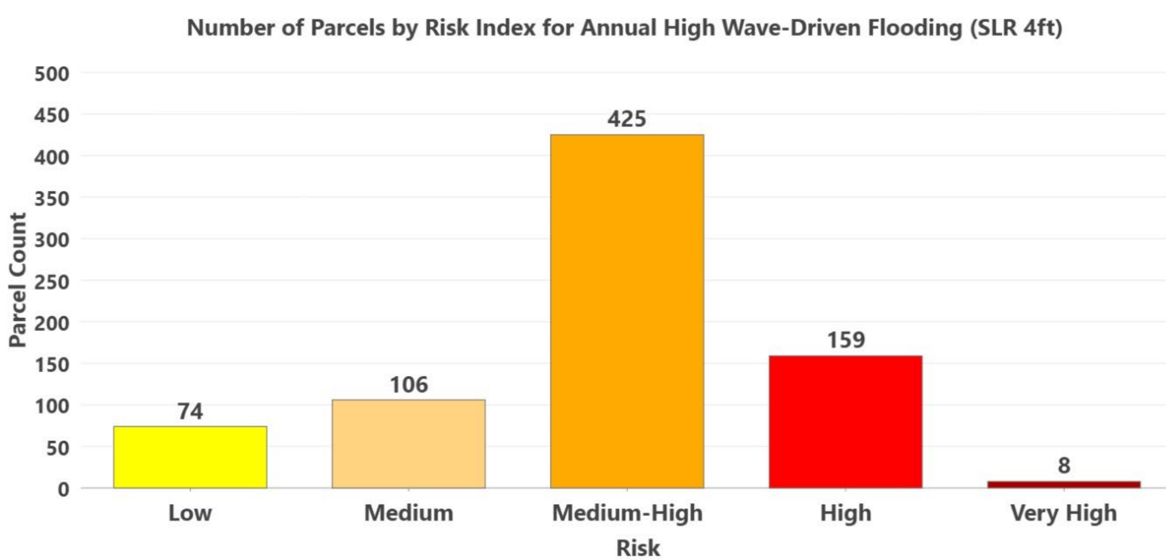


Figure 22. Number of parcels by risk rating for annual high wave-driven flooding with 4 ft of sea level rise

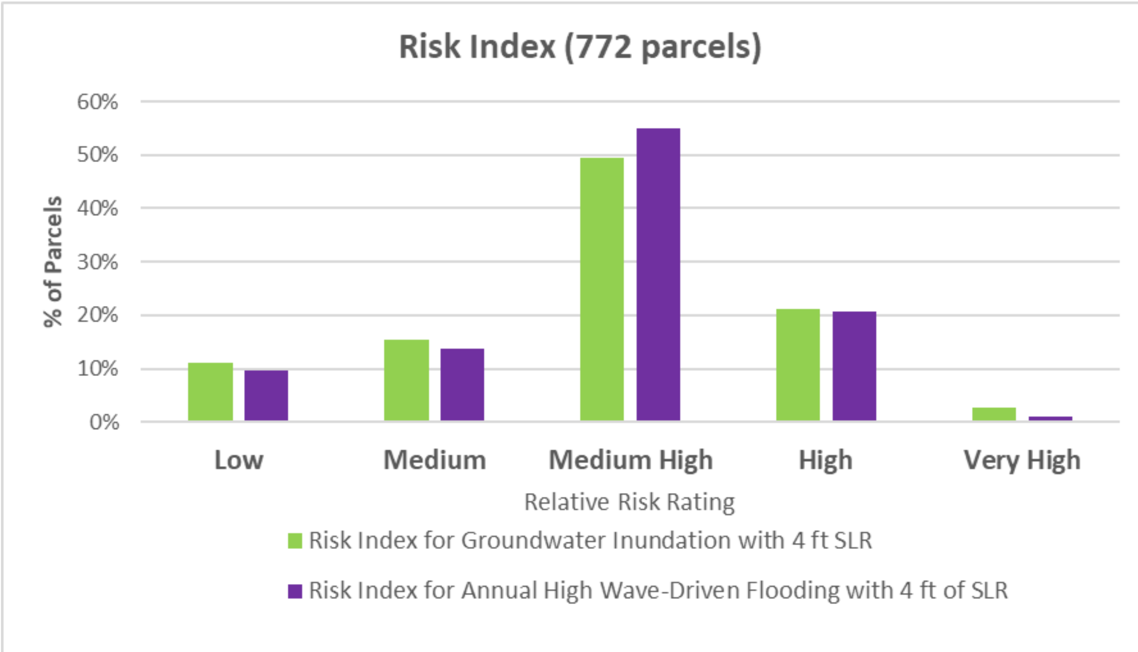


Figure 23. Percent of parcels by risk index

Risk Index for Groundwater Inundation (4ft SLR)

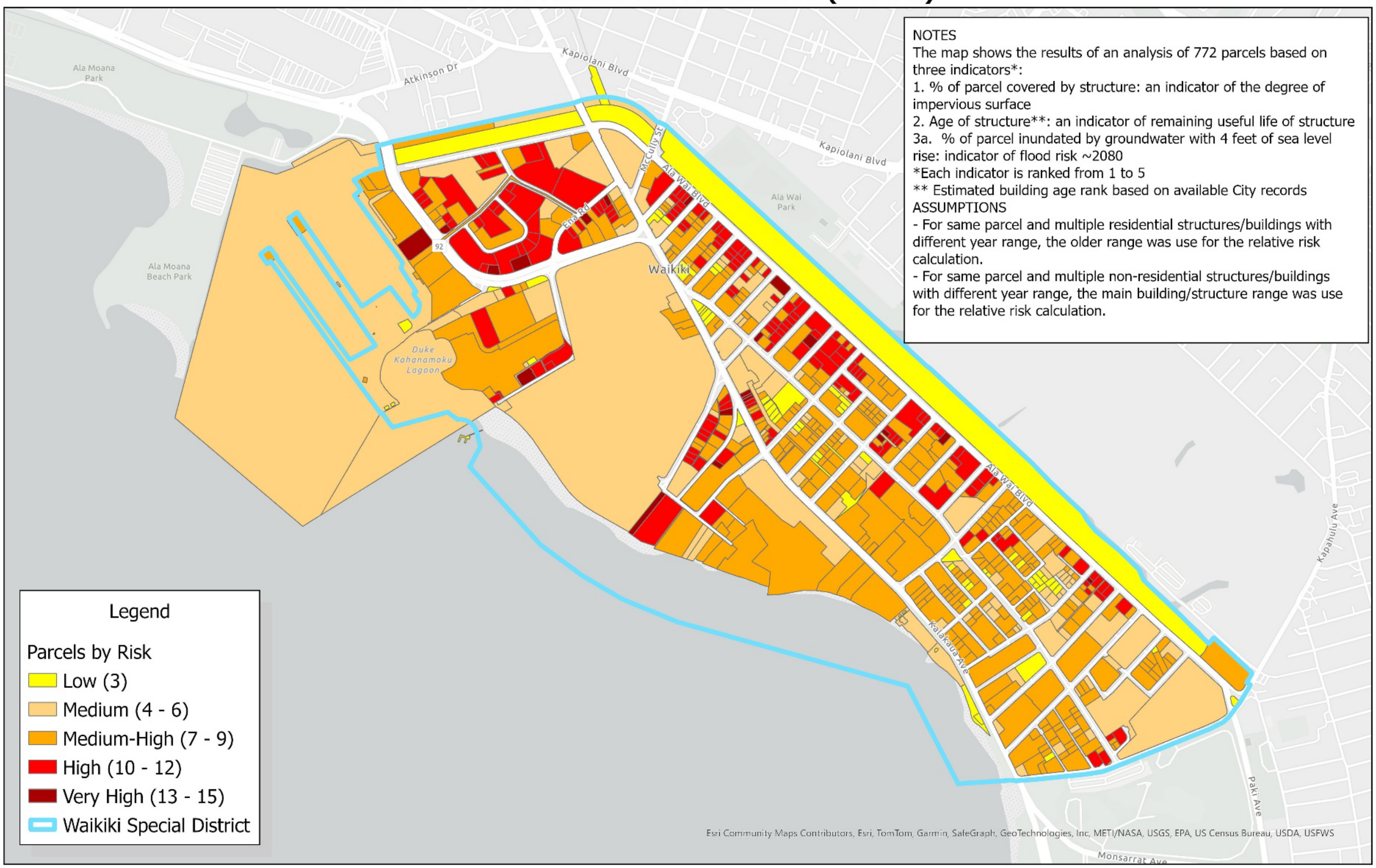


Figure 24. Risk index for groundwater inundation with 4 feet of sea level rise

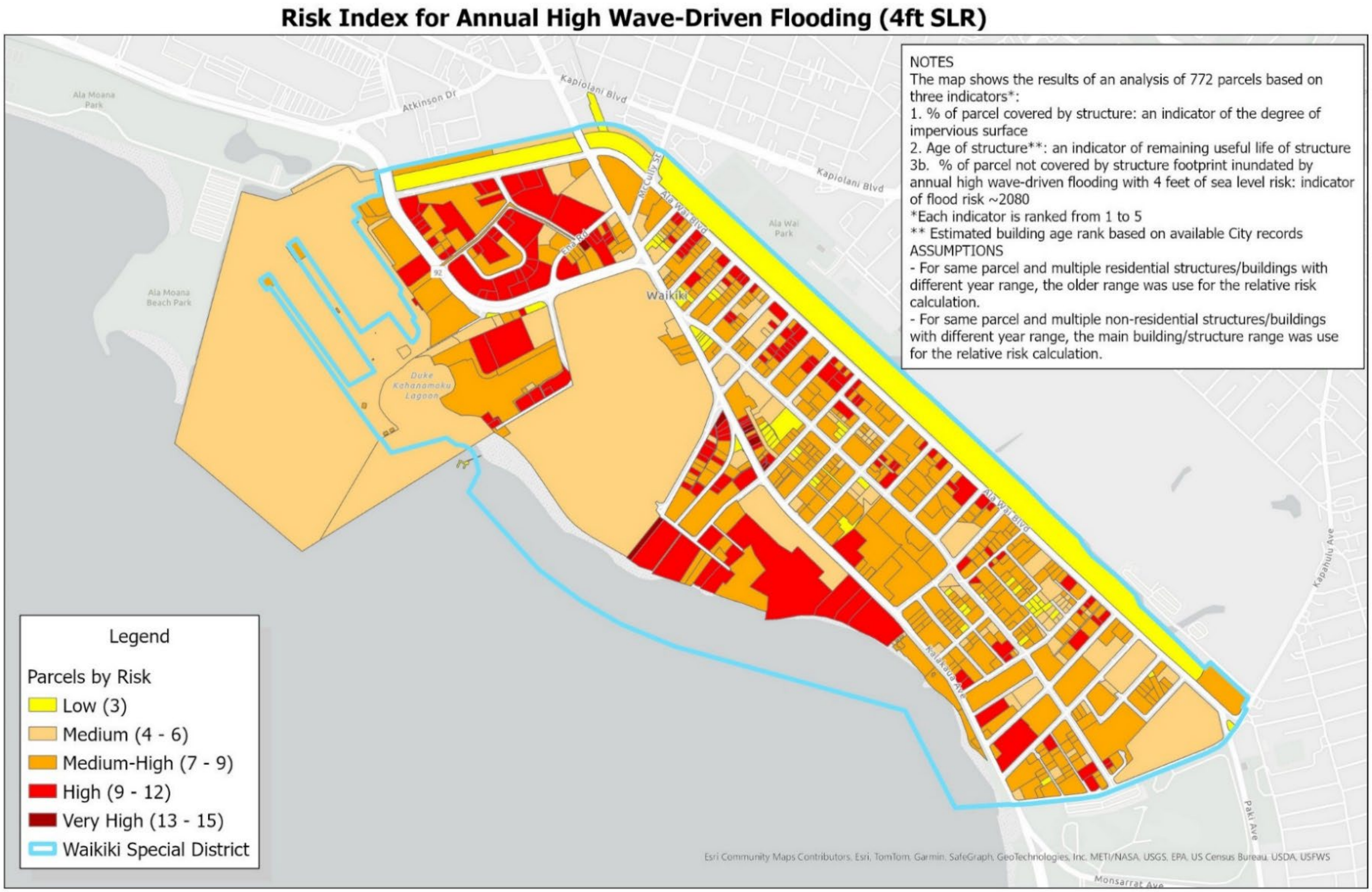


Figure 25. Risk index for annual high wave-driven flooding with 4 feet of sea level rise

Climate Hazards Considered and Cascading and Compounding Effects

The NCA5 states that *climate change is increasing the chances of multiple climate hazards occurring simultaneously or consecutively across the US and its territories. Such interactions between multiple hazards across space or time, known as compound events, exacerbate the societal and ecosystem impacts of individual hazards and hinder the ability of communities, particularly frontline communities, to respond and cope. Therefore, infrastructure design, planning, governance, and disaster preparedness for compound events are critical for building resilient systems.* [35]

The WSD is highly vulnerable to multiple climate hazards that can occur simultaneously and consecutively (**Figure 26**). Globally, air and sea surface temperatures are rising from unbated anthropogenic sources of greenhouse gas emissions. Global warming is resulting in sea level rise, heat extremes, and changes in rainfall patterns. Sea level rise, together with climate variability and high tide and extreme rainfall events increase the risk of chronic and event-based flooding.

Urban development patterns exacerbate climate change impacts such as increases in heat and flooding. [36] Dense development in and along the shoreline in the WSD is both vulnerable to and compounds the risks of climate change. Heat extremes are exacerbated by urban development and loss of tree canopy with rising and more saline groundwater. Flooding is exacerbated with a lack of permeable surfaces.

Contaminated sites, cesspools, and leaky sewer systems release methane gas that can accumulate in voids subsurface and contaminants that can be released to the environment posing public safety and environmental risks. [37] As contaminated sites become inundated from sea level rise, groundwater inundation or flooding, the oxygen supply decreases, leading to enhanced production of methane. Methane production with sea-level rise has been predicted using modeling. [38] Subsurface methane levels often spike during high tides and heavy rains. Soil composition and flooding also influences the generation of methane gas. [39] The WSD, once a marsh, is a source of organic matter that decomposes and can serve as another subsurface source of methane gas. When these sources of methane gas accumulate under impervious surfaces, they can pose a risk to human health and safety with rising sea level and storms.

[35] Singh, D., A.R. Crimmins, J.M. Pflug, P.L. Barnard, J.F. Helgeson, A. Hoell, F.H. Jacobs, M.G. Jacox, A. Jerolleman, and M.F. Wehner, 2023: Focus on compound events. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.F1.

[36] Chu, E.K., M.M. Fry, J. Chakraborty, S.-M. Cheong, C. Clavin, M. Coffman, D.M. Hondula, D. Hsu, V.L. Jennings, J.M. Keenan, A. Kosmal, T.A. Muñoz-Erickson, and N.T.O. Jelks, 2023: Ch. 12. Built environment, urban systems, and cities. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH12

[37] Felton, D. and van der Zander, I. (2021). Risks of Sea Level Rise and Increased Flooding on Known Chemical

Contamination in Hawaii. Memorandum from the Hawaii Department of Health, Office of Hazard Evaluation and Emergency Response (2021).

[38] Lu, X., Zhou, Zhoung, Q., Prigent, C, Liu, Y., & Teuling, A. (2018). Increasing methane emissions from natural land ecosystems due to sea-level rise. Journal of Geophysical Research: Biogeosciences, 123, 1756-1768. https://doi.org/10.1029/2017JG004273.

[39] King, G. M. and Henry, K (2019). Impacts of Experimental Flooding on Microbial Communities and Methane Fluxes in an Urban Meadow, Baton Rouge, Louisiana. Front. Ecol. Evol. 7:288. Doi:10.3389/fevo.2019.00288

The following section describes the climate risks considered for this WSD Risk Profile, all of which contribute to the cascading and compounding effects described in the near and long-term outlooks for Waikīkī.

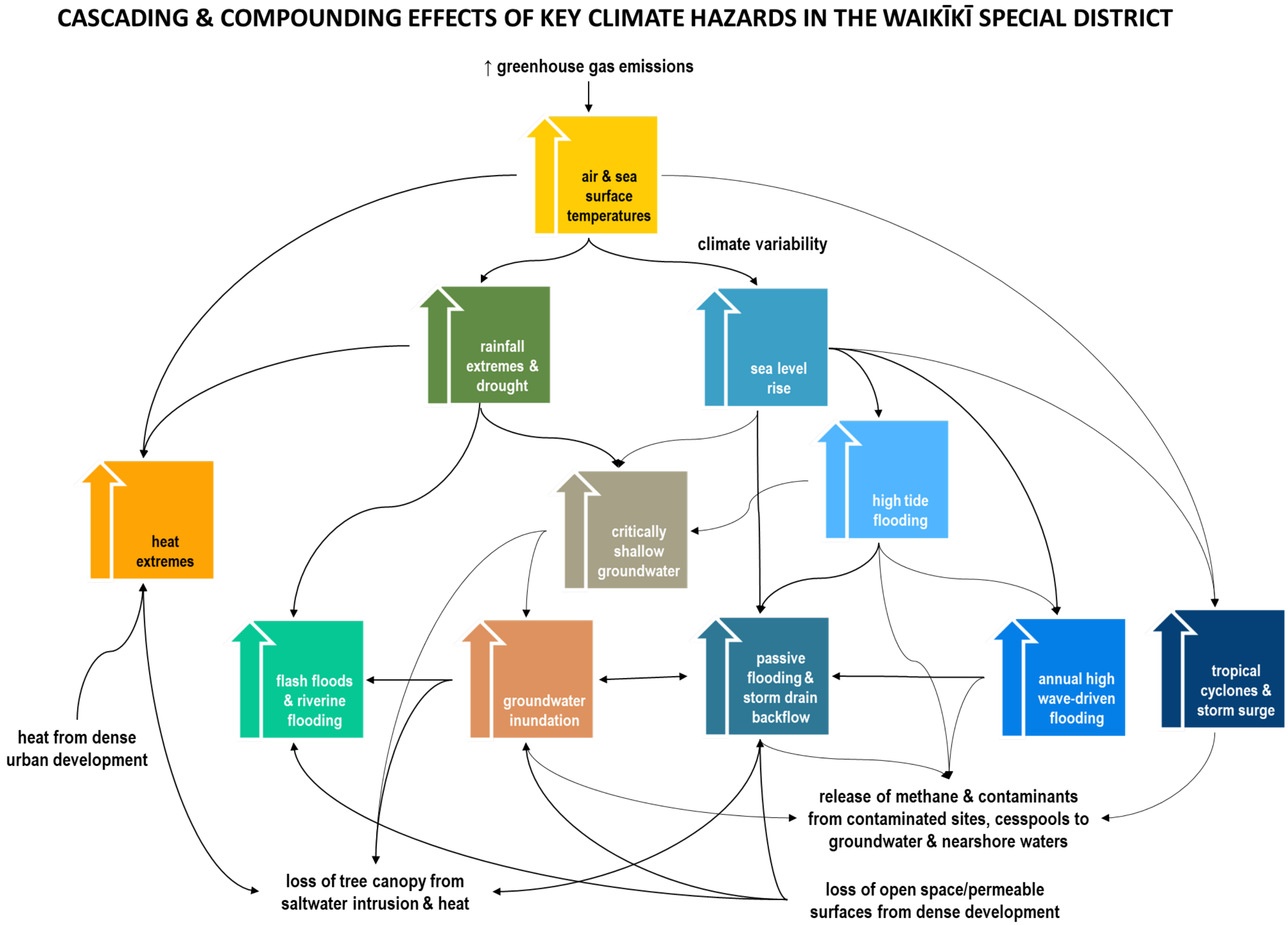


Figure 26. Cascading and compounding effects of climate hazards in the Waikīkī Special District

GREENHOUSE GAS EMISSIONS

Greenhouse gas emissions from human activities are warming the atmosphere, ocean and land at an unprecedented rate. [40] Increased fossil fuel combustion, cement production, deforestation, and other human activities [41] have raised the average concentration of carbon dioxide over the last 200 years,[42] higher than any time in at least 800,000 years (**Figure 27**). [43]

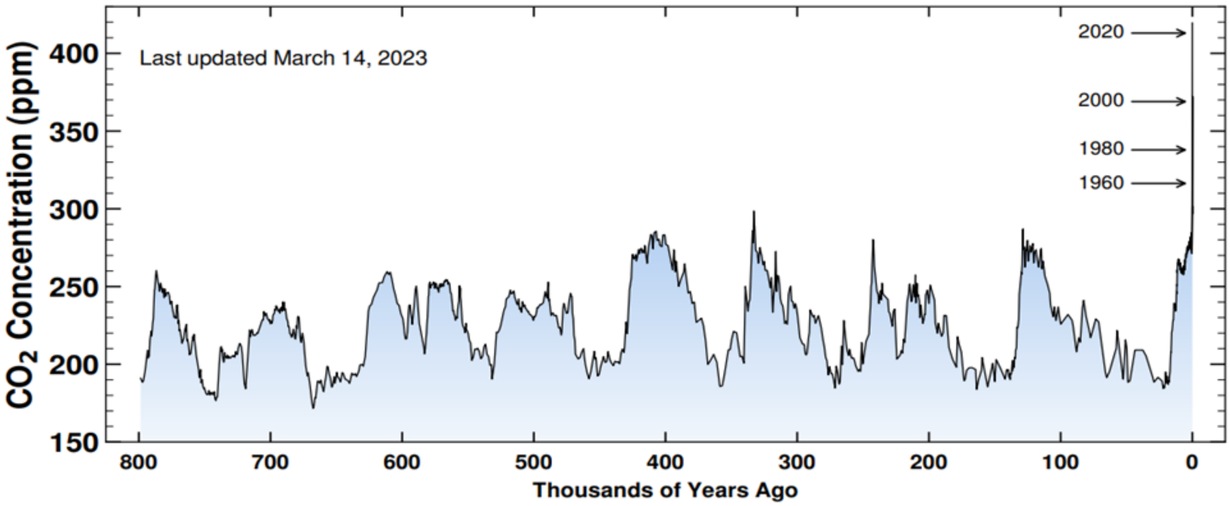


Figure 27. Global carbon dioxide concentration over the last 800,000 years (ice core data before 1958. Mauna Loa data after 1958)

[40] IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32, doi:10.1017/9781009157896.001.

[41] Friedlingstein, P., et al. (2020) Global Carbon Budget 2020, Earth Syst. Sci. Data, 12, 3269–3340, https://doi.org/10.5194/essd-12-3269-2020

[42] Lüthi, D., M. Le Floch, B. Bereiter, T. Blunier, J.-M. Barnola, U. Siegenthaler, D. Raynaud, J. Jouzel, H. Fischer, K. Kawamura, and T.F. Stocker. 2008. High-resolution carbon dioxide concentration record 650,000-800,000 years before present. Nature, Vol. 453, pp. 379-382, 15 May 2008. https://keelingcurve.ucsd.edu/

[43] C. D. Keeling, S. C. Piper, R. B. Bacastow, M. Wahlen, T. P. Whorf, M. Heimann, and H. A. Meijer, Exchanges of atmospheric CO_2 and 13CO2 with the terrestrial biosphere and oceans from 1978 to 2000. I. Global aspects, SIO Reference Series, No. 01-06, Scripps Institution of Oceanography, San Diego, 88 pages, 2001. http://escholarship.org/uc/item/09v319r9

AIR AND SEA SURFACE TEMPERATURE

With increasing greenhouse gas emissions, global warming of 2°C above pre-industrial periods (1850–1900) is expected by the 2040s. [44] This level of global warming is considered a critical threshold above which dangerous and cascading effects of human-generated climate change will occur. Increasing greenhouse gas emissions result in global warming and greater absorption of carbon dioxide in the ocean, which decreases ocean pH (increases acidity).

Temperatures across the Hawaiian Islands have increased since 1950 with a sharp increase since 2010 (**Figure 27**). [45] Hawaiʻi temperatures are expected to increase between 2° F and 10° F by 2100 depending on future greenhouse gas emission trends. Coastal areas around O'ahu are especially susceptible to increased temperatures, with longer stretches of temperatures well above 80 °F (**Figure 29**). [46]

Excess heat trapped in the Earth system is absorbed by the ocean. Increasing ocean heat content is contributing to ocean heat waves, coral bleaching, and sea level rise from melting of glaciers and ice sheets around Greenland and Antarctica. [47]

Assuming continued and increased fossil fuel use, ocean warming is projected to cause severe bleaching in the coming decades, like what was experienced in 2015. Severe coral bleaching is expected to occur on an annual basis across Hawaiʻi by 2048 and on reefs fronting Waikīkī by 2052 (**Figure 30**). [48] Further, rising levels of carbon dioxide dissolved in the ocean and the resulting increase in acidity changes the balance of minerals in the water. [49] Ocean acidification makes it more difficult for corals, some types of plankton, and other creatures to produce calcium carbonate used to produce hard skeletons or shells, making it more difficult for these animals to thrive and jeopardizing the health of the reef. Coral reefs provide many ecosystem services, one of which is reducing coastal flood risk. [50] A warmer ocean and more acidic ocean stresses coral reef ecosystems reducing their capacity to protect the shoreline from waves and storm surge.

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[44] Taejin Park, Hirofumi Hashimoto, Weile Wang, Bridget Thrasher, Andrew R. Michaelis, Tsengdar Lee, Ian G. Brosnan, Ramakrishna R. Nemani, 2022. What Does Global Land Climate Look Like at 2°C Warming. Earth's Future: Volume11, Issue 5. doi.org/10.1029/2022EF003330

[45] Stevens, L.E., R. Frankson, K.E. Kunkel, P.-S. Chu, and W. Sweet (2022). Hawaiʻi State Climate Summary 2022. NOAA Technical Report NESDIS 150-HI. NOAA/NESDIS, Silver Spring, MD, 5 pp. https://statesummaries.ncics.org/chapter/hi/

[46] Hawaiʻi Department of Transportation. 2021. Hawaiʻi Highways, Climate Adaptation Action Plan, Exposure Assessments, https://hidot.Hawaiʻi.gov/wp-content/uploads/2021/07/HDOT-Climate-Resilience-Action-Plan-Exposure-Assessments-April-2021.pdf

[47] Dahlman, L. and Lindsey, R. 2022. Climate Change: Ocean Heat Content. https://www.climate.gov/news-features/understanding-climate/climate-change-ocean-heat-content#:~:text=More%20than%2090%20percent%20of,NOAA%20Climate.gov%20graph

[48] Gove JM, Maynard JA, Lecky J, Tracey DP, Allen ME, Asner GP, Conklin C, Couch C, Hum K, Ingram RJ, Kindinger TL, Leong K, Oleson KLL, Towle EK, van Hooidonk R, Williams GJ, Hospital J. 2022. 2022 Ecosystem Status Report for Hawaiʻi. Pacific Islands Fisheries Science Center, PIFSC Special Publication, SP-23-01, 91p. doi:10.25923/r53p-fn97

[49] EPA (2022). Climate Change Indicators: Ocean Acidity. https://www.epa.gov/climate-indicators/climate-change-indicators-ocean-acidity

[50] Reguero, B.G., Storlazzi, C.D., Gibbs, A.E., Shope, J.B., Cole, A.D., Cumming, K.A., and Beck, M.W., 2021, The value of U.S. coral reefs for flood risk reduction: Nature-Sustainability, 2398-9629, doi: 10.1038/s41893-021-00706-6

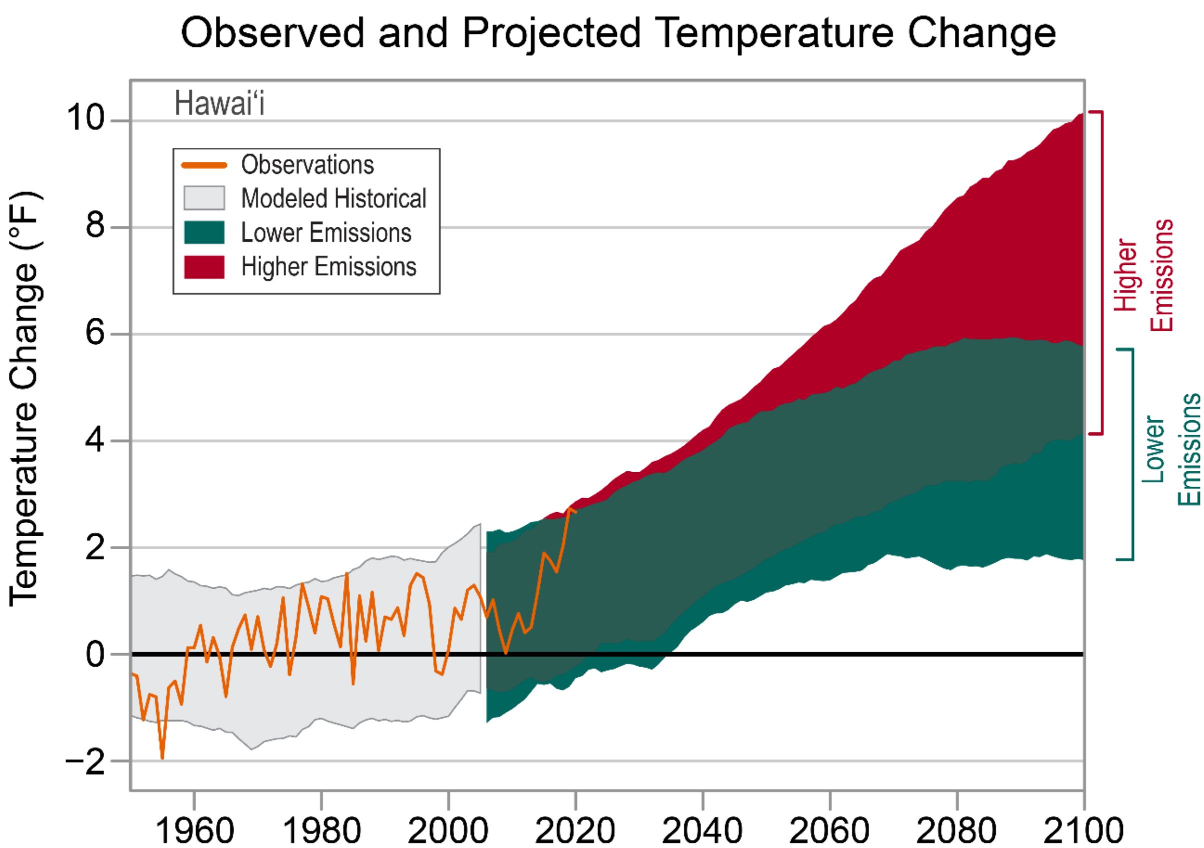

Figure 28. Observed and projected temperature change compared to the 1951 to 1980 average in near surface air temperature in Hawaiʻi (Stevens et al., 2022)

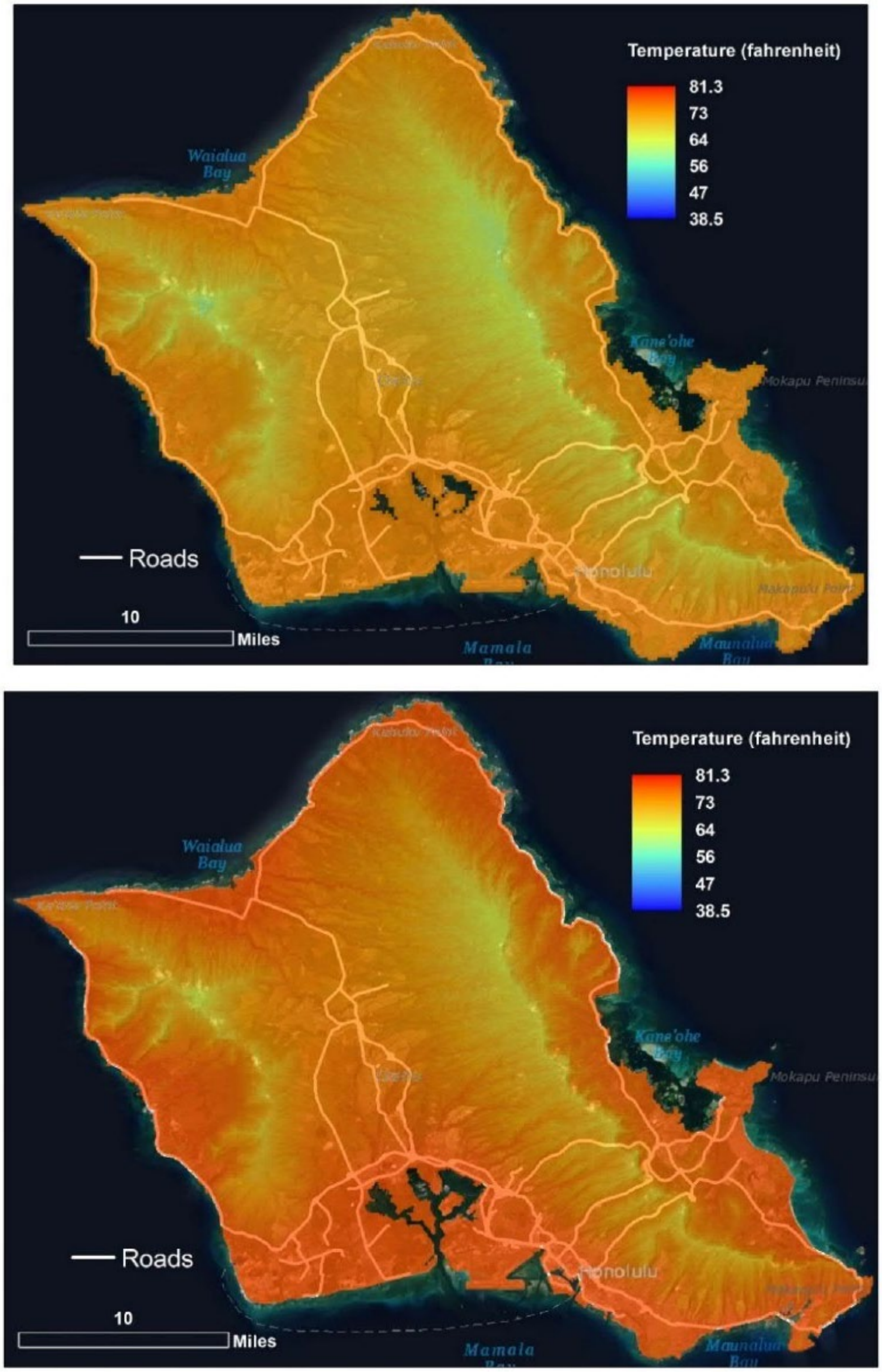

Figure 29. Annual mean temperature values in (top) middle and (bottom) end of the century (RPC8.5 emissions scenario, 97.5th-percentile of climate model ensemble results) for Oʻahu (Hawaiʻi Department of Transportation, 2021)

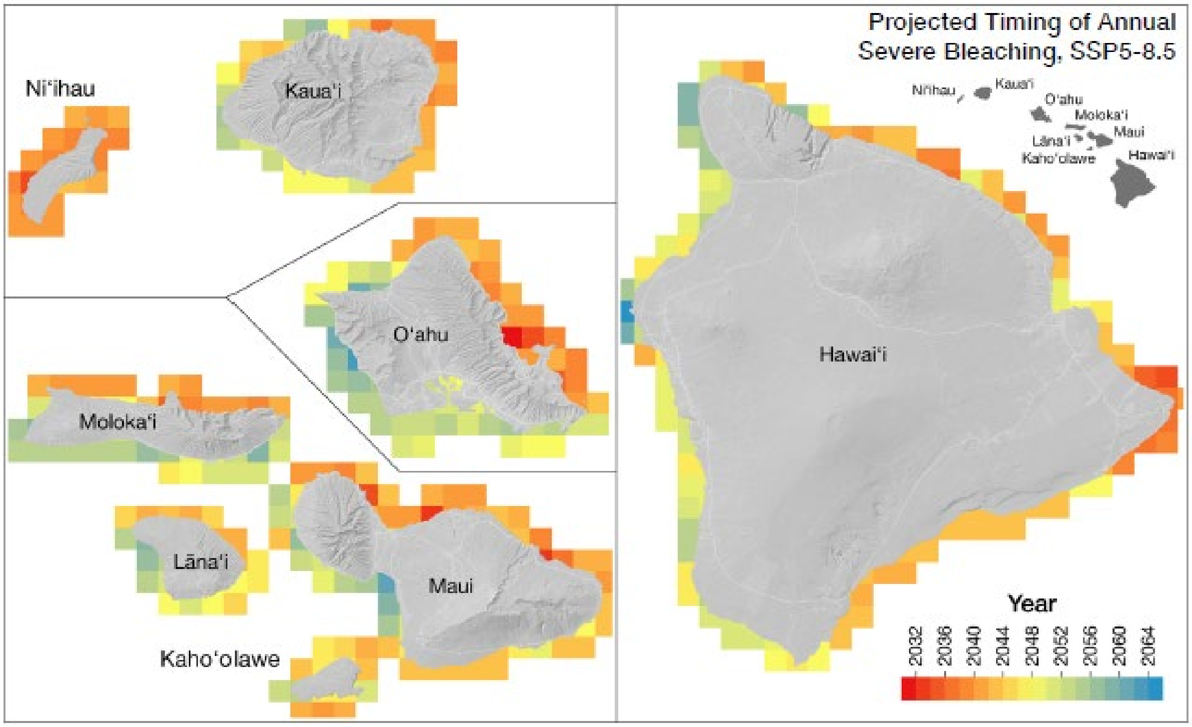

Figure 30. Climate model projections of projected timing of annual severe bleaching under emissions scenario SSP5-8.5, which characterizes current greenhouse gas emissions concentrations and growth (Gove et al., 2022)

DROUGHT AND EXTREME RAINFALL

Globally, climate change is predicted to result in greater precipitation extremes and more frequent and longer droughts.[51] Efforts to model future trends in precipitation in the Hawaiian Islands remain uncertain with projections for the end of this century ranging from small increases to a 30% increase in rainfall in wet areas and from a small decrease to a decrease of up to 60% in dry areas.[52]

Hawaiʻi has experienced a statewide decline in average annual rainfall in recent decades. Rainfall trends from 1920 to 2012 show a decrease in annual rainfall for all Hawaiian Islands.[53] The worst drought of the past century occurred on Hawaiʻi Island from 2007 to 2014. Droughts have become hotter and longer, cover larger areas, and are increasingly exacerbated by human demands for water.[54]

The number of extreme rainfall events (days with precipitation of 3 inches or more) in Hawai'i has varied over time but with increasing drought, have become less frequent for Oʻahu.[55] Over the last 80 years, the number of extreme rainfall events at the Honolulu International Airport ranged from 0 to 6 events per year (**Figure 31**).[56] The average number of extreme rainfall events remains low, less than 1 event per year (**Table 6**).

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[51] Marra, J.J., and Kruk, M.C. (2017) State of Environmental Conditions in Hawaiʻi and the U.S. Affiliated Pacific Islands under a Changing Climate. Retrieved from: https://coralreefwatch.noaa.gov/satellite/publications/state_of_the_environment_2017_hawaii-usapi_noaa-nesdis-ncei_oct2017.pdf

[52] U.S. Global Change Research Program, 2018: Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA. doi:10.7930/NCA4.2018.

[53] Frazier, A. G., & Giambelluca, T. W. (2017). Spatial trend analysis of Hawaiian rainfall from 1920 to 2012. International journal of climatology, 37(5), 2522-2531. doi:10.1002/joc.4862

[54] Crausbay, S.; Ramirez, A.R.; Carter, S.L.; Cross, M.S.; Hall, K.R.; Bathke, D.J.; Betancourt, J.L.; Colt, S.; Cravens, A.E.; Dalton, M.S.; et al. (2017). Defining Ecological Drought for the Twenty-First Century. Bull. Am. Meteorol. Soc. 98, 2543–2550.

[55] Stevens, L.E., R. Frankson, K.E. Kunkel, P.-S. Chu, and W. Sweet, 2022: Hawai'i State Climate Summary 2022. NOAA Technical Report NESDIS 150-HI. NOAA/NESDIS, Silver Spring, MD, 5 pp.

[56] Climate Explorer. https://crt-climate-explorer.nemac.org/historical_thresholds/?area-id=hawaii_north&area-label=Northern+Hawaiian+Islands+%28Honolulu+County%2C+Kaua%CA%BBi+County%29&zoom=9.88&lat=21.29&lon=-157.9&mode=thresholds&threshold=2.0&window=1&threshold-variable=precipitation&station=USW00022521&station-name=HONOLULU+INTL+AP

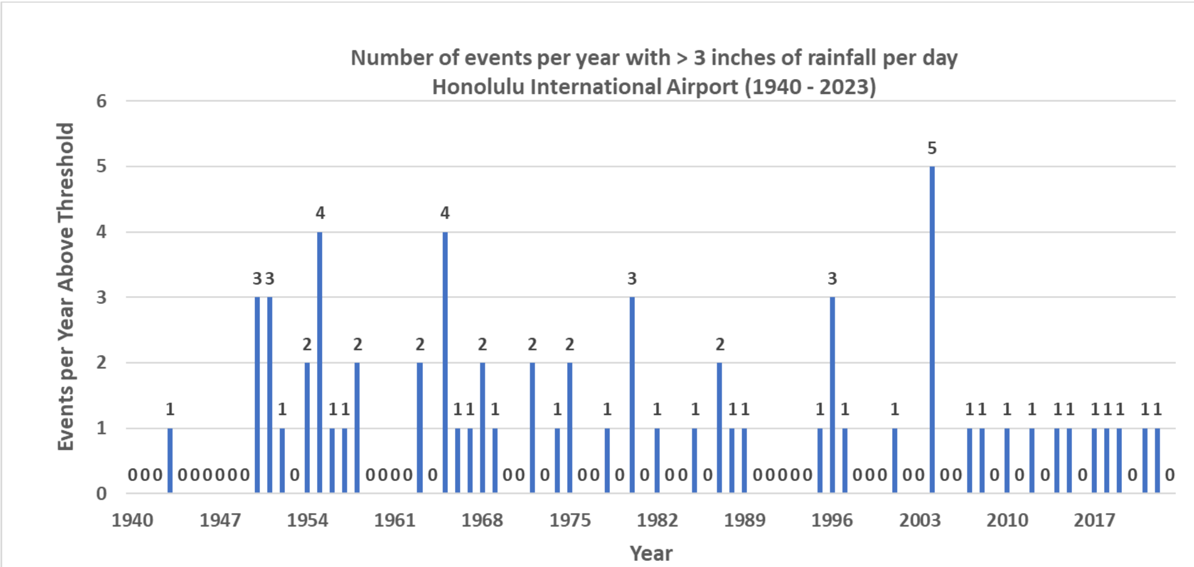

Figure 31. Number of rainfall events >3 inches per day (Honolulu International Airport, 1940 – 2023, Climate Explorer)

Table 6. Average number of rainfall events >3 inches per day (Honolulu International Airport, 2004 – 2023, Climate Explorer)

Rainfall Threshold	Average Number of Rainfall Events Exceeding 3 inches per Day (Honolulu International Airport)		
	20 years (2004 - 2023)	10 years (2014 - 2023)	5 years (2019 - 2023)
>3 inches rainfall	0.8	0.7	0.6

A Kona Low is an extreme rainfall event that originates from a deep kink in the jet stream (a band of strong winds high in the atmosphere that steer weather systems) that sinks south and pinches off, leaving behind a low-pressure circulation that is cut off from the main core of the jet. [57] These cut-off lows can linger for several days. The Kona Low gets its name from the change in wind direction that occurs when such a storm moves over the islands. Hawai'i is dominated by the trade winds that blow in from the northeast. However, the counter-clockwise flow around a Kona Low located west of Hawaii results in southwesterly winds over the islands, which is typically the leeward or “Kona” side. Kona storms are common between October and April. The storms draw abundant moisture up from the warm tropical waters that surround Hawai'i, which can then interact with the topography of the islands to produce heavy rains. The 2021 Kona Low rainfall event was one of 4 events in the last 80 years that exceeded 7 inches (7.4 inches) in a day (**Figure 32**).[58]

[57] NASA Earth Observatory (2023) Kona Low over Hawaiʻi, https://earthobservatory.nasa.gov/images/19423/kona-low-over-hawaii

[58] Climate Explorer. https://crt-climate-explorer.nemac.org/historical_thresholds/?area-id=hawaii_north&area-label=Northern+Hawaiian+Islands+%28Honolulu+County%2C+Kaua%CA%BBi+County%29&zoom=9.88&lat=21.29&lon=-157.9&mode=thresholds&threshold=2.0&window=1&threshold-variable=precipitation&station=USW00022521&station-name=HONOLULU+INTL+AP

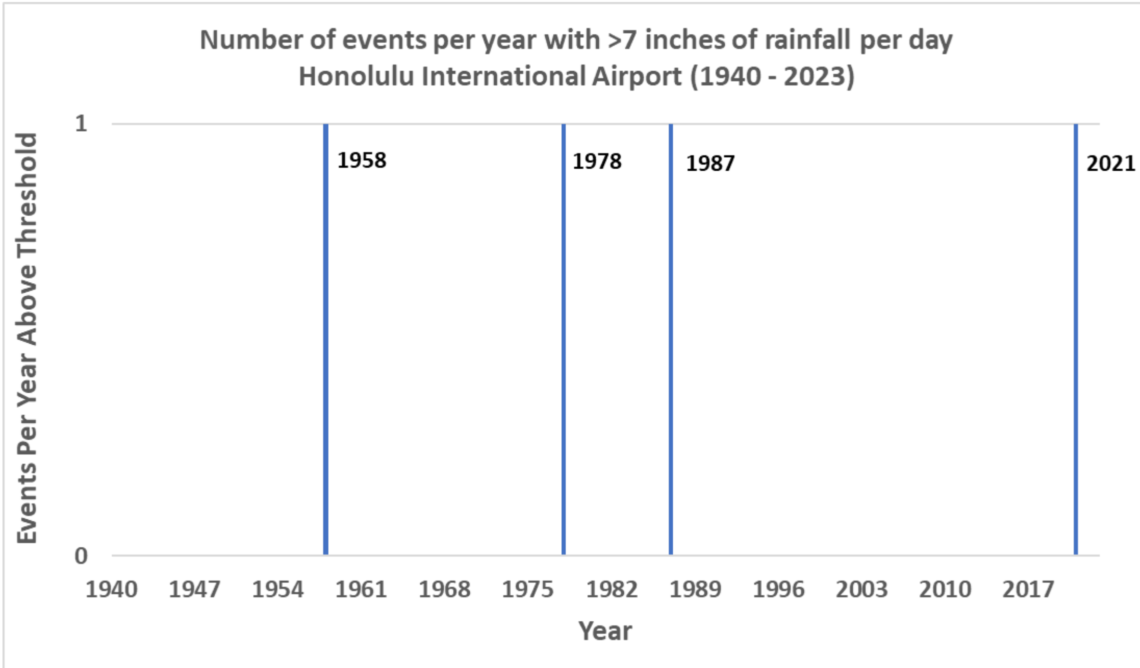

Figure 32. Number of rainfall events above 7 inches per day (Honolulu International Airport, 1940 – 2023, Climate Explorer)

Estimated historical and future rainfall estimates are provided for different return intervals in **Table 7**. [59] Based on the 24-hour rainfall, the 2021 Kona Low rainfall event was likely a 50-year return interval. As global temperature increases, hourly and 24-hour rainfall is estimated to increase. The greatest 24-hour rainfall, 17.4 inches, was recorded from March 5 – 6, 1958 at a gauge at the Federal Building in downtown Honolulu. [60]

Table 7. Estimated historical and future rainfall estimates at the Honolulu International Airport (Kunkel, 2020)

Return Interval	Year/Scenario	Source	1-hour (inches)	24-hour (inches)
10-year (10% annual chance event)	2011	NOAA Atlas 14	2.24 (2.02-2.50)	6.61 (5.76-7.53)
50-year (2% annual chance event)	2011	NOAA Atlas 14	2.97 (2.58-3.38)	9.62 (8.25-11.1)
100-year (1% annual chance event)	2011	NOAA Atlas 14	3.28 (2.79-3.76)	11.0 (8025-12.8)
10-year (10% annual chance event)	2055, RCP 8.5	SERDP	2.64 (2.22-3.08)	7.79 (6.44-9.20)
50-year (2% annual chance event)	2055, RCP 8.5	SERDP	3.50 (2.88-4.12)	11.32 (9.26-13.44)
100-year (1% annual chance event)	2055, RCP 8.5	SERDP	3.87 (3.14-4.58)	12.97 (10.54-15.45)

[59] Kunkel, K.E. (2020) Incorporation of the Effects of Future Anthropogenically Forced Climate Change in Intensity-Duration-Frequency Design Values. SERDP project number: RC-2517. North Carolina Institute for Climate Studies and North Carolina State University September 4, 2020. Version 2; https://precipitationfrequency.ncics.org/index.html

[60] Western Regional Climate Center. https://wrcc.dri.edu/Climate/narrative_hi.php#:~:text=At%20Honolulu%20the%20greatest%2024,Building%20in%20the%20downtown%20area.

Climate change is also expected to influence the timing and intensity of the El Niño–Southern Oscillation. Rainfall patterns in Hawaiʻi are influenced by natural climate variability from the El Niño-Southern Oscillation, the Pacific Decadal Oscillation, and the Pacific North American teleconnection pattern. [61] Recent climate models suggest that both El Niño and La Niña extremes will double in the 21st century compared to the previous century. This would have significant impacts not just on precipitation patterns in the Pacific region but also air and ocean temperatures, water levels, trade winds, and storms. [62] Extreme rainfall events increase in La Niña years and decrease in El Niño years. [63] Regardless of the uncertainty surrounding projections for future rainfall patterns in Hawaiʻi, rising sea levels and groundwater inundation will reduce drainage capacity and increase the risk of flooding when heavy rainfall events do occur.

[61] Frazier, A. G., Elison Timm, O., Giambelluca, T. W., & Diaz, H. F. (2017). The influence of ENSO, PDO [Pacific Decadal Oscillation] and PNA [Pacific North American teleconnection pattern] on secular rainfall variations in Hawaiʻi. Climate dynamics, 51(5-6), 2127-2140. doi:10.1007/s00382-017-4003-4

[62] Perlwitz, J., T. Knutson, J. P. Kossin, and A. N. LeGrande. (2017) Large-Scale Circulation and Climate Variability. Climate Science Special Report: Fourth National Climate Assessment, Volume I. Wuebbles, D. J., D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, Eds., U.S. Global Change Research Program, Washington, DC, USA, 161–184. doi:10.7930/J0RV0KVQ

[63] Chen, Y. R., & Chu, P. S. (2014). doi:10.1002/joc.3950

SEA LEVEL RISE

Sea level is rising globally, and the rate of sea level rise is accelerating due to unabated, human-induced emissions of greenhouse gases. [64] Sea level rise is resulting from global warming which drives the melting of global ice caps and glaciers and thermal ocean expansion. Sea level will continue to rise even if global warming is halted, as greenhouse gas emissions have a lag effect on temperature. [65] Sea level rise exacerbates all types of flooding including high-tide flooding, chronic coastal flooding, groundwater inundation, and storm surge.

A key message of the National Climate Assessment Report 5 states the following: *Rising sea levels threaten infrastructure and local economies and exacerbate existing inequities. Climate change, particularly sea level rise, will continue to negatively impact the built environment (very likely, high confidence) and will harm numerous sectors of the islands' economies (very likely, high confidence). Sea level rise intensifies loss of territory and exclusive economic zones, particularly in low islands (high confidence). Climate-driven changes will exacerbate existing social challenges by disrupting livelihoods (likely, medium confidence). Adaptation to climate change and recovery from disasters is logistically challenging and disproportionately more expensive in the islands (high confidence). Government and community groups have developed innovative ways to reduce emissions and improve resilience by moving toward renewable energy and green infrastructure, nature-based urban planning, forward-looking building codes, and sustainable and equitable economic growth, guided by Western science and Traditional Knowledge.*[66]

The U.S. Interagency Sea Level Rise Scenario Tool provides a range of sea level rise scenarios based on the most up-to-date scientific literature on sea level rise for Honolulu (**Figure 33**). [67] Based on these projections, the City and County of Honolulu Climate Change Commission's updated sea level rise guidance recommends the following: [68]

- The Low and Intermediate-Low scenarios are inappropriate to use for planning because present-day sea level rise acceleration is already on-track 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, 5.8 ft 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.

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[64] Dangendorf, S., Hay, C., Calafat, F.M. et al. Persistent acceleration in global sea-level rise since the 1960s. Nat. Clim. Chang. 9, 705–710 (2019). https://doi.org/10.1038/s41558-019-0531-8

[65] IPCC (2023) Synthesis Report of the IPCC Sixth Assessment (AR6), Summary for Policy Makers (2023) https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_SPM.pdf

[66] Frazier, A.G., M.-V.V. Johnson, L. Berio Fortini, C.P. Giardina, Z.N. Grecni, H.H. Kane, V.W. Keener, R. King, R.A. MacKenzie, M. Nobrega-Olivera, K.L.L. Oleson, C.K. Shuler, A.K. Singeo, C.D. Storlazzi, R.J. Wallsgrove, and P.A. Woodworth-Jefcoats, 2023: Ch. 30. Hawaiʻi and US-Affiliated Pacific Islands. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH30

U.S.

[67] Interagency Sea Level Rise Scenario Tool, https://sealevel.nasa.gov/data_tools/18

[68] City and County of Honolulu Climate Change Commission, 2022. Sea Level Rise II: Guidance Document, https://static1.squarespace.com/static/5e3885654a153a6ef84e6c9c/t/62f46b3fff589f651af14410/1660185409937/HonoluluClimateChangeCommission-SeaLevelRiseGuidance_Updated-July2022.pdf

- In implementing Intermediate and Intermediate-High sea level rise scenarios, all projects should apply design elevations relative to mean higher high water (MHHW) as a datum. Projects with low tolerance for flood risk should add additional design elevation to account for compound events (e.g., an additional 1 ft for extreme or "king" tides, 1 ft for runoff accumulation in light of drainage failure at high tides).

The approximate decade and sea level rise projection for intermediate and intermediate high scenarios is shown in **Table 8**. The intermediate high scenario is adopted for AW2050 recommendations.

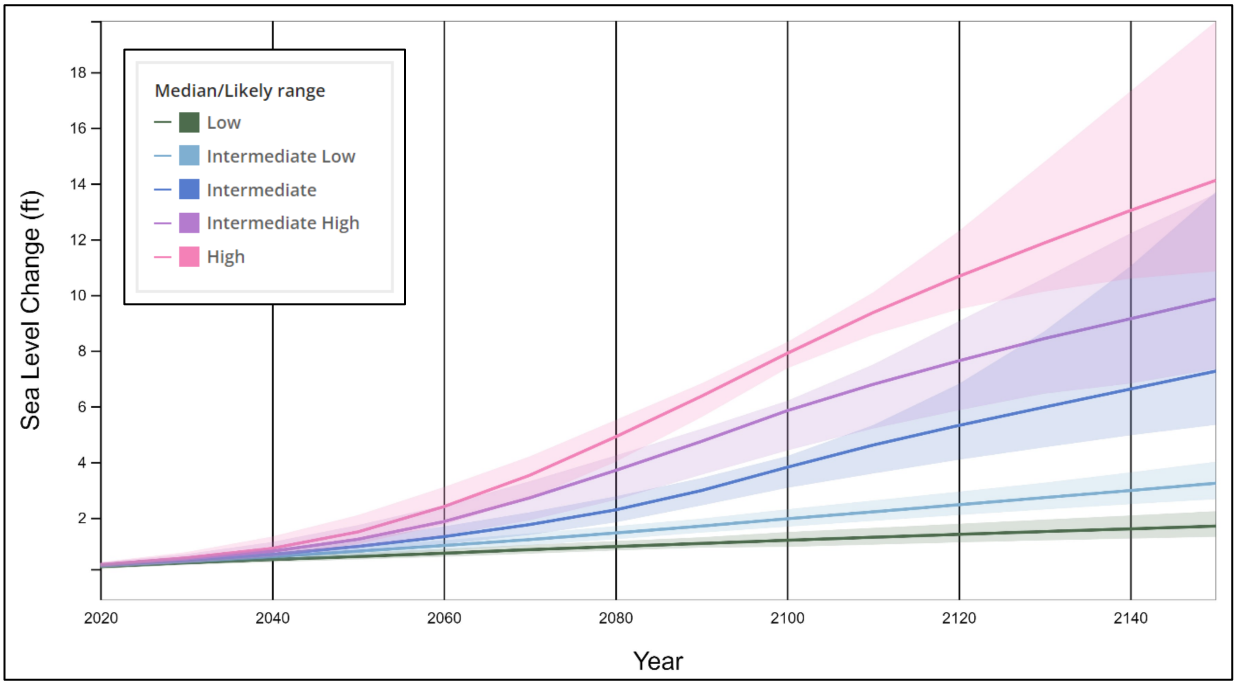

Figure 33. Sea level rise projections by scenario for Honolulu, Hawai'i relative to a baseline year of 2000 (Interagency Sea Level Rise Scenario Tool, 2022)

Table 8. Approximate decade by sea level rise projection for intermediate and intermediate high sea level rise scenarios for Honolulu, Hawai'i (Interagency Sea Level Rise Scenario Tool, 2022)

Sea Level Rise Scenario	Approximate Decade by Sea Level Rise Projection					
	~1 ft SLR	~2 ft SLR	~3 ft SLR	~4 ft SLR	~5 ft SLR	~6 ft SLR
Intermediate	~2050	~2080	~2090	~2100	~2120	~2130
Intermediate-High	~2040	~2060	~2070	~2080	~2090	~2100

EXTREME HEAT EVENTS

Honolulu is already experiencing a significant increase in the number of days with temperatures above 90° F. Models predict a possible increase in average temperatures of 2.7 to 4.5°F by 2050, causing more frequent heat waves and contributing to more severe drought and wildfire conditions. The number of hot days per year in Hawaiʻi has increased dramatically over the last decade (**Figure 34**). [69] The number of hot days increased dramatically during the 2015–2020 period, with a multiyear average more than double the long-term average. The City's Climate Commission is working on new guidance on extreme heat events.

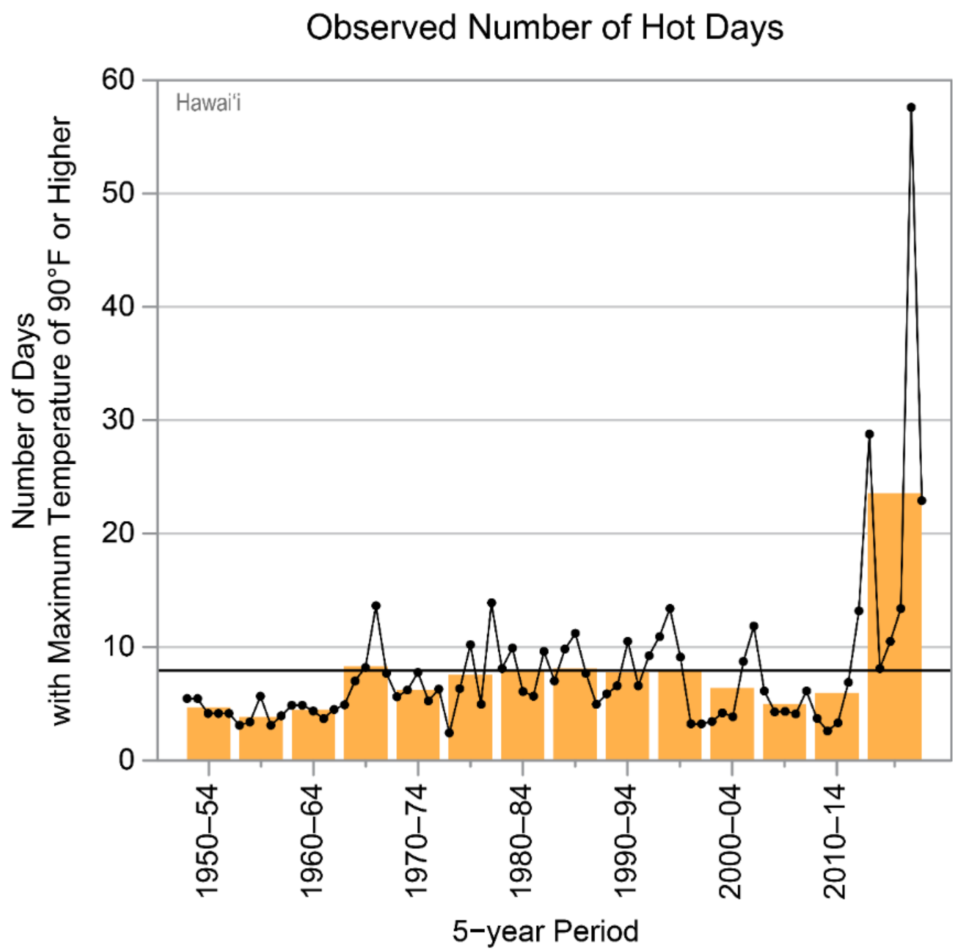

Figure 34. Observed number of hot days (dots show annual average, bars show 5-year average) in Hawaiʻi (Stevens, et al., 2022)

[69] Stevens, L.E., R. Frankson, K.E. Kunkel, P.-S. Chu, and W. Sweet (2022). Hawaiʻi State Climate Summary 2022. NOAA Technical Report NESDIS 150-HI. NOAA/NESDIS, Silver Spring, MD, 5 pp. https://statesummaries.ncics.org/chapter/hi/

Climate change is increasing the frequency, intensity, and duration of heat extremes, putting individuals and communities at risk.[70] Warmer temperatures negatively impact air quality and exacerbate asthma, allergies, and respiratory illnesses. [71] More frequent extreme heat events may also result in a rise of heat related deaths and illnesses including heatstroke, cardiovascular, and kidney disease especially among children and the elderly.[72]

The WSD is vulnerable and contributes to heat extremes because urbanized areas absorb and retain greater amounts of heat compared to rural areas.[73] This "urban heat island effect" occurring in densely developed areas is the result of, among other factors, lower vegetation coverage and a prevalence of dark-colored surfaces such as parking lots, roadways, and roofs absorbing sunlight and reemitting the energy as heat. A heat index was developed based on data collected by community volunteers and the City on August 31, 2019 (**Figure 35**).[74] On this day, the high temperature tied the hottest-ever recorded for Honolulu.

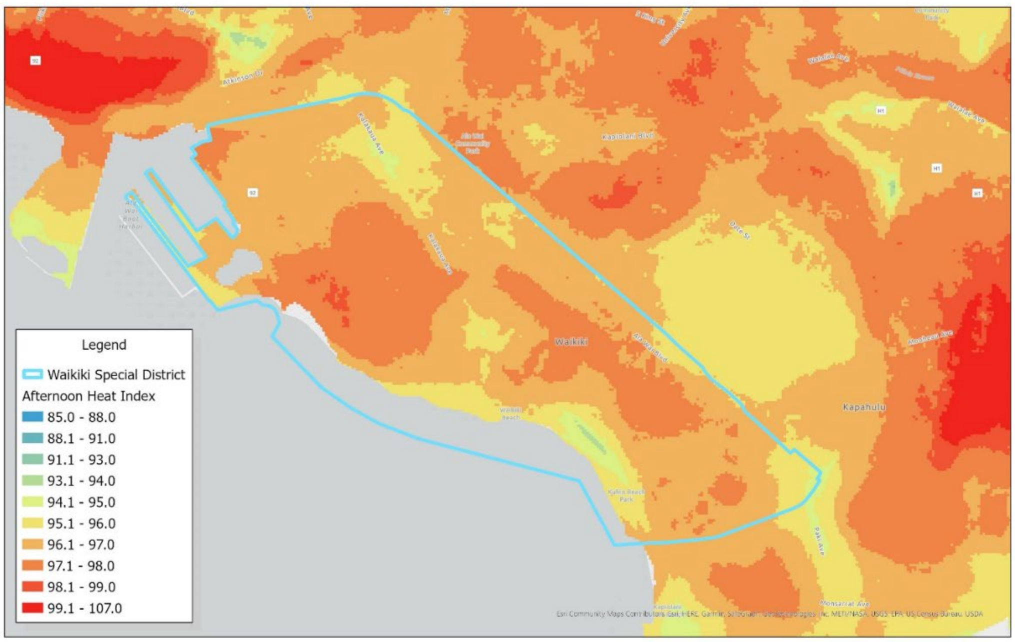

Figure 35. Afternoon heat index for the Waikīkī Special District on August 31, 2019 (City & County of Honolulu, Climate Ready O'ahu)

[70] Frazier, A.G., M.-V.V. Johnson, L. Berio Fortini, C.P. Giardina, Z.N. Grecni, H.H. Kane, V.W. Keener, R. King, R.A. MacKenzie, M. Nobrega-Olivera, K.L.L. Oleson, C.K. Shuler, A.K. Singeo, C.D. Storlazzi, R.J. Wallsgrove, and P.A. Woodworth-Jefcoats, 2023: Ch. 30. Hawai'i and US-Affiliated Pacific Islands. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH30

[71] U.S. Global Change Research Program (2016). The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment, Chapter 3: Air Quality Impacts. Retrieved from: https://health2016.globalchange.gov/air-quality-impacts

[72] Hawaii Department of Health, https://health.hawaii.gov/heer/climate-change-health-each-impact/

[73] U.S. Environmental Protection Agency (2008). Reducing Urban Heat Islands: Compendium of Strategies. Retrieved from: https://www.epa.gov/heat-islands/heat-island-compendium

[74] City and County of Honolulu, Climate Ready O'ahu, Community Heat Map. Retrieved from: https://www.honolulugis.org/apps/climate-ready-oahu-web-explorer-/explore

EPISODIC FLOODING

The WSD is exposed to multiple types of episodic flooding which are exacerbated by climate change and sea level rise.

High Tide Flooding

As sea level rises, it no longer takes a strong storm or a hurricane to cause coastal flooding. [75] High tide flooding occurs when sea level rise combines with local factors to push water levels above the normal high tide mark. Shifts in ocean currents and prevailing winds and strong tidal forces (which occur during full or new moon) can all cause high tide-driven flooding, inundating streets even on sunny days.

High tide flooding events are expected to become more frequent (**Figure 36**). [76] An inflection point in the number of days of high tide flooding will occur around 2037 when high tide-driven flooding will accelerate from 2 days per year to 63 day per year before the year 2050. This projection assumes sea level rise projections under the intermediate scenario. This increase will likely occur sooner under the intermediate high sea level rise scenario.

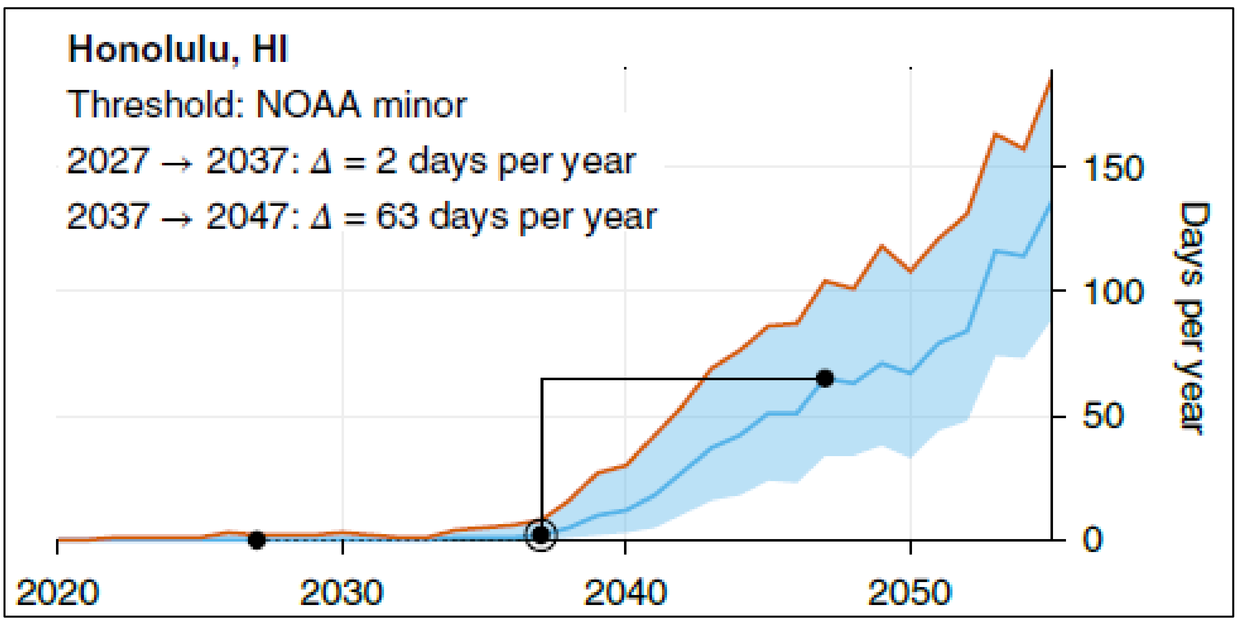

Figure 36. Projections of annual counts of high tide flood days in Honolulu (Thompson et al., 2021)

[75] NOAA. What is high tide flooding? https://oceanservice.noaa.gov/facts/high-tide-flooding.html#:~:text=High%20tide%20flooding%20occurs%20when,streets%20even%20on%20sunny%20days.

[76] Thompson, P.R., Widlansky, M.J., Hamlington, B.D., Merrifield, M.A., Marra, J.J, Mitchum, G.T. & Sweet, W. (2021) Rapid increases and extreme months in projections of United States high-tide flooding. Nat. Clim. Chang. 11, 584–590 https://doi.org/10.1038/s41558-021-01077-8

Annual High Wave-Driven Flooding

Hawaiʻi is exposed to large waves annually on all open coasts due to our location in the Central North Pacific Ocean. The distance over which waves run-up and wash across the shoreline will increase with sea level rise. As water levels increase, less wave energy will be dissipated through breaking on nearshore reefs and waves will arrive at a higher elevation at the shoreline. [77]

Wave-driven flooding was modeled by the UH SOEST Climate Resilience Collaborative with a two-dimensional high-resolution digital surface model using the phase-resolving model BOSZ (Boussinesq Ocean and Surf Zone). [78] The simulations are done for annually-recurring wave heights from multiple dominant wave directions. The statistics of wave inputs are determined from 40-year-long SWAN (Simulating Waves Nearshore) wave hindcasts for the years 1980-2020. Annual high wave-driven flooding in the WSD with sea level rise is shown in **Figure 37**.[79]

[77] UH SOEST Climate Resilience Collaborative. https://www.soest.hawaii.edu/crc/slr-viewer/documentation/#annual-high-wave-flooding-info

[78] Volker Roeber, Kwok Fai Cheung (2012). Boussinesq-type model for energetic breaking waves in fringing reef environments, Coastal Engineering,70: 1 – 20. ISSN 0378-3839, https://doi.org/10.1016/j.coastaleng.2012.06.001.

[79] UH SOEST Climate Resilience Collaborative (CRC) https://www.soest.hawaii.edu/crc/index.php/about/#about-us

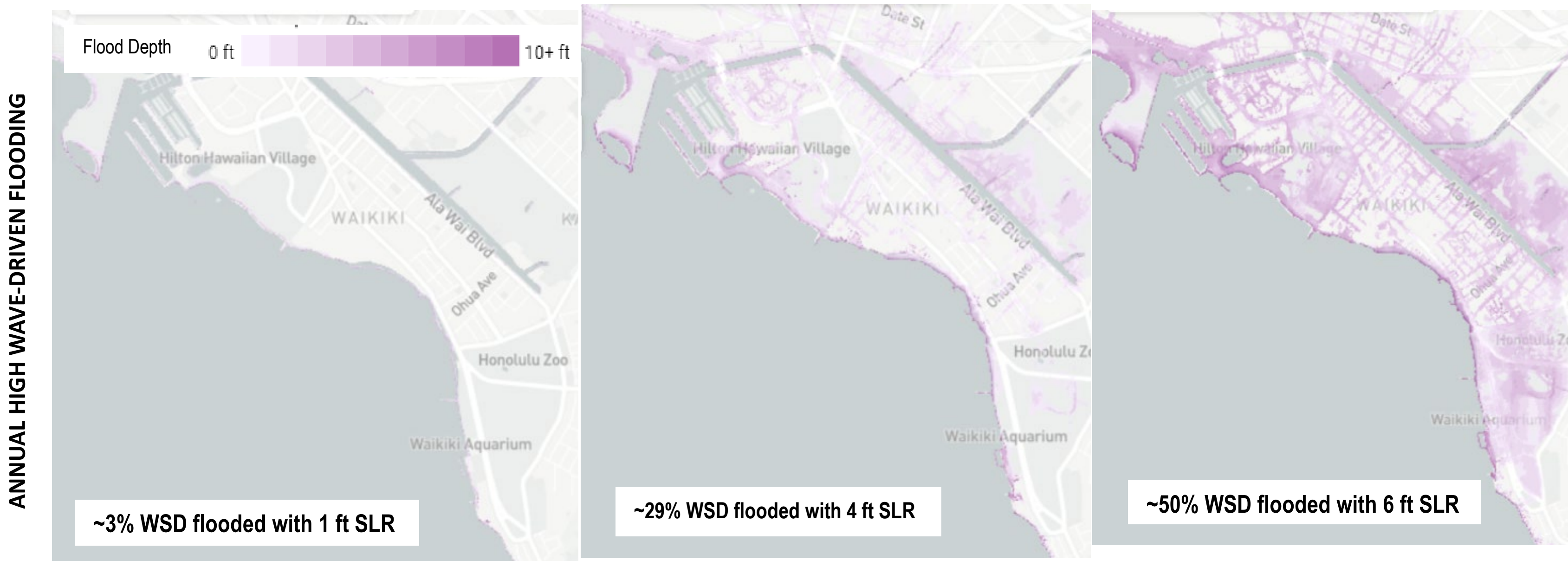

Figure 37. Modeled annual high wave-driven flooding extent and flood depth with sea level rise in the Waikīkī Special District (relative to 2020 sea level rise baseline, UH SOEST Climate Viewer 2024)

Special Flood Hazard Areas and Flash Flooding

Extreme rainfall events in the Hawaiian Islands have become more frequent.[80] Flood hazard areas, identified on the Flood Insurance Rate Map, are identified as a Special Flood Hazard Area (SFHA). SFHAs identify areas at risk from infrequent but severe storm-induced wave events and riverine flood events that are based upon historical records. The SFHA is also referred to as the 1-percent annual chance flood, base flood, or 100-year flood. The WSD includes the coastal flood zone (VE with waves greater than 3 feet in height) and riverine flood zones (AE, and AO Zones) (**Figure 38**). Except for X and XS zones which indicate areas of moderate to minimum flood risk, the WSD is largely dominated by high-risk zones.

As SFHAs are based on historical records, the State of Hawaiʻi used the modeled 1% annual-chance-coastal flood zone with sea level rise (1%CFZ) to estimate coastal flood extents and wave heights for wave-generating events with sea level rise.[81] This modeling estimates the change in flood risk from a 1%-annual chance coastal flood event with sea level rise and the height of structure damaging waves (**Figure 39**).

A flash flood is caused by heavy or excessive rainfall in a short period of time, generally less than 6 hours. Flash floods are usually characterized by raging torrents after heavy rains that rip through riverbeds and urban areas. Flash floods can occur within minutes or a few hours of excessive rainfall. Equally important is that flash floods can also occur outside SFHA.

[80] Chen, Y. R., & Chu, P. S. (2014). Trends in precipitation extremes and return levels in the Hawaiian Islands under a changing climate. International Journal of Climatology, 34(15), 3913-3925. doi:10.1002/joc.3950

[81] Tetra Tech Inc. (2018). State of Hawaiʻi 2018 Hazard Mitigation Plan

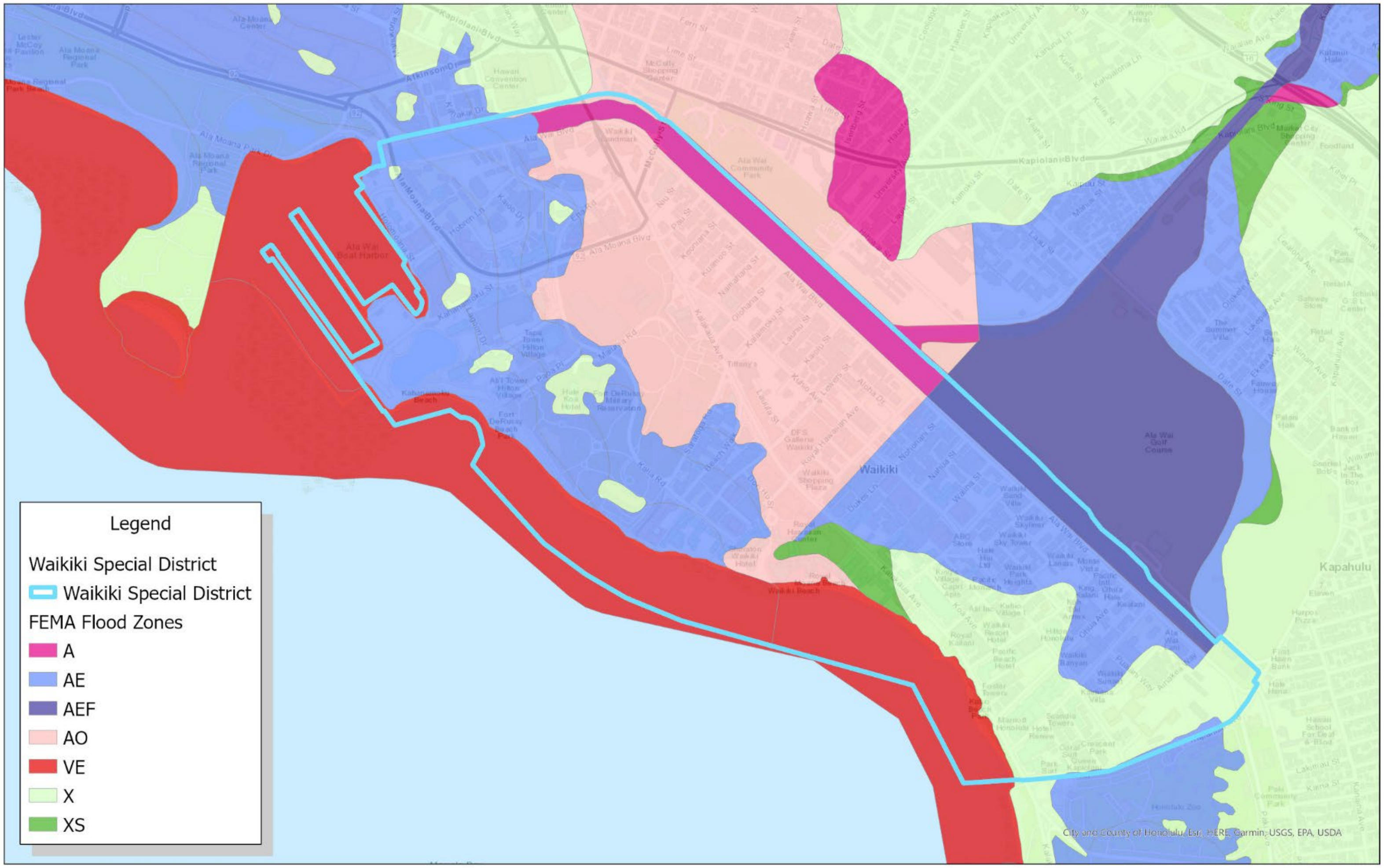

Figure 38. Special Flood Hazard Areas in the Waikīkī Special District

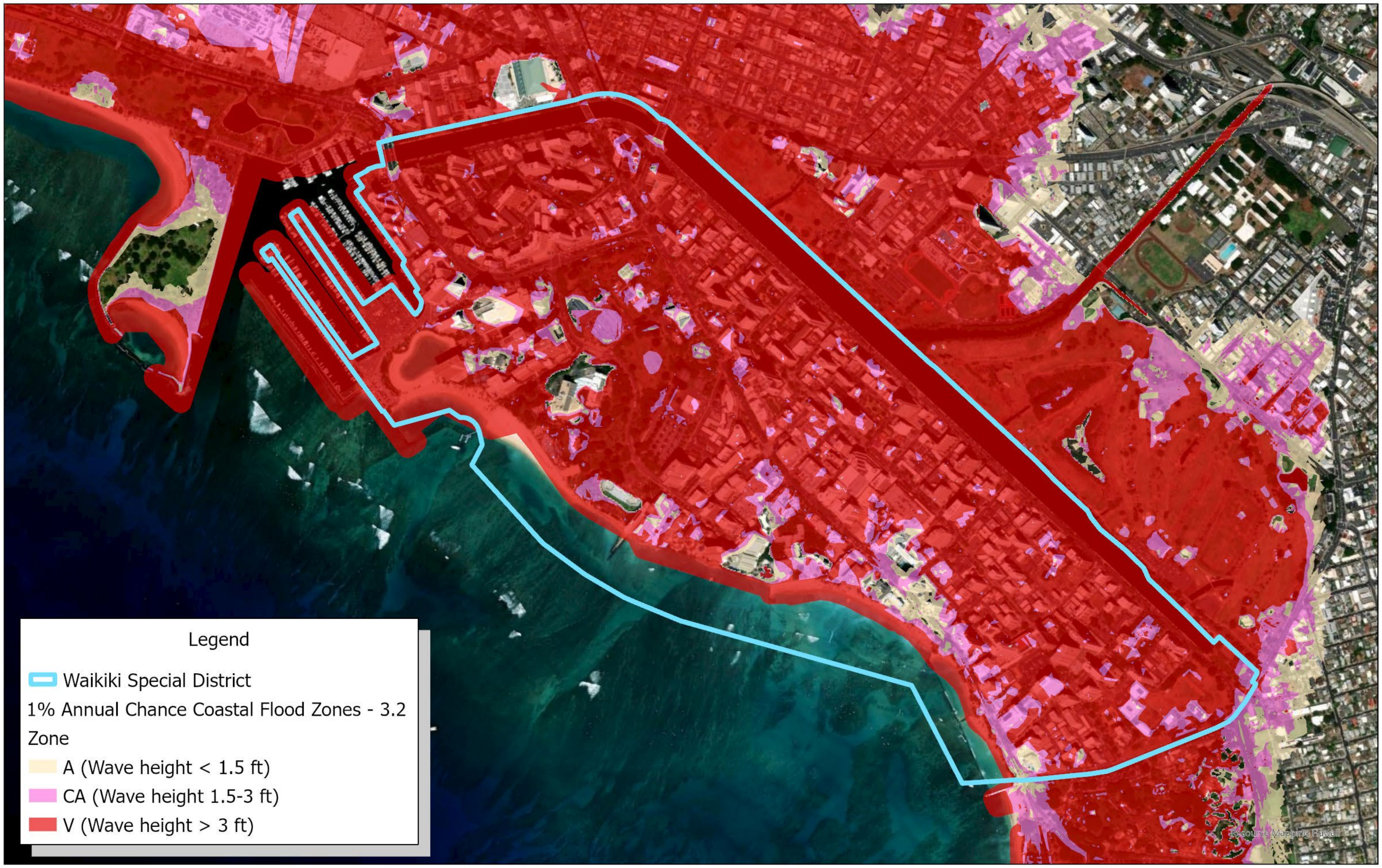

Figure 39. Modeled 1%-annual chance coastal flood event with 3.2 feet of sea level rise (Tetra Tech, Inc. 2018)

CHRONIC FLOODING

Chronic flooding with sea level rise in the WSD is characterized by modeling of groundwater inundation, direct marine or passive flooding, and flooding from drainage backflow (**Figure 40**). These chronic flood hazards need to be considered together to address infrastructure failure with rising sea level and compound flood events. [82]

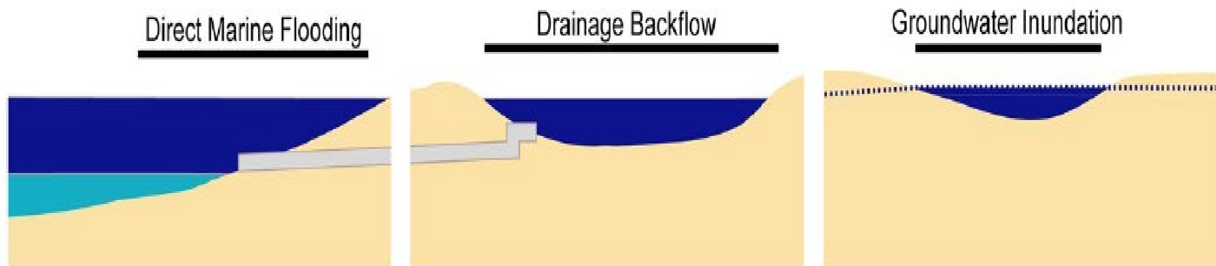

Figure 40. Types of chronic flooding (Habel et al., 2020)

Groundwater Inundation and Critically Shallow Groundwater

Groundwater inundation describes flooding that occurs as groundwater is lifted above the elevation of the ground surface. [83] Shallow water tables present in coastal areas contribute to an increased risk of groundwater inundation and saltwater intrusion. In coastal areas with porous subsurface geology, groundwater inundation increases episodically with high tides and riverine flooding and chronically with sea level rise. Groundwater inundation will occur regardless of shoreline hardening. [84]

Groundwater inundation will be a key driver of flooding in WSD. Approximately 30 percent of the WSD and 70% of the WSD will be inundated by groundwater with 4 feet and 6 feet of sea level rise, respectively (**Figure 41**). [85]

Before groundwater rises above the land surface and causes flooding, the depth of groundwater below the surface is already having substantial impacts on subsurface infrastructure and the road base. Critically shallow groundwater, <5 ft below the ground surface is damaging to roadbeds and utilities. [86] Today, the extent of critically shallow groundwater covers approximately 58% of WSD (**Figure 42**).

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[82] Habel, S., Fletcher, C.H., Anderson, T.R. & Thompson, P.R. (2020). Sea-Level Rise Induced Multi-Mechanism Flooding and Contribution to Urban Infrastructure Failure. Sci Rep 10, 3796. https://doi.org/10.1038/s41598-020-60762-4

[83] UH SOEST Climate Resilience Collaborative. https://www.soest.hawaii.edu/crc/slr-viewer/documentation/#groundwater-info

[84] Habel, S., 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. http://dx.doi.org/10.1016/j.watres.2017.02.035.

[85] UH SOEST Climate Resilience Collaborative. https://www.soest.hawaii.edu/crc/slr-viewer/

[86] Habel, S. Fletcher, C.H., Barbee, M.M., Fornace, K.L. (2024). Hidden Threat: The Influence of Sea-Level Rise on Coastal Groundwater and the Convergence of Impacts on Municipal Infrastructure. Annu. Rev. Mar. Sci. 16:9.1–9.23 https://doi.org/10.1146/annurev-marine-020923-120737

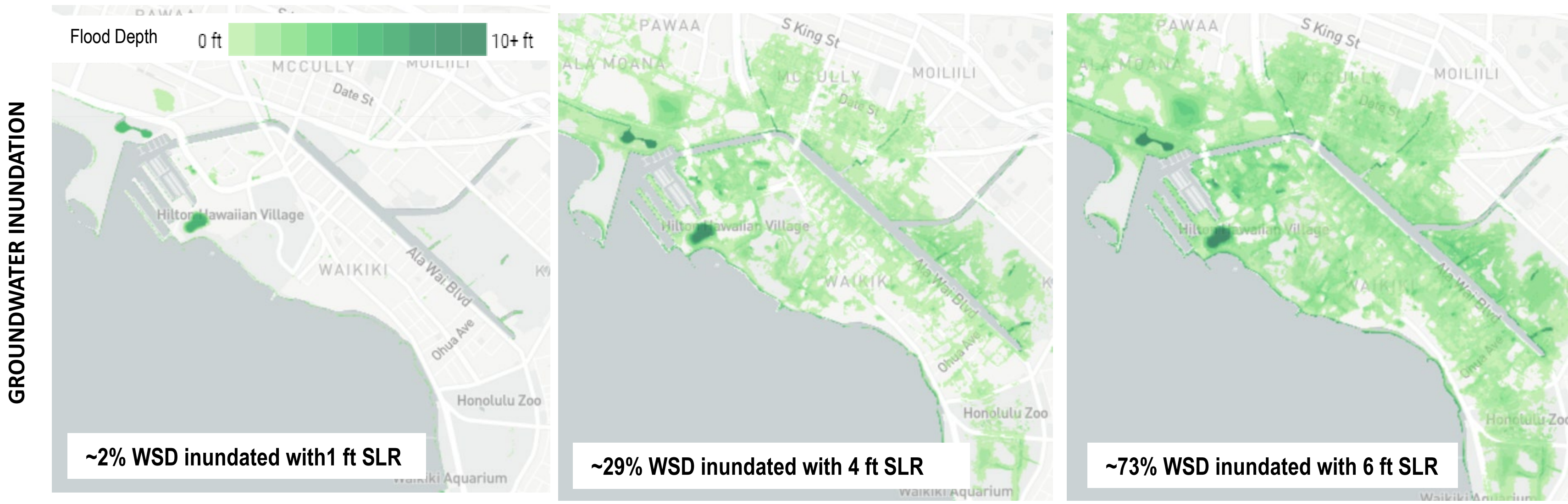

Figure 41. Modeled groundwater inundation extent and flood depth with sea level rise in the Waikīkī Special District (relative to 2020 sea level rise baseline, UH SOEST Climate Viewer 2024)

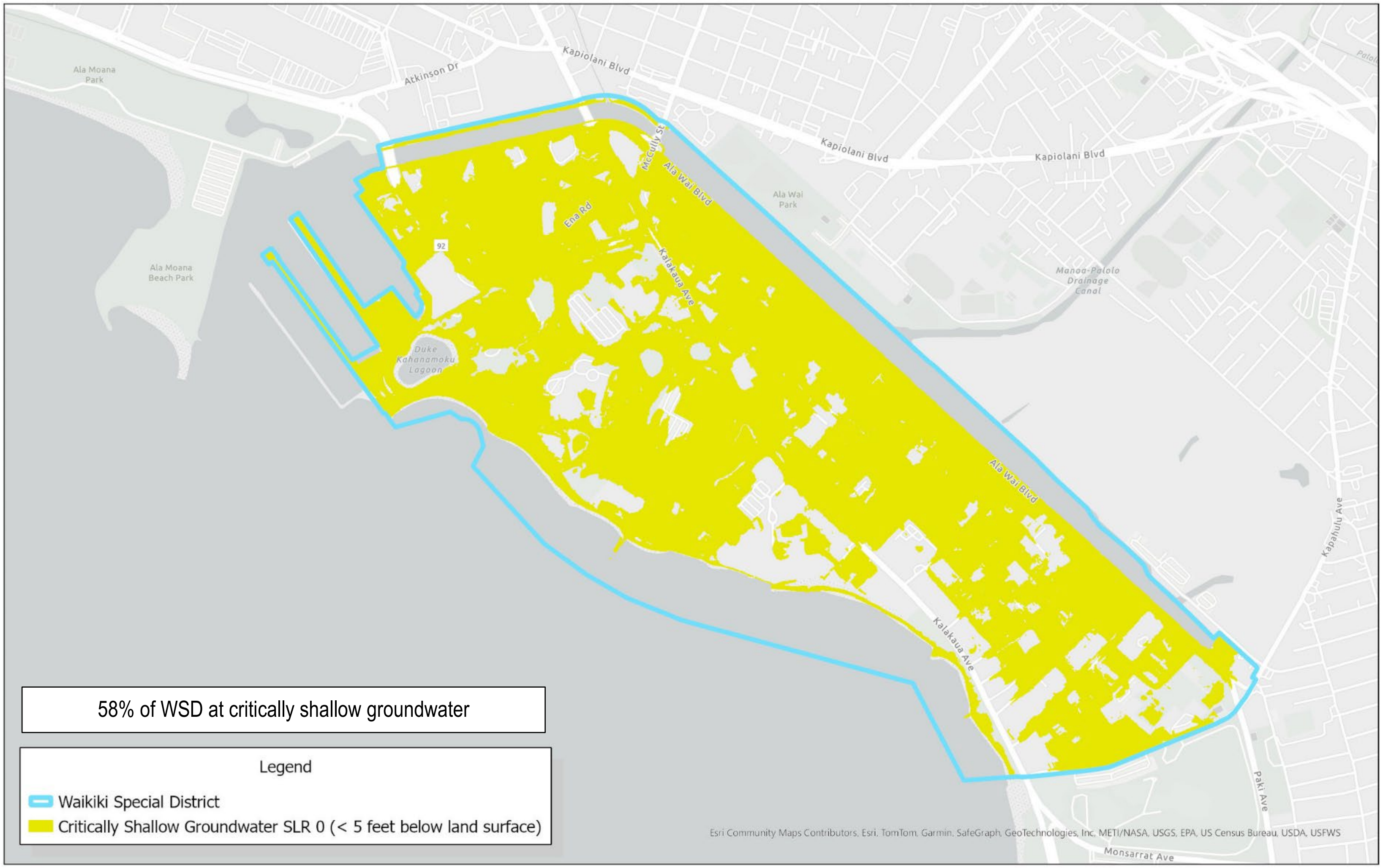

Figure 42. Modeled critically shallow groundwater in the Waikīkī Special District (<5 feet below land surface relative to 2020 sea level rise baseline, UH SOEST Coastal Resilience Collaborative, 2024)

Passive Flooding and Storm Drain Backflow

Passive flooding or direct marine inundation describes flooding that occurs by direct surficial connection to marine waters [87] Passive flooding characterizes low-lying areas susceptible to flooding by sea level rise. Passive flooding includes areas that are hydrologically connected to the ocean (marine flooding) and low-lying areas that are not hydrologically connected to the ocean (groundwater) and does not include waves. Storm drain backflow originates from a marine source and emerges from gravity-flow drainage networks as sea level rises. Passive flooding and storm drain backflow was modeled by the Climate Resilience Collaborative at the University of Hawaiʻi School of Ocean and Earth Science and Technology. [88] Passive flooding and storm drain backflow with sea level rise is shown in **Figure 43**.

[87] Habel, S., Fletcher, C.H., Anderson, T.R. & Thompson, P.R. (2020). Sea-Level Rise Induced Multi-Mechanism Flooding and Contribution to Urban Infrastructure Failure. Sci Rep 10, 3796. https://doi.org/10.1038/s41598-020-60762-4

[88] UH SOEST Climate Resilience Collaborative. https://www.soest.hawaii.edu/crc/slr-viewer/documentation/#passive-flooding-info

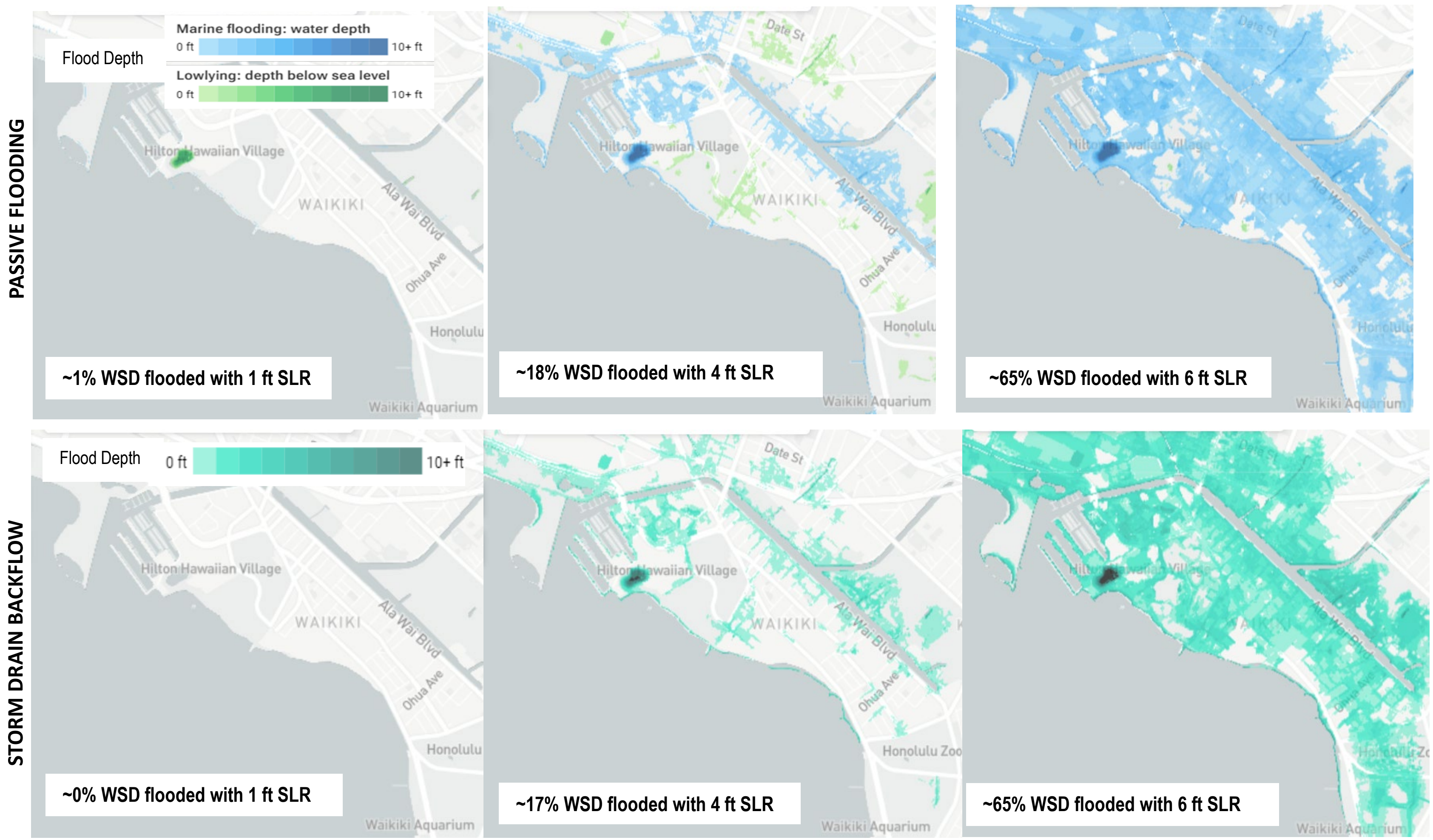

Figure 43. Comparison of modeled passive flooding (upper) drainage backflow (lower) extent and flood depth with sea level rise in the Waikīkī Special District (relative to 2020 sea level rise baseline, UH SOEST Climate Viewer 2023

TROPICAL CYCLONES AND STORM SURGE

Tropical cyclones are still considered rare events in Hawaiʻi but could become more powerful and possibly more frequent due to climate change as storm tracks shift northward. Powerful tropical cyclones result in high winds, greater area impacted by flooding, stronger storm surge. Sea level rise increases storm surge-related flooding along the coast. Because a significant portion of Hawaii's population, economic assets, and critical infrastructure are concentrated within Honolulu's primary urban core, a tropical cyclone hitting the area would have major statewide impacts.

Climate models project an increase in tropical cyclones near Hawaiʻi as the zone of tropical cyclone formation shifts poleward away from equatorial areas. [89] More frequent tropical cyclones are projected for the waters near Hawaiʻi as storms are projected to follow new tracks that bring them into the region of Hawaiʻi more often.[90] Major tropical cyclones have become 15 percent more likely over the past 40 years. [91] A warming ocean results in less cold subsurface water to dampen tropical cyclone activity. Increasing sea surface temperature in areas of tropical cyclone formation relevant to Hawaiʻi suggests a connection to increased tropical cyclone intensity.[92] 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. [93]

Sea level rise increases storm surge-related flooding from tropical cyclones along the coast (**Figure 44**). [94] While the spatial extent of flooding is similar between the two scenarios, the depth of flooding increases creating more hazard exposure for critical infrastructure.

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[89] Sharmila, S., and Walsh, K.J.E. (2018) Recent poleward shift of tropical cyclone formation linked to Hadley cell expansion. Nature Clim Change 8, 730–736. https://doi.org/10.1038/s41558-018-0227-5

[90] Murakami, H., Wang, B., Li, T. et al. (2013) Projected increase in tropical cyclones near Hawaii. Nature Clim Change 3, 749–754. https://doi.org/10.1038/nclimate1890

[91] Kossin, J.P., et al. (2020) Global increase in major tropical cyclone exceedance probability over the past four decades. PNAS, DOI: 10.1073/pnas.1920849117

[92] Defforge, C.L., Merlis, T.M. (2017) Observed warming trend in sea surface temperature at tropical cyclone genesis, Geophys. Res. Lett., 44, 1034–1040, doi:10.1002/2016GL071045.

[93] 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

[94] PacIOOS (2023). pacioos.hawaii.edu/shoreline/slr-honolulu/

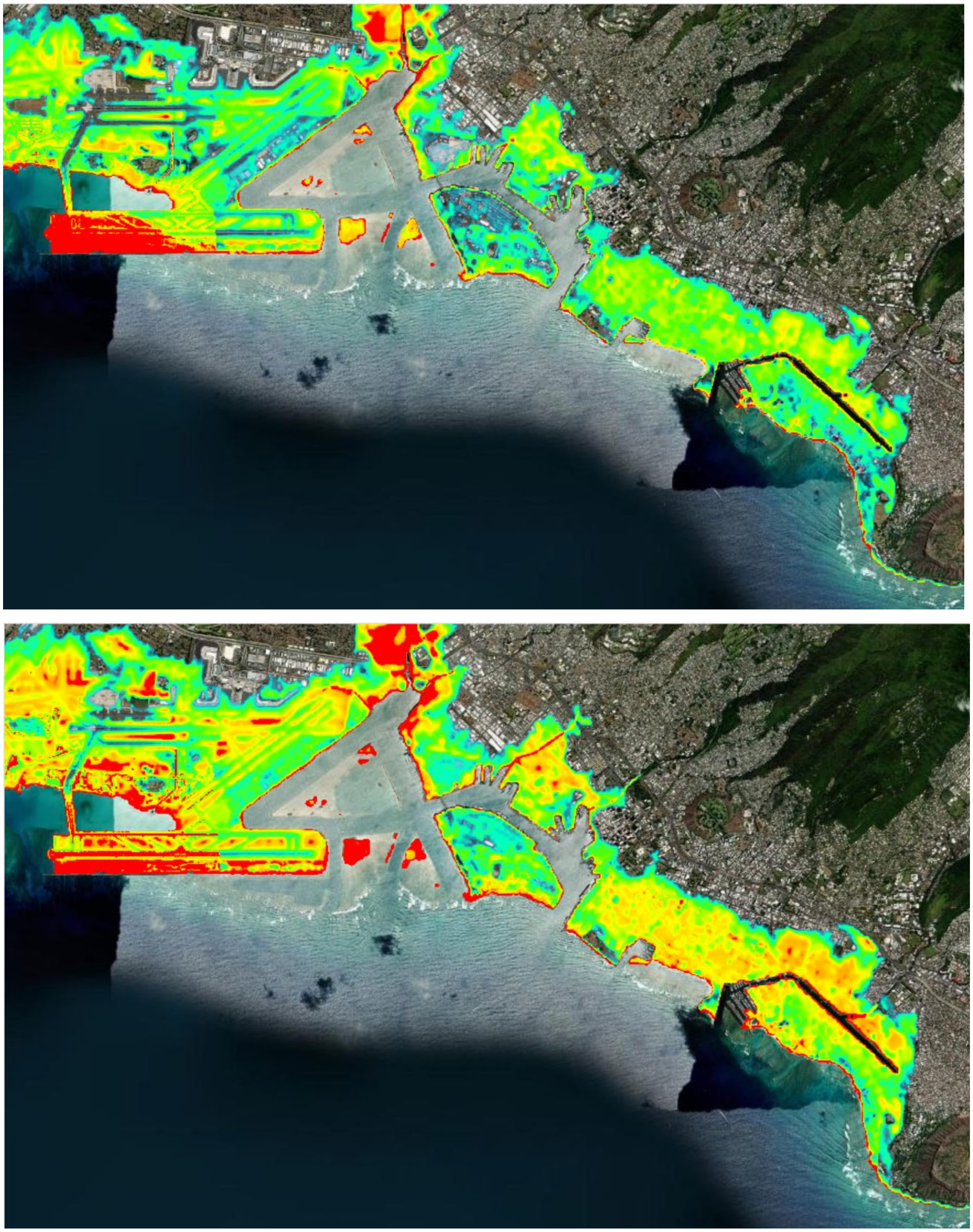

Figure 44. Modeled hurricane storm surge inundation based on a Category 4 hurricane striking the urban Honolulu with 1.6 feet (top) and 3.3 feet of sea level rise (PacIOOS, 2023)

COMPOUND FLOODING

The WSD is at risk to compound flooding. Compound flooding refers to flooding that occurs when multiple flood drivers occur simultaneously or within close succession, resulting in more significant impacts. [95] In Hawai'i, these events are often a result of heavy rainfall coinciding with high tide. [96] Compound flooding will occur in stages as sea level rises (**Figure 45**). The study of compound flooding is a growing area of research aimed at improving projections of flooding from complex interactions between multiple episodic and chronic flood hazards including tides, rainfall, riverine flooding, groundwater flooding, tropical cyclones and storm surge with sea level rise. [97]

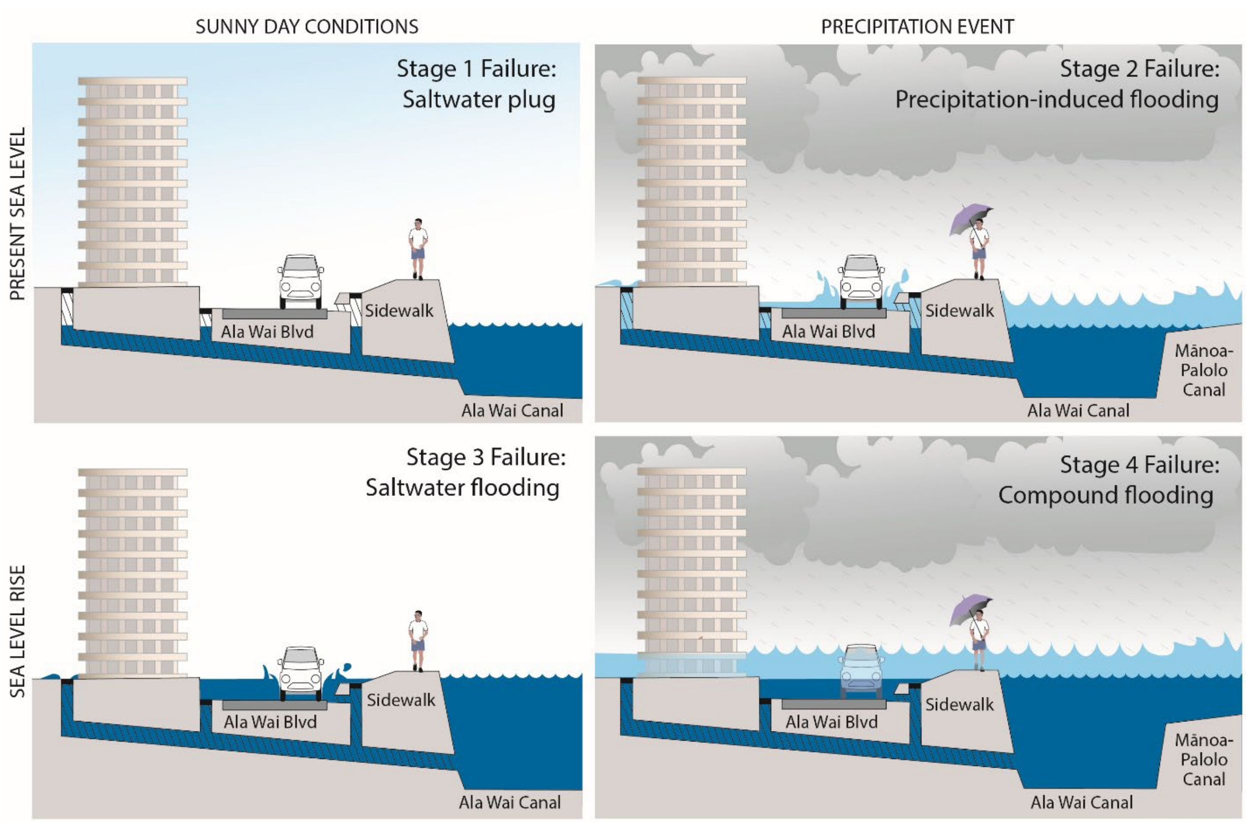

Figure 45. Stages of compound flooding with sea level rise (UH SOEST Climate Resilience Collaborative)

The Kona Low, that drenched the State from December 4 – 6, 2021 is one example of compound flooding. 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 in higher than the predicted astronomical tide. [98] The rainfall total for the 3-day period (72 hours) at the Honolulu Airport was 9.28 inches. Thunderstorms with heavy rainfall moved over Oʻahu from the south caused flooding in

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[95] Ghanbari, M., Arabi, M., Kao, S.-C., Obeysekera, J., & Sweet, W. (2021). Climate change and changes in compound coastal-riverine flooding hazard along the U.S. coasts. Earth's Future, 9, e2021EF002055. https://doi.org/10.1029/2021EF002055

[96] Yamamoto, K., UH SOEST, Climate Resilience Collaborative

[97] Francisco, P., Nardi, F., Melesse, A. , Obeysekera, J., Castelli F., Price, R.M, Crowl, T. and Gonzalez-Ramirez, N. Compound flood modeling framework for surface–subsurface water interactions. Nat. Hazards Earth Syst. Sci., 22, 775–793, https://doi.org/10.5194/nhess-22-775-2022

[98] UH SOEST Climate Viewer. https://www.soest.hawaii.edu/crc/slr-viewer/documentation/#compound-flooding-info

numerous locations across the south side of the island damaging a power substation which cut electrical service to Downtown Honolulu businesses and residents and closing a section of the H-1 Freeway westbound through Honolulu.

Flooding from this rainfall event was compounded by the occurrence of high tides during the period when the Kona Low passed over the state (**Figure 46**) which intensify wave run-up and groundwater inundation. Using the 2021 Kona Low event, the UH SOEST Climate Resilience Collaborative modeled compound flooding with sea level rise (**Figure 47**). [99]

[99] UH SOEST Climate Resilience Collaborative (CRC) https://www.soest.hawaii.edu/crc/index.php/about/#about-us

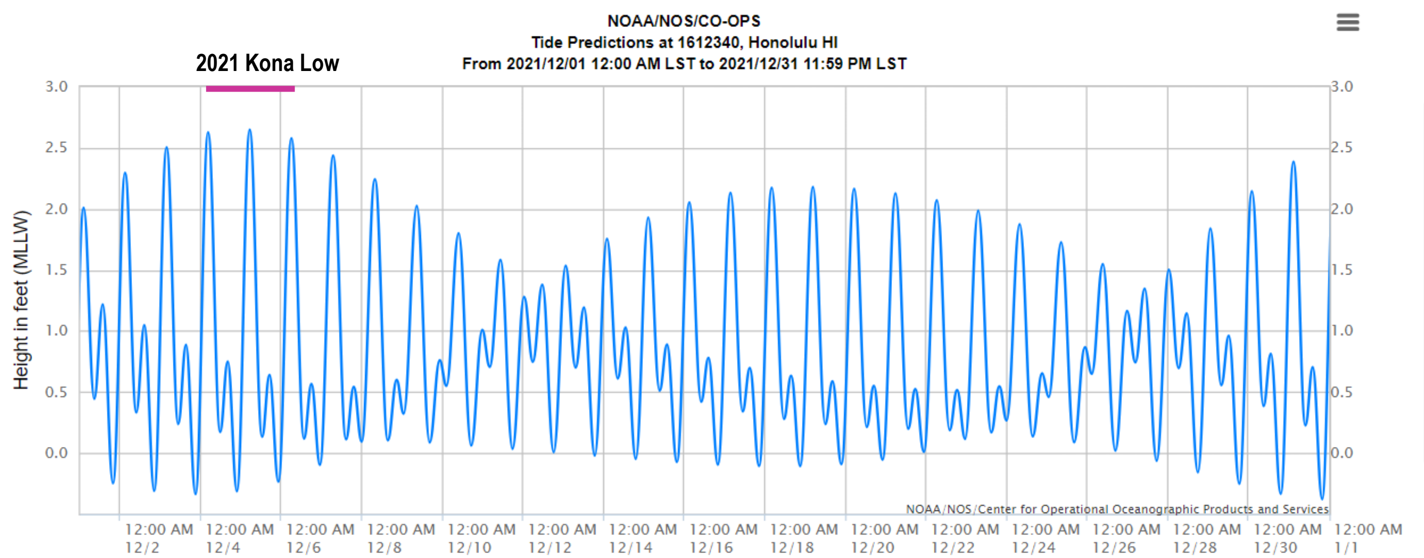

Figure 46. Tide predictions for Honolulu tide gauge from December 1– 31, 2021

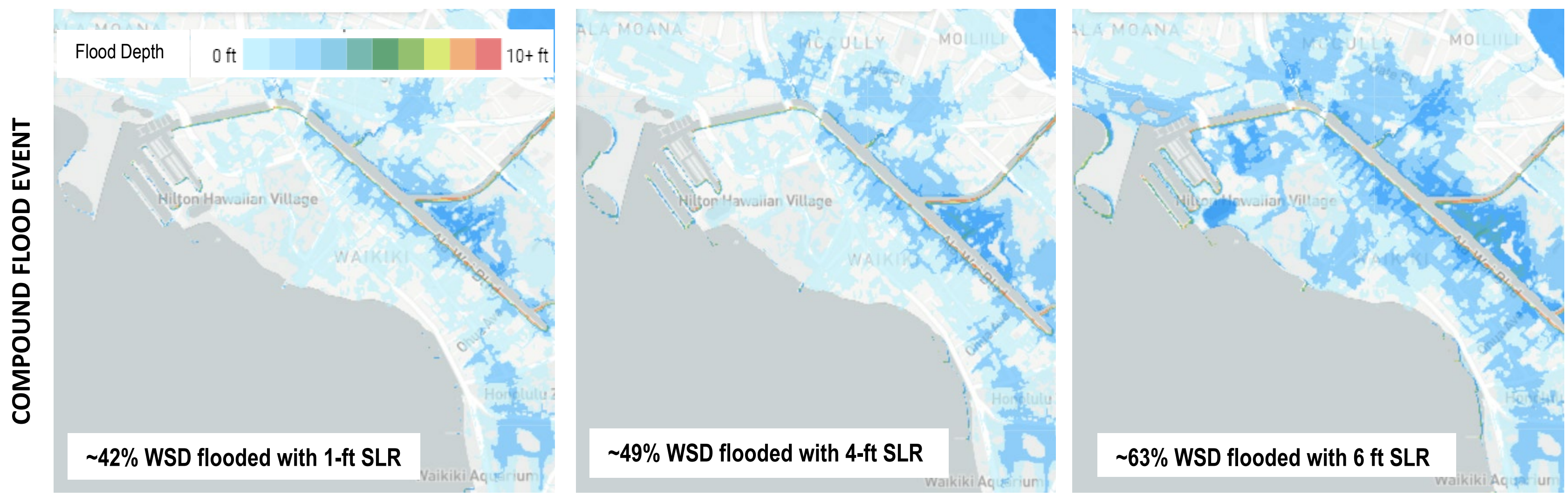

Figure 47. Modeled compound flooding extent and flood depth with sea level rise based on the 2021 Kona Low in the Waikīkī Special District (relative to 2020 sea level rise baseline UH SOEST Climate Viewer 2024)

Conclusion

The WSD is currently vulnerable to global climate change driven impacts and will only become more so over time. Waikīkī's development trajectory as a filled natural wetland with a highly engineered shoreline will continue to exacerbate the climate challenges faced by infrastructure, structures, and the community in the highly developed resort and residential neighborhood. Current and projected high groundwater, shoreline erosion, compound flooding, and other climate stressors must be considered as integral to decisions made for the future of the WSD.

RECOMMENDATIONS FRAMEWORK

A recommendations framework (**Table 9**) for the AW2050 Special Area Plan effort was developed and included in this profile based on the near-term and long-term climate risk thresholds and inputs from interviews with City departments and the One Water Working Group. Plan Recommendations will focus on: (1) City organization and policy frameworks needs and knowledge/resource gaps for planning for current and future climate impacts, (2) actionable, near-term adaptation and hazard mitigation guidance and public projects for existing structures and infrastructure, and (3) due to the many unknowns in the future of the WSD, recommendations for new development or redevelopment and new infrastructure to address long-term (beyond 2050) climate risks. The AW2050 Special Area Plan will focus on identifying the challenges and questions that need to be answered at a broad public policy level for adapting to chronic and widespread flooding. Given the long-life span of buildings and infrastructure, in many cases, it will be recommended that decisions regarding the suite of possible responses including protection/elevation, managed retreat, accommodation, and ecosystem preservation/restoration, be brought to the forefront through related resilience and infrastructure planning efforts and public dialogue. The AW2050 Special Area Plan will be completed in 2025.

Table 9. Recommendations framework for AW2050

Climate Risk Thresholds	Recommendations Typology
	CITY ORGANIZATION & POLICY FRAMEWORK
	• Use Climate Thresholds and Relative Flood Risk Index to establish risk outlook and impact progression for the WSD. • Identify knowledge gaps and data needs for long-term adaptation planning related to design guidelines, regulations, and long-term land use and supporting infrastructure • Identify City organizational capacity and collaboration needs • Identify planning horizons and integrated processes needed for adaptation planning and implementation
NEAR-TERM CLIMATE RISK THRESHOLDS (~2020 – 2050)	**EXISTING & PLANNED STRUCTURES & INFRASTRUCTURE**
• Heat Extremes • High Tide-Driven Flooding • Critically Shallow Groundwater Depth (<5 feet below ground surface) • Compound Flooding	• Identify adaptation and hazard mitigation measures and guidance (voluntary and regulatory) • Identify public infrastructure improvements and potential pilot infrastructure projects, especially for incorporation into the City's One Water Master Plan • Develop a procedure for level of service determinations and investigate harmonization agreements • Identify high-level research needs: engineering studies, costing studies, funding strategies
LONG-TERM CLIMATE RISK THRESHOLDS (~2050 – 2100)	**NEW DEVELOPMENT/REDEVELOPMENT & INFRASTRUCTURE**
• Annual High Wave-Driven Flooding • Groundwater Inundation • Passive Flooding & Storm Drain Backflow • Compounding Effects of Near-term Climate Risks	• Identify long-term adaptation strategies including protection/elevation, managed retreat, accommodation, and ecosystem preservation/restoration • Provide general recommendations for an adapt-in-place scenario • Consider using Climate Thresholds and Relative Flood Risk Index to establish long-term planning benchmarks