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4637

Impacts of Climate Change on Honolulu Water Supplies and Planning Strategies for Mitigation

Board of Water Supply

Impacts of Climate Change on Honolulu Water Supplies and Planning Strategies for Mitigation

Prepared by:

Dean Nakano, Lynn Williams Stephens, Jonathan Turk, Susan Mukai, and Joanie Stultz
Brown and Caldwell

Co-sponsored by:

Honolulu Board of Water Supply

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Abstract and Benefits

Abstract:

Utilities are facing unpredictable climate-related risks to their water supplies and infrastructure. Long-range water resource planning must account for a changing climate, in addition to historical weather patterns and population growth, to realistically plan for the future.

The Honolulu Board of Water Supply (BWS) and The Water Research Foundation (WRF) undertook a vulnerability assessment to identify and mitigate climate change risks to: (1) water supply from forecasted temperature and precipitation changes, (2) groundwater quality from projected sea level rise, and (3) coastal water system infrastructure from projected sea level rise.

This project evaluated potential climate change impacts on current estimates of groundwater sustainable yield (the chief source of BWS's water supply) and pipeline infrastructure assets, and identified a suite of strategies to address the anticipated changes. This project supports WRF's Climate Change Strategic Initiative objective to provide water utilities with a set of tools to assess their vulnerabilities and develop applicable adaptation strategies. This project's approach for the development of adaptive management strategies can be used as a guide for other utilities in evaluating and planning for the impact of climate change on water quantity, quality, and infrastructure.

Benefits:

- Provides a detailed case study for how to apply a scenario planning approach to identify vulnerabilities from climate change
- Describes the uncertainty in climate change modeling and identifies adaptive strategies and triggers for water supply and infrastructure resiliency
- Presents a method for evaluating future groundwater sustainable yields
- Examines a framework for collaboration with other agencies in a region for sea level rise, taking a One Water approach

Keywords: climate change adaptation, scenario planning, sea level rise, vulnerabilities analysis, sustainable yield, adaptation strategies, framework for collaboration, resiliency planning, pilot areas

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Acronyms and Abbreviations

°C	degree(s) Celsius
°F	degree(s) Fahrenheit
ac	acre(s)
ac-ft	acre-foot/feet
AR5	IPCC Fifth Assessment Report
BWS	(City and County of Honolulu) Board of Water Supply
CCCRT	City Climate Change Resiliency Team
CGB	Community Growth Boundary
CICAP	Center for Island Climate Adaptation and Policy
CIP	Capital Improvement Program
CMIP5	Coupled Modeled Intercomparison Project 5
CWRM	Commission on Water Resource Management
DDC	(City and County of Honolulu) Department of Design and Construction
DEM	digital elevation model
DFM	(City and County of Honolulu) Department of Facility Maintenance
DLNR	(State of Hawaii) Department of Land and Natural Resources
DOH	(State of Hawaii) Department of Health
DOT	(State of Hawaii) Department of Transportation
DPP	(City and County of Honolulu) Department of Planning and Permitting
DSPM	decision support planning method
DTS	(City and County of Honolulu) Department of Transportation Services
EIS	environmental impact statement
ENV	(City and County of Honolulu) Department of Environmental Services
ET	evapotranspiration
FIRM	Flood Insurance Rate Map
ft	foot/feet
GCM	general circulation model
GHG	greenhouse gas
GIS	geographic information system
gpcd	gallons per capita day
HRSD	Hampton Roads Sanitation District
HTA	Hawaii Tourism Authority
in.	inch(es)
IPCC	Intergovernmental Panel on Climate Change
L	liter(s)
m	meter(s)
mg	milligram(s)
mgd	million gallons per day
MHHW	mean higher high water
MMT	monthly maximum tide

N/A	not applicable
NOAA	National Oceanic and Atmospheric Administration
OCCSR	Office of Climate Change, Sustainability, and Resiliency
ORMP	Ocean Resources Management Plan
OWMP	Oahu Water Management Plan
PAC	Project Advisory Committee
PacIOOS	Pacific Islands Ocean Observing System
PIRCA	Pacific Islands Regional Climate Assessment
PUC	Primary Urban Center
PVC	polyvinyl chloride
RAM	Robust Analytical Model
RCM	regional climate model
RCP	Representative Concentration Pathway
Road Map	Road Map to Climate Change Resiliency
Sea Grant	University of Hawaii Sea Grant College Program
SLH	Session Laws of Hawaii
SLREA	sea level rise exposure areas
SOEST	School of Ocean and Earth Science and Technology
SY	sustainable yield
TAC	Technical Advisory Committee
TOD	transit-oriented development
UH	University of Hawaii
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
WMP	*Water Master Plan*
WRF	Water Research Foundation
WRMSE	weighted root mean square error
WRPP	Water Resource Protection Plan
WUP	water use permit
yr	year(s)

Executive Summary

There is always uncertainty in future planning. climate change increases the need for making critical decisions despite this uncertainty, given the potential magnitude of consequences. Traditional water utility planning assumes that past hydrologic conditions will be seen in the future. With climate change, future climate and hydrologic conditions can be significantly different from those in the past. The scale and timing of future climate and hydrologic conditions are highly uncertain (along with the indeterminate impacts to other traditional planning parameters including water demands and regulatory requirements), which adds complexity for water utility managers who need to be prepared for future changes that are not yet known.

ES.1 Purpose

The Honolulu Board of Water Supply (BWS) is committed to providing Oahu's population with safe, dependable, and affordable water. BWS distributes approximately 145 million gallons per day (mgd) of potable water and 10 mgd of non-potable water to roughly 1 million customers on Oahu. The BWS potable water system includes 2,100 miles of pipe, 386 source and booster pumps, 212 water sources (wells, tunnels, and shafts), and 171 water storage reservoirs.

This project's objectives were to evaluate climate change impacts on BWS's source water and infrastructure assets, and identify a suite of strategies to address the anticipated changes. This project also supports The Water Research Foundation's (WRF's) Climate Change Strategic Initiative objective to provide water utilities with a set of tools to assess their vulnerabilities and develop applicable adaptation strategies. Other utilities can use this approach for the development of adaptive management strategies as a guide in evaluating the impact of climate change on water quantity, quality, and infrastructure.

The project took a One Water approach and involved other essential stakeholders to prepare for climate change impacts. This is an important addition to the project, as successful implementation of climate change adaptation strategies will require significant coordination among multiple state and county agencies and other stakeholders. Specifically, this additional scope included the following objectives:

- Increase the understanding of common risks associated with climate change impacts upon critical infrastructure under the jurisdiction of different City and County of Honolulu agencies
- Educate the key agencies and stakeholders on the planning framework that BWS is using to identify vulnerabilities and strategies
- Perform a high-level gap analysis of common "sector"-based strategies (e.g., protection of critical infrastructure) developed or planned for implementation by affected agencies, including identification of specific recommendations for increased coordination and collaborative implementation of adaptation strategies
- Begin initial brainstorming toward development of an overall framework for collaboration and implementation of climate change adaptation strategies for purposes of coordinating mutually beneficial strategies and/or projects

ES.2 Approach

An adaptive planning, and more specifically a scenario planning, approach was used to evaluate climate change impacts and develop adaptive strategies. Adaptive planning is a long-term planning method that uses an iterative process to promote flexible decision making in the face of uncertainties and to increase an organization's preparedness. This planning approach can be implemented for a range of potential changing conditions including factors such as future climate projections, water supply demands, and economic development to promote flexibility to changing circumstances.

Because of the uncertainties in climate modeling, adaptive management is considered one of the best options for utilities. This project's approach also incorporates the climate change framework developed by the State Office of Planning in the Hawaii Ocean Resources Management Plan (ORMP), which outlines a step-by-step process by which the State of Hawaii can benefit from, and continue developing, plans and make informed decisions on climate change adaptation (HCZMP 2010).

Climate modeling is not a precise predictive tool. As such, planning and strategies must be developed that monitor changes and provide some guidance as to when an action should be implemented. Given the high degree of uncertainty with climate change impacts, near-term utility investments should be directed toward actions that are effective across a range of future scenarios. Other adaptation activities can be added as climate change science evolves.

The basic approach to adaptive management includes:

- Understanding and prioritizing risks
- Developing strategies to reduce risks
- Implementing strategies
- Reevaluating strategies as more information becomes available

This project focused on understanding and prioritizing risks and developing strategies to reduce risks.

In climate change planning, there are several approaches for identifying and prioritizing risks and determining adaptation options, referred to as decision support planning methods (DSPMs) (Means et al. 2010). This project used a DSPM that incorporates scenario planning into the water planning process. Figure ES-1 depicts the scenario planning process where a set of plausible scenarios is selected. The goal of the scenario planning process is not to predict specific events, but to identify and assess several potential futures that together capture relevant uncertainties and driving forces. The focus of the scenario planning process is on strategies that seek to be robust and help mitigate multiple futures and represent no-regrets strategies. This DSPM can be useful in planning not only for climatic uncertainty, but also for uncertainty about demands and regulatory, economic, environmental, and cultural conditions affecting water utilities. This DSPM identifies triggers or signposts that cause an action to take place.

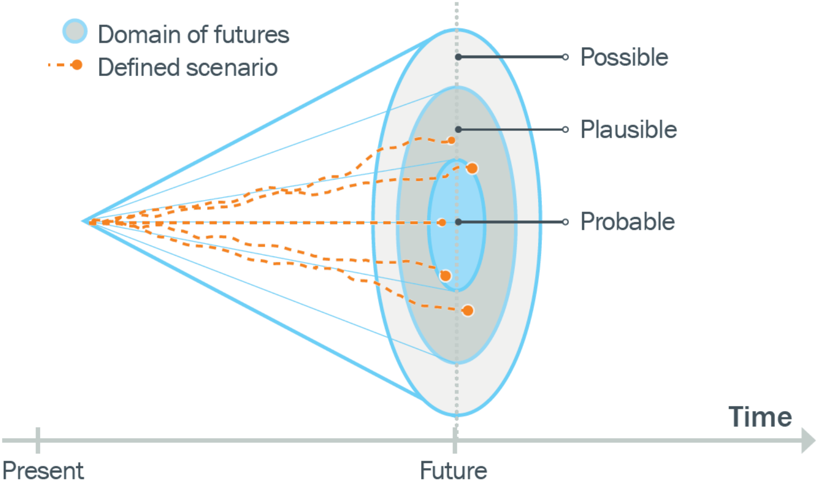


Figure ES-1. Plausible Scenarios in the Cone of Uncertainty Depict How Current Events and Trends May Play Out over Time.

For this project, the following variables were determined to be significant for long-term planning:

- Sea level rise
- Sustainable yield, which is affected by precipitation, temperature, and land use
- Water demand

Within the island of Oahu, there are designated land use planning districts and aquifer sectors. Water demands were assessed for each of the eight land use planning districts, which are consistent with the BWS watershed management plans. Each land use planning district uses the City and County of Honolulu Department of Planning and Permitting's (DPP's) development plan boundaries. Figure ES-2 shows the eight planning districts that divide Oahu: Waianae, Ewa, North Shore, Koolauloa, Koolaupoko, Central Oahu, Primary Urban Center (PUC), and East Honolulu. Aquifer recharge was assessed based on the individual aquifer sector and system boundaries defined by the Commission on Water Resource Management (CWRM), and this information was matched up as closely as possible to the land use planning districts to assess future water supply vulnerabilities.

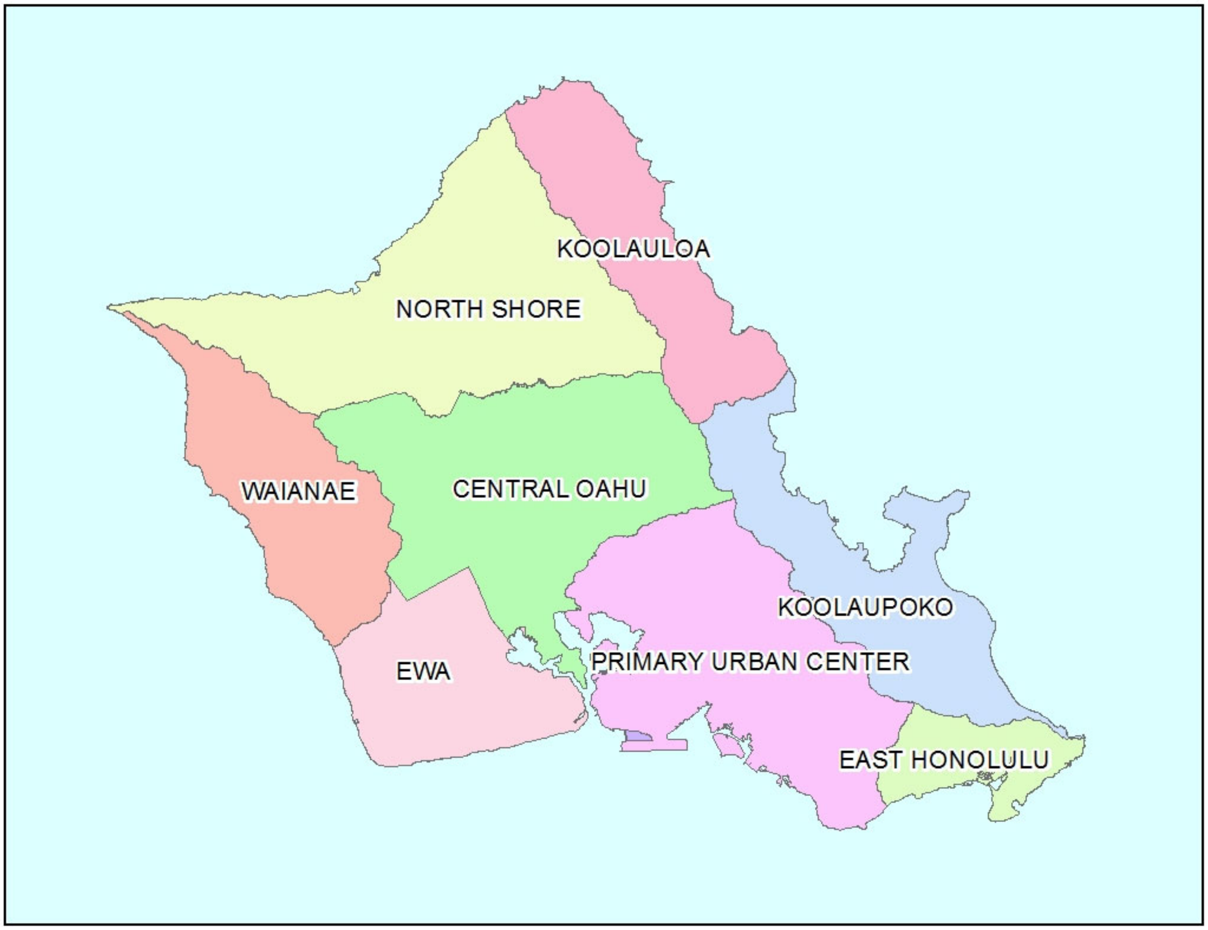


Figure ES-2. Development Plan Boundaries.
Source: Data from State of Hawaii Office of Planning 2006.

Figure ES-3 shows the overall vulnerability assessment approach. The climate change projections for sea level rise were used to analyze impacts to BWS's infrastructure for each of the sea level rise hazards, with coastal erosion being the most severe, followed by marine inundation and groundwater inundation. The length of pipeline affected by marine inundation increased five-fold (from 14,308 feet to 60,409 feet) with an increase in sea level rise from 1.1 feet to 3.2 feet. The increase in pipe length influenced by groundwater inundation is even more dramatic over the 50-year planning horizon, increasing from approximately 700 feet of pipe to 52,000 feet from 2050 to 2100. Excel and geographic information system (GIS) databases were created to summarize infrastructure vulnerabilities to individual assets based on pipe size and material for each sea level rise scenario. The Excel database will be incorporated into BWS's existing CapPlan asset management tool to prioritize individual pipe replacements based on additional parameters beyond sea level rise risk, such as criticality.

Forecasted future temperature and precipitation data were used to assess impacts to BWS's groundwater sources from one general circulation model (GCM) (CMIP5), two emission scenarios (Representative Concentration Pathways [RCPs] 4.5 and 8.5), and two downscaling methods (statistical and dynamical). Increased temperatures and changes to seasonal rainfalls were used to examine future recharge and potential changes in sustainable yield, current water use permit (WUP) allocations, and forecasted water demands. Given the range of projections, strategies deemed practical for multiple futures were identified and prioritized.

Water quality vulnerabilities were also assessed to understand how sea level rise could impact salinity in groundwater aquifers. Water quality vulnerabilities were not evaluated to the same extent as water supply and infrastructure asset vulnerabilities.

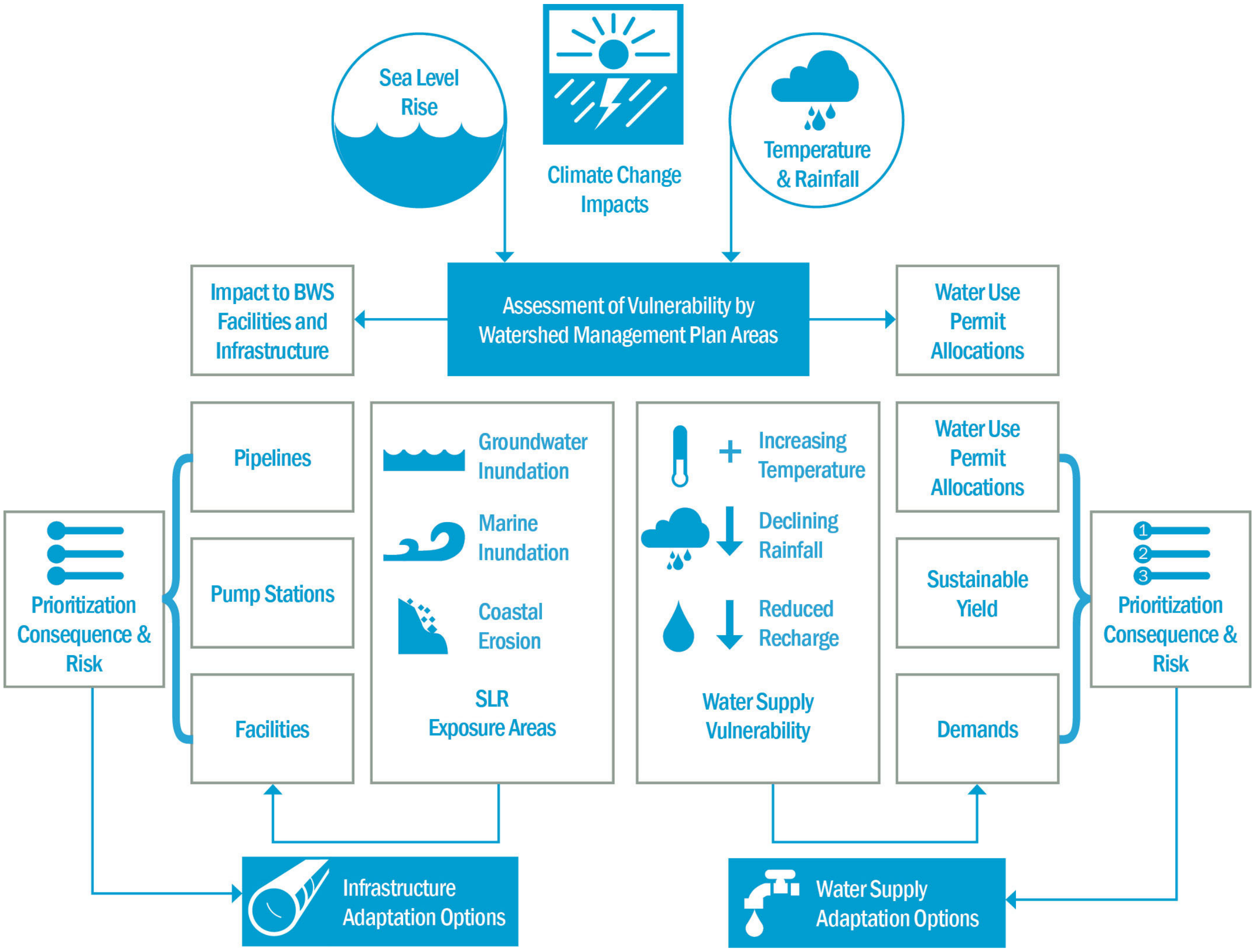


Figure ES-3. Overall Vulnerability Assessment Approach to Identifying Adaptation Strategies.

ES.3 Findings

This study primarily focused on the impacts of climate change on BWS infrastructure and the effects on groundwater sustainable yield (i.e., water availability/reliability).

ES.3.1 Groundwater Sources

Based on the most probable water demand projections through 2040 noted in the BWS Water Master Plan (WMP), groundwater supplies would be available even during drought conditions. Should future growth follow the WMP projections of high demand through 2040, existing groundwater supply during drought conditions may be limited, requiring development of alternative sources. This limitation does not account for climate change impacts and any potential reduction in sustainable yields. The current estimate of sustainable yield for Oahu is 407 million gallons per day (mgd) and, based on potential changes in rainfall and recharge, the projected low estimate of island-wide sustainable yield was 300.4 mgd. When compared against this lower estimate of sustainable yield, current island-wide WUP allocations (as of 2016) totaling 276.5 mgd, inclusive of BWS permitted use, are still below the projected low estimate of 300.4 mgd.

One limitation of the evaluation is that recharge is examined on an aquifer sector basis for the island, comprising 23 groundwater aquifer systems, while water demands are forecasted based on population growth within each of the land use districts. A one-to-one comparison between estimated aquifer sector sustainable yield to projected water demand by land use districts could not be made as these areas do not share similar boundaries. Additionally, in-district water demands are not met solely through sources within the district, and may be supplied or augmented via water transfers between districts. Projections, however, can be made as to the future availability of existing sources within each aquifer sector based on potential reductions in sustainable yield.

Under the low-recharge scenario, Waianae had the largest potential reductions in individual aquifer system sustainable yield (ranging from -62 percent to -72 percent) with an overall potential reduction of over 10 mgd for the aquifer sector. WUP allocations, however, would not be affected in this area as the Waianae Aquifer Sector is not presently regulated as a water management area by the CWRM. Alternatively, under the high-recharge scenario, Windward aquifer systems exhibited positive increases in sustainable yield (ranging from +11 percent to +18 percent) with an overall increase of over 12 mgd for the entire aquifer sector.

An in-depth analysis of available supply relative to the current/future transfer of water supply between districts was not performed as part of this study. Several aquifer sectors (North and Windward) were noted as having excess supply and limited water demand based on 2016 permitted use and BWS projected water demands. BWS has the operational flexibility to transfer water between various land use districts, and a more detailed assessment of supply, considering water transferability between districts, may need to be conducted in the future to better understand potential supply shortfalls associated with decreasing precipitation trends due to climate change. While this study provides insight to the possible range of impacts to sustainable yield throughout Oahu's aquifer sectors, additional recharge analyses and modeling should be completed to assess long-range impacts from climate change following the CWRM's framework and approach for sustainable yield updates.

Drinking water sources located along the coastline of Oahu face risks from sea level rise. Researchers have shown that coastal groundwater levels will rise simultaneously with sea level (Rotzoll and Fletcher 2013). If water supply sources are drawing water at or near the transition zone between fresh water and salt water, the salinity of that well is projected to increase. If climate change increases the frequency and occurrence of drought conditions, increased pumpage can cause up-coning of the basal aquifer, further affecting water quality and the utility of impacted sources, particularly deep groundwater basal sources. BWS has developed an extensive groundwater monitoring program that includes 29 deep monitor wells and 12 water level monitor wells on Oahu. BWS uses data from the deep monitor wells to identify changes in the freshwater lens thickness, while data from the water level monitor wells are used to monitor the changes in groundwater elevation. The extent of saltwater intrusion and behavior of the freshwater and transition zone over time due to climate change (e.g., sea level rise and/or declining rainfall) should continue to be monitored by BWS and other agencies.

ES.3.2 Sea Level Rise

The vulnerability assessment found that none of the groundwater wells, treatment systems, or pump stations are located within the sea level rise exposure area (SLREA) boundaries evaluated in this project. Of the pipeline infrastructure in the SLREA, approximately 0.1 percent was expected to be inundated by mid-century (from approximately 1 foot of sea level rise), and approximately 1 percent was expected to be inundated by end of century (from approximately 3.2 feet of sea level rise). If sea levels continue to rise to 6 feet, the magnitude of infrastructure impacted will increase greatly.

BWS pipe diameters range from 2 to 42 inches, and the pipe materials in the system include ductile iron, cast iron, galvanized iron, polyvinyl chloride (PVC), concrete cylinder, copper, and asbestos cement. Of these pipe sizes and materials, 8- and 12-inch-diameter pipe and cast-iron and ductile-iron pipe were most impacted.

Specific districts are more vulnerable to sea level rise infrastructure impacts. Koolaupoko and PUC have the most feet of pipe impacted by marine and groundwater inundation. PUC, specifically the West Waikiki region within PUC, was recommended as a pilot area to implement adaptation strategies.

ES.3.3 Adaptation Strategies Summary

A key outcome of this project was the development of a prioritized list of actions for near-term, mid-term, and long-term implementation to address a range of potential changing conditions (Table ES-1). The goal of this task is to develop an adaptive planning process that is both iterative and flexible to accommodate future uncertainties, and that identifies options and strategies to address forecasted water supply and infrastructure impacts.

Identification of no-regrets strategies that provide benefits under current and potential future climate conditions was performed in consultation with BWS, the Technical Advisory Committee (TAC), and the Project Advisory Committee (PAC). Implementing appropriate (no-regrets) strategies can reduce risk while making utilities more resilient to future climate change, ensuring that investments are worthwhile regardless of which climate future unfolds. Multiple one-day workshops were held with BWS staff, the TAC, and the PAC to inform these individuals of the vulnerability assessment approach and to develop strategies for climate change adaptation.

An important trigger or indicator for sea level rise is the frequency and severity of “nuisance” intermittent flooding events. These nuisance events serve as precursors to longer-term, more significant impacts of sea level rise. A nuisance flooding trigger of 24 times per year triggers several planning, design, and construction adaptation strategies. Given that 3.2 feet of sea level rise could occur by the end of the century, a mid-century trigger was adapting to high-tide flooding associated with this projected sea level rise. At the end of century, a 6 feet of sea level rise benchmark was identified to assist with longer-term sea level rise projections.

For water supply adaptation actions, the timing of implementation of strategies will ultimately be based on future trends and changes in water demand, source capacity, and sustainable yields. Some early no-regrets actions include implementation of more aggressive water conservation, expanded use of recycled water, and increased well monitoring.

Saltwater intrusion is the main water quality concern identified through this project. Continued monitoring of water quality is recommended. Additionally, development of additional triggers and actions for individual wells in response to rising trends in chloride concentrations should be developed in consultation with BWS, the Department of Health (DOH), and CWRM. In addition to more aggressive water conservation and expanded use of recycled water, adaptation options may include raising well pumps; abandoning impacted wells; and developing alternative water supplies, such as desalination, stormwater capture and reuse, and implementing brackish water treatment. A cost/benefit analysis should be done as part of a further assessment of these adaptation options.

Adaptation measures should be tied to specific triggers or milestones such that mitigation options can be implemented or constructed before the event occurs. Timing of these actions will be key to successfully moving from visioning, design, and implementation of critical adaptation measures.

Table ES-1. Summary of Adaptation Options and Triggers.

Category	Near-term Strategies	Mid-term Strategies	Long-term Strategies	Triggers for Mid-term Strategies
Infrastructure resilience	• Increased collaboration with other County and City of Honolulu agencies through a coordinated framework • Expanded coordination with State, federal, and private-sector efforts	• Implementation of early/phased adaptation measures and strategies for priority/pilot areas	• Expansion of applicable and/or tested strategies to additional regions	• Intermediate scenario for nuisance flooding (24 times per year)
Water supply	• Advancement of research and monitoring • Increased water conservation	• New source development • Expanded use of recycled water • Supply augmentation through stormwater capture and recharge	• Development of alternative potable and non-potable sources (e.g., desalination or indirect potable reuse and aquifer storage and recovery)	• Well water levels and chloride levels • Projected water demands within 90 percent of available supply during drought conditions • Projected reductions in sustainable yields or WUP allocations by CWRM
Water quality	• Develop triggerable actions for specific chloride concentrations • Implement additional monitoring wells	• Well optimization (adjustment of pump settings) • Planning and design of brackish groundwater treatment options or other sources of supplies	• Abandonment and siting of new wells or other sources of water supply	• Chloride levels of 250 mg/L

An important outcome of this effort was the development of a proposed County framework for coordination of agency efforts associated with climate change mitigation and adaptation. When embarking on new collaborations or new approaches, it is beneficial to start small and build on successes by first setting a coordinated framework that can be practically implemented and that will be long-lasting. This proposed framework is intended to support, and lead to, identification of selected pilot areas for which adaptive options can be prioritized and strategically implemented.

The study culminated in the development of a proposed Sea Level Rise Action Strategy that is intended to serve as a template for future implementation of recommended adaptation options. Development of the Sea Level Rise Action Strategy incorporated a qualitative approach for identifying and assembling planning, design, and construction measures into an adaptive plan based upon existing data and available information. Each proposed action item is tied to a specific time frame for initiation and completion, and/or to a recommended trigger or milestone for implementation, such as 1.7 feet of flooding based on an occurrence of 24 times per year. Certain actions should be implemented concurrently, while others may be incrementally undertaken or, in the case of planning, design, and construction, will need to be sequentially phased over time for implementation.

The Office of Climate Change, Sustainability, and Resiliency (OCCSR), together with BWS, should champion further sustained discussion and take steps in collaboration with other city agencies to assess and validate the feasibility of the adaptation options set forth in the Sea Level Rise Action Strategy, including evaluation of the positive or negative effects of these actions in preparing for future climate change. No-regrets strategies such as updating flood risk and drainage master plans incorporating future sea level rise scenarios should be immediately programmed for implementation. The identification of priority areas and site-specific design of sea level rise adaptation options, together with pilot implementation of such measures, will ultimately determine their success (or failure), and can offer lessons learned that can be applied elsewhere across the island.

This study used the best information that was available to assess climate change vulnerabilities and develop adaptive strategies. As additional climate change projections and modeling results become available, this study should be updated periodically (every 5 to 10 years) to reflect the latest data and scientific knowledge. A key goal of this study was to lay the groundwork and establish a framework that BWS could use to revise this study over time as additional information becomes available to better prepare for an uncertain climate change future.

Shortly after the completion of the draft report for this project, the Intergovernmental Panel on Climate Change (IPCC) issued a special report on the "impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, building on the IPCC Fifth Assessment Report (AR5), in the context of strengthening the global response to the threat of climate change, sustainable development and efforts to eradicate poverty" (IPCC 2018). IPCC's special report, issued in October 2018, assesses projected impacts associated with a global average warming of 1.5°C, as well as higher levels of warming. The report further describes the ethical considerations of climate change and the principle of equity that are central to this study, noting that many potential mitigation efforts "fall disproportionately on the poor and vulnerable" (Allen et al. 2018).

The IPCC special report centers on "climate-resilient development pathways," seeking to attain sustainable development goals, climate adaptation and mitigation, eradication of poverty, and reduction of inequalities. The report notes that to limit warming to 1.5°C will require a global transformation that incorporates trade-offs and synergies between mitigation, adaptation, and sustainable development that is tied to a framework, which incorporates "geophysical, environmental-ecological, technological, economic, socio-cultural, and institutional" considerations.

Transition to climate-resilient development pathways will require "institutional integration, adequate finance and technology, and attention to issues of power, values, and inequalities to maximize the benefits of pursuing climate stabilization at 1.5°C and the goals of sustainable development at multiple scales of human and natural systems from global, regional, national to local and community levels" (Allen et al. 2018).

Future updates and planning strategies for mitigating climate change impacts on the Honolulu Board of Water Supply infrastructure and water supplies should incorporate new information on climatic projections (such as forthcoming IPCC reports) to better determine which emission scenarios and associated magnitude of impacts is most probable based on the ever-increasing body of scientific data. Even with new scientific data from the IPCC and other sources of information, there will still be uncertainty. This is why it is important to pursue low regret adaptive strategies that mitigate climate change effects for a multitude of future scenarios where critical investments can be made in time to prepare for the future.

The assessment methodology and proposed framework identified for development of adaptive management strategies can hopefully serve as a guide for other utilities in evaluating and planning for the impacts of climate change on water quantity, quality, and infrastructure. Given the uncertainty of climate change, triggers are important to identify when an adaptation action should be implemented. Ideally, the triggers identified in Table ES-1 will spur ideas for other organizations.

One main outcome of this study was the realization that one entity cannot take a "go-it-alone" approach. Climate change adaptation at this island-wide scale requires a One Water approach to leverage financial capacity of each organization and cost-benefits of collaboration. It also ensures that the improvements will provide the most benefit to the community. It is important to start small, as demonstrated with the recommendation of pilot areas where this collaborative framework can be implemented. This report provides a framework for how a collaborative process can be initiated to understand climate change science and potential impacts, and to cooperatively begin a path forward towards resiliency.

ES.4 Related WRF Research

- An Integrated Modeling and Decision Framework to Evaluate Adaptation Strategies for Sustainable Drinking Water Utility Management Under Drought and Climate Change (project 4636)
- Effects of Climate Change on Water Utility Planning Criteria and Design Standards (project 4154)
- Mapping Climate Exposure and Climate Information Needs to Water Utility Business Functions (project 4729)
- State Survey of Climate Change Resiliency Efforts (project 4730)
- Water Utilities and Climate Change: A Research Workshop on Effective System Adaptation (project 4228)
- Water/Wastewater Utilities and Extreme Climate and Weather Events: Case Studies on Community Response, Lessons Learned, Adaptation, and Planning Needs for the Future (project 1338)

CHAPTER 1

Project Background

1.1 Project Summary

Hawaii's water resources are dependent almost exclusively on rainfall (and fog drip to a lesser degree), and any changes in the frequency and duration of droughts and rainfall patterns can affect Hawaii's groundwater and surface water supplies. The University of Hawaii (UH) and United States Geological Survey (USGS) have documented significant trends of reduced rainfall, higher evaporation rates, and declining stream flow in recent decades. In 2014, the Hawaii State Legislature found that climate change is now the paramount challenge of this century, posing both an urgent and long-term threat to the state's economy, sustainability, security, and way of life. Research is needed to increase the understanding of climate impacts on Oahu's water resources, assessing water system vulnerabilities to potential climate changes, incorporating climate change into water utility planning, and implementing adaptation strategies.

1.2 Project Objectives

This project's objective was to evaluate climate change impacts on the Honolulu Board of Water Supply's (BWS's) water supply and its pipeline infrastructure assets and to identify a suite of strategies to address the anticipated changes. This project also supports the Water Research Foundation's (WRF) Climate Change Strategic Initiative objective to provide water utilities with a set of tools to assess their vulnerabilities and develop applicable adaptation strategies. Other utilities can use this approach for the development of adaptive management strategies as a guide in evaluating the impact of climate change on water quantity, quality, and infrastructure.

The project was amended to expand the project scope to take a One Water approach and involve other essential stakeholders to prepare for climate change impacts. This is an important addition to the project as successful implementation of climate change adaptation strategies will require significant coordination among multiple State and County agencies and other stakeholders. Specifically, this additional scope included the following objectives:

- Increase the understanding of common risks associated with climate change impacts upon critical infrastructure under the jurisdiction of different City and County of Honolulu agencies
- Educate the key agencies and stakeholders on the planning framework that BWS is using to identify vulnerabilities and strategies
- Perform a high-level gap analysis of common "sector"-based strategies (e.g., protection of critical infrastructure) developed or planned for implementation by affected agencies, including identification of specific recommendations for increased coordination and collaborative implementation of adaptation strategies
- Begin initial brainstorming toward development of an overall framework for collaboration and implementation of climate change adaptation strategies for purposes of coordinating mutually beneficial strategies and/or projects

1.3 Related Ongoing Climate Change Studies and Initiatives

The State of Hawaii has passed various legislation enacting support for planning and mitigation of climate change impacts. In 2007, Act 234 established the State's policy framework to address Hawaii's greenhouse gas emissions seeking to reduce levels to 1990 estimates by January 2020 (Act 234 2007). In

August 2011, the State Office of Planning held workshops in cooperation with the Army Corps of Engineers and the National Oceanic and Atmospheric Administration (NOAA) to develop a climate change policy to help mitigate the effects of climate change, which led to the passage of Act 286, Session Laws of Hawaii (SLH) 2012 (Act 286 2012). Act 286, now codified as Hawaii Revised Statutes Chapter 226 Section 109, added climate change adaptation priority guidelines to the Hawaii State Planning Act (UH CICAP 2010, Act 286 2012, HRS 2017b). These priority guidelines included the following key elements:

- Encourage community stewardship groups and local stakeholders to participate in planning and implementation of climate change policies
- Consider native Hawaiian traditional knowledge and practices in planning for the impacts of climate change
- Explore adaptation strategies that moderate harm or exploit beneficial opportunities in response to actual or expected climate change impacts to the natural and built environments
- Promote sector resilience in areas such as water, roads, airports, and public health, by encouraging the identification of climate change threats, assessment of potential consequences, and evaluation of adaptation options

In 2014, Act 83 which is also known as the Hawaii Climate Adaptation Initiative Act was passed establishing an Interagency Climate Adaptation Committee to be placed within the State Department of Land and Natural Resources (DLNR) focusing on sea level rise vulnerability and adaptation (Act 83 2014). Subsequently, Act 32, SLH 2017 was passed requiring the State of Hawaii to expand strategies and mechanisms to reduce greenhouse gas emissions statewide in alignment with the principle and goals adopted in the Paris Agreement, which was adopted by 195 nations in 2016 (Act 32 2017). Act 32, SLH 2017 amended Chapter 225P, Hawaii Revised Statutes by renaming the Interagency Climate Adaptation Committee to the Hawaii Climate Change Mitigation and Adaptation Commission, as well as designating various tasks to the State Climate Commission related to climate change mitigation and adaptation, including development of a statewide sea level rise vulnerability and adaptation report by December 31, 2017 (HRS 2017a).

With these legislative guidelines in place, the State Office of Planning and DLNR have developed policies and plans for climate change adaptation, including drafting a framework for climate change adaptation by identifying sectors affected by climate change and outlining a process for coordinated statewide adaptation planning. These efforts culminated with the development of DLNR's 2017 *Hawaii Sea Level Rise Vulnerability and Adaptation Report*, which included a statewide assessment of Hawaii's vulnerability to sea level rise and recommendations to reduce the State's exposure to the impacts of sea level rise (State DLNR 2017).

Similar policy guidance and directives were also recently issued specific to the City and County of Honolulu. In June 2018, the City Climate Change Commission adopted sea level rise guidance and recommendations for Oahu that build upon the State's 2017 *Hawaii Sea Level Rise Vulnerability and Adaptation Report* and other scientific and federal research. The report noted that in the absence of any response actions, 3.2 feet of sea level rise would result in:

- 9,400 acres (ac) of land (over half of which is in the Urban Land Use District) will experience chronic flooding, erosion, and/or high wave impacts;
- $12.9 billion in land assets being threatened (not including public infrastructure);
- 13,300 residents will be displaced;
- 3,880 structures will be flooded; and
- 17.7 miles of roadways will be flooded.

On July 16, 2018, the Honolulu Mayor issued Directive No. 18-01 to all department and agency heads, which set forth the following purpose, scope, and policy:

- Establishment of policies to address, minimize risks, and adapt to the impacts of climate change and sea level rise in accordance with the findings and recommendations found within the City Climate Change Commission's Sea Level Rise Guidance document adopted on June 5, 2018.
- The City Climate Change Commission's Sea Level Rise Guidance document and Climate Change Brief shall apply to all executive branch departments and agencies.
- Each department shall consider the need for both climate change mitigation and adaptation and shall take a proactive approach to reducing greenhouse gas emissions and adapting to sea level rise impacts. Departments and agencies shall also align programs wherever possible to help protect and prepare infrastructure, assets, and the public for the physical and economic impacts of climate change (Directive 18-01 2018).

The City Climate Change Commission's Sea Level Rise Guidance document and Mayor's Directive emphasized that all city departments and agencies should be proactive in planning for climate change mitigation and adaptation, as well as to work together to develop and implement land use policies, hazard mitigation actions, and design and construction standards to mitigate and adapt to the impacts of climate change and sea level rise (Directive 18-01 2018). The City Climate Change Commission's 2018 Sea Level Rise Guidance document and the 2018 Mayor's Directive are further described in Chapter 6 of the report.

Additional relevant studies that were recently completed related to climate change studies and adaptation in Hawaii include:

- UH studies such as the *Development of a model to simulate groundwater inundation induced by sea-level rise and high tides in Honolulu, Hawaii* (Habel et al. 2017)
- The Pacific Islands Regional Climate Assessment's (PIRCA) *Expert Consensus on Downscaled Climate Projections for the Main Hawaiian Islands* (PIRCA 2016)
- The *Ala Wai Canal Flood Risk Management Study* by the Army Corps of Engineers (USACE 2017)

This climate change study provided a unique opportunity to build upon this work and to focus on the associated need for the development of specific adaptive management strategies for BWS to mitigate the risks identified from climate modeling efforts.

1.4 Overview of the BWS System and Other Pertinent Studies

BWS distributes approximately 145 million gallons per day (mgd) of potable water and 10 mgd of non-potable water to roughly 1 million customers on Oahu. The BWS potable water system includes 2,100 miles of pipe, 386 source and booster pumps, 212 water sources (wells, tunnels, and shafts), and 171 water storage reservoirs.

BWS is committed to providing Oahu's population with safe, dependable, and affordable water and has developed a comprehensive 30-year *Water Master Plan* (WMP) to evaluate its entire water system, quantify future demands and source options, and identify necessary improvements, while balancing the needs and costs of providing a continued acceptable level of service (CDM Smith 2016). A public draft of the WMP was released in July 2016. The WMP efforts include, but are not limited to, the assessment of existing infrastructure and other assets, development of future water demand projections through 2040, identification of future supplies and facility improvements, and development of a prioritized 30-year Capital Improvement Program (CIP) and financial plan for implementation of these projects.

BWS also developed a *Strategic Plan* that focuses upon the following three goals:

- **Resource sustainability:** to protect and manage its groundwater supplies and watersheds through adaptive and integrated strategies
- **Operational sustainability:** to foster a resilient and collaborative organization using effective and proactive operational practices consistent with current industry standards
- **Financial sustainability:** to implement sound fiscal strategies to finance its operating and capital needs to provide dependable and affordable water service (CDM Smith 2016)

A strategic objective of BWS's resource sustainability goal calls for adaptation to climate change to manage Oahu's water resources and to protect the island's limited water supply. To meet this objective, BWS has commenced several programmatic initiatives including, but not limited to, the WMP, *Oahu Water Management Plan* (OWMP), *Water Conservation Plan,* and Energy Savings Program.

This WRF-tailored collaboration project with BWS focuses upon identification of adaptive management strategies to mitigate against climate change impacts while staying in alignment with ongoing BWS initiatives, such as the WMP and OWMP.

1.5 Climate Change Planning Approach

The purpose of an adaptive management plan is to identify adaptation strategies that can be used to address high-priority vulnerabilities related to climate change. Adaptive management is a flexible strategy for developing, evaluating, and making decisions. One of the goals of adaptive management planning is to establish a plan that can be implemented for a range of potential changing conditions. Because of the uncertainties in climate modeling, adaptive management is considered one of the best options for utilities. This plan's approach also incorporates the climate change framework developed in the 2009 *Ocean Resources Management Plan*, which outlines a step-by-step process by which the State of Hawaii can benefit from, continue developing plans, and make informed decisions on climate change adaptation (HCZMP 2010).

It is not possible to produce precise anthropogenic climate change projections. As such, planning and strategies must be developed that monitor changes and provide some guidance as to when an action should be implemented. Given the high degree of uncertainty with climate change impacts, near-term utility investments should be directed toward actions that are effective across a range of future scenarios. Other adaptation activities can be added as climate change science evolves.

The basic approach to adaptive management, shown in Figure 1-1, includes understanding and prioritizing risks, developing strategies to reduce risks, implementing strategies, and reevaluating strategies as more information becomes available. This approach involves looking through the lens of multiple future scenarios and developing short-, mid-, and long-term actions that can be initiated for a more robust and reliable water system. Adaptive management's flexible approach makes it valuable in making decisions in an uncertain environment. It proves especially useful in the context of climate change planning because it is an iterative process. The strategies will be periodically modified based on monitoring results and updated climate change projections. New strategies will be developed and implemented based on new information as the iterative process continues.

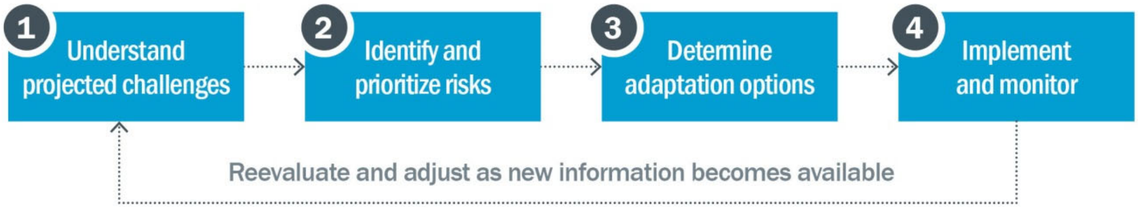


Figure 1-1. Overview of the Adaptive Management Process.

A challenge for adapting to climate change is incorporating the results from a vulnerability assessment into a utility's short- and long-term planning processes. There are several approaches for climate change planning to identify and prioritize risks and determine adaptation options, referred to as decision support planning methods (DSPMs) (Means et al. 2010). WRF's climate change adaptation planning highlights the following DSPMs:

- Classic decision analysis
- Traditional scenario planning
- Robust decision making
- Real options
- Portfolio planning

Our approach incorporates a DSPM that incorporates scenario planning into the water planning process. Figure 1-2 depicts the scenario planning process where a set of plausible scenarios are selected. The goal of the scenario planning process is not to predict specific events but to identify and assess several potential futures that together capture relevant uncertainties and driving forces. The focus of the scenario planning process is on strategies that seek to be robust, help mitigate multiple futures, and represent no-regrets strategies. This DSPM can be useful in planning not only for climatic uncertainty but also for uncertainty about regulatory, economic, environmental, and cultural conditions affecting water utilities. This DSPM identifies triggers that cause an action to take place.

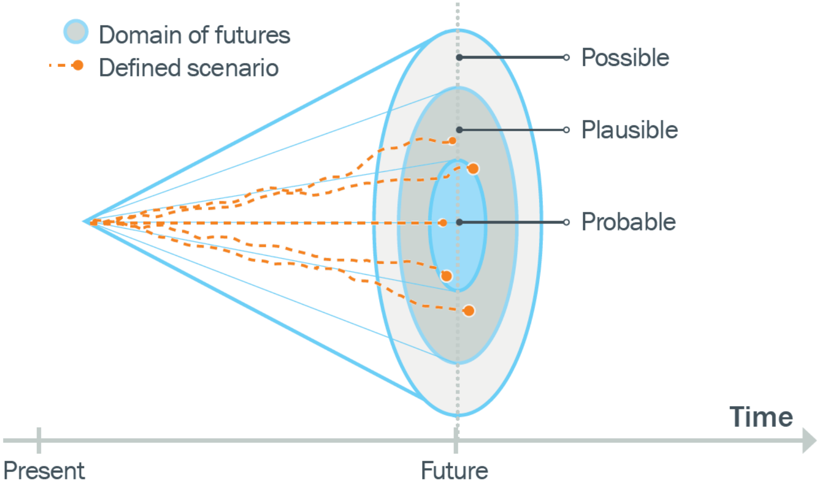


Figure 1-2. Plausible Scenarios in the Cone of Uncertainty Depict How Current Events and Trends May Play Out over Time.

1.6 Geographic Areas for Assessment

Climate change vulnerabilities were assessed for eight geographic boundaries. These eight boundaries are consistent with the BWS watershed management plans, which use the City and County of Honolulu

Department of Planning and Permitting's (DPP's) development plan boundaries. Figure 1-3 shows the eight planning districts that divide Oahu: Waianae, Ewa, North Shore, Koolauloa, Koolaupoko, Central Oahu, Primary Urban Center (PUC), and East Honolulu.

These eight districts each have their own watershed management plan and associated water supply and demand projections. Water demand projections are based on DPP population projections, BWS per capita demand projections, and future land use projections based on master plans, district development and sustainable community plans, and stakeholder input.

Using best available information, this climate change study analyzed the effects of climate change on Oahu as a whole. Some aspects of climate change and its related impacts were assessed and described in the context of its corresponding planning district, whereas other impacts such as the effects on total groundwater supply were examined island-wide.

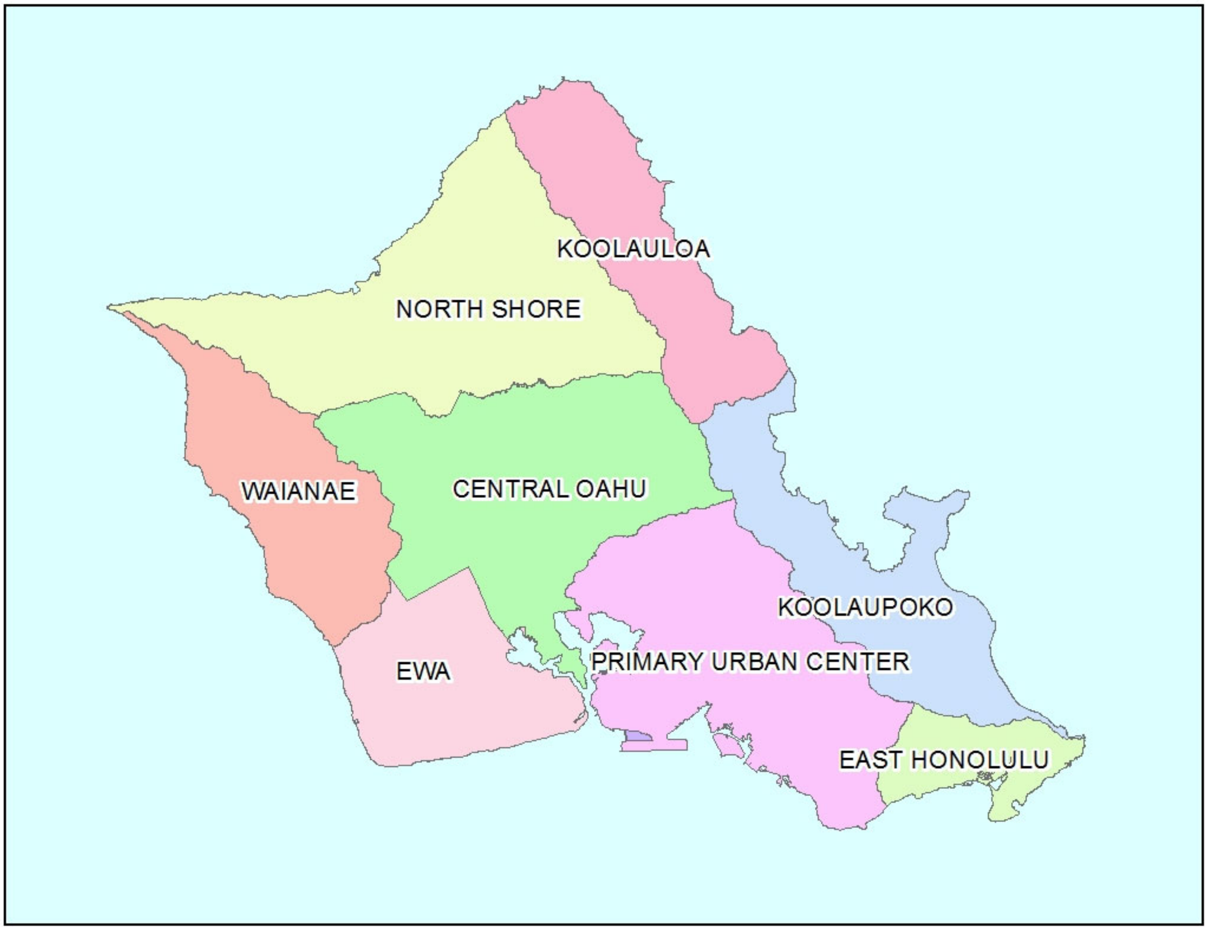


Figure 1-3. Development Plan Boundaries.

Source: Data from State of Hawaii Office of Planning 2006.

CHAPTER 2

Climate Change Projections

This section summarizes climate change impacts for Oahu with a focus on sea level rise, temperature, and precipitation. The data presented in this section are based on the Intergovernmental Panel on Climate Change's (IPCC's) *Fifth Assessment Report* (AR5) (IPCC 2013). The climate projections vary depending on the assumption of future carbon emissions. Some models assume that the planet will start to curtail carbon emissions, such as Representative Concentration Pathway (RCP) 2.6. Other models assume that carbon emissions will continue to increase with population growth (RCPs 6.0 and 8.5). The RCPs are numbered based on radiative forcing projections (from +2.6 to +8.5 watts per square meter) through 2100. Figure 2-1 shows the carbon emission projections for each RCP scenario.

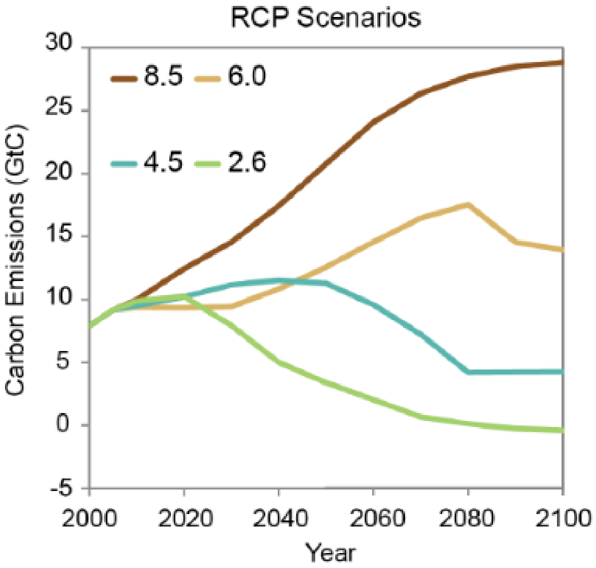


Figure 2-1. Future Carbon Emission Projections for Each RCP Scenario.
Source: Melillo et al. 2014.

Greenhouse gas (GHG) emissions cause the climate to change through atmospheric warming and other chemical processes. Even if the world stopped generating new GHGs, the atmosphere would continue to warm for hundreds of years (PIRCA 2016).

2.1 Sea Level Rise Hazards

Rising sea levels will escalate the threat to groundwater aquifers and critical infrastructure. According to the 2012 USGS National Assessment of Shoreline Change, 70 percent of beaches on Kauai, Oahu, and Maui are eroding with an average long-term rate of 0.11 meter (m) per year (Fletcher et al. 2012). Twenty-two kilometers, or 9 percent of beaches on the three islands, were completely lost to erosion over the past century (Rotzoll and Fletcher 2013).

The sea level rise and coastal erosion data presented in this section are based on work done by UH Professor Chip Fletcher and his research group. Professor Fletcher created a model based on the sea level rise model published in 2013 by the IPCC's AR5 for the RCP 8.5 emissions scenario (IPCC 2013).

Figure 2-2 presents the range of estimates for global mean sea level rise from the Coupled Modeled Intercomparison Project Phase 5 (CMIP5) climate projections.

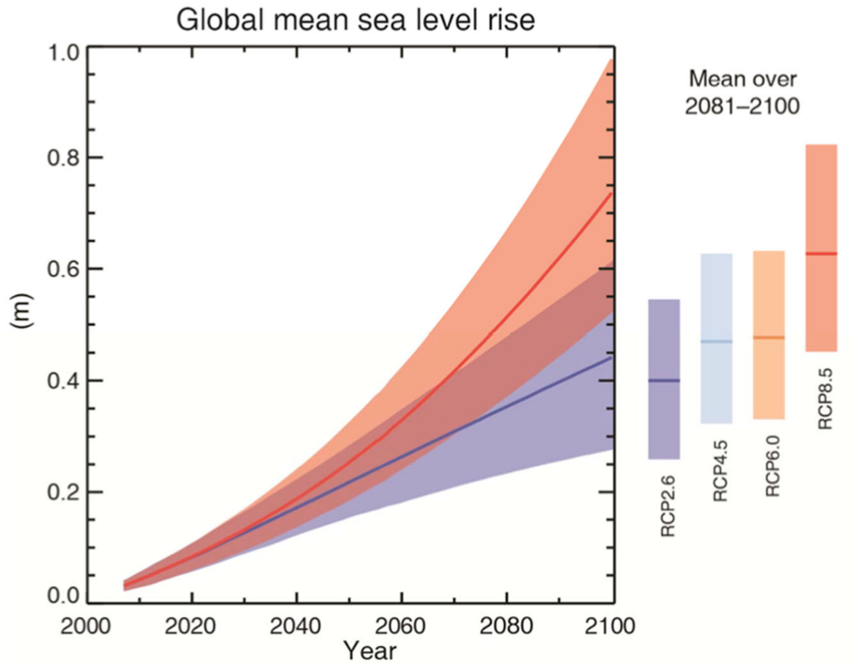


Figure 2-2. Range of Estimates of Global Mean Sea Level Rise Data from the Combination of CMIP5 Models RCP 2.6 (purple) and RCP 8.5 (red) Scenarios.

Source: Stocker et al. 2013.

The RCP 8.5 emission scenario, presented in Figure 2-2, is an internationally recognized projection of future sea level and thus is supported by the best available science. Additional contributions to the understanding of future sea level have been published since this IPCC 2013 report, but these publications have not been modeled as a single holistic product that considers all potential influences on global sea level rise. In every case of improved sea level understanding, any changes to future projections have indicated that the IPCC projections in 2013 are underestimates of the problem.

In addition, sea level science has advanced significantly over the last few years. Researchers have an improved understanding of the complex behaviors of the large, land-based ice sheets in Greenland and Antarctica under global warming. A more recent publication by NOAA projects that global mean sea level could rise sooner than previously thought, with the possibility of 2.0 to 2.7 meters or 6.0 to 8.1 feet (ft) of global mean sea level rise by the end of this century (Sweet et al. 2017). The AR5 stresses the central or "likely" range of 21st century rise in global mean sea level based primarily on process-based models and those projections are based on having at least a 66 percent chance of containing the true value. But there is also roughly a one-third probability that sea level rise by 2100 may lie outside the "likely" range. There is a potential shift in when the sea level rise projections may occur. Sweet et al. (2017) projects that 3 feet or more of sea level rise may occur as early as 2060. Questions remain on the exact timing of the trajectories and this speaks to the value of using scenario planning and triggers for adaptive actions.

Using the IPCC-AR5 model for RCP 8.5, various sea level rise hazards for 2030, 2050, and 2100 were projected and are presented in Table 2-1. As these years imply a degree of precision that the modeling does not actually bear out (as discussed above), it is best to refer to these periods as "pre-mid-century," "mid-century," and "end of century," realizing that the timing of these projections may shift. Though

RCP 8.5 is supposed to represent the most extreme sea level rise projection, more recent data suggests that this may be more of an average (Sweet et al. 2017).

Table 2-1. Projected Sea Level Rise (IPCC AR5 RCP 8.5).

Source: Data from Stocker et al. 2013.

Year	Period	Projected Sea Level Rise (ft)
2030	Pre-mid-century	0.6
2050	Mid-century	1.1
2100	End of century	3.2

This modeling is used to project the hazards of:

- Coastal erosion on sandy shorelines
- Wave flooding associated with seasonal high waves (not storm waves)
- Low-lying areas vulnerable to groundwater inundation, drainage infrastructure inundation, and poor drainage following rainstorms
- Marine inundation by direct seawater flowing into topographically connected areas

The modeling depicts these conditions during high-tide conditions referred to as mean higher high water (MHHW), which is the average of the higher high water height of each tidal day. The sea level rise modeling was integrated with geographic information system (GIS) infrastructure data. Figure 2-3 shows the island-wide sea level rise hazards at 3.2 feet of sea level rise.

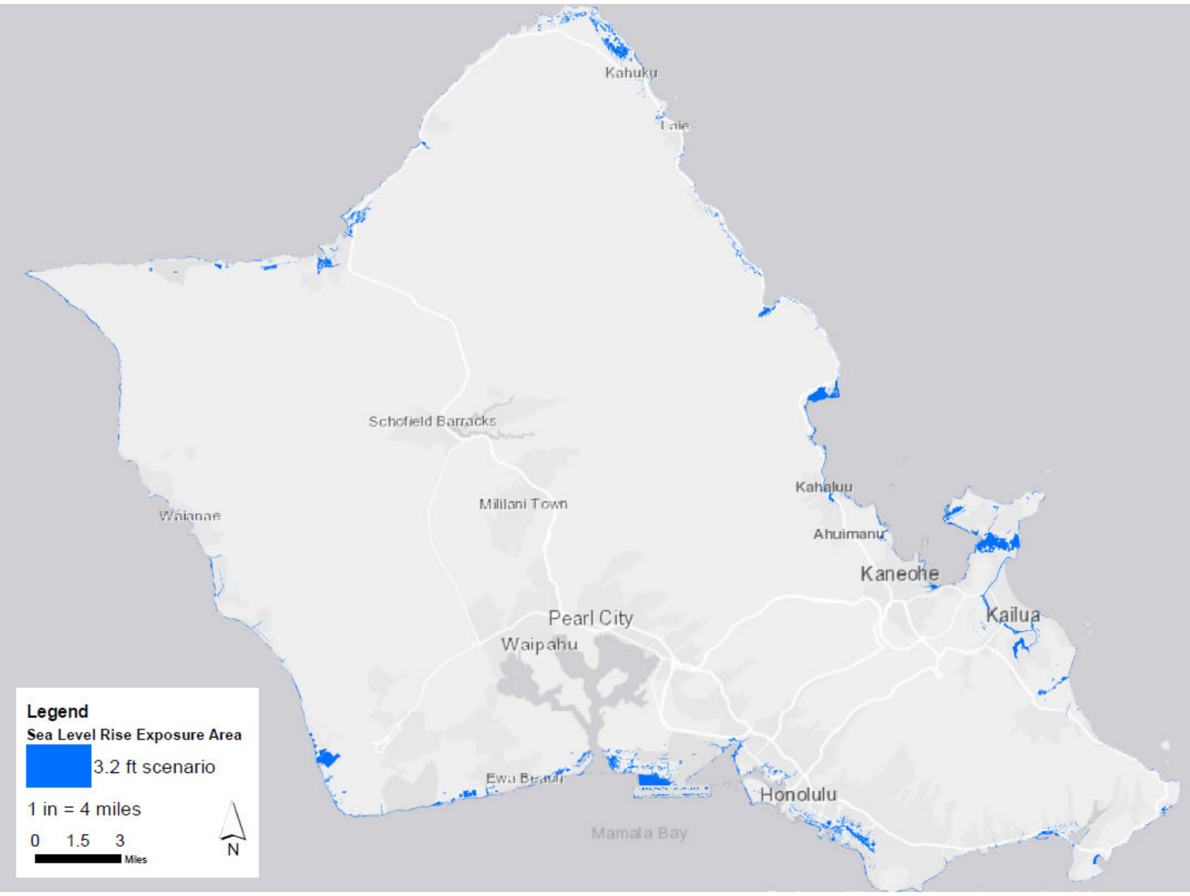


Figure 2-3. Sea Level Rise Hazard Areas on Oahu.

The details of the erosion, wave flooding, groundwater inundation, and marine inundation are not visible at an island-wide scale. Therefore, it is necessary to examine small areas within the specific geographic boundaries to visualize the infrastructure impacts. Select locations on Oahu were chosen to highlight projected future impacts from sea level rise based on infrastructure proximity and economic impact. These projected hazard maps are presented in Appendix A. These sea level rise data which are based on RCP 8.5 are also available to the public for the entire State of Hawaii through the Pacific Islands Ocean Observing System (PacIOOS) called the Hawaii Sea Level Rise Viewer (UH SOEST 2017).

2.1.1 Erosion

Coastal erosion modeling was conducted to project the extent of future erosion along coastal areas due to sea level rise based on the IPCC RCP 8.5 sea level rise scenarios for 2030, 2050, and 2100, as published in the international peer-reviewed journal *Natural Hazards* (Anderson et al. 2015). The erosion hazard lines are located at the 80 percent cumulative probability contour indicating 80 percent confidence that there will be no erosion landward of that line based on the model and the IPCC RCP 8.5 sea level rise scenarios. The model uses historical data on shoreline change in combination with a geometric model of beach migration tied to projected sea level rise to project the extent of coastal erosion. The erosion hazard data were available island-wide, with gaps in the erosion hazard lines along the coast where rocky coasts or bluffs were located. Exposure to coastal erosion was not modeled for rocky coasts or bluffs because those areas may be less-erodible but also prone to sudden failures, and do not behave as the majority of the shoreline when exposed to sea level rise. In addition, existing seawalls or other shoreline hardening/armoring and the effects of sea level rise on nearshore sediment processes were also not included in the coastal erosion modeling.

Infrastructure impacts from coastal erosion were evaluated within the watershed planning areas to identify critical at-risk roadways. The projected erosion hazard lines are presented in Appendix A on Figures A-1 through A-4 for seal level rise scenarios in 2030, 2050, and 2100 in the areas with future impacts from erosion. Figures A-1 and A-2 present the erosion hazards for Waikiki in the PUC and Kaaawa in the Koolauloa region, respectively. In Kaaawa, Highway 83 is projected to be vulnerable to erosion as early as 2030, or pre-mid-century. Erosion hazards for Maili Beach in Waianae and Ewa Beach in Ewa are presented in Figures A-3 and A-4, respectively. Highway 83 in the Waianae region has projected vulnerability pre-mid-century. In addition, the neighborhood of Iroquois Point in Ewa has several roadways projected to be impacted by erosion by 2030 including Edgewater Drive, Albatross Avenue, Bittern Avenue, and Iroquois Ave.

2.1.2 Groundwater Inundation and Marine Inundation

As sea level rises, the groundwater table in the coastal plain will rise and eventually breach the land surface. When this happens, a wetland is created. The water table typically lies at an elevation of approximately mean sea level, and in coastal areas within the Honolulu region, the water table may be located only a couple of feet below the ground surface. When it rains, some rainwater infiltrates into the ground and can raise the water table closer to the land surface. The dry zone between the water table and the land surface is called the vadose zone, and this zone narrows under conditions of high tide and during rain events. During high tide and rain events, there is a greater likelihood of flooding, and even one foot of sea level rise will impact low-lying areas under such conditions.

Additionally, drainage infrastructure designed to divert runoff into the ocean may back up with seawater and cease to be an effective means of draining the land surface. Again, during high tide and heavy rainfall, the conditions that promote flooding are greater. Thus, the projected first noticeable impacts of sea level rise will be the failure of drainage infrastructure during heavy rain events, leading to standing water and flooding that impacts communities, businesses, infrastructure, and ecosystems. The groundwater inundation information presented in Appendix A is based on MHHW levels.

There were two hazard data sets representing marine inundation and groundwater inundation prepared by the UH research team that were available for the island of Oahu as follows:

- **Bathtub modeling data for the entire island of Oahu:** Marine inundation occurs as the ocean rises and seawater flows across shorelines, into canals, and into estuary and stream channels. This phenomenon can be simulated as static flooding, sometimes referred to as "bathtub modeling." Modeling data for Oahu were used to identify the static flooding from marine inundation and groundwater inundation. The hazard is depicted simply by defining cells in a high-resolution digital elevation model (DEM) that fall below MHHW and that are connected to the ocean, during future positions of sea level. These areas will be permanently flooded and become a new seafloor. Inundation areas were derived from a DEM and an MHHW tidal stage surface and are in the form of polygon layers (GIS compatible). The marine inundation hazard is depicted simply by defining cells in a DEM that fall below the MHHW and that are connected to the ocean during future elevations of sea level. The groundwater inundation hazard is determined by subtracting the land surface with an assumed sea level rise from the MHHW surface to identify where the MHHW is above the surface. One limitation of these data is that the groundwater inundation hazard boundary accounts only for areas above ground when the water table reaches the surface, not the exact extent of where the water table may impact buried pipelines below the surface.
- **Groundwater inundation water table data for Waikiki only:** Water table data were developed from a high-resolution DEM and the average monthly maximum tidal (MMT) stage surface to show the unsaturated space above the water table (positive values) and flood depth (negative values). Simulations represented increases in the water table with increases in sea level of 1.05 feet, 2.0 feet, and 3.2 feet. One major limitation for these data is that they were available only for the Waikiki area. In addition, this data set is in the form of raster files, which are not directly compatible with our approach to clip the pipe data by an impacted area without extensive geoprocessing.

As a result of the limited geographical reach of the water table data set and the incompatible data format, the bathtub modeling results were used for the assessment.

Figures A-5 through A-12 in Appendix A depict projected groundwater inundation and marine inundation in the PUC (Iwilei and Waikiki), East Honolulu (Hawaii Kai), and North Shore boundary regions. Separate figures are shown for mid-century (2050) and end of century (2100). In some regions, the groundwater inundation becomes quite pronounced at the end of the century. In Waikiki, shown below in Figure 2-4, Ala Wai Community Park and Ala Wai Elementary School are projected to be mostly flooded by marine water. Infrastructure near Hausten Street and Date Street, as well as Lime Street and Paani Street, are expected to have groundwater inundation.

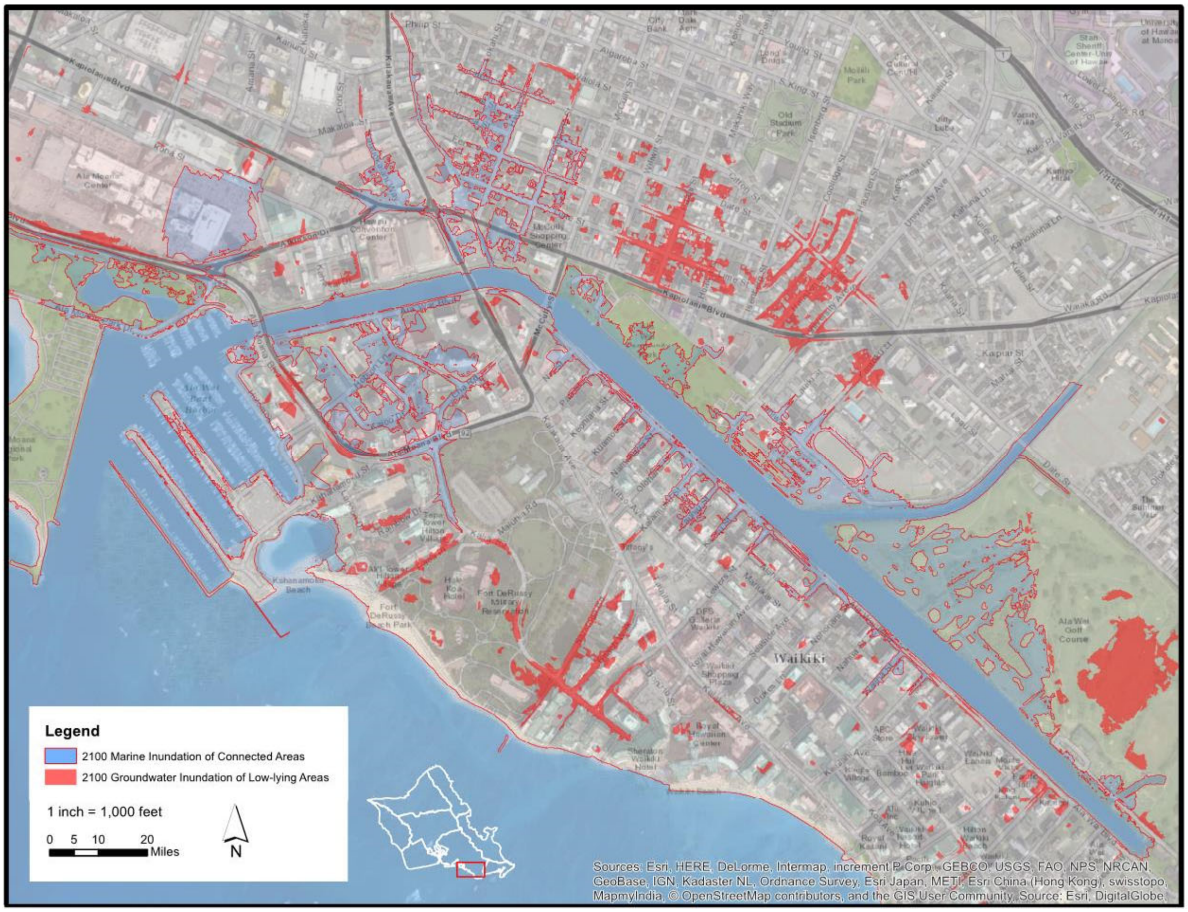


Figure 2-4. Marine and Groundwater Inundation in Waikiki in 2100.
Source: Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

Figures A-13 and A-14 depict the depth of the marine inundation for Waikiki for mid-century and end of century, respectively. An area east of Kalakaua Avenue is projected to have marine inundation ranging from a depth of 0.8 feet to 3.3 feet in 2050 (Figure A-13). In 2100, additional areas are projected to be impacted by marine inundation. Areas north and south of the Ala Wai Canal are projected to have marine inundation with depths of water up to 3.3 feet (yellow shown on Figure A-14).

2.1.3 Wave Inundation

Wave impacts under sea level rise are depicted as seasonal high waves as recorded by observation buoys in Hawaiian waters. These seasonal waves, specific to individual coastal segments, are modeled using XBEACH, an open source numerical modeling package available from Deltares. As sea level rises, model results indicate that these waves reach farther inland from the shoreline and constitute a dynamic hazard to the environment and infrastructure of the coastal zone. The XBEACH model outputs velocity and depths of annual swells incorporating sea level rise and MHHW. The XBEACH model does not account for tsunamis or major storm surges, only seasonal waves. The XBEACH modeling was used to conduct a geospatial analysis in GIS for Oahu (Anderson and Fletcher 2017). Figures A-15 and A-16 show seasonal high wave flooding depth compared to projected marine inundation (dark red line) for Waikiki in the PUC for mid-century and end of century, respectively. At the end of the century, the seasonal high wave flooding surpasses the end of century projections for marine inundation (Figure A-16). Areas along the Waikiki coast are projected to see flooding up to 4.9 feet.

2.2 Temperature Projections

Based on general circulation models (GCMs), which simulate the response of the global climate system to increasing GHG concentrations, temperatures in Hawaii are expected to increase over the next century (Stocker et al. 2013, Lindsey and Dahlman 2018). The magnitude and rate of the projected temperature increases depend on the RCP scenario chosen, especially beyond mid-century. Table 2-2 and Figure 2-5 summarize the projections for each RCP scenario. With increasing RCP scenarios, it assumes an increasing temperature based on increasing carbon emissions.

Table 2-2. Global Mean Surface Temperature Change (°F).

Source: Data from Stocker et al. 2013.

Scenario	2046–2065		2081–2100	
	Mean (°F)	Likely Range (5%–95% model ranges) (°F)	Mean (°F)	Likely Range (5%–95% model ranges) (°F)
RCP 2.6	1.8	0.72–2.9	1.8	0.5–3.1
RCP 4.5	2.5	1.6–3.6	3.2	2.0–4.7
RCP 6.0	2.3	1.4–3.2	4.0	2.5–5.6
RCP 8.5	3.6	2.5–4.7	6.7	4.7–8.6

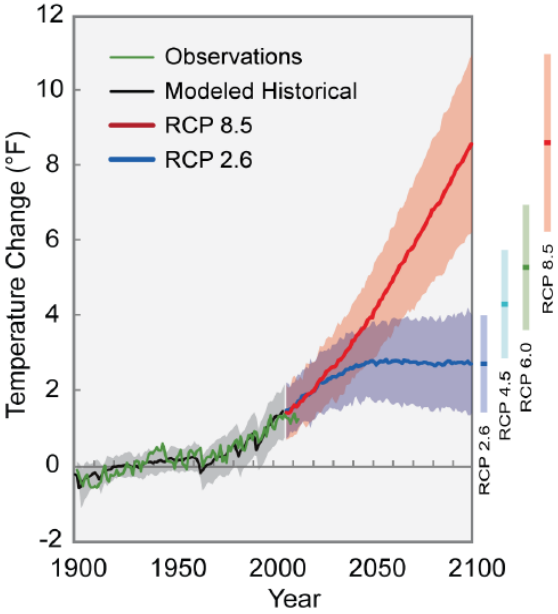


Figure 2-5. Global Mean Temperature Projections through 2100 Relative to 1901–1960.

Source: Stocker et al. 2013.

A comparison of historical mean and projected temperatures for Oahu is summarized in this section. Historically, there was an increase in the average air temperature in Hawaii from 1916 to 2006 (Keener et al. 2012). Historical and projected temperatures for Oahu were analyzed in each of the eight planning regions (Table 2-3). The historical mean temperature data presented in Table 2-3 were obtained from the University of Hawaii's *Climate of Hawaii* website (Giambelluca et al. 2014, UH Geography Department 2014). The projected temperatures in Table 2-3 are based on statistical downscaling of CMIP5 RCP 4.5 and RCP 8.5 (Timm et al. 2015).

Table 2-3. Historical and Projected Mean Annual Air Temperature.

Source: Data from Giambelluca et al. 2014 and Timm et al. 2015.

District	Historical (1957–1981) (°F)	Mid-Century (2040–2069)		End of Century (2070–2099)	
		RCP 4.5 (°F)	RCP 8.5 (°F)	RCP 4.5 (°F)	RCP 8.5 (°F)
Koolauloa	71.3	73.6	74.6	74.2	76.9
North Shore	70.8	73.0	74.0	73.7	76.4
Waianae	71.9	74.2	75.2	74.8	77.5
Koolaupoko	72.7	74.9	75.9	75.6	78.2
Central Oahu	70.2	72.5	73.5	73.1	75.8
Ewa	73.6	75.9	76.9	76.5	79.2
East Honolulu	72.5	74.7	75.8	75.4	78.1
PUC	71.9	74.1	75.2	74.8	77.5

The historical mean annual temperature on Oahu ranges from 70 to 74 degrees Fahrenheit (°F). The projected mid-century annual mean air temperature increases by approximately 2.3°F to 3.3°F for RCPs 4.5 and 8.5, respectively. At the end of the century, the average annual mean temperature for the period is projected to increase by approximately 2.9°F to 5.6°F when compared to historical annual mean temperatures. The projected temperature at the end of the century is projected to range from 73°F to 79°F for RCPs 4.5 and 8.5, respectively, depending on the district location. There is variability in the projection of increased temperatures, but all climate scenario models project an increase in temperature.

2.3 Precipitation

The level of uncertainty associated with precipitation projections is much greater than the uncertainty associated with temperature. Additionally, climate models look at long-term projections to understand impacts from typical variability. However, a limitation of GCM and regional climate model (RCMs) climate change projection data is that extreme events are not accurately modeled or captured (Jiang et al. 2013). Section 2.3.1 presents historical precipitation data and Section 2.3.2 summarizes seasonal precipitation projections.

2.3.1 Historical Precipitation

Historically, a downward trend in rainfall has been observed across Hawaii since the beginning of the 20th century and an even steeper negative trend since 1980 (Keener et al. 2012). According to the U.S. Drought Monitor map, Hawaii has experienced severe drought conditions somewhere in the state since June 2008 (National Weather Service 2014). The Hawaiian Islands have observed an increase in the number of annual consecutive dry days when comparing the period from 1950–1970 to 1980–2011, indicating a tendency for more prolonged dry periods (Keener et al. 2012). Figure 2-6 shows the downward trend in the winter rainfall index which was derived from rainfall data from Oahu, Kauai, and Hawaii Island (Chu and Chen 2005). According to the UH Sea Grant College Program (Sea Grant), Center for Island Climate Adaptation and Policy (UH CICAP) Hawaii’s Changing Climate Briefing Sheet, rainfall and stream flow have decreased while the intensity of rainstorms has increased (UH CICAP 2010).

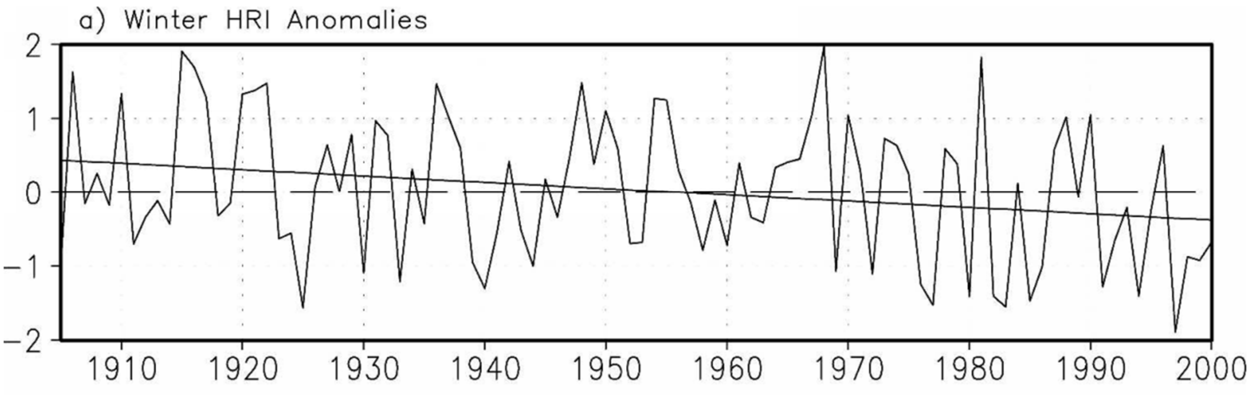


Figure 2-6. Interannual and Interdecadal Rainfall Variations in the Hawaiian Islands.
Source: Chu and Chen 2005. © American Meteorological Society. Used with permission.

Figure 2-7 shows the spatial distribution of mean annual rainfall from 1987 to 2007 (Giambelluca et al. 2013). Table 2-4 shows the historical annual average precipitation from 1987 to 2007 for each of the eight planning districts, as well as the wet (November-April) and dry (May-October) seasonal averages. The Koolauloa region receives the greatest amount of annual average rainfall, averaging 97 inches (in.) from 1987 through 2007. The highest rainfall values occur over the Koolau Mountains on the windward (eastern) side of the island. Locally higher rainfall also occurs over the Waianae Mountains on the leeward (western) side. The Ewa and Waianae regions located on the southwest side of Oahu receive the least amount of annual average rainfall at 25 and 38 inches, respectively.

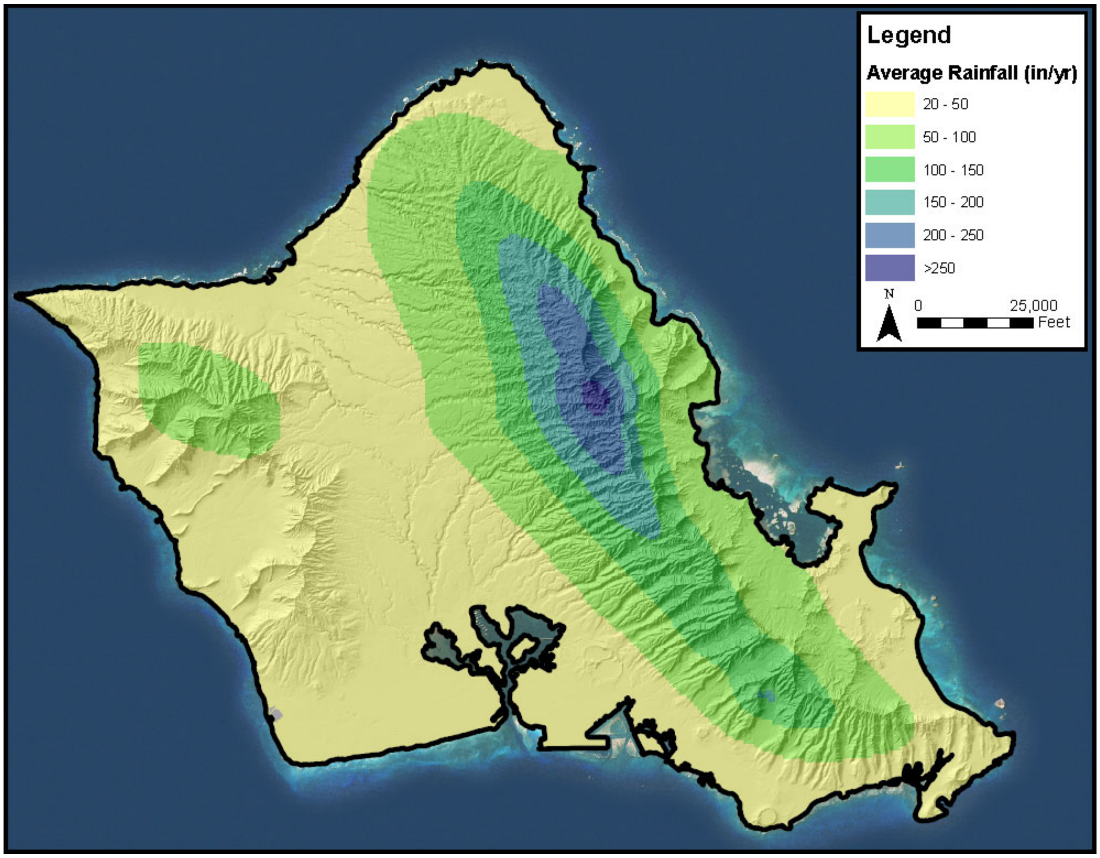


Figure 2-7. Oahu Mean Annual Rainfall (1978–2007).
Source: Data from Giambelluca et al. 2013.

Table 2-4. Historical Annual Average and Wet and Dry Seasonal Precipitation.

Source: Data from Giambelluca et al. 2013.

District	Historical Averages (1978–2007)		
	Annual (in.)	Wet Season (Nov – Apr) (in.)	Dry Season (May – Oct) (in.)
Koolauloa	97.0	54.6	42.4
North Shore	67.7	40.1	27.6
Waianae	38.3	25.5	12.8
Koolaupoko	67.8	41.2	26.5
Central Oahu	72.6	41.4	31.1
Ewa	25.2	17.1	8.2
East Honolulu	45.1	30.0	15.1
PUC	68.7	39.2	29.6

2.3.2 Seasonal Precipitation Projections

With assessing climate change projections, it is important to look at seasonal variations to precipitation because there can be more changes not captured in annual averages. Typically, GCMs have a resolution of 150 to 30 kilometers by 150 to 300 kilometers (UNFCCC 2018). GCMs are downscaled to assess local seasonal impacts. There are also multiple approaches to downscaling GCMs (PIRCA 2016, UNFCCC 2018):

- **Statistical downscaling** uses observed local climate data and GCM data to project how the future will change. Future variables from GCM projections are used to develop statistical relationships and estimate local future climate.
- **Dynamical downscaling** uses atmospheric physics to make GCM projections relevant regionally and requires high-performance computing resources to simulate how the climate reacts to increased GHG concentrations using a limited-area, high-resolution model driven by boundary conditions from a GCM.

Given the uncertainty in climate projection data, it is valuable to assess multiple RCPs and downscaling methods. Projections for the end of century from both statistical and dynamical downscaled RCMs give a range of results. A comparison of the wet and dry season precipitation projections for the end of the century for statistical and dynamical downscaled data for Oahu is shown in Figure 2-8. The statistical downscaling is based on CMIP5, RCP 8.5 from 2071 through 2100 and the dynamical downscaling is based on CMIP5, RCP 8.5 from 2080 through 2099. The statistical downscaling method projects drier conditions during the dry season while the dynamical downscaling method projects higher amounts of precipitation. Similar to the dry season, during the wet season the statistical downscaling method also projects drier conditions when compared to the dynamical downscaling projections.

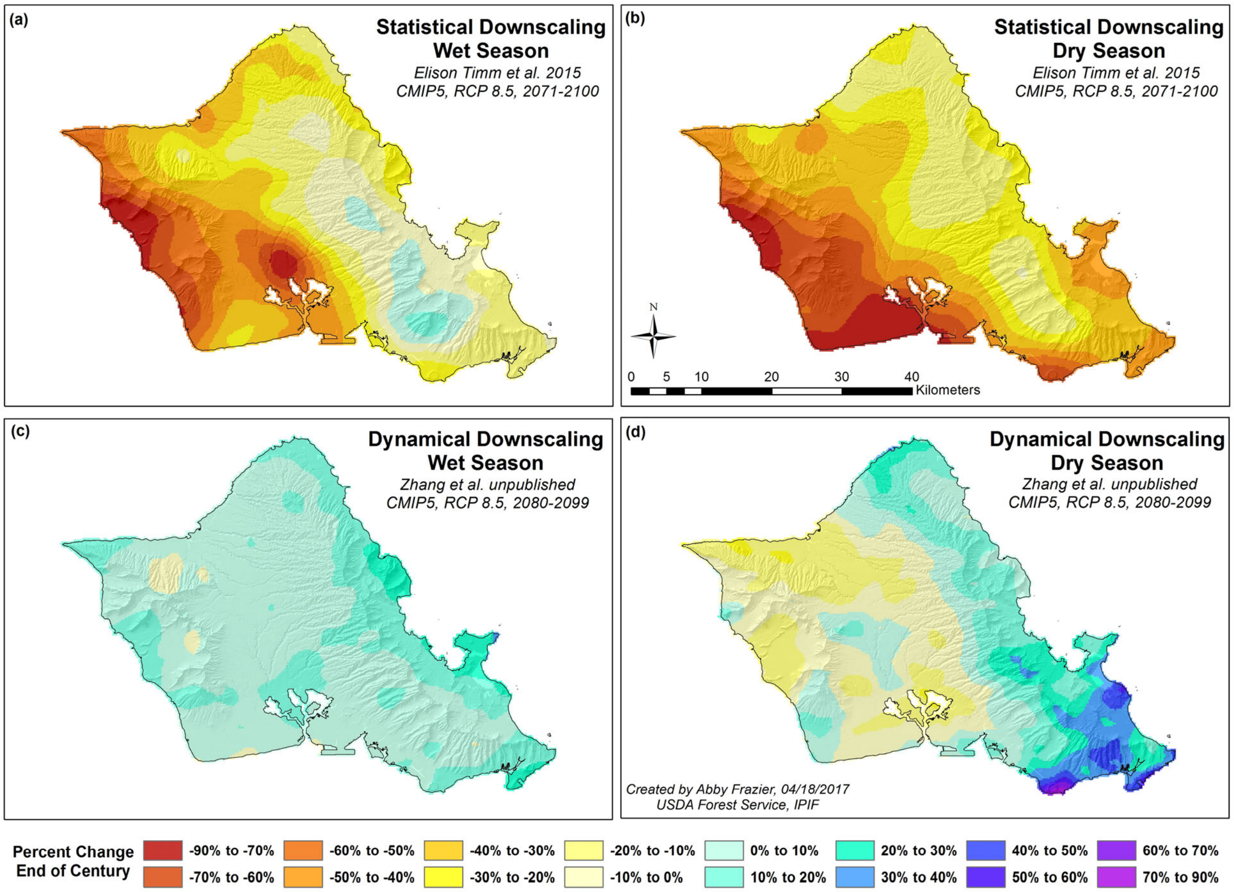


Figure 2-8. Comparison of Percent Change in Wet and Dry Season Rainfall Projected for the End of the Century on Oahu Using Statistical and Dynamical Downscaling.

Source: Figure developed by Abby Frazier, April 2017. Data from Timm et al. 2015 and Zhang et al. 2016.

The projected wet season precipitation for mid-century and end-of-century compared to historical wet averages for Oahu are presented in Table 2-5 based on the statistical downscaling of both RCP 4.5 and 8.5 scenarios. The statistical downscaled results of both RCP 4.5 and 8.5 scenarios project a reduction in precipitation for mid-century and end of century for the wet season. Mid-century precipitation reductions range from 5 to 44 percent for the eight districts. The greatest reduction in precipitation during the wet season occurs in the Waianae region, followed by the Ewa region, both of which already receive a low amount of precipitation when compared to the other regions.

Table 2-5 also presents wet season precipitation for the end of century based on dynamical downscaling for RCP 4.5 and 8.5 scenarios. The dynamical downscaled results vary between projections of wetter regions and dryer regions. End of century precipitation projections show an increase in precipitation from 3 to 14 percent for the eight districts. The dynamical and statistical downscaling end of century data show contrasting projections. While the Waianae region is projected to have a 42 to 61 percent reduction in precipitation based on statistical downscaling, it is projected to have an 8 to 9 percent increase in precipitation based on dynamical downscaling. This data highlights the uncertainty in climate change projections and why it is important to consider multiple scenarios in climate change assessments.

The dry season precipitation projections for Oahu for mid-century and end of century, compared to historical dry averages, are presented in Table 2-6. Similar to the wet season projections, the statistical downscaling for the dry season also projects reductions in precipitation for both mid-century and end of century. On average, the RCP 4.5 and RCP 8.5 scenarios project a 24 to 32 percent reduction, respectively, in rainfall across Oahu in mid-century. The largest mid-century precipitation reductions are projected in the Ewa region, followed by the Waianae, East Honolulu, Central Oahu, and PUC regions.

Table 2-6 also presents dry season precipitation for the end of century based on dynamical downscaling for RCP 4.5 and 8.5 scenarios. During the dry season, the dynamical downscaled results vary between projections of wetter and dryer regions. End of century precipitation projections range from -8 to 35 percent for the eight districts. Similar to the statistical downscaling, the Waianae region is projected to have the greatest reduction in precipitation. The Koolaupoko region.

The dynamically downscaled precipitation results in Tables 2-5 and 2-6 were calculated by Abby Frazier of the East-West Center using Chunxi Zhang's CMIP5 Dynamical Downscaling results for Oahu. The calculations were done using the Change Factor Method used by Victoria Keener and Pacific RISA in the USGS *Maui Groundwater Project* which is currently under review and expected to be published in 2019 (Mair et al. forthcoming). The calculations took the percent change in precipitation from the dynamical downscaled results and applied those percentages to the historical rainfall based on the Rainfall Atlas data to derive the future precipitation in inches for dynamical downscaling.

Both the statistical and dynamical downscaling results for both RCP 4.5 and 8.5 (Timm et al. 2015, Zhang et al. 2016) were used to project future sustainable yields (SY) and future water supply vulnerabilities, which are further discussed in Section 4.3.

Table 2-5. Historical and Projected Wet Season Precipitation (in.).

Source: Statistical data from Giambelluca et al. 2013 and Timm et al. 2015. Dynamical data from Abby Frazier of the East-West Center 2019 and Zhang et al. 2016.

District	Historical Wet Averages (1978–2007)	Statistical Downscaling Mid-Century Wet Season (2040–2069)			Statistical Downscaling End of Century Wet Season (2070–2099)			Dynamical Downscaling End of Century Wet Season (2080-2099)		
		RCP 4.5 (in.)	RCP 8.5 (in.)	Percent Change[a]	RCP 4.5 (in.)	RCP 8.5 (in.)	Percent Change[a]	RCP 4.5 (in.)	RCP 8.5 (in.)	Percent Change[a]
Koolauloa	54.6	47.3	46.6	-13% to -15%	46.3	43.7	-15% to -20%	57.2	62.1	5% to 14%
North Shore	40.1	33.3	32.6	-17% to -19%	32.3	29.9	-19% to -25%	42.0	42.1	5%
Waianae	25.5	16.5	14.3	-35% to -44%	14.7	10.0	-42% to -61%	27.7	27.5	9% to 8%
Koolaupoko	41.2	38.5	39.0	-7% to -5%	38.2	38.1	-7% to -8%	42.3	47.0	3% to 14%
Central Oahu	41.4	33.3	32.2	-20% to -22%	32.0	28.2	-23% to -32%	44.3	44.1	7%
Ewa	17.1	12.3	11.6	-28% to -32%	11.5	9.4	-33% to -45%	18.8	18.2	10% to 6%
East Honolulu	30.0	26.7	26.7	-11%	26.1	26.0	-13% to -14%	32.0	33.8	7% to 13%
PUC	39.2	34.9	26.5	-11% to -10%	34.5	33.5	-12% to -14%	39.9	42.2	2% to 8%

a. Percent change range corresponds to projections for RCPs 4.5 and 8.5, respectively in comparison to historical wet averages.

Table 2-6. Historical and Projected Dry Season Precipitation (in.).

Source: Statistical data from Giambelluca et al. 2013 and Timm et al. 2015. Dynamical data from Abby Frazier of the East-West Center 2019 and Zhang et al. 2016.

District	Historical Dry Averages (1978–2007)	Statistical Downscaling Mid-Century Dry Season (2040–2069)			Statistical Downscaling End of Century Dry Season (2070–2099)			Dynamical Downscaling End of Century Dry Season (2080-2099)		
		RCP 4.5 (in.)	RCP 8.5 (in.)	Percent Change[a]	RCP 4.5 (in.)	RCP 8.5 (in.)	Percent Change[a]	RCP 4.5 (in.)	RCP 8.5 (in.)	Percent Change[a]
Koolauloa	42.4	38.4	36.8	-9% to -13%	37.4	34.5	-12% to -19%	46.2	47.2	9% to 11%
North Shore	27.6	23.4	22.0	-15% to -21%	22.8	19.6	-17% to -29%	28.8	26.3	4% to -5%
Waianae	12.8	9.0	7.6	-30% to -41%	8.9	5.2	-30% to -60%	12.2	11.8	-5% to -8%
Koolaupoko	26.5	22.2	20.5	-16% to -23%	21.5	18.1	-19% to -32%	28.5	33.0	8% to 25%
Central Oahu	31.1	25.5	23.6	-18% to -24%	25.1	20.6	-20% to -34%	32.5	30.5	5% to -2%
Ewa	8.2	5.1	4.1	-37% to -50%	4.9	2.5	-39% to -70%	8.5	8.0	3% to -2%
East Honolulu	15.1	12.0	10.9	-21% to -28%	11.8	9.2	-22% to -39%	15.4	20.3	2% to 35%
PUC	29.6	24.2	22.4	-18% to -24%	23.7	20.0	-20% to -32%	30.2	32.4	2% to 10%

a. Percent change range corresponds to projections for RCPs 4.5 and 8.5, respectively in comparison to historical dry averages.

2.4 Climate Change Projection Conclusions

Both statistical and dynamical downscaling results for both RCP 4.5 and 8.5 were used to project future sustainable yields and future water supply vulnerabilities in Chapter 4. RCP 8.5 was used to project future sea level rise to assess infrastructure impacts.

In general, the following climate trends are projected:

- Ambient air temperatures will rise
- Sea level rise will continue to occur affecting coastal infrastructure
- The leeward side of Oahu will be increasingly drier in the dry season

CHAPTER 3

Land Use and Water Demand Projections

3.1 Land Use Projections

Oahu is currently divided into three different state land use districts: agricultural, conservation, and urban. The breakdown of land uses island-wide is shown in Figure 3-1.

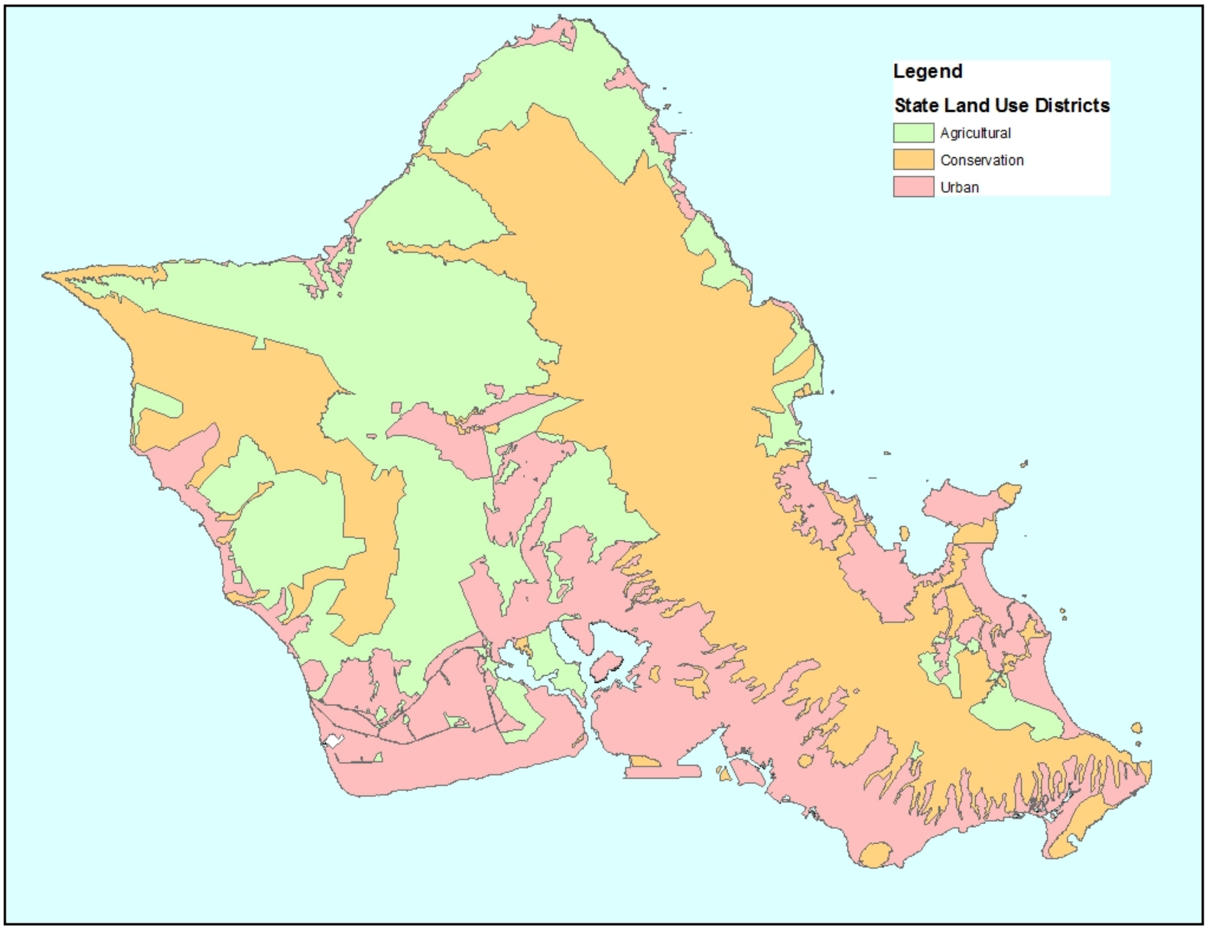


Figure 3-1. Statewide Land Use.

Source: Data from State of Hawaii Office of Planning 2006.

Conservation land is generally located along the Koolau and Waianae mountain ranges. Agricultural land is located mainly in the North Shore, Waianae, Central Oahu, and Ewa areas. Urban zoned land can be found in all areas but is located mainly in Ewa, Central Oahu, PUC, East Honolulu, and Koolaupoko. These land use categories are further divided into county zoning categories. A map showing the grouped county zoning classifications is shown in Figure 3-2.

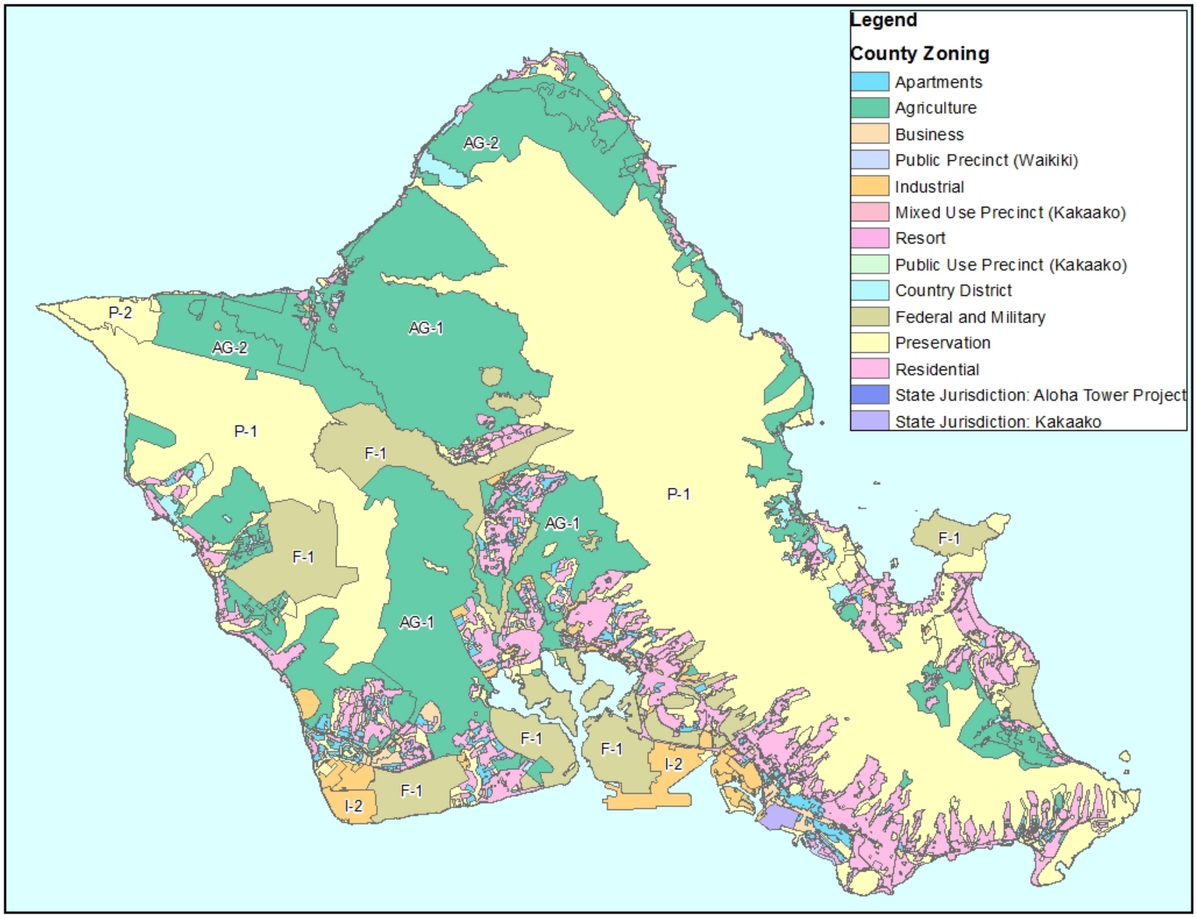


Figure 3-2. Oahu County Zoning.
Source: Data from State of Hawaii Office of Planning 2006.

Each district's watershed management plan discusses the current and projected land uses and associated water demands. However, there is no pictorial map showing projected land use. Table 3-1 summarizes the projected land use based on information taken from the individual watershed management plans that were approved or are in draft phase. Although future land use cannot be easily mapped out, there are policies that guide and limit where urban expansion can occur. As an example, the DPP *Central Oahu Sustainable Communities Plan* describes the Community Growth Boundary (CGB) as the boundary between urban areas and protected agricultural and open space areas (DPP 2015). The island-wide CGB is shown in Figure 3-3.

Table 3-1. Projected Land Use.

Land Use District	Projection Year	Projected Agricultural Land Use (ac)	Projected Population Change (people)
Waianae	2030	+ 275	+ 8,357
Koolauloa	2030	+ 2,100–3,300	+ 2,100
Koolaupoko	2030	+ 398	- 3,234
North Shore	2035	+ 4,100	+ 1,800
Ewa[a]	2035	+ 1,997	+ 62,567
Central Oahu[b]	2040	N/A	N/A
PUC[b]	2040	N/A	N/A
East Honolulu[b]	2040	N/A	N/A

a. The Ewa Watershed Management Plan has not been approved by City Council.
b. The Central Oahu, PUC, and East Honolulu watershed management plans do not have public review drafts available.

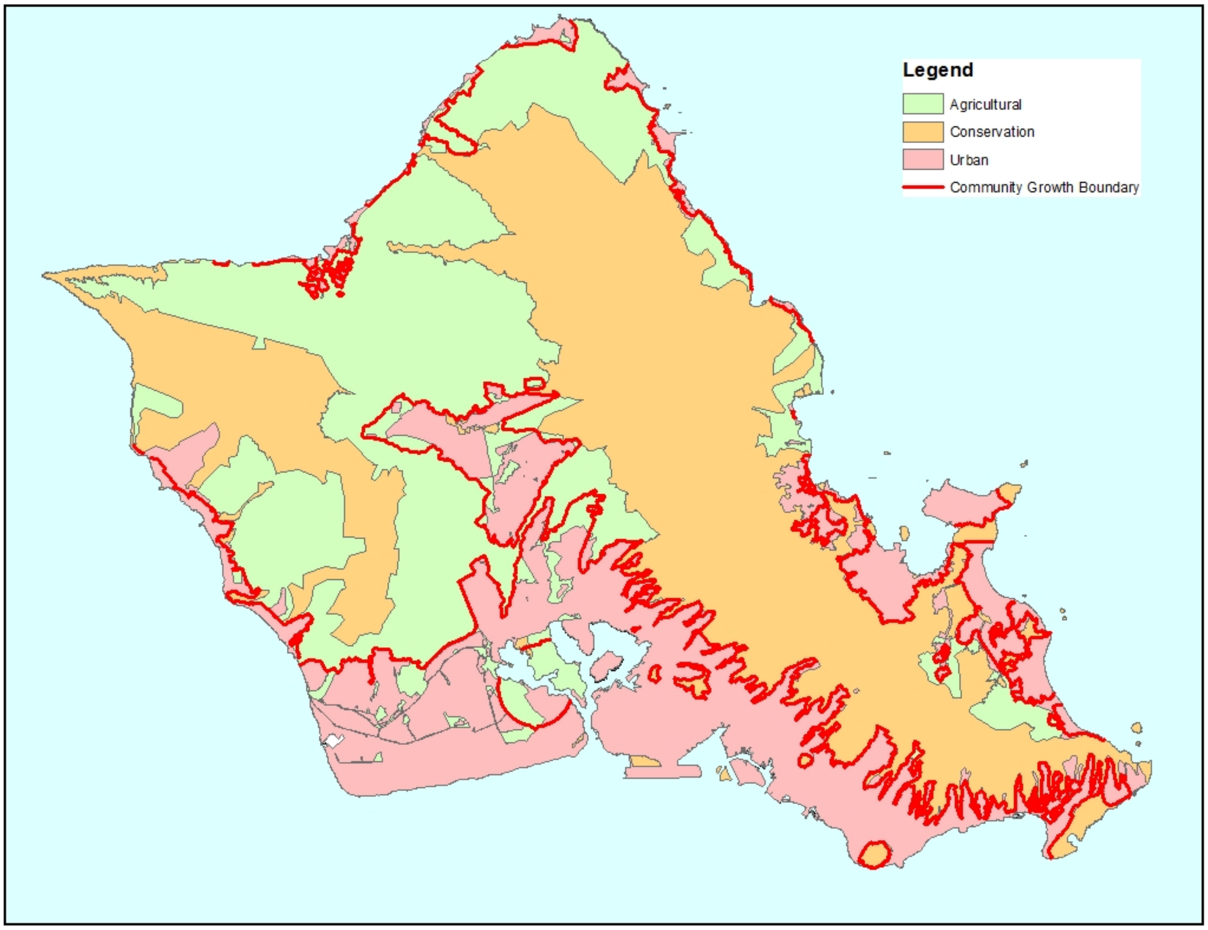


Figure 3-3. Community Growth Boundary.
Source: Data from State of Hawaii Office of Planning 2006.

The CGB includes existing master planned developments and protects prime agricultural land and conservation land located outside of this boundary. Some of the objectives of creating the CGB listed in the *Central Oahu Sustainable Communities Plan* include promoting an efficient pattern of urban development and supporting the full development of the PUC and Secondary Urban Center (DPP 2015). It can be assumed that urban growth will occur only within the CGB, and agricultural land and open space outside this boundary will be preserved.

3.2 Population Projections

The BWS WMP includes population and water demand projections through 2040 that are based on DPP population projections (CDM Smith 2016). The projections for 2050 and 2100 were extrapolated from these data by assuming that the 30-year growth rates identified in the BWS WMP will continue beyond 2040. Table 3-2 shows the population projections through 2100 for each district.

Table 3-2. BWS Served Population Estimates.

Source: Adapted from CDM Smith 2016. The columns for 2050 and 2100 were added using extrapolated data.

District	2010 Population	Projected BWS-Served Population (excludes population served by other water supply systems)							
		2015	2020	2025	2030	2035	2040	2050	2100
PUC	461,000	465,900	70,800	475,700	480,600	485,600	490,500	500,333	559,333
Ewa	92,100	104,600	117,100	129,600	142,100	154,600	167,100	192,100	342,100
Central Oahu	141,000	145,000	148,900	152,900	156,800	160,700	164,700	172,600	220,000
Waianae	47,200	48,000	48,900	49,700	50,600	51,400	52,300	54,000	64,200
North Shore	14,500	14,800	15,100	15,400	15,700	16,000	16,300	16,900	20,500
Koolauloa	9,500	9,700	10,000	10,200	10,500	10,700	11,000	11,500	14,500
Koolaupoko	108,500	108,000	107,600	107,100	106,600	106,200	105,700	104,767	99,167
East Honolulu	48,100	48,000	48,000	47,900	47,900	47,800	47,800	47,700	47,100
Total	921,900	944,000	966,400	988,500	1,010,800	1,033,000	1,055,400	1,099,900	1,366,900

There is a wide range of projected population growth rates through 2040, ranging from -3 percent to +81 percent for each district. The total population served by BWS is projected to increase by 14 percent between 2010 and 2040, which is less than 1 percent annual growth. Continuing the same annual growth rate, the BWS-served population could grow by more than 48 percent between 2010 and 2100.

3.3 Water Demand Projections

The BWS WMP lays out the historical potable water demands for Oahu between 1980 and 2010 (CDM Smith 2016). The BWS-served population increased by 42 percent during that period, but because of conservation measures, increases in water and sewer rates, and other factors, the BWS water demand increased by only about 10 percent. Table 3-3 contains information about BWS demand trends taken from the BWS WMP (CDM Smith 2016). The 30-year trend shows an overall increase in BWS water demand with a drop in demand for a few of the districts.

Table 3-3. BWS Water Demand.

Source: CDM Smith 2016.

District	1980 (mgd)	1990 (mgd)	2000 (mgd)	2010 (mgd)	30-year Growth
PUC	77.1	88.6	76.5	69.5	-10%
Ewa	7.8	10.6	15.3	17.1	119%
Central Oahu	11.5	15.0	19.4	17.8	55%
Waianae	7.7	9.1	9.3	9.2	19%
North Shore	2.3	3.2	2.8	2.9	26%
Koolauloa	1.5	2.9	1.5	1.4	-1%
Koolaupoko	16.0	17.7	19.6	15.9	-1%
East Honolulu	6.2	8.7	10.1	9.3	50%
Total	130.1	155.6	154.5	143.1	10%

Using the estimated population projections for each watershed management plan area and the water demand methodology set forth in the BWS WMP, an estimation of the most probable future demand projections and high-range demand projections was completed for 2050 and 2100. The most probable future demand projection and high-range demand projections are based on the following equations:

*Most probable future demand projection = total population * BWS projected future per capita demand*
*High-range demand projection = [2040 high-range water demand projection] + [incremental future population * BWS projected declining per capita demand]*

The projected gallons per capita day (gpcd) expected for each district in 2040 was used for the 2050 and 2100 forecasted water demands (e.g., 140 gpcd for the PUC, 120 gpcd for Central Oahu, etc.). The results from applying this methodology to estimate future water demands are summarized in Tables 3-4 and 3-5. The Ewa region is projected to have the highest increase in most probable demand. From 2012 through 2050, the projected demand is expected to increase by about 64 percent. Water demands are expected to decrease the most in the Koolaupoko region, with the most probable water demand decreasing by 17 percent between 2012 and 2050. Overall, the total BWS most probable water demand is expected to increase by 10 percent between 2012 and 2050 and by 38 percent between 2012 and 2100.

The high-range projected water demand in Table 3-5 shows an even greater increase in demand between 2012 and 2050, and between 2012 and 2100. The total BWS high-range water demand is projected to increase by 19 percent by 2050 and by 47 percent by 2100.

Table 3-4. Most Probable BWS Water Demand Projection by District.

Source: 2012 and 2040 data from CDM Smith 2016; projections for 2050 and 2100 were extrapolated.

Districts	2012 Actual Demand (mgd)	2040 Projected Demand (mgd)	2050 Projected Demand (mgd)	2100 Projected Demand (mgd)	Change in Demand	
					2012–2050	2012–2100
PUC	67.4	68.7	70.05	78.31	4%	16%
Ewa	18.7	26.7	30.74	54.74	64%	193%
Central Oahu	17.2	19.8	20.71	26.40	20%	53%
Waianae	9.7	8.9	9.18	10.91	-5%	13%
North Shore	3.4	3.3	3.38	4.10	-1%	21%
Koolauloa	1.2	1.5	1.61	2.03	34%	69%
Koolaupoko	18.4	15.3	15.19	14.38	-17%	-22%
East Honolulu	8.9	8.6	8.59	8.48	-4%	-5%
Total	144.9	152.8	159.44	199.34	10%	38%

Table 3-5. High-Range BWS Water Demand Projection by District.

Source: 2012 and 2040 data from CDM Smith 2016; projections for 2050 and 2100 were extrapolated.

Districts	2012 Actual Demand (mgd)	2040 Projected Demand (mgd)	2050 Projected Demand (mgd)	2100 Projected Demand (mgd)	Change in Demand	
					2012–2050	2012–2100
PUC	67.4	74.4	75.8	84.0	12%	25%
Ewa	18.7	28.2	32.2	56.2	72%	201%
Central Oahu	17.2	20.8	21.7	27.4	26%	60%
Waianae	9.7	10.6	10.9	12.6	12%	30%
North Shore	3.4	3.8	3.9	4.6	15%	36%
Koolauloa	1.2	1.4	1.5	1.9	23%	58%
Koolaupoko	18.4	18.4	18.3	17.5	-1%	-5%
East Honolulu	8.9	8.9	8.9	8.8	0%	-1%
Total	144.9	166.5	173.2	213.1	19%	47%

Based on BWS's Strategic Plan Vision of "Water for Life" and mission, to provide safe, dependable, and affordable water now and into the future, BWS developed "Water for Life" drought estimates based on sustainable pumpage goals for each groundwater source. BWS developed normal rainfall and drought estimates based on an assessment of historical source pumpage, head levels, deep monitor well data, and chloride trends (CDM Smith 2016). The difference between the normal rainfall and drought yield estimates is approximately 20 mgd, as shown in Figure 3-4. Future water demands beyond 2040 are shown as a range in the shaded blue region. Per capita demands may decrease through conservation efforts.

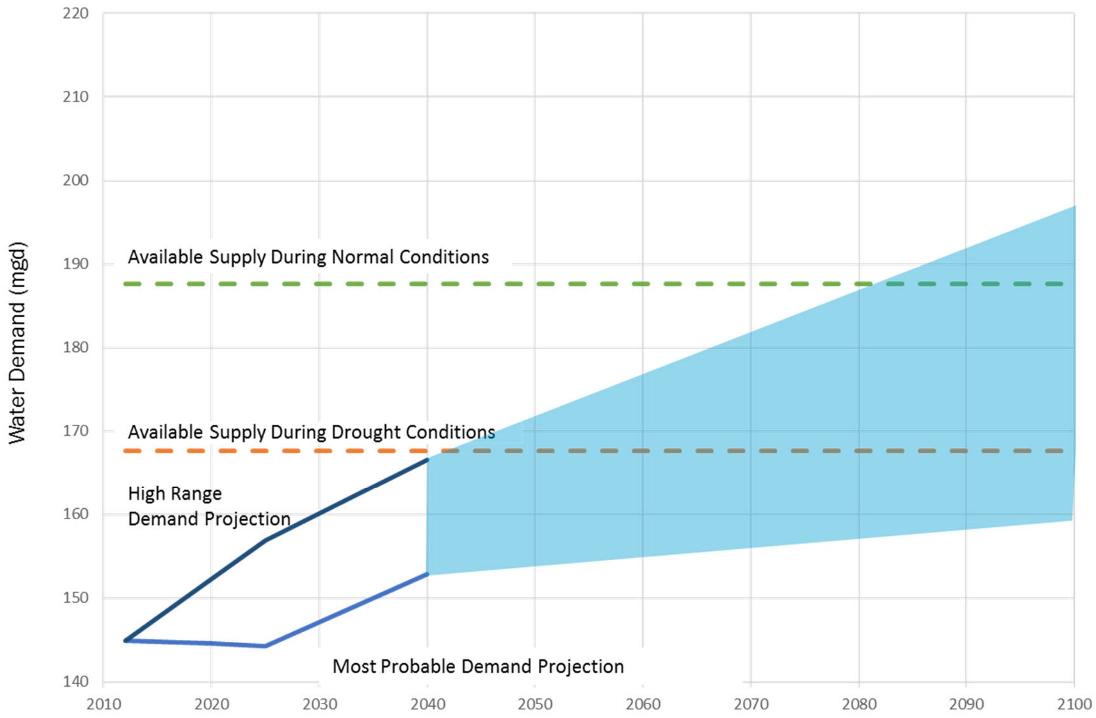


Figure 3-4. BWS Average Annual Demand Projections and Currently Planned Supplies.
Source: Adapted from CDM Smith 2016.

The sustainable pumpage goals effectively establish operating guidelines within the Commission on Water Resource Management (CWRM) permitted use and BWS estimated available supply during normal and drought conditions. These operational boundaries currently provide acceptable guidance and timing for implementation of future adaptation strategies based on the forecast of the most probable and high-range demand projections through 2040. The current 2040 forecast for the high-range demand indicates a future “trigger point” for drought mitigation actions. Projections for the high-range demand beyond 2040 are expected to exceed this drought condition threshold established by BWS.

The projected water demands described in this chapter are based on the assumption that the population continues to change at the same rate that it has averaged over the past 30 years. This assumption does not account for the potentially limited ability of districts to accommodate substantial growth. For example, adequate housing may not be available to accommodate projected growth rates.

For the water demand projections presented in Tables 3-4 and 3-5 for 2050 and 2100, per capita water demands were assumed to remain constant as reflected in the draft BWS WMP for 2040 (CDM Smith 2016). This assumption does not account for increased conservation, increased non-potable water sources, and other factors that could reduce per-capita potable water demand. Additionally, the current projections of water demands do not account for potential reductions in surface water availability due to climate change or more restrictive minimum instream flow requirements. Such changes could affect available irrigation water supply, leading to increased demand for BWS water supply for future agricultural uses. The data shown in Figure 3-4 assume that the amount of supply under various conditions will remain steady through 2100 and do not take into account the potential effects of future climate change.

CHAPTER 4

Vulnerability Assessment

4.1 Scenario Planning and Vulnerability Assessment Approach

Scenario planning is a foresight tool used to develop flexible long-term strategies under uncertainty by helping decision makers think about plausible ways in which the future might play out. The tool helps to define a small number of stories that allow resource managers to rehearse what they might do under a certain set of future conditions, which, taken together, can be valuable in setting strategy and policy for an uncertain future (refer to Figure 1-2). The process (1) identifies two or three critical variables (driving forces such as precipitation, urban development, or sea level rise) believed to be most important to defining a diverse range of plausible future conditions, and (2) builds a small number of scenarios around contrasting combinations of these variables considered key to addressing management issues.

For this project, the following variables were determined to be significant for long-term planning:

- Sea level rise
- Sustainable yield, which is affected by precipitation, temperature, and land use
- Water demand

Scenario planning tools examine a range of plausible futures but are not reliant on known probability distributions. These help BWS and its stakeholders initiate policies and planning activities that address a range of potential situations and assess the time frames needed to make decisions.

Figure 4-1 shows the overall vulnerability assessment approach used in the study. The climate change projections for sea level rise were used to analyze impacts to BWS's infrastructure for each of the sea level rise hazards with coastal erosion being the most severe, followed by marine inundation and groundwater inundation. Each of these hazards was assessed and an overall database was created to assist BWS in prioritizing investments based on overall risk, likelihood of the infrastructure being affected, and the consequence of failure.

An assessment of potentially at-risk bridges on Oahu was not specifically included in this study, however, the vulnerability of bridge infrastructure should be included in subsequent evaluations of climate change impacts as many bridges currently support existing BWS pipeline crossings. A brief discussion of potentially impacted bridges is included in Section 4.2.

Future forecasted temperature and precipitation data were used to assess impacts to BWS's water supply and sources. Increasing temperatures and seasonal declining rainfalls were used to examine recharge and water use permit (WUP) allocations, sustainable yield, and future projected water demands. Given the range of projections using the statistical and dynamical downscaling methods, strategies that are practical for multiple futures were prioritized.

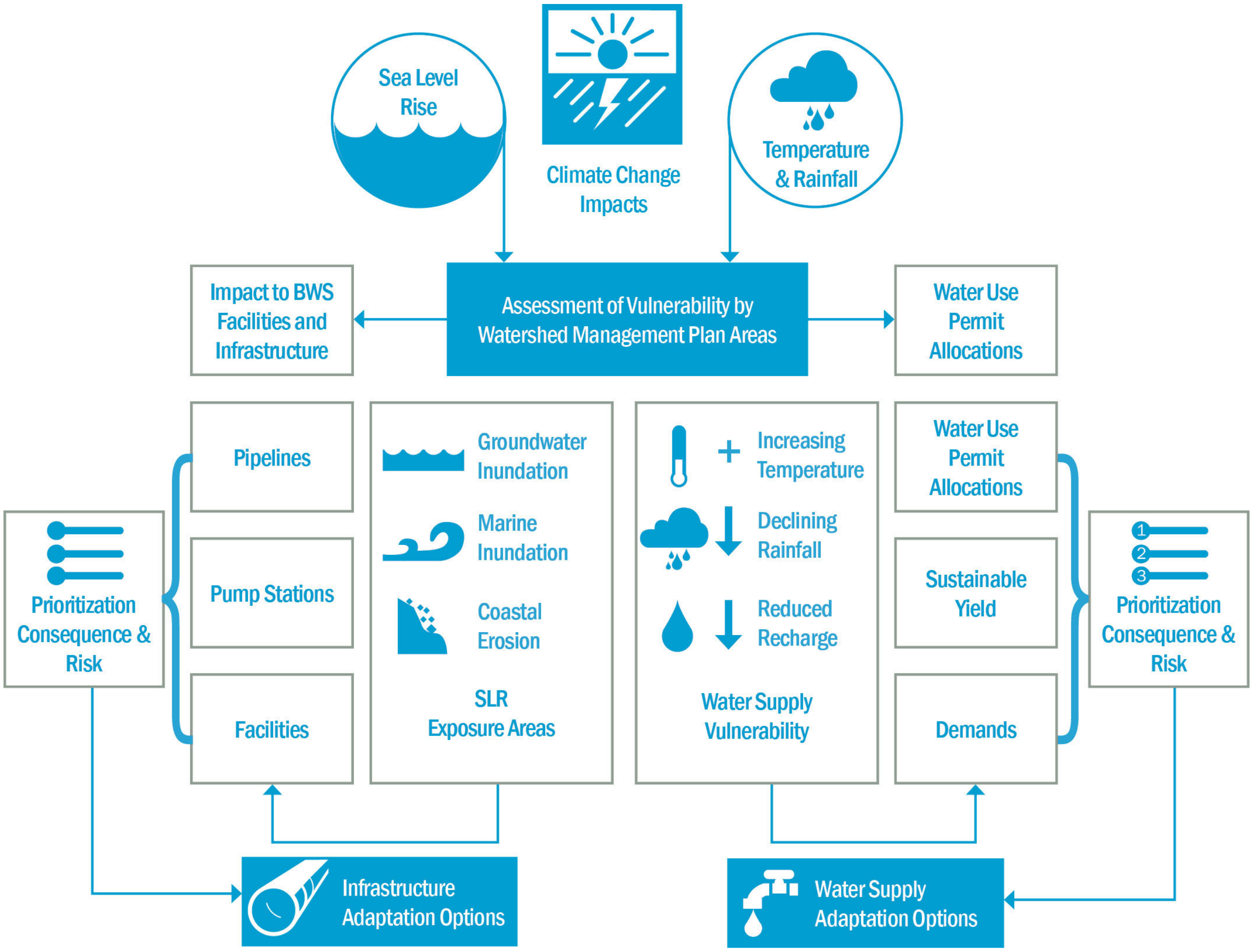


Figure 4-1. Overall Vulnerability Assessment Approach to Identifying Adaptation Strategies.

Section 4.2 describes the detailed approach to analyzing infrastructure vulnerabilities. Sections 4.3 and 4.4 describe the detailed vulnerability approach and assessment results for water supply and water quality, respectively.

4.2 Infrastructure Vulnerabilities

The following sections provide an assessment of vulnerabilities, as well as the approach to prioritize infrastructure risks, to BWS infrastructure as a result of sea level rise hazards. The climate change projections for sea level rise based on RCP 8.5 were used to assess impacts to BWS' facilities and infrastructure for each of the sea level rise hazards: coastal erosion, marine inundation, and groundwater inundation. Of the sea level rise hazards, coastal erosion was determined to have the highest risk followed by marine inundation and groundwater inundation.

4.2.1 Infrastructure Vulnerability Assessment Approach

The entire BWS pipeline database was evaluated for impacts from marine inundation as well as groundwater inundation for all pipe sizes. Impacts to BWS infrastructure from coastal erosion were evaluated within the watershed management plan areas using a desktop assessment, rather than clipping the areas, because of limitations of the erosion data set format. BWS infrastructure, specifically drinking water pipelines, will be impacted by sea level rise as early as 2030. However, to provide a longer planning horizon, impacts were evaluated for the mid-century and end of century periods, 2050 and 2100 respectively.

Originally, the intent of the infrastructure assessment was to provide BWS with a database to understand the impacts from sea level rise at a pipe-specific level for planning CIP projects. However, through discussion with BWS, the team learned about BWS's existing asset risk prioritization tool, referred to as CapPlan, which is being developed to include risks associated with the sea level rise hazards directly. As a result, the scope of the evaluation for this study was refined to focus on the overall scale of the impacts and trends to inform the development of adaptive strategies. BWS will identify specific at-risk pipelines using its CapPlan tool by combining the sea level rise hazards with other critical risk factors in the CapPlan (e.g., predictive break number, traffic loading, proximity to hospital and critical facilities, etc.).

For the evaluation, the full BWS pipe infrastructure database was clipped by the marine inundation and groundwater inundation boundaries to create a database of the impacted infrastructure using ArcGIS geospatial tools, and this area is referred to as the sea level rise exposure area (SLREA). The data were then merged with the eight planning regions so future data could be sorted by region. BWS provided relevant pipe attributes such as pipe length, diameter, material, year of installation, and CapPlan outputs. The full list of attributes can be found in Appendix B.

The clipped data were then exported to an Excel database. Two new attributes were created in the database to indicate the hazard in 2050 and the hazard in 2100. The possible hazard combinations between the planning horizons were then ranked in order of risk based on an understanding of the hierarchy of vulnerabilities from seawater intrusion versus groundwater inundation. Additionally, a pipe segment impacted in both planning horizons was prioritized over a pipe segment that is not impacted until 2100.

4.2.2 Infrastructure Vulnerability Assessment Results

Table 4-1 summarizes the analysis of the infrastructure hazards for two sea level rise scenarios including all pipe diameters ranging from 1.25-inches to 42-inches. The length of pipeline affected by marine inundation increased five-fold with an increase in sea level rise from 1.1 feet to 3.2 feet. The increase in pipe length influenced by groundwater inundation is even more dramatic over the 50-year planning horizon, increasing from approximately 700 feet of pipe to 52,000 feet from 2050 to 2100. As sea level rises, the water table is assumed to rise proportionally, resulting in a significant increase in low-lying areas that will be inundated by groundwater in addition to those impacted by sea level rise.

Overall, the percentage of BWS pipe infrastructure impacted by marine inundation increases from 0.1 to 0.6 percent as sea level rise increases from 1.1 to 3.2 feet (Table 4-1). The percentage of pipe impacted by groundwater inundation was minor (0.01 percent) with 1.1 feet of sea level rise but increased to 0.5 percent with a sea level rise increase to 3.2 feet.

Table 4-1. Pipe Lengths Impacted Island-Wide by Hazard.

Time Period	Planning Scenario Year	Sea Level Rise (ft)	Pipe Length for All Diameters 1.25 in. to 42 in. (ft)		Percent of BWS Infrastructure Impacted[a]	
			Marine Inundation	Groundwater Inundation	Marine Inundation	Groundwater Inundation
Mid-century	2050	1.1	14,038	772	0.1%	0.01%
End of century	2100	3.2	60,409	52,026	0.6%	0.5%

a. Percentage based on the total affected length of pipeline from sea level rise compared to all of BWS's pipelines including potable and non-potable water infrastructure.

Figures 4-2 and Figure 4-3 present the pipe lengths within the marine inundation and groundwater inundation hazard areas by pipe size for the two scenarios, respectively. Most of the pipe lengths impacted by marine inundation in 2050 are 6-, 8-, 12-, and 30-inch-diameter pipelines, while the pipe lengths impacted by groundwater inundation are mostly 8- and 12-inch diameters. In 2100, most of the impacted pipelines are 8- and 12-inch-diameters for both marine inundation and groundwater inundation. The pipe lengths below 8-inch diameter represent 8 to 18 percent of the total pipe lengths impacted between the scenarios.

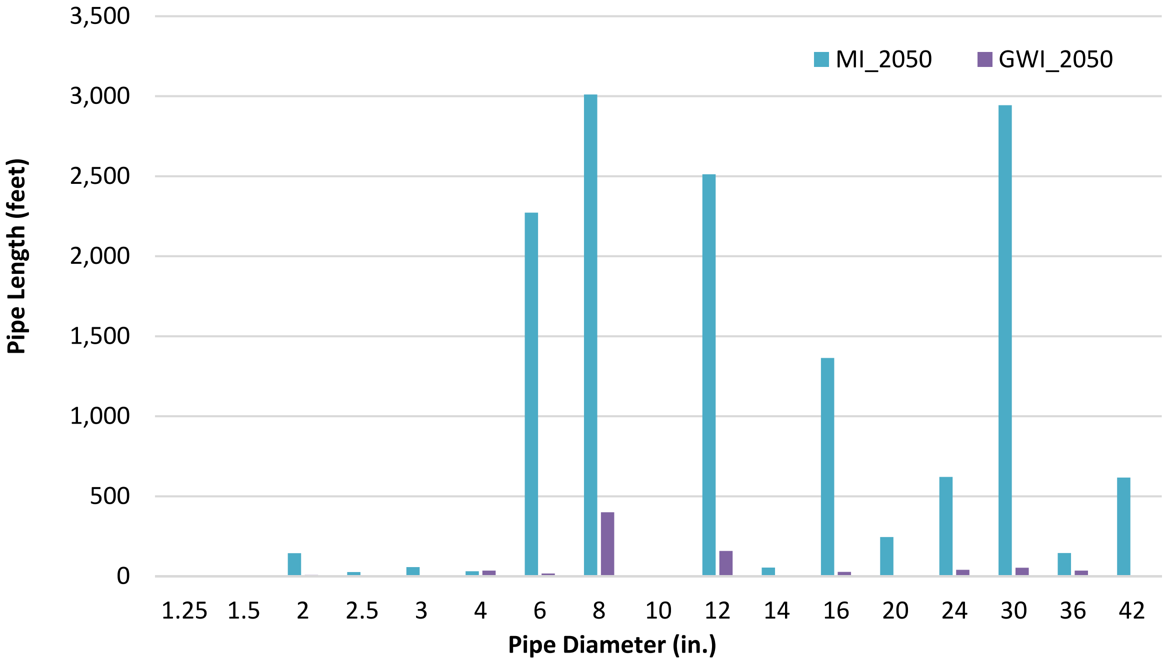


Figure 4-2. Pipe Lengths Impacted by Marine Inundation and Groundwater Inundation in 2050 (1.1 ft Sea Level Rise).

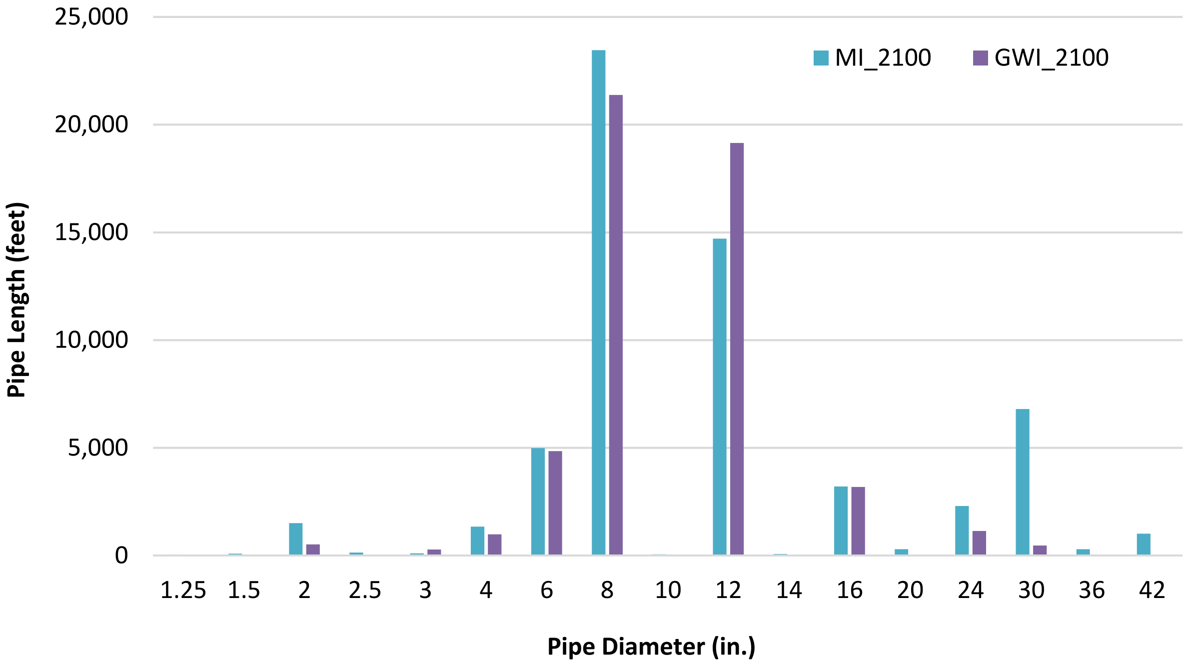


Figure 4-3. Pipe Lengths Impacted by Marine Inundation and Groundwater Inundation in 2100 (3.2 ft Sea Level Rise).

Figures 4-4 through 4-7 distinguish sea level rise exposure by type of pipe material and pipe diameter. With 1.1 feet of sea level rise it can be reasonably expected that 6-inch-diameter or smaller cast iron pipe is likely to be most affected by seawater intrusion, followed by midsize ductile-iron pipe (8- to 20-inch diameter) and 24- to 30-inch-diameter concrete pipe (Figure 4-4). Pipes impacted by groundwater inundation from 1.1 feet of sea level rise will primarily be 8-inch-diameter ductile iron and cast iron (Figure 4-5). With the increase in sea level rise to 3.2 feet, the amount of pipe lengths impacted increased for all pipe types. The distribution of pipe types impacted by marine inundation stayed fairly consistent between the two scenarios, with 8- to 14-inch-diameter polyvinyl chloride (PVC) surpassing concrete (Figure 4-6). In contrast, the dominant pipe type impacted by groundwater inundation was 8- to 14-inch-diameter cast iron (Figure 4-7).

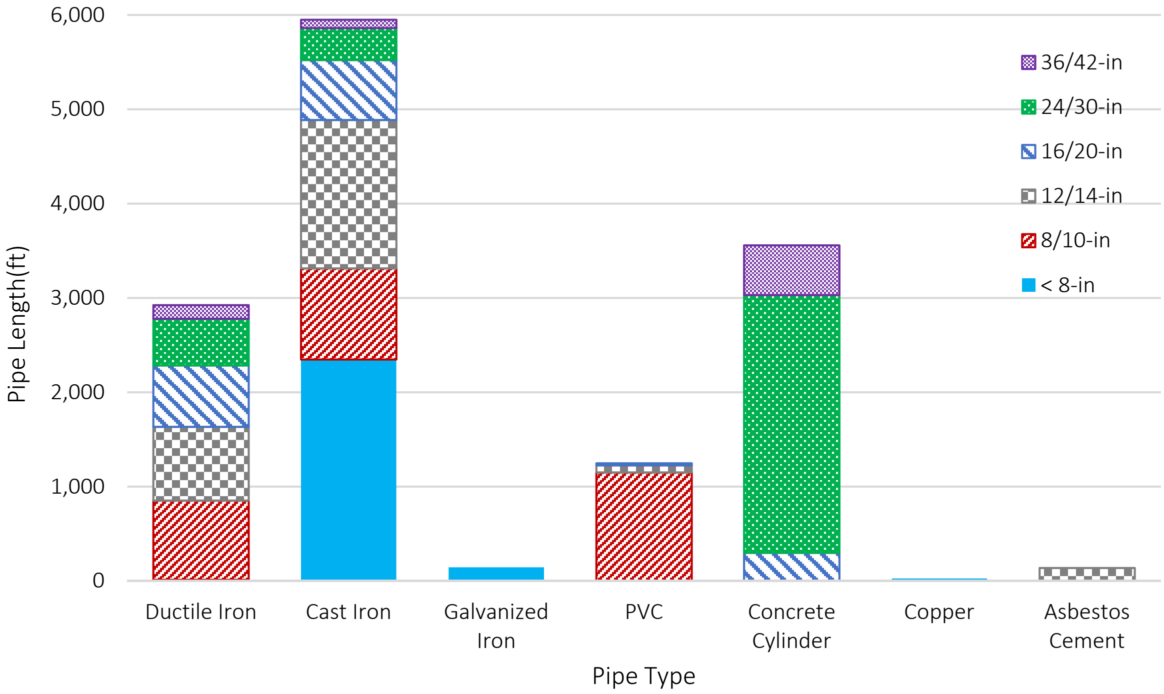


Figure 4-4. Pipelines Impacted by Marine Inundation in 2050 by Pipe Type and Diameter.

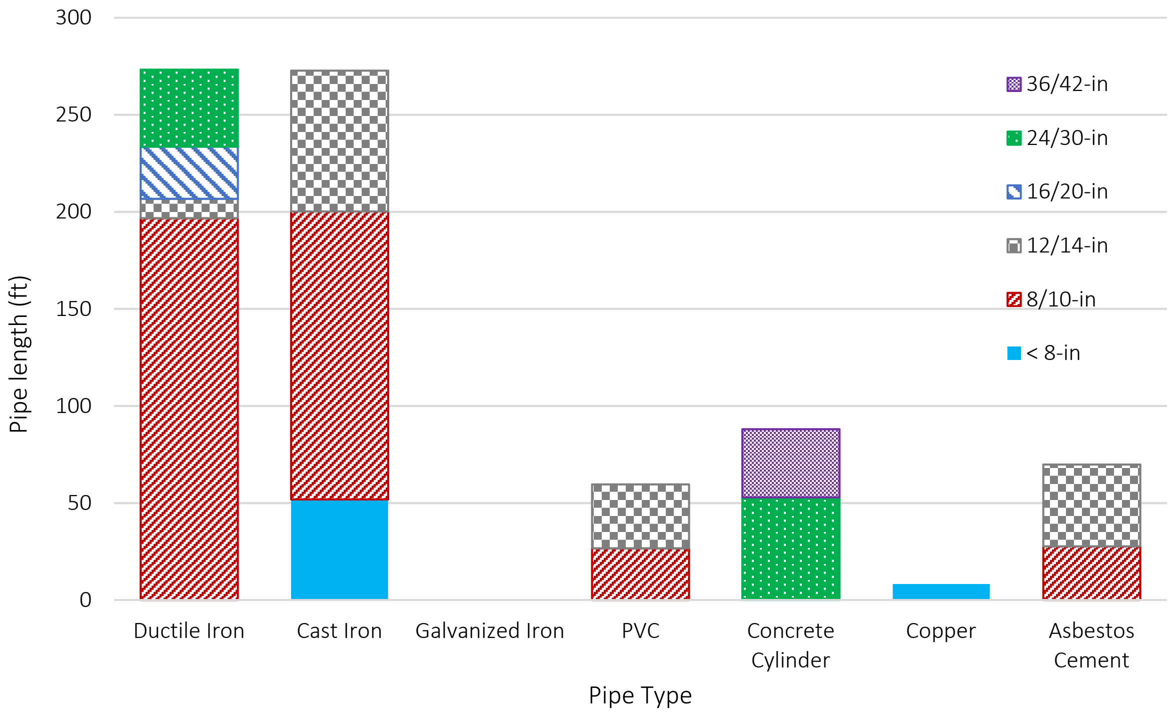


Figure 4-5. Pipelines Impacted by Groundwater Inundation in 2050 by Pipe Type and Diameter.

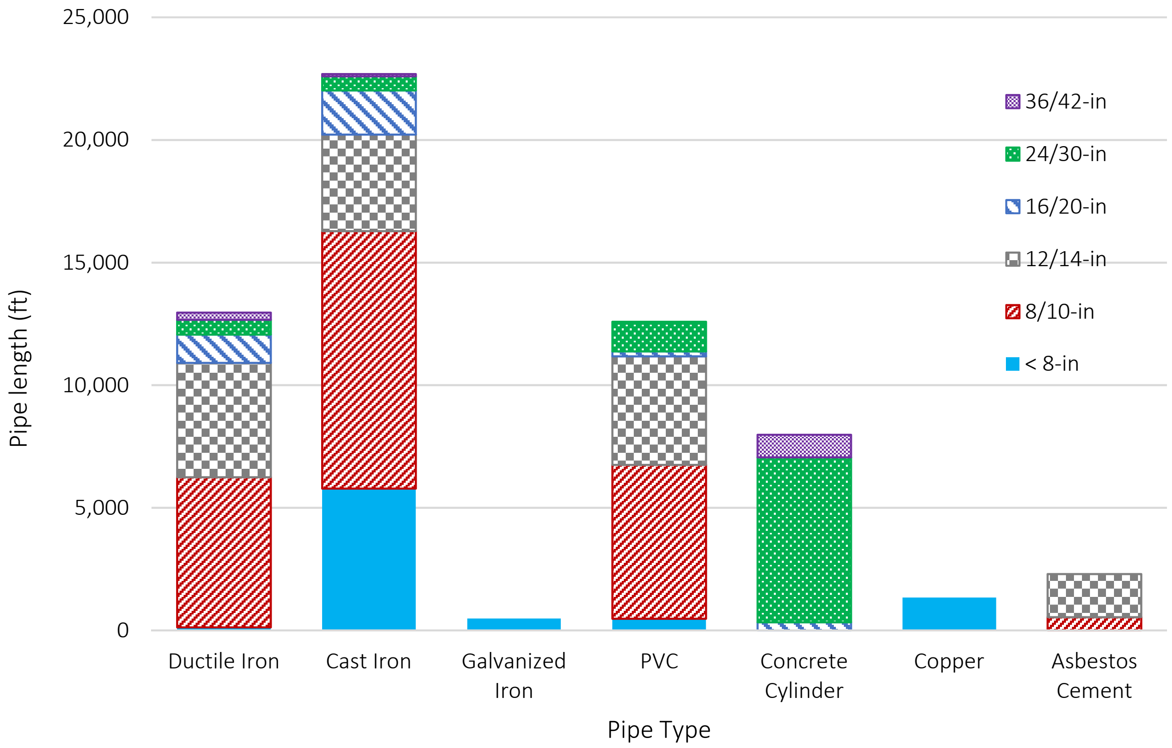


Figure 4-6. Pipelines Impacted by Marine Inundation in 2100 by Pipe Type and Diameter.

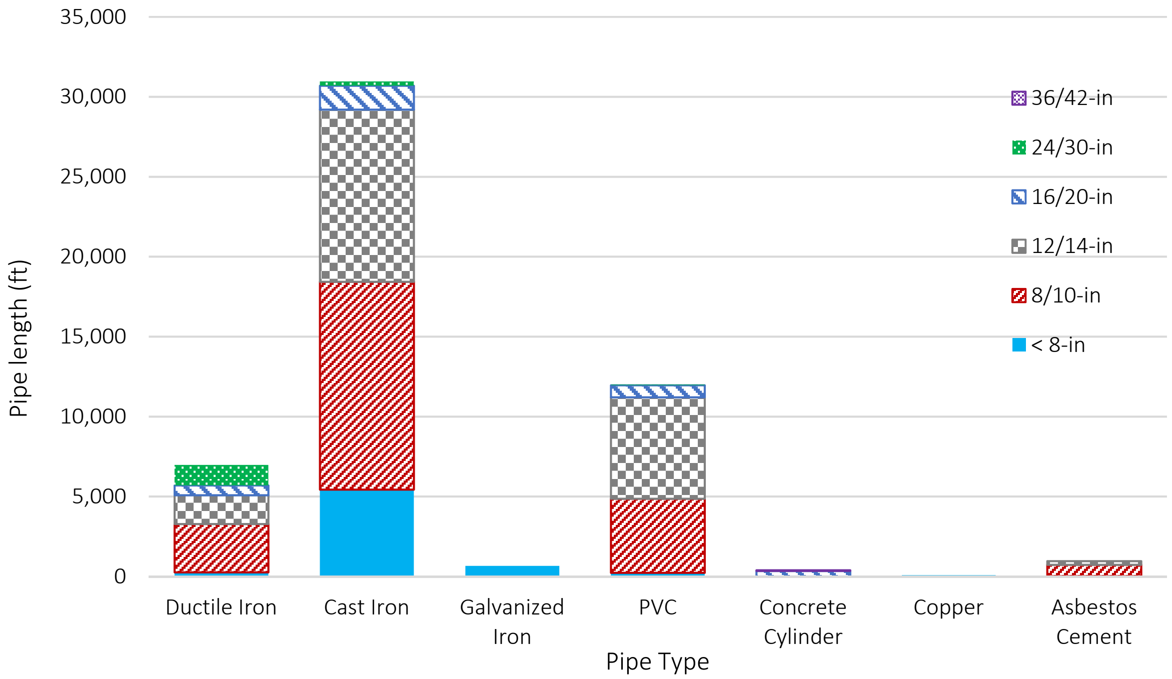


Figure 4-7. Pipelines Impacted by Groundwater Inundation in 2100 by Pipe Type and Diameter.

Tables 4-2 and 4-3 provide a summary of the pipe lengths impacted by marine inundation and groundwater inundation summarized by district. In 2050 Koolaupoko will have the most feet of pipe impacted by marine inundation. However, in 2100, the impacted pipe lengths in the PUC surpass the other areas (about 53 percent). For groundwater inundation impacts, the PUC and Koolaupoko areas have the most pipe length impacted in 2050. Then in 2100, the pipe length impacted by groundwater inundation increased for all areas, but most is within the PUC (about 85 percent).

Table 4-2. Summary of Pipe Lengths Impacted by Marine Inundation Island-Wide.

Watershed Planning District	Year	Sea Level Rise (ft)	Pipe Length Affected by Marine Inundation Hazard (ft)										
			8 in.	10 in.	12 in.	14 in.	16 in.	20 in.	24 in.	30 in.	36 in.	42 in.	Total
Mid-Century													
PUC	2050	1	47	0	980	0	256	0	78	250	0	293	1,905
Ewa	2050	1	0	0	0	0	17	0	0	0	0	0	17
Waianae	2050	1	500	0	167	0	111	113	82	0	0	0	973
North Shore	2050	1	192	0	201	0	415	0	0	0	0	0	808
Koolauloa	2050	1	146	0	472	0	272	132	0	497	145	0	1,664
Koolaupoko	2050	1	2,036	0	472	54	140	0	137	2,197	0	323	5,359
East Honolulu	2050	1	89	0	219	0	153	0	324	0	0	0	784
End of Century													
PUC	2100	3.2	14,571	0	10,691	0	1,511	0	97	261	0	320	27,451
Ewa	2100	3.2	0	0	0	0	20	0	0	0	0	0	20
Waianae	2100	3.2	550	0	173	0	125	125	94	0	0	0	1,068
North Shore	2100	3.2	562	0	613	0	526	0	0	0	0	0	1,700
Koolauloa	2100	3.2	205	0	778	0	441	171	0	666	292	0	2,553
Koolaupoko	2100	3.2	4,405	56	2,202	72	163	0	157	5,871	0	693	13,620
East Honolulu	2100	3.2	3,160	0	254	0	417	0	1,953	0	0	0	5,785

Table 4-3. Summary of Pipe Lengths Impacted by Groundwater Inundation Island-Wide.

Watershed Planning District	Year	Sea Level Rise (ft)	Pipe Length Affected by Groundwater Inundation Hazard (ft)										
			8 in.	10 in.	12 in.	14 in.	16 in.	20 in.	24 in.	30 in.	36 in.	42 in.	Total
Mid-Century													
PUC	2050	1	268	0	0	0	0	0	0	0	0	0	268
Ewa	2050	1	0	0	0	0	0	0	0	0	0	0	0
Waianae	2050	1	42	0	0	0	0	0	40	0	0	0	82
North Shore	2050	1	0	0	68	0	0	0	0	0	0	0	68
Koolauloa	2050	1	0	0	10	0	27	0	0	0	0	0	37
Koolaupoko	2050	1	89	0	80	0	0	0	0	53	35	0	257
East Honolulu	2050	1	0	0	0	0	0	0	0	0	0	0	0
End of Century													
PUC	2100	3.2	17,164	0	17,588	0	2,833	0	630	461	0	0	38,676
Ewa	2100	3.2	1,539	0	1,082	0	0	11	0	0	0	0	2,632
Waianae	2100	3.2	500	0	3	0	0	0	83	0	0	0	586
North Shore	2100	3.2	8	0	272	0	27	0	0	0	0	0	306
Koolauloa	2100	3.2	0	0	8	0	323	0	0	3	0	0	334
Koolaupoko	2100	3.2	1,471	0	192	0	0	0	0	0	35	0	1,698
East Honolulu	2100	3.2	694	0	0	0	0	0	426	0	0	0	1,120

The following figures illustrate the various sea level hazards, using the Waikiki area as a representative example of the other affected regions. Figure 4-8 shows the coastal erosion hazard in a portion of Waikiki for 1 foot and 3.2 feet of sea level rise. Coastal erosion is expected to affect a section of a 16-inch-diameter ductile-iron pipe along Kalakaua Avenue with 1 foot of sea level rise. With 3.2 feet of sea level rise, impact upon larger sections of this 16-inch-diameter ductile-iron pipe is projected as the erosion moves farther inland (Figure 4-8).

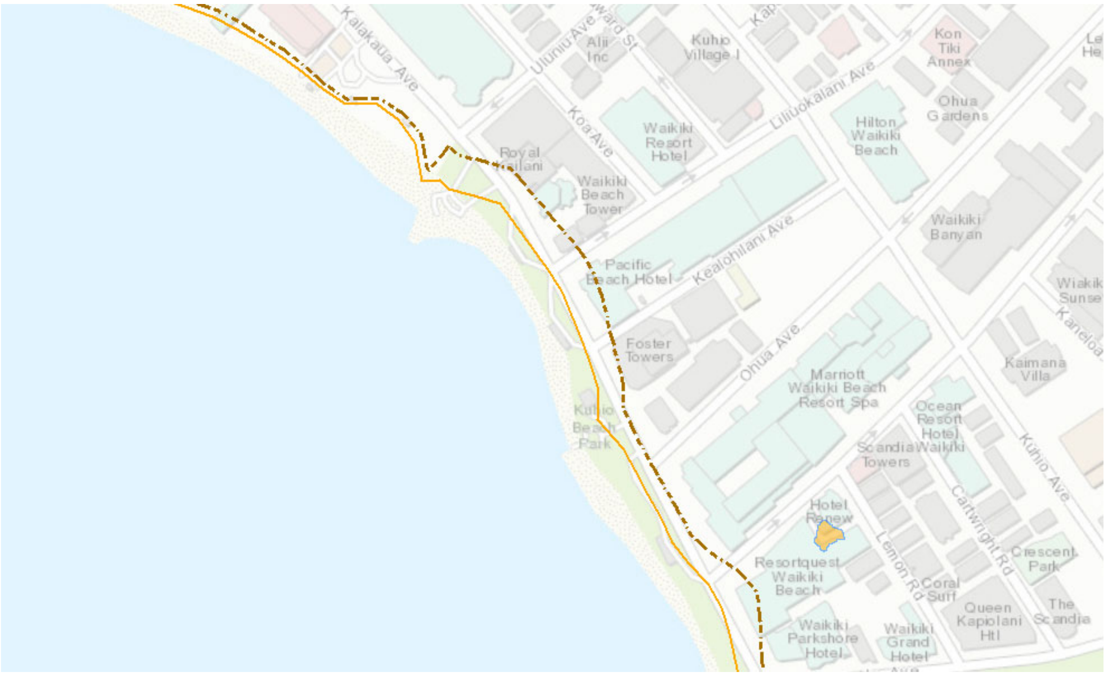


Figure 4-8. Coastal Erosion Impacts along Kalakaua Avenue in Waikiki.
1 ft of sea level rise (orange line) and 3.2 ft (brown dashed line).
Source: Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

Figure 4-9 shows marine inundation (brown outline) and groundwater inundation (red shading) for the Waikiki region. Significant portions of Waikiki (like the area centered around Hobron Lane and bounded by Ala Moana Boulevard, Ala Wai Boulevard, and Kalakaua Avenue circled in Figure 4-9), are projected to be flooded by marine water, whereas other areas near Hausten Street, Date Street, Lime Street, and Paani Street, as well as Ala Moana Boulevard are projected to be impacted by groundwater inundation. Areas north and south of the Ala Wai Canal are similarly projected to be impacted by both marine inundation and groundwater inundation.

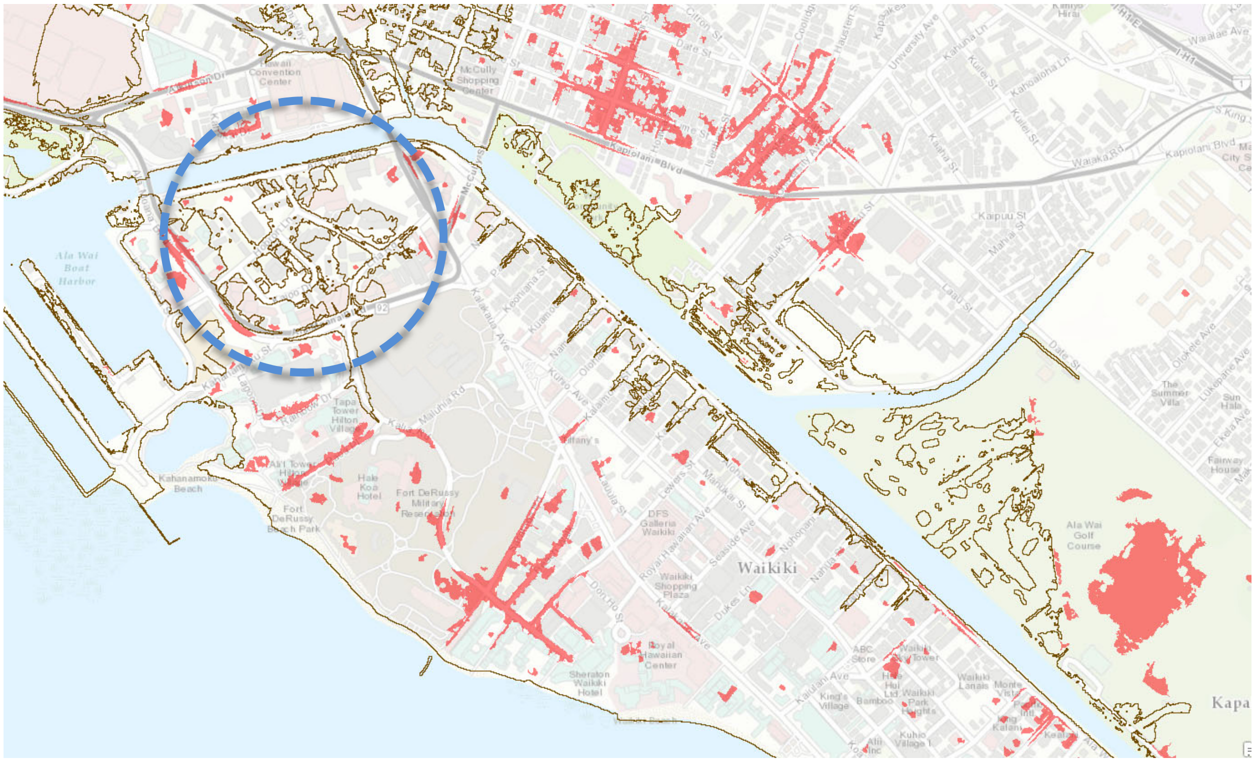


Figure 4-9. Groundwater Inundation and Marine Inundation in Waikiki with 3.2 ft of Sea Level Rise. Groundwater inundation shown in red shading. Marine inundation shown in brown outline. *Source:* Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

Figures 4-10 through 4-12 show the areas inundated in Waikiki from 4 feet, 5 feet, and 6 feet of sea level rise, respectively. Large areas of land are shown to be affected by sea level rise estimates in this range. Accordingly, most infrastructure in these areas near the coastline would be impacted in these sea level rise scenarios.

Figure 4-10. Groundwater Inundation and Marine Inundation in Waikiki with 4 ft of Sea Level Rise.
Groundwater inundation shown in green. Marine Inundation shown in blue.
Source: NOAA 2018.

Figure 4-11. Groundwater Inundation and Marine Inundation in Waikiki with 5 ft of Sea Level Rise.
Groundwater inundation shown in green. Marine inundation shown in blue.
Source: NOAA 2018.

Figure 4-12. Groundwater Inundation and Marine Inundation in Waikiki with 6 ft of Sea Level Rise.
Groundwater inundation shown in green. Marine inundation shown in blue.
Source: NOAA 2018.

4.2.3 Infrastructure Vulnerability Assessment Conclusions

The climate change projections for sea level rise were used to assess impacts to BWS's facilities and infrastructure for each of the sea level rise hazards: coastal erosion, marine inundation, and groundwater inundation. Coastal erosion has the most immediately severe impact, followed by marine inundation and groundwater inundation. A detailed database and GIS maps were created to summarize infrastructure vulnerabilities based on each sea level rise hazard type. This database will be incorporated into BWS's existing CapPlan asset management tool to prioritize individual pipe replacements.

Specific districts are more vulnerable to sea level rise infrastructure impacts. In 2050, the district of Koolaupoko has the most feet of pipe impacted by marine inundation. However, in 2100, the impacted pipe lengths in the PUC surpasses the other areas (about 53 percent). For groundwater inundation impacts, the PUC and Koolaupoko areas have the most pipe length impacted in 2050. Then in 2100, the pipe length impacted by groundwater inundation increased for all areas, but most is within the PUC (about 85 percent).

Adaptation options associated with coastal erosion may be limited to pipeline relocation or hardening. Other utility infrastructure that share these common roadway corridors will similarly be impacted, warranting development of a coordinated adaptation strategy between affected agencies. Pipeline corrosion impacts associated with marine inundation and groundwater inundation were also identified as a potential concern, as evidenced in the findings of the Hampton Roads Sanitation District (HRSD) in Virginia, which assessed corrosion for two pipelines exposed to tidal influences. Some sections of pipe were fully submerged while other pipe sections were subjected to tidally influenced wet/dry cycles. While corrosion impacts apply to both, the HRSD assessment found that the tidally affected pipeline segment had more corrosion on the outside surface.

In addition to concerns about pipe corrosion leading to main breaks, there are also important considerations about maintaining adequate pressures to prevent contamination and the requirements for dewatering during water main repairs or replacements due to increased flooding and rising groundwater levels. Increased dewatering may require longer time frames to complete repairs and may lead to longer service disruptions to the public.

As noted above, an evaluation of potentially at-risk bridges on Oahu was not conducted as part of this study, however, the potential impacts associated with pipeline crossing along existing bridge structures should be noted and included in future assessments. Currently, the main causes of damage to coastal infrastructure is generally associated with storm surge and wave action. In addition to bridge damage caused by debris impact and scour, bridge submergence due to inundation can result in upward hydrostatic buoyancy forces on existing bridge structures. Hydrodynamic uplift and lateral loading on bridges can also occur from storm generated wave actions. Bridge displacement (vertical or horizontal) would damage existing pipeline infrastructure, which currently utilize bridge structures for support/transmission across streams, etc.

Based on a 2011 study (Lum 2011), 11 out of the 26 bridges surveyed around the island of Oahu met the criteria of providing critical service routes and being used for support of existing BWS infrastructure. These bridges, shown on Figure 4-13, included:

- Kuliouou Stream Bridge
- Kahaluu Stream Bridge
- New South Punaluu Bridge
- Ukoa Pond Bridge
- Old Makaha #3A Bridge
- New Makaha #3A Bridge
- Maipalaoa (Maili Channel) Bridge
- Moanalua Stream Bridge
- Kalihi Stream Bridge
- Nimitz Highway (at Aloha Tower Slip Cover #2)
- Nimitz Highway (at Aloha Tower Slip Cover #3)

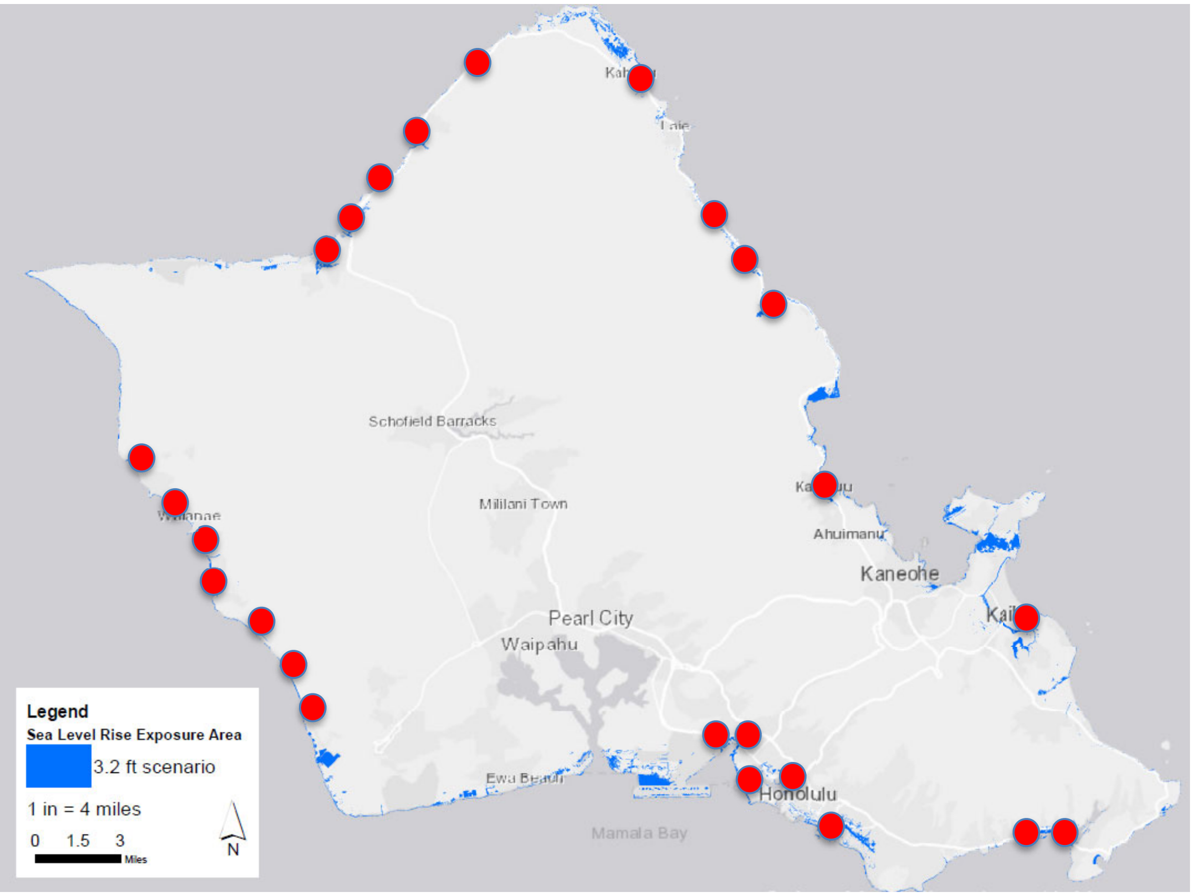


Figure 4-13. Locations of Low Elevation/Coastal Bridge Crossings.

4.3 Water Supply Vulnerabilities

Precipitation shifts and changes in rainfall patterns will have dramatic effects on surface water, groundwater storage, and overall water supply. This section describes the approach used to assess groundwater supply vulnerabilities from future climate change projections.

USGS is a partner on this project, and the original scope of work intended to use USGS water-budget and groundwater flow models to quantify groundwater recharge for select climate and land-cover changes on Oahu and use these recharge distributions in an island-wide groundwater flow model to evaluate the effects of these changes on groundwater availability. The groundwater flow model was going to be evaluated for future groundwater withdrawal scenarios. Preliminary results were expected in 2016, but because of unforeseen issues in the model calibration, the models were not available for this study. Brown and Caldwell developed an alternative approach to estimating impacts to groundwater recharge, which is described in detail in subsequent sections.

4.3.1 Current Sustainable Yield

Groundwater withdrawals are regulated and permitted in accordance with sustainable yields established by CWRM for the 23 aquifer systems on Oahu and were last updated in 2008. The existing sustainable yields assigned to each aquifer system area were determined by CWRM. The Hawaii State Water Code defines sustainable yield as the “maximum rate at which water may be withdrawn from a water source without impairing the utility or quality of the water source” as determined by the CWRM (CWRM 2008, HRS 2013).

According to the 2008 *Water Resource Protection Plan* (WRPP), CWRM inventoried all groundwater hydrologic units and conducted an evaluation of sustainable yield estimates for all aquifer system areas (CWRM 2008). CWRM reviewed the sustainable yield calculation models, recharge calculations, deep monitoring well data, historical pumping data, numerical models for projecting infrastructure safe yields, and other hydrogeologic data and studies. CWRM also compared the previously adopted sustainable yields from 2006 with those projected by other models. Based on that review, CWRM selected the most appropriate sustainable yield for each aquifer system and CWRM reduced Oahu's sustainable yield by 39 mgd in 2008 from 446 mgd to 407 mgd. Figure 4-14 shows the breakdown of Oahu's 2008 sustainable yields (CWRM 2008).

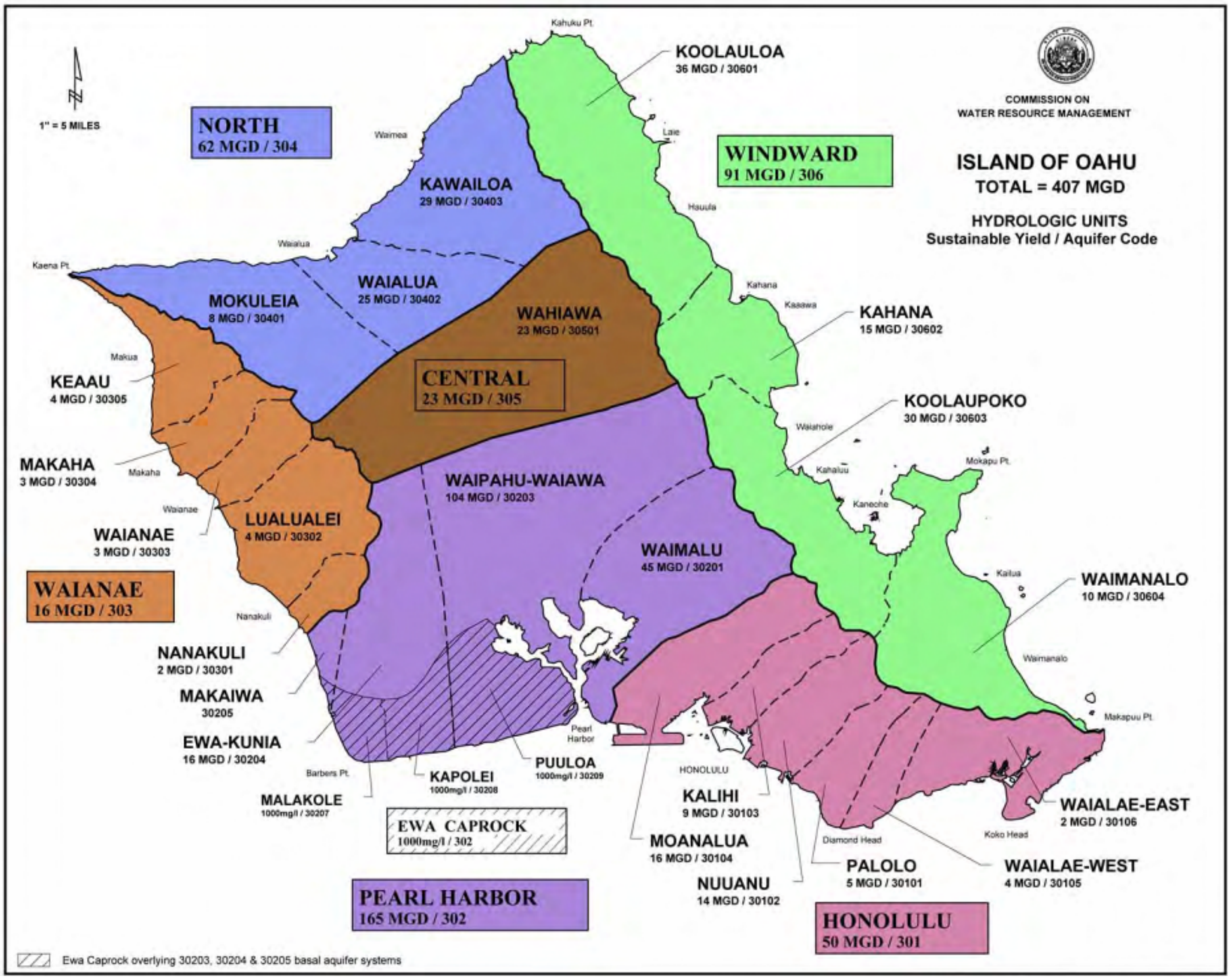


Figure 4-14. Oahu 2008 Sustainable Yields.
Source: CWRM 2008.

The existing source yields determined by BWS, including CWRM-established sustainable yields, may be adjusted upon future forecasts of precipitation and aquifer recharge. Corresponding WUP allocations may also be adjusted in certain areas.

The BWS WMP notes the following:

> Where assessed and permitted use exceeds the normal rainfall estimate, such as in Honolulu and Windward, the BWS goal is to reduce average day pumping to allow the source to recover so more water can be available during drought. Where assessed and

> permitted use is less than normal rainfall estimates, such as in Pearl Harbor, the BWS is intending to apply for more permitted use when growth occurs and more water is needed. (CDM Smith 2016).

Current sustainable yield, WUP allocations, unallocated sustainable yield, and sustainable yield less 2010 water use are determined based on CWRM aquifer sectors and system areas. BWS has also established well yields for each of its groundwater sources for operational guidance during "normal rainfall" and "drought" conditions (see Figure 3-4).

4.3.2 Groundwater Recharge Estimation Approach

The rainfall-recharge relationship was developed by fitting a linear-regression model to current estimates of rainfall and recharge. The linear-regression model was then used to estimate changes in recharge based on projected rainfall from six climate scenarios. The approach was adapted from the methods described by Izuka et al. (2010), wherein single- and multi-segment linear-regression models were developed to describe the relationships between recharge and various explanatory variables (e.g., rainfall).

USGS developed estimates of recharge for Oahu using spatially distributed estimates of water-budget inflows and outflows (Engott et al. 2017). The recharge estimates were based on a 30-year period from 1978 to 2007 and land uses in 2010 (which are referred to as the present period). Inflows to the water-budget model included rainfall, fog drip, applied irrigation water, and water leaking from water-distribution systems and septic systems. Outflows from the water-budget model (excluding recharge) included runoff, evapotranspiration (ET), canopy evaporation, and storm-drain capture. Recharge was calculated as the net difference between all inflows and outflows.

Inflows and outflows were represented by GIS coverages that reflected the spatial variability of each parameter over Oahu. The recharge estimates were calculated by performing a spatial intersection of all inflow/outflow coverages from the water-budget data set (Engott et al. 2017). The spatial intersection produced approximately 400,000 polygons covering Oahu, each with its own unique combination of inflows, outflows, and resulting contribution to the island-wide water budget.

The rainfall coverage used in the USGS water-budget model was downloaded from the Rainfall Atlas of Hawaii (Giambelluca et al. 2013). The rainfall data represent mean annual rainfall over the 30-year period from 1978 to 2007. Other inflows/outflows were estimated from properties such as 2010 land use (e.g., forest, agriculture, developed, grassland, etc.), elevation, slope, fog cover, etc. Rainfall is the dominant source of inflow to the Oahu water budget, representing approximately 93 percent of all inflow. Figure 4-15 shows the spatial distribution of mean annual recharge estimated by USGS (Engott et al. 2017). The spatial distribution of recharge is similar to the distribution of rainfall (Figure 2-5), reflecting the dominance of rainfall as an inflow to the water budget. However, the recharge estimates exhibit more local spatial variability than rainfall due to the effects of the other spatially variable inflows and outflows. The linear-regression modeling approach used to develop the rainfall-recharge relationship is more fully described in Appendix C.

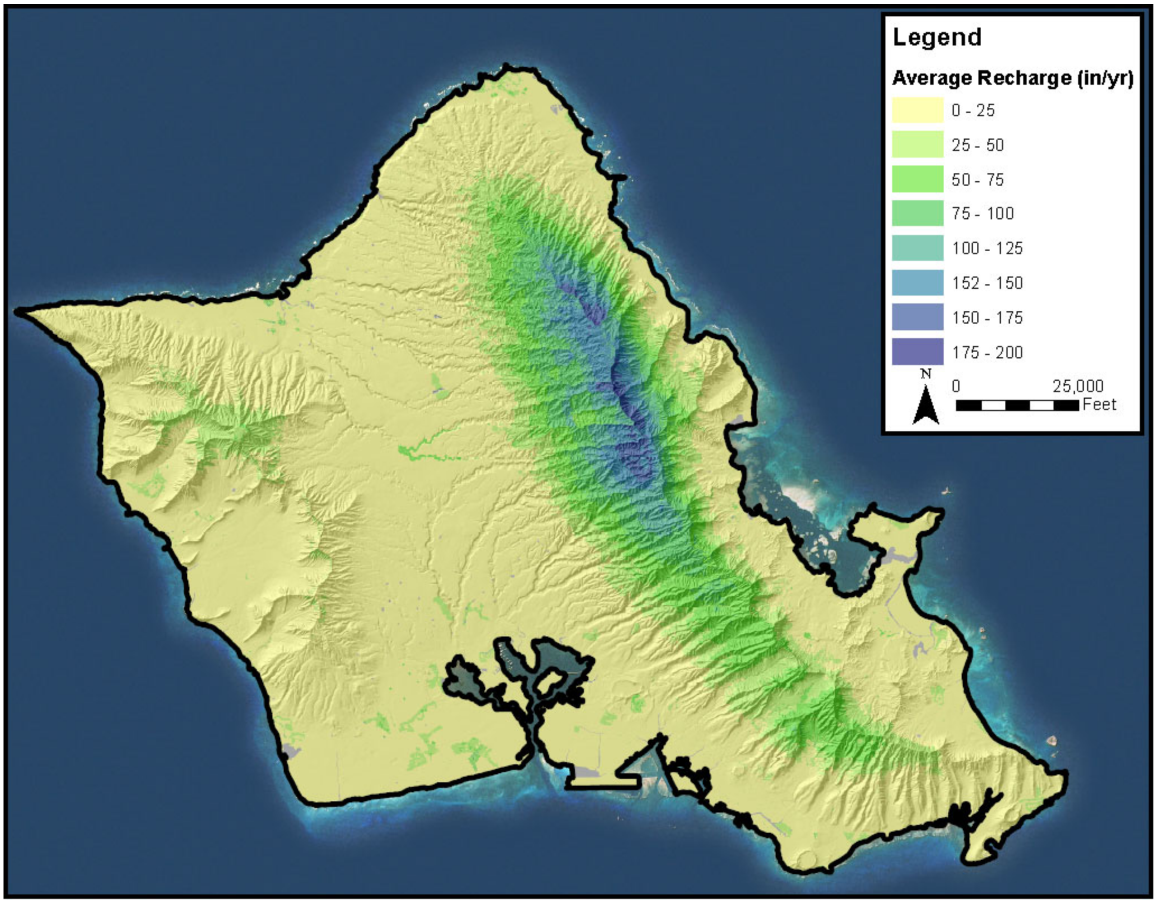


Figure 4-15. Oahu Mean Annual Recharge (1978–2007).
Source: Data from Engott et al. 2017.

Changes in recharge were estimated using three data sets for projected rainfall developed using different climate downscaling methodologies and periods. The first data set represents dynamically downscaled rainfall projections for the period 2080–2099 (Zhang et al. 2016). The second and third data sets represent statistically downscaled rainfall projections for the periods 2041–2070 (mid-century) and 2071–2100 (late-century) (Timm et al. 2015). Each of the three data sets contains rainfall projections based on two GHG RCPs: RCP 4.5 and RCP 8.5, for a total of six climate change scenarios. These six scenarios were evaluated to provide an envelope of plausible futures for mid-century and end-of-century planning.

All calculation steps to determine recharge estimates were implemented digitally using ArcGIS ModelBuilder as detailed in Appendix C. The linear-regression model was used to calculate recharge in both the present and future periods to attempt to minimize the effects of spatial bias in the performance of the model. The alternative would have been to compare the projected future recharge to the estimates of recharge presented by the USGS water-budget model (Engott et al. 2017), which would have introduced significant spatial bias into the estimates of future changes in recharge.

Appendix C contains maps of the projected changes in rainfall for the dynamically downscaled data set. Positive values indicate more rainfall and negative values indicate less rainfall. The changes in rainfall are also aggregated within DLNR aquifer boundaries.

Sustainable yield generally represents a fraction of the precipitation-derived recharge received by an aquifer. This is true for all of Oahu's aquifers, with the exception of the Waipahu-Waiawa, Ewa-Kunia, and Waialua units, which receive interflow from other units. Sustainable yields for Oahu's aquifers were developed using the robust analytical model, RAM or RAM2 (CWRM 2008; Mink 1981; Liu 2007). RAM, and more recently RAM2, have been used to estimate sustainable yields using a simplified analytical process that accounts for temporal variability of simulated inflows and outflows, and aquifer head conditions. The accuracy and utilization of the model relies on several simplifying assumptions for the spatial variability of aquifer hydraulic properties.

The relationship between groundwater recharge and sustainable yield is complicated by other components of the aquifer water budget, but recharge generally remains the dominant source of inflow. Quantification of the impacts to sustainable yield from the projected changes in recharge may require updates to the previous RAM modeling work, a significant effort, and was beyond the scope of this project. However, because groundwater recharge is generally a dominant term in the estimation of sustainable yield, the ratio of recharge to sustainable yield can provide a simple comparison of relative impacts.

To assess the range of potential impacts to sustainable yield, a simplified approach was used to extrapolate the projected changes in recharge to changes in sustainable yield. Following this approach, estimated changes in groundwater recharge from the six climate scenarios were compared to the ratios of existing sustainable yield to groundwater recharge. First, the ratios of current CWRM sustainable yield (CWRM 2008) and USGS groundwater recharge (1978–2007 climate and 2010 land use data) (Engott et al. 2017) were tabulated by aquifer. Then, the potential impacts to sustainable yield were estimated from the projected changes in recharge and the current sustainable yield: groundwater recharge ratio. This extrapolation assumes that the ratio of sustainable yield to groundwater recharge is constant for each aquifer, an assumption drawn from the concept of uniform aquifer properties and boundary conditions. Because the current sustainable yield estimates were derived from RAM modeling work, the simplistic approach of extrapolating sustainable yield from the ratio of sustainable yield to recharge provides only a rough or qualitative estimate of the potential impacts from climate change.

4.3.3 Water Supply Vulnerability Assessment Results

The projected recharge is presented for each of the six climate change scenarios in Appendix C. Within each scenario, projected recharge is calculated for each aquifer. The results shown in Table C-3 indicate a range of possible outcomes for projected recharge, with the potential for both increases and decreases in recharge.

The two dynamical downscaling scenarios of RCP 4.5 and 8.5 project increased recharge island-wide in the 2080–2099 period, which is consistent with the increased precipitation under these scenarios. The RCP 8.5 scenario indicates slightly more recharge (+6.6 percent) compared to the RCP 4.5 scenario (+4.8 percent). Almost all aquifers are projected to experience increased recharge, with increases ranging between 0.3 percent and 21.5 percent. Aquifers that experience decreases are concentrated largely in the northwest corner of Oahu, although projected decreases are relatively small (-0.3 percent to -5.1 percent).

In contrast to the dynamically downscaled scenario, the four statistical downscaling scenarios (RCP 4.5 and 8.5 for the time frames of 2041-2070 and 2071-2100) project decreased recharge both island-wide and within each aquifer due to decreased precipitation. Island-wide, projected decreases in recharge range from 15.7 percent to 24.2 percent. Decreases in recharge are generally more pronounced in the 2071–2100 period compared to the 2041–2070 period. Decreases in recharge are also more pronounced under the RCP 8.5 scenario compared to the RCP 4.5 scenario. Within the aquifers, projected decreases in recharge range between 2.8 percent and 72.1 percent. The figures in Appendix C indicate that, regardless of scenario, the aquifers that experience the largest decreases in recharge are located on the leeward (western) side of Oahu.

The rainfall-recharge regression relationships and projected changes in groundwater recharge from climate change scenarios can inform future water supply planning by comparing demand projections to the range of potential impacts to sustainable yield. The range (minimum to maximum) of projected groundwater recharge based on the six climate projections were used to extrapolate the impacts to sustainable yield. The following are the outcomes of the steps taken to complete the groundwater recharge analysis:

- The current recharge and sustainable yield for each aquifer, along with the lowest and highest projections of groundwater recharge, are provided in Table 4-4.
- Extrapolated impacts to sustainable yield are provided in Table 4-5.
- The current sustainable yields and 2016 total permitted allocation from all groundwater users are summarized in Table 4-6.
- Comparisons of the existing and projected changes in recharge and sustainable yields are shown graphically in Appendix C.
- The Oahu aquifer map, with current and projected future sustainable yields, is provided as Figure 4-16.

It is unknown to the research team which RCM (statistical or dynamical) is most accurate, so both contexts were considered when forming adaptive strategies. Emphasis was put on identifying specific vulnerable land use districts where there was a gap between long-term forecasted demands and projected sustainable yields. If there is excess recharge as the dynamical model projects, there will be less concern related to water supply and more concern for drainage around storm events, which is not in the direct purview of BWS but important when considering sea level rise (see Chapter 6).

Table 4-4. Potential Impacts to Groundwater Recharge by Aquifer Sector.

Source: Aquifer and current sustainable yield estimates from CWRM 2008. Recharge values derived from Engott et al. 2017.

Aquifer Identification, Current Sustainable Yield, and Recharge									Climate Projection Scenarios: Percent Change in Recharge			
Aquifer Sector	Aquifer Unit Name	Aquifer Unit Code	SY (mgd)	SY: Total by Sector (mgd)	RCH (mgd)	RCH: Total by Sector (mgd)	SY/RCH	SY: RCH Ratio by Sector	Low Recharge	High Recharge	Low Recharge	High Recharge
Honolulu	Palolo	30101	5	50	8	74	0.60	0.68	-14.1%	9.4%	-15.4%	10.5%
	Nuuanu	30102	14		19		0.75		-5.6%	9.2%		
	Kalihi	30103	9		11		0.85		-10.2%	9.8%		
	Moanalua	30104	16		21		0.77		-15.2%	9.9%		
	Waialae-West	30105	4		6		0.72		-31.6%	12.2%		
	Waialae-East	30106	2		10		0.20		-31.8%	15.3%		
Pearl Harbor	Waimalu	30201	45	165	63	176	0.72	0.94	-20.7%	9.0%	--23.0%	6.7%
	Waipahu-Waiawa	30203	104		97		1.08		-19.1%	4.5%		
	Ewa-Kunia	30204	16		15		1.09		-54.4%	11.0%		
	Makaiwa	30205	NA		1		NA		-64.8%	8.0%		
Waianae	Nanakuli	30301	2	16	3	37	0.66	0.43	-63.3%	21.5%	-66.4%	5.2%
	Lualualei	30302	4		11		0.37		-62.3%	7.8%		
	Waianae	30303	3		7		0.42		-72.1%	4.7%		
	Makaha	30304	3		9		0.35		-71.9%	0.8%		
	Keaau	30305	4		8		0.51		-61.8%	0.5%		
North	Mokuleia	30401	8	62	22	69	0.37	0.90	-50.5%	-1.7%	-40.7%	5.8%
	Waialua	30402	25		13		1.86		-32.3%	8.1%		
	Kawailoa	30403	29		34		0.85		-37.9%	9.6%		
Central	Wahiawa	30501	23	23	129	129	0.18	0.18	-21.4%	5.9%	-21.4%	5.9%
Windward	Koolauloa	30601	36	91	76	176	0.47	0.52	-31.0%	11.0%	-26.1%	13.4%
	Kahana	30602	15		43		0.35		-22.3%	12.7%		
	Koolaupoko	30603	30		39		0.77		-22.1%	18.2%		
	Waimanalo	30604	10		17		0.59		-23.0%	14.9%		

Climate projection scenarios as summarized in Table 4-1.

Table 4-5. Potential Impacts to Sustainable Yield by Aquifer Sector.

Source: Aquifer and current sustainable yield estimates from CWRM 2008. Recharge values derived from Engott et al. 2017.

Aquifer Identification, Current Sustainable Yield, and Recharge							**Climate Projection Scenarios: Change in Sustainable Yield**							
Aquifer Sector	Aquifer Unit Name	Aquifer Unit Code	SY (mgd)	SY: Total by Sector (mgd)	RCH (mgd)	RCH: Total by Sector (mgd)	Low Estimate SY (mgd)	Change in SY (mgd)	Percent Change SY	Low Estimate SY: by Sector	High Estimate SY (mgd)	Change in SY (mgd)	Percent Change SY	High Estimate SY: by Sector
Honolulu	Palolo	30101	5	50	8	74	4.3	(0.7)	-14.1%	43.3	5.5	0.5	9.4%	55.0
	Nuuanu	30102	14		19		13.2	(0.8)	-5.6%		15.3	1.3	9.2%	
	Kalihi	30103	9		11		8.1	(0.9)	-10.2%		9.9	0.9	9.8%	
	Moanalua	30104	16		21		13.6	(2.4)	-15.2%		17.6	1.6	9.9%	
	Waialae-West	30105	4		6		2.7	(1.3)	-31.6%		4.5	0.5	12.2%	
	Waialae-East	30106	2		10		1.4	(0.6)	-31.8%		2.3	0.3	15.3%	
Pearl Harbor	Waimalu	30201	45	165	63	176	35.7	(9.3)	-20.7%	127.1	49.1	4.1	9.0%	175.5
	Waipahu-Waiawa	30203	104		97		84.1	(19.9)	-19.1%		108.7	4.7	4.5%	
	Ewa-Kunia	30204	16		15		7.3	(8.7)	-54.4%		17.8	1.8	11.0%	
	Makaiwa	30205	NA		1		NA	NA	NA		NA	NA	NA	
Waianae	Nanakuli	30301	2	16	3	37	0.7	(1.3)	-63.3%	5.4	2.4	0.4	21.5%	16.9
	Lualualei	30302	4		11		1.5	(2.5)	-62.3%		4.3	0.3	7.8%	
	Waianae	30303	3		7		0.8	(2.2)	-72.1%		3.1	0.1	4.7%	
	Makaha	30304	3		9		0.8	(2.2)	-71.9%		3.0	0.0	0.8%	
	Keaau	30305	4		8		1.5	(2.5)	-61.8%		4.0	0.0	0.5%	
North	Mokuleia	30401	8	62	22	69	4.0	(4.0)	-50.5%	38.9	7.9	(0.1)	-1.7%	66.7
	Waialua	30402	25		13		16.9	(8.1)	-32.3%		27.0	2.0	8.1%	
	Kawailoa	30403	29		34		18.0	(11.0)	-37.9%		31.8	2.8	9.6%	
Central	Wahiawa	30501	23	23	129	129	18.1	(4.9)	-21.4%	18.1	24.4	1.4	5.9%	24.4
Windward	Koolauloa	30601	36	91	76	176	24.8	(11.2)	-31.0%	67.6	40.0	4.0	11.0%	103.8
	Kahana	30602	15		43		11.7	(3.3)	-22.3%		16.9	1.9	12.7%	
	Koolaupoko	30603	30		39		23.4	(6.6)	-22.1%		35	5.47	18%	
	Waimanalo	30604	10		17		7.7	(2.3)	-23.0%		11	1.49	15%	

Climate projection scenarios as summarized in Table 4-1.

Table 4-6. Projected Surplus and Deficits in Sustainable Yield Based on 2016 Water Use Data.

Source: Aquifer and current sustainable yield estimates from CWRM 2008. Recharge values derived from Engott et al. 2017.

Aquifer Identification				2016 Water Use Data				Projected Range of Sustainable Yield			
Aquifer Sector	Aquifer Unit Name	Current (2008) SY (mgd)	Current (2008) SY: Sector (mgd)	2016 All Permitted Uses (mgd)	2016 All Permitted Uses: Sector (mgd)	2016 Pumping (mgd)	2016 Pumping: Sector (mgd)	Low Estimate SY (mgd)	Low Estimate SY (mgd): Sector	High Estimate SY (mgd)	High Estimate SY (mgd): Sector
Honolulu	Palolo	5	50	5.6	53.1	5.8	43.6	4.3	43.3	5.5	55.0
	Nuuanu	14		15.2		17.1		13.2		15.3	
	Kalihi	9		8.8		5.5		8.1		9.9	
	Moanalua	16		20.0		11.5		13.6		17.6	
	Waialae-West	4		2.8		1.8		2.7		4.5	
	Waialae-East	2		0.8		1.9		1.4		2.3	
Pearl Harbor	Waimalu	45	165	47.0	148.0	37.6	101.7	35.7	127.1	49.1	175.5
	Waipahu-Waiawa	104		85.5		54.5		84.1		108.7	
	Ewa-Kunia	16		15.5		9.6		7.3		17.8	
	Makaiwa	NA		NA		NA		NA		NA	
Waianae	Nanakuli	2	16	NA	NA	NA	5.8	0.7	5.4	2.4	16.9
	Lualualei	4		NA		0.4		1.5		4.3	
	Waianae	3		NA		2.8		0.8		3.1	
	Makaha	3		NA		2.7		0.8		3.0	
	Keaau	4		NA		0.0		1.5		4.0	
North	Mokuleia	8	62	7.6	19.2	0.3	4.3	4.0	38.9	7.9	66.7
	Waialua	25		9.8		3.8		16.9		27.0	
	Kawailoa	29		1.8		0.1		18.0		31.8	
Central	Wahiawa	23	23	23.0	23.0	8.7	8.7	18.1	18.1	24.4	24.4
Windward	Koolauloa	36	91	20.0	33.2	7.1	18.8	24.8	67.6	40.0	103.8
	Kahana	15		1.1		0.8		11.7		16.9	
	Koolaupoko	30		10.3		10.1		23.4		35.5	
	Waimanalo	10		1.8		0.9		7.7		11.5	

Climate projection scenarios as summarized in Table 4-1.

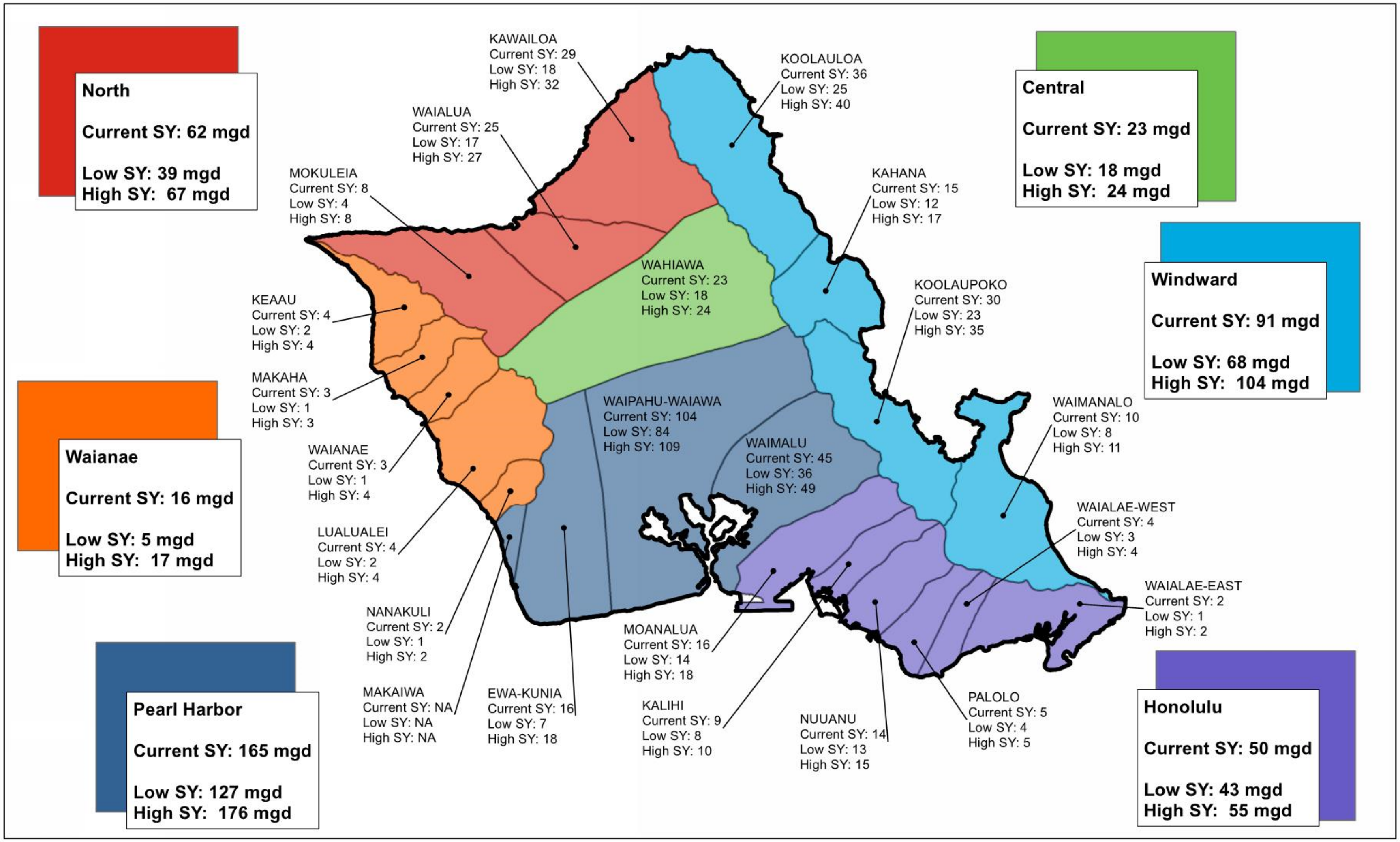


Figure 4-16. Current Sustainable Yields and Potential Range of Sustainable Yields from Climate Forecasts.

4.3.4 Water Supply Vulnerability Assessment Conclusions

The evaluation of potential impacts to sustainable yield and water supply for current/future demand can be summarized as follows:

- The percent change in estimated sustainable yield for the 23 aquifer systems ranged from -5.6% to -71.9% under the "low projections" of recharge, and +0.5% to +21.5% under the "high projections" of recharge.
- Compared against the current (2008) estimate of sustainable yield of 407 mgd, future projections of estimated sustainable yield based upon the various climate change scenarios ranged from a low of 300.4 mgd to a high of 442.3 mgd.
- Island-wide WUP allocations (2016) totaling 276.5 mgd, inclusive of BWS permitted use, is less than the projected low estimate of an island-wide sustainable yield of 300.4 mgd. However, CWRM manages groundwater resources by aquifer system area, and each aquifer system area needs to be evaluated individually for exceedances of sustainable yield.
- Based on the definitions of most probable and high range demand projections in Section 3.3, the most probable BWS water demand projections for 2050 and 2100 were estimated at 159 mgd and 199 mgd, respectively, and the high range BWS water demand projections for 2050 and 2100 were estimated at 173 mgd and 213 mgd, respectively.
- The timing and degree of any future reduction of sustainable yield (and/or WUP allocations) by the CWRM is uncertain but most surely will be based on future trends related to precipitation and recharge across all aquifer systems/sectors.

Estimations of future groundwater recharge and sustainable yields for the Oahu aquifers are provided for comparative analyses and planning purposes. The range of potential impacts to sustainable yield at the aquifer level was used to assess infrastructure and water resources constraints as a function of changing climate conditions. As previously described, the estimation of sustainable yield for regulatory purposes is defined using the RAM. Extrapolated sustainable yield estimates are based only on the ratio of current recharge and sustainable yield extrapolated to the future recharge projections. This simple process overlooks the interflows between aquifers and other source and sink terms that may change in the future but provides an approximate range of conditions to support future planning work. While providing insight to the possible range of impacts to sustainable yield throughout Oahu's aquifer systems, additional recharge analyses and RAM modeling should be completed to assess long-range impacts from climate change following CWRM's framework and approach for sustainable yield updates. This additional effort may provide additional certainty in the modeling of sustainable yield to produce results suitable for regulatory purposes, improving on the planning-level results provided herein.

4.4 Water Quality Impacts

Drinking water sources located along the coastline of Oahu face risks from sea level rise. UH researchers have shown that coastal groundwater levels will rise simultaneously with sea level (Rotzoll and Fletcher 2013). Additionally, a recent study sponsored by BWS showed that this rise in groundwater levels will result in groundwater inundation of large areas of urban Honolulu during periods of high tides (Habel et al. 2017).

Groundwater inundation of coastal areas is a direct result of the underlying aquifer responding to sea level rise. The freshwater lens that makes up the upper part of the basal aquifer will rise, decreasing the depth at which fresh water transitions to salt water. If water supply sources are drawing water at or near this transition zone, this may result in having to seek other sources of drinking water, or potentially increase the need for brackish groundwater treatment to remove salt from the water. If climate change increases the frequency and occurrence of drought conditions, increased pumpage can cause up-coning of the basal aquifer, further affecting water quality and the utility of impacted sources, particularly deep groundwater basal sources. The extent of saltwater intrusion and behavior of the freshwater and transition zone over time due to climate change (e.g., sea level rise and/or declining rainfall) should continue to be monitored by BWS and other agencies.

4.4.1 Chloride Impacts to Drinking Water Sources

Chloride in small concentrations is not harmful to humans, but in concentrations above 250 milligrams per liter (mg/L), or 2 percent that of seawater, it imparts a salty taste in water that is objectionable to many people. By definition, the transition zone is the vertical zone with water quality that varies from 250 mg/L chloride to 19,000 mg/L chloride (approximately seawater). The midpoint of the transition zone is defined as the area in the vertical profile where the water contains 9,500 mg/L chloride. Because the amount of water that can be developed from a freshwater lens for potable use is constrained by the salinity of the water, the elevation of the top of the transition zone (where chloride concentration is 2 percent that of seawater) and the thickness of the transition zone are important. The transition zone is in constant flux, responding to changes caused by variations in pumping and groundwater recharge (CWRM 2008).

BWS has developed an extensive groundwater monitoring program that includes 29 deep monitoring wells and 12 water level monitoring wells on Oahu. Figure 4-17 shows a schematic diagram of a deep monitoring well. BWS uses data from the deep monitoring wells to identify changes in the freshwater lens thickness, while data from the water level monitoring wells are used to observe the changes in groundwater elevation. Together the monitoring wells allow BWS to manage pumping to prevent saltwater intrusion into its drinking water wells. This system of monitoring wells is important to tracking changes in the source aquifers that may be exacerbated by climate change in the future.

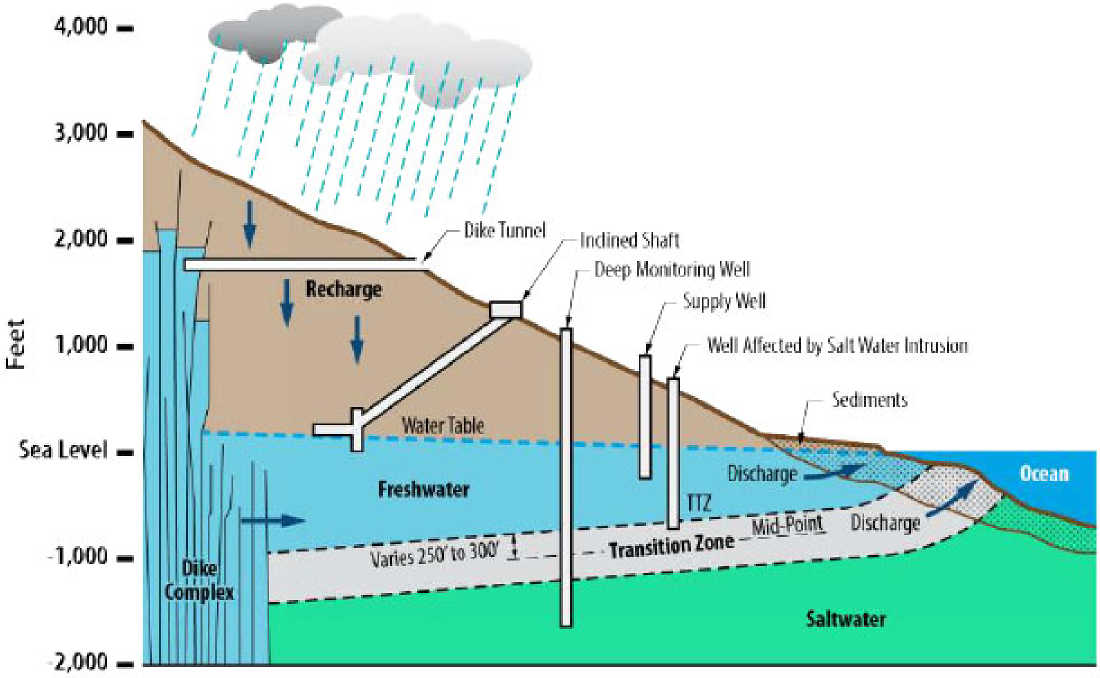


Figure 4-17. Schematic Diagram of a Deep Monitoring Well.
Source: CDM Smith 2016.

CWRM identified 16 well sources or batteries of wells on Oahu (inclusive of BWS and private wells) as being potentially affected by rising chloride concentrations. The specific BWS sources include:

- BWS Beretania Station (1851-12, 1851-13, 1851-24, and 1851-31 through -35)
- BWS Makakilo Well (2004-04)
- BWS Honouliuli I (2303-01, -02)
- BWS Barbers Point Irrigation Wells (2006-14, -15)
- BWS Honouliuli II Well 3 (2303-05)
- BWS Honouliuli II Wells (2303-03, -04)

The pump location/setting of these wells may need to be modified and/or the well may need to be backfilled because of their present depth in relationship to the potential upward shift of the transition/saltwater lens of the basal aquifer. Should pumpage in Pearl Harbor Aquifer Sector approach established sustainable yields, the present potential for saltwater intrusion would be exacerbated with sea level rise. Wellhead protection measures may also need to be enhanced in anticipation of increased flooding and groundwater and marine inundation to mitigate against potential surface contamination.

4.4.2 Sea Level Rise and Cesspools

According to the 2017 Report to the Legislature for Act 125, Oahu has 11,300 cesspools that put 7.5 million gallons of raw sewage into the groundwater and surface waters every day, potentially harming public health and the environment, including beaches, recreational waters, and coral reefs (DOH 2017). The state relies on groundwater for more than 90 percent of its drinking water. Cesspools should be phased out to eliminate threats to drinking water and recreational waters. The Kahaluu Area is assigned as Priority Area 1 with 740 cesspools, while Diamond Head, Ewa, Waialua, and Waimanalo are assigned as Priority Area 3 (see Table 4-7 and Figure 4-18). Many of the cesspools located in the Kahaluu Area are located near perennial streams and overflow because of the wet climate and shallow depth to groundwater (DOH 2017). These streams then transport coral-harming nutrients and bacteria to Kahaluu Lagoon and Kaneohe Bay (DOH 2017).

Table 4-7. Oahu Cesspools by Location.

Source: DOH 2017.

Location	Priority Level	Number of Cesspools	Effluent Discharge (mgd)
Kahaluu	1	740	0.44
Diamond Head	3	240	0.17
Ewa	3	1,100	0.71
Waialua	3	1,080	0.75
Waimanalo	3	530	0.35
Total		3,690	2.42

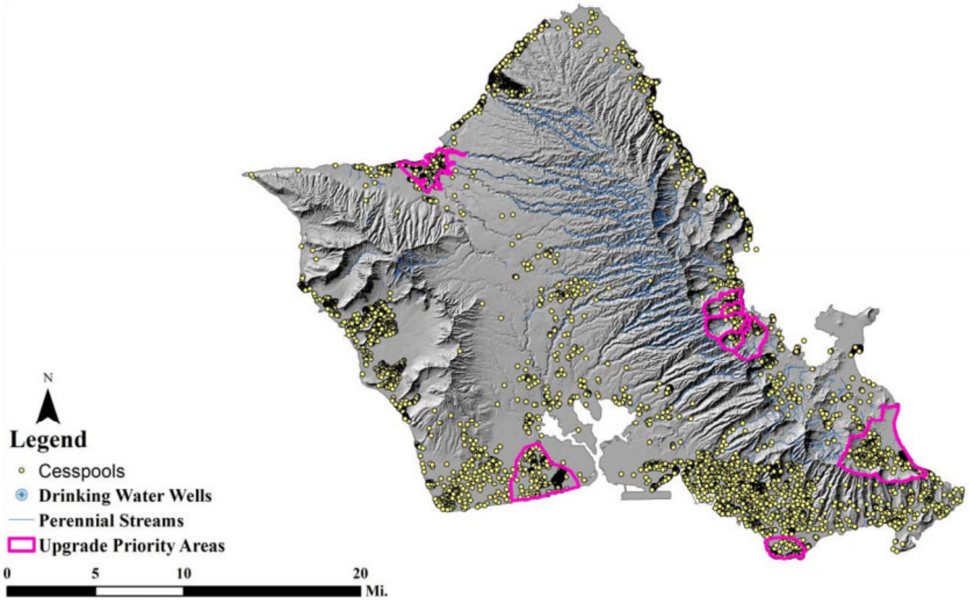


Figure 4-18. Oahu Cesspool Locations, Priority Areas, and Perennial Streams.
Source: DOH 2017.

The State of Hawaii Department of Health (DOH) identified nearly 1,000 cesspools on Oahu that are within 200 feet of the shoreline. These cesspools are at high risk of being inundated because of sea level rise and will result in a degradation of groundwater quality (DOH 2017).

Two legislative acts, Act 125 in 2017 and Act 132 in 2018, require upgrades, conversion, or sewer connection of all cesspools in the state of Hawaii before 2050 unless otherwise exempted. Act 125 requires DOH to evaluate cesspools and develop a prioritization method for cesspool upgrades (Act 125 2017). Act 132 establishes a Cesspool Conversion Working Group within DOH to develop a comprehensive plan for the conversion of all statewide cesspools by 2050 and provides funding to UH in consultation with DOH to conduct a comprehensive statewide study of sewage contamination in nearshore marine areas; and appropriated funding to the DOH to conduct research or gather technical assistance on other issues identified by the Cesspool Conversion Working Group (Act 132 2018). The average cost for cesspool upgrades is $20,000 and based on a statewide total of 88,000 cesspools, the total cost of the required upgrades is estimated at $1.75 billion (DOH 2017).

4.4.3 Water Quality Assessment Conclusions

Evaluation of water quality impacts were limited to consultations with CWRM and the DOH, Safe Drinking Water Branch, and no additional research or specific water quality-related analysis was performed as part of this study. Both regulatory agencies noted ongoing planning efforts to update key components of the Hawaii Water Plan, specifically CWRM's WRPP and DOH's Water Quality Plan, which will incorporate recommended climate change mitigation policies and adaptive measures to protect against future water quality impacts and degradation of existing sources of groundwater supplies.

CHAPTER 5

Adaptive Strategies

5.1 Strategy Development Approach

Impacts of climate change on BWS infrastructure and the effects on groundwater sustainable yield (i.e., water availability/reliability) were the primary focus of this study. Integrating climate change data with information generated as part of this assessment required a decision-making framework to inform and implement specific actions to mitigate and/or adapt to projected impacts. Strategies need to be identified which incorporate utility initiatives such as BWS's WMP, to protect specific assets and to meet agency goals for resiliency and sustainability. An integrated and coordinated approach must be implemented to effectively plan for and address future BWS water supply and infrastructure vulnerabilities.

Some potential adaptive measures may be simply improving existing measures already in place to improve current capabilities or to develop new projects to adapt to climate change. For each adaptation measure, projected costs, timing, and applicability must be weighed in deciding upon actual implementation of repairs, retrofits, and/or construction of new facilities, assets, or water supplies.

A key outcome of this project was the development of a prioritized list of actions for near-term, mid-term, and long-term implementation to address a range of potential changing conditions. The goal being to develop an adaptive planning process that is both iterative and flexible to accommodate future uncertainties and that identify options and strategies to address forecasted water supply and infrastructure impacts.

Identification of no-regrets strategies that provide benefits under current and potential future climate conditions was performed in consultation with BWS, the Technical Advisory Committee (TAC), and the Project Advisory Committee (PAC). Implementing appropriate (no-regrets) strategies can reduce risk while making utilities more resilient to future climate change, ensuring that investments are worthwhile regardless of which climate future unfolds.

Multiple one-day workshops were held with BWS staff, the TAC, and PAC, to inform these individuals of the vulnerability assessment approach and to develop strategies for climate change adaptation. The next several sections describe the adaptation options that were brainstormed, including identification of possible triggers for implementation of these strategies.

The initial workshop engagement identified that one of the first no-regrets strategies was the need for increased collaboration and coordination between City departments (discussed in Chapter 6). In addition to BWS, other agency assets and infrastructure under the jurisdiction of the City and County of Honolulu Department of Environmental Services (ENV) and Department of Facility Maintenance (DFM) and others will also be affected by climate change on Oahu. It is informative and essential that key stakeholders come together to identify potential projects that will be mutually beneficial, to identify cost-sharing opportunities, and to better understand ongoing planning efforts of other entities. Examples of such coordination include but are not limited to, future development within SLREA and addressing water demand and infrastructure requirements for future population growth.

5.1.1 Adaptation Examples from Other Cities

To inform the discussion and brainstorming of adaptation strategies, a literature review of other cities' strategies was conducted. Table 5-1 highlights adaptive strategies by other coastal cities for sea level rise mitigation.

Table 5-1. Other City Adaptation Strategies for Sea Level Rise.

Location (reference[s])	Adaptation Strategies
New York City (City of New York 2013, NYC 2017)	• Barriers • Temporary sandbags • Increasing building code elevation requirements by 16 in. for structures expected to be in use beyond 2040, and by 3 ft for those expected to last to the end of century • Green roof or permeable pavement to relieve stress on drainage systems • Flood Hazard Mapper to view areas of potential flooding
New Orleans/ Louisiana (Coastal Protection and Restoration Authority of Louisiana 2017)	• Floodproof nonresidential structures in areas with projected 100-year flood depths of 3 ft or less • Elevate residential structures located in areas with a projected 100-year flood depth between 3 and 14 ft so that the lowest floors are higher than projected flood depths • Voluntary residential acquisition in areas where the projected 100-year flood depths make elevation or floodproofing infeasible and where residential structures would need to be elevated higher than 14 ft
Miami (Miami-Dade County 2016, Mowry and Kremers 2017)	• Roads were raised and major pumps were installed • Installing up to 80 pump stations throughout the city Site scale: • Elevate buildings • Floodproof buildings • Elevate the height of the interior finished floor elevation • Elevate mechanical systems • Avoid below-grade parking or basements • Augment low-lying agricultural areas affected by rising groundwater levels with additional fill • Increase storage and infiltration of rainwater on site with swales, rain gardens, rain barrels, etc. Neighborhood/block scale: • Redevelop and elevate flood-prone areas • Abandon septic tanks and connect to sanitary sewer networks • Elevate roadways • Increase pump capacities • Install backflow preventers to restrict flow of seawater into the stormwater system • Reengineer outlets of canal to prevent flooding at high tide • Elevate flood-prone areas on fill Regional scale: • Strengthen building codes to require greater freeboard • Limit redevelopment in high-hazard areas to resilient buildings • Retrofit bridges or culverts that are significantly limiting, or are expecting to limit, conveyance in the future
Boston (City of Boston 2016)	• Leverage building cycles: taking adaptation actions within the context of the building cycle can reduce disruption and cost such as installing green infrastructure as part of a road reconstruction project rather than as a standalone project • Decentralized, distributed stormwater storage to be flexible to handle increased storm intensity • Installation of backflow preventers for all buildings with plumbing fixtures below the manhole cover serving the building; prevents sewer from entering back into a building during overflow events • Installation of tide gates on private storm drain outfalls • Hard-engineered coastal infrastructure such as levees, floodwalls, or gates to reduce storm surge • Green infrastructure such as wetlands or living shorelines to protect against chronic flooding events like future high tides or minor storms • Establish a planning flood elevation for zoning regulations in the future floodplain • Retrofit existing buildings to withstand flooding

(continued)

Table 5-1. Continued.

Location (reference[s])	Adaptation Strategies
San Francisco: Ocean Beach (SPUR 2012)	• Beach nourishment • Move roads inland, away from the coast • Construct terraced, vegetated seawall with cobble toe • Place a cobble berm over important buried infrastructure and cover with sand to serve as wave dissipation • Suggested that they conduct pilot studies of dynamic coastal protection

5.2 Infrastructure Strategies

The adaptation of existing infrastructure to climate change can be implemented in part through regular maintenance, upgrades, prevention of damages from extreme weather events, and investments in adaptation to projected hazards. The incorporation of climate change triggers or milestones into planning, design, construction, and maintenance of BWS infrastructure and assets is an appropriate policy approach to address climate change. The benefits resulting from these initiatives would range from enhanced water supply sustainability, increased longevity of infrastructure and other facility assets, and a decrease in future operation, maintenance, and repair costs associated with early implementation of adaptation options.

Accelerated sea level rise and increased vulnerability in coastal areas emphasize the need for prioritized planning and implementation of adaptation strategies. Projected sea level rise impacts based on present scientific research should guide the examination of implementable strategies to protect the natural environment and existing/future developments, including vulnerable population and infrastructure along the coast. Several considerations should be evaluated when determining strategies and making decisions to reduce vulnerability. Key statutes, regulations, and other policies that currently define how State and County agencies are individually responding to sea level rise must be assessed to identify areas of alignment, which can facilitate early implementation of adaptation options.

Specific infrastructure-related strategies currently include replacement of corrosion-prone pipelines, hardening of existing infrastructure (e.g., concrete jacketing of pipelines), and relocation or elevation of existing and/or new pipelines and ancillary facilities in conjunction with future elevated roadways. Implementation, however, of certain measures such as pipeline relocation may be constrained by land availability, including needed coordination with other utility relocation or elevation efforts.

BWS has analyzed its inventory of pipelines to estimate their expected service life, which varies based on the type of material. The WMP developed estimated lifespan projections for BWS pipelines and performed a failure factor analysis, which identified main break factors such as age, pipe material, location (e.g., coastal zones), pressure, and pipe diameter. These data were used to support a subsequent pipeline risk analysis (CapPlan) to rank pipeline segments based on the risk that each segment contributes within the entire pipeline system (CDM Smith 2016).

BWS also performed a pipeline materials and corrosion control evaluation, which included current corrosion control specifications and details, forensic studies on failed cast iron and PVC pipe segments, and consultation with corrosion specialists. No pipeline material changes were recommended and BWS continues to specify/use ductile iron pipe material with Class 53 minimum thickness for better corrosion protection. PVC pipe up to 16 inches in diameter with DF14 wall thickness may be allowed in selected cases for lower-pressure pipes. Further revisions regarding allowable PVC specifications may be forthcoming and use of concrete cylinder pipes is no longer approved by BWS (CDM Smith 2016).

The WMP notes that failure factor analysis and pipeline risk analysis will assist BWS in the prioritization of pipeline replacements with the goal of replacing 20 miles of pipeline per year. Risk-based prioritization together with metrics relating to pipeline system health set forth in the BWS WMP currently guide annual pipeline replacement projects for BWS. Recommended infrastructure adaptation measures include:

- The WMP recommendation (COND-8): "Adopt and apply better-than-current industry 'best practices' for design, material specifications, concurrent use of multiple methods of corrosion control, and a long-term commitment to monitoring and testing of cathodic protection systems" should be fully implemented in preparation for and in response to sea level rise.
- The BWS condition assessments and pipeline analyses should be augmented using future projections of SLREA and coastal erosion to reprioritize potentially impacted pipeline segments.
- BWS's 30-year CIP should be regularly reviewed and prioritized based on new or updated climate change information, existing system conditions, and required infrastructure improvements.
- BWS should also consider a designated annual allocation of its budget for climate change planning and adaptation, with provisions for progressively increased funding based on projected milestones and/or timelines for escalating sea level rise impacts. Early implementation milestones may be based initially on "nuisance" factors (e.g., frequency of intermittent flood events), which can serve as designated precursors to longer-term, more significant impacts of sea level rise.

5.3 Water Supply Strategies

BWS's WMP notes that "there are several issues that could potentially affect Oahu's water supply reliability, such as water quality concerns and climate change. The BWS is actively addressing these concerns by continuously monitoring its system, maintaining operation flexibility, investing in alternative supply sources, and researching the implications of climate change adaptation" (CDM Smith 2016). BWS customers form the largest user base on the island and, as of 2010, BWS's supply comprised 93 percent groundwater, 5 percent recycled water, and 2 percent brackish non-potable water.

BWS currently balances its supply and demand through the following practices and policies:

- Operating groundwater sources within sustainable yields
- Moving water from where it is to where it is needed, taking only what is needed, without causing harm, and without wasting it
- Developing new groundwater sources for growth and reliability
- Protecting and maintaining the quality of drinking water groundwater resources
- Planning for sufficient water for agricultural uses
- Diversifying supply to address uncertainty
- Monitoring trends and adjusting as necessary

The assessment of water supply vulnerabilities related to potential climate change impacts (discussed in Section 4.3) can be summarized as follows:

- Projected changes in groundwater recharge based on specific climate change scenarios can inform future water supply planning by comparing water demand projections to a range of potential impacts to sustainable yield.
- The range of potential impacts to sustainable yield at the aquifer sector and system level can be used to assess infrastructure and water resources constraints as a function of changing climate conditions.

- Additional recharge analyses and RAM modeling should be completed to assess long-range impacts from climate change following CWRM's framework and approach for sustainable yield updates.
- The projected ranges of low to high estimates of future sustainable yield for each aquifer system/sector can be used as an interim guide for water supply planning, particularly with respect to the future availability and transfer of water supply between districts.
- The low-recharge scenario projects a range of sustainable yield reductions from 6 percent to 72 percent, representing the worst-case water supply scenario for BWS. Under the worst-case low-recharge scenario, current in-district water sources may be affected limiting or reducing out-of-district transfers
- Some of the aquifer system areas within the Honolulu Sector are currently over-allocated and over-pumped above the sustainable yield, which was an artifact created when the CWRM aquifer system boundaries were adopted in 1990. CWRM is monitoring conditions to determine whether sustainable yield should be adjusted based on operational experience or whether the allocations and pumpage should be reduced.

BWS appropriately recognizes the importance and need to plan for future water supply uncertainties. Adaptive measures that are planned by BWS include supporting further research in understanding and mitigating climate change impacts, promotion of more aggressive water conservation, continued groundwater monitoring to assess the health and potential change in aquifer condition, adjusting operational practices and procedures to meet current and projected customer demands, and developing alternative sources of potable and non-potable water supplies.

The specific measures being undertaken by BWS to address climate change (identified in BWS's WMP) can be summarized as follows:

- Collaboration with USGS, UH, and other agencies such as the CWRM, to advance the current understanding of future recharge and impacts to groundwater and surface water supplies.
- BWS in cooperation with USGS is also undertaking development and use of a three-dimensional, solute transport groundwater model for:
  - Evaluating source yields to prevent up-coning and saltwater intrusion during normal rainfall and drought events
  - Optimizing the pumping of existing sources
  - Evaluating aquifer sustainable yields as allocations and pumping approach sustainable yield limits
  - Siting and sizing new sources to sustainably develop remaining groundwater supplies
- Increasing operational flexibility within BWS's integrated network of water supply sources and inter-district transfers of water supply in conjunction with current sustainable yield estimates and WUP allocations.
- Increasing supply through diversification of potable and non-potable water supplies to meet projected demands. In addition to new groundwater sources, alternative supply sources include increased recycled water supply and future desalination projects. The Kalaeloa Seawater Desalination Plant is currently targeted for construction in the early 2020 timeframe and will provide an additional 1.0 mgd of potable water supply to the Ewa district of Oahu with the flexibility for further expansion, as needed. The Kapolei Brackish Desalination Plant is also on the planning horizon and is expected to produce an additional 0.7 mgd of potable water supply. A total of 15 to 23 mgd of alternative potable and non-potable sources were identified in the BWS WMP.
- Enhanced water conservation will be advocated and implemented through best management practices and policies, public outreach, and water conservation education to promote behavioral

changes and optimize resource sustainability. The goal is to reduce current demand from 157 gpcd to 100 gpcd or lower.

- Other water conservation measures related to infrastructure design and construction, and system operation and maintenance, include but are not limited to leak detection, repair, and maintenance to prevent water loss; promoting demand-side management programs for large water users; potential expansion of water conservation requirements for new developments (e.g., transit-oriented development [TOD]); and developing new conservation opportunities such as stormwater recapture and reuse, rain barrel catchment, and aquifer storage and recharge.
- Continued watershed management and protection to maintain healthy watersheds that serve a critical function in collecting rainfall and recharging the groundwater aquifer systems through partnerships with government agencies, private landowners, and other stakeholders.

Additional adaptation options developed through the workshop discussions for specific vulnerabilities are summarized in Table 5-2.

Table 5-2. Adaptation Strategies Identified for Specific Water Supply Vulnerabilities.

Vulnerability	Policy	Planning	Operational	Capital Improvement
Extended drought periods	•CWRM can implement water shortage plans •Enhance policy related to existing set points for curtailment (caution, alert, and critical) •Automated shutoffs to irrigation •Mandatory conservation •Develop drought rate structure •Supporting and developing improved El Niño forecasting tools	•Explore pricing structure (e.g., Irvine, California; Boulder, Colorado) •Conservation Tree (more progressively intense) •Onsite reuse of graywater in large buildings for non-potable purposes •Continued update of the Hawaii Drought Plan (Updated in 2017)	•Setting pumping limits to adjust to declining water levels and high chloride levels •Continue to reduce water loss (10.5% now, 8.0% goal)	•Reservoir storage for increased stormwater capture •Drill more wells farther inland •Desalination •Indirect potable reuse through aquifer recharge •Improve infrastructure and the ability to increase/adjust water transfers •Drill additional deep monitor wells and increase rainfall data collection
Reduced sustainable yields	All of the above (except drilling new wells), implementation of water shortage plans, and development of drought rate structures, which will depend on the degree and location of the sustainable yield reduction will apply, including some of the strategies noted for "Increased demand and new water users" and "Shift in saltwater-groundwater interface."			
More extreme rainfall events	•Support stormwater capture and reuse •Form a stormwater utility	•Expand rainwater catchment program for homes •Determine treatment requirements and design standards for stormwater capture and reuse in combination with green infrastructure	•Implement stormwater capture and reuse at existing facilities	•Implement stormwater capture and reuse to reduce runoff during significant rainfall events, including incorporation of: - Stormwater drywell cartridge filtration to filter stormwater for treatment prior to soil infiltration - Use of existing dams, no new dams likely - Large inflatable rainwater catchment devices - Green infrastructure - Minimize site impervious area •Aquifer recharge: water banking
Increased demand and new water users	•Rate structure to promote conservation •New development requiring dual plumbing within bldg. •Encouraging other sectors to use less water and implement more conservation (e.g., ag, military)	•Emergency agreement with Navy	•Optimize source production and transfer of water supply between districts	•Additional storage and development of new sources of potable and non-potable supply
Shift in saltwater-groundwater interface	•Public awareness campaign: promoting increased conservation	•Identifying available surface water resources •Tie land use policy with water policy •Reduce intensive water use development	•Distribute pumping to shallow wells •Adjustment of pumps in well shafts •Wellfield management •Enhanced monitoring of aquifer conditions	•Modify or develop new wells inland •Repeat alternative supplies discussed above

Figure 5-1 shows the projected 2040 in-district demand and out-of-district transfers based on existing estimates of sustainable yield and current WUP allocations. Under the worst-case scenario of potential sustainable yield reductions due to lower rainfall and recharge projections, current inter-district transfers of water supply will need to be optimized and balanced through new wells and greater diversification of water supply sources.

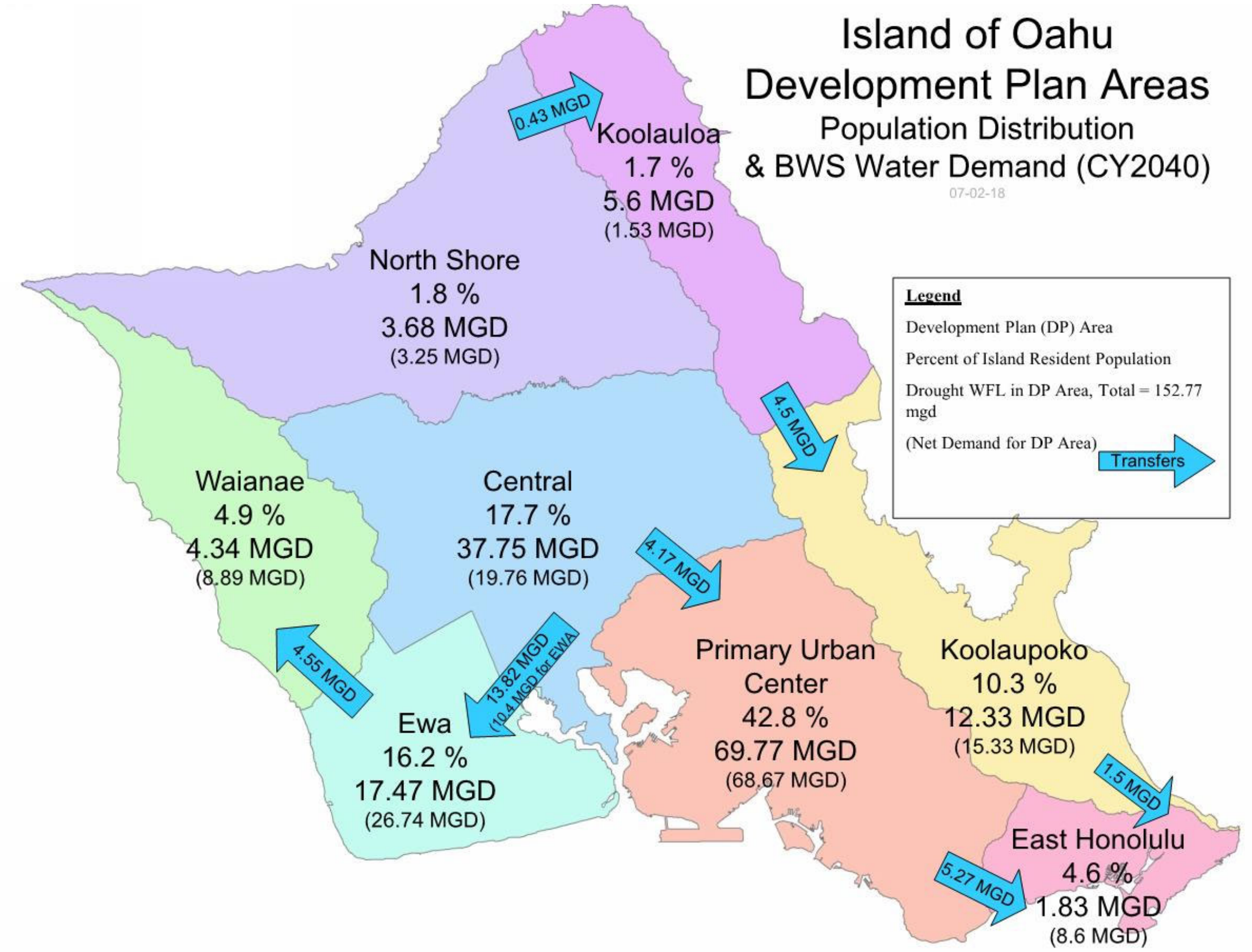


Figure 5-1. 2040 Projected District Demands and Transfers.
Source: BWS 2019.

Water conservation techniques and the use of water-saving devices can also be effective strategies to deal with water shortage due to climate change. Improvement in water supply planning and use will be critical in areas susceptible to drought, requiring closer management of local resources. Other feasible solutions to address the problem of reduced water supply may include incentives to decrease tourism-related water use in accommodations, restaurants, activities, infrastructure, and energy and food production.

BWS is also responsible for the preparation and updating of the OWMP, which comprises eight component parts mirroring the eight planning districts administered by DPP. The OWMP effectively serves as BWS's resource management plan, whereas the WMP represents BWS's infrastructure planning component. The OWMP is required by the State Water Code (Chapter 174C, Hawaii Revised Statutes) and is adopted by ordinance by the City Council (HRS 2013).

Each component part of the OWMP sets forth district-specific policies, watershed and water supply projects, programs, and strategies to address a range of water management-related issues (e.g., groundwater supply, watershed protection, etc.). The respective watershed management plans that make up the overall OWMP are designed to align with the City's land use plans and projections to ensure available water supplies where future demand is projected.

The Waianae, Koolauloa, Koolaupoko, and North Shore Watershed Management Plans have been completed. The Ewa, Central Oahu, and PUC Watershed Management Plans are currently under development with the final East Honolulu Watershed Management Plan to be undertaken shortly. Those plans that are currently under development, including the forthcoming East Honolulu WMP, will be required to incorporate future climate change impacts within their respective assessment of long-range water supply needs.

5.4 Source Water Quality Strategies

Although the impacts of climate change have the potential to affect water quality, much has been done to prepare for and adapt to these changes—such as establishing early warning systems for extreme events, taking steps to reduce vulnerabilities, raising awareness, and ensuring that infrastructure is built to accommodate anticipated future changes in climate. Understanding the threats that climate change poses is the first step in working proactively to lower risks and be prepared.

Changes in water levels and chlorides may not manifest immediately, and the time lag between pumping activities and aquifer response may be several months long, whereby the immediate correlation between pumpage, chlorides, and water levels cannot be immediately determined. Long-term data collection allows for the identification of emerging trends and the monitoring of the effects of natural climatic variations and induced stresses upon the aquifer system. As the demand for high-quality groundwater continues to increase, long-term monitoring data will be essential to determining the response of Oahu's aquifers to climatic variability, changing land use, and increasing withdrawals. Such data will be useful in defining trends, detecting groundwater threats, and determining the best management and adaptive measures.

Chapter III of BWS's Rules and Regulations sets forth provisions for the protection, development, and conservation of water resources to protect and prevent against contamination of groundwater resources. These provisions include monitoring of water levels and chloride concentrations during low groundwater level conditions. Specific voluntary, as well as mandatory, action items have been established for three thresholds (caution, alert, and critical) to protect the utility and water quality of the aquifer during low groundwater conditions (BWS 2010).

The DOH Wastewater Branch has also completed an update of its Reuse Guidelines to promote increased water reuse for activities such as landscape irrigation, which reduces the amount of drinking water that is used for these purposes (DOH 2016). In addition, DOH is working with other agencies and groups throughout the state to increase collaboration, streamline decision-making processes, and promote information sharing related to climate change to help elevate awareness of environmental impacts and the need for adaptation.

On a larger scale, BWS and DOH work together to monitor and protect the island's groundwater resources. This collaborative approach includes:

- Meeting all State and federal drinking water standards and reviewing proposed activities over the potable aquifer system above the "no-pass" zone and within source water protection areas

delineated by DOH, which were based on capture zones using 2- and 10-year contaminant time of travel
- Working with USGS and CWRM to sample and monitor groundwater sources to regularly assess groundwater quality to ensure compliance with State and federal drinking water standards
- Educating consumers about the quality and safety of BWS's drinking water sources and the general public's role in protecting and preserving the island's watershed and water resources

BWS continuously monitors water levels and manages its sources to prevent increased chloride concentrations, which can reduce the utility of existing sources. BWS has some operational flexibility to reduce pumpage at various sources to protect and maintain the viability of these sources. Fourteen groundwater index wells are routinely monitored, and BWS's Rules and Regulations provide for specific responses associated with three low-groundwater level conditions: caution, alert, and critical. Response actions include notices calling for voluntary cutbacks of water use (e.g., reduction of irrigation use), mandatory restrictions, and more aggressive actions such as "increased rates, reduced allocations, flow restrictors on meters, or civil actions" (CDM Smith 2016, BWS 2010).

In the event of water quality impacts, water supply production at affected sources may need to be curtailed or shifted to other aquifer sources that are not impacted. BWS's integrated distribution system currently provides some flexibility to shift supply from one source to another without significant impact to the system or disruption of water supply to its customers.

Proactive measures identified in the BWS WMP that may be implemented in response to water quality impacts include renovating source water tunnels and shafts (as needed) to improve sanitary seals and address drainage issues associated with microbial risks, right-sizing pumps to limit chloride intrusion based on sustainable yield, building blending facilities, and developing new sources (CDM Smith 2016).

The CWRM WRPP recommends that County planning and water departments like the BWS should work together with DOH to integrate protection strategies and plans to ensure that public water systems continue to meet applicable drinking water requirements. Water quality-based strategies and actions should include establishing priorities based on characterization of the resource; defining authorities, roles, responsibilities, and resources and coordinating mechanisms across relevant federal, State, and local programs for addressing identified groundwater protection priorities; and enhancing data collection and management to measure progress and reevaluate priorities associated with all groundwater protection programs (CWRM 2008).

The specific measures being undertaken by BWS to address climate change identified in BWS's WMP can be summarized as follows:

- Continued monitoring of shallow and deep monitoring wells to inform BWS on changes to the salinity profile (i.e., rise in chloride levels) of the island's groundwater aquifer system, and making operational adjustments to ensure that customer demands can be met in a sustainable manner
- BWS will monitor trends to ensure a sustainable water supply and to protect existing sources of water supply from degradation due to pesticides, fertilizers, chemicals, and leaking underground storage tanks to avoid potential contamination of groundwater sources
- Coordinating with entities such as USGS, UH, DOH, and CWRM regarding monitoring, and supporting research to better understand and evaluate potential impacts on the health of groundwater aquifer systems
- Continued public outreach and education regarding water quality, protecting the environment, and managing Oahu's important watersheds (CDM Smith 2016)

5.5 Adaptation Strategies Summary

The following section summarizes the adaptation options and triggers for the specific vulnerabilities. Table 5-3 summarizes some of the adaptation options and triggers. An important indicator for sea level rise is the frequency and severity of “nuisance” intermittent flooding events. These nuisance events serve as precursors to longer-term, more significant impacts of sea level rise. Through collaboration with UH Professor Chip Fletcher, we have proposed the use of this criterion as a recommended trigger for implementing design and construction activities in specific pilot areas (further detailed in Chapter 6).

For water supply adaptation actions, the timing and of the implementation of strategies discussed in Section 5.3 will ultimately be based on future trends and changes in water demand, source capacity, and sustainable yields. Some early no-regrets actions include implementation of more aggressive water conservation and increased well monitoring.

Saltwater intrusion is the main water quality concern identified through this project. Continued monitoring of water quality and development of additional triggers and actions in response to rising trends in chloride concentrations should be developed in consultation with BWS, DOH, and CWRM as a recommended next step.

An important outcome of this effort was the development of a proposed County framework for coordination of agency efforts associated with climate change mitigation and adaptation, which is further discussed in Chapter 6. When embarking on new collaborations or new approaches, it is beneficial to start small and build on successes by first setting a coordinated framework that can be practically implemented and which will be long-lasting. This proposed framework is intended to support and lead to identification of selected pilot areas for which adaptive options can be prioritized and strategically implemented.

Table 5-3. Summary of Adaptation Options and Triggers.

Category	Near-term Strategies (present-2035)	Mid-term Strategies (2035-2050)	Long-term Strategies (2050-2100)	Triggers for Mid-term Strategies
Infrastructure resilience	• Increased collaboration with other County and City of Honolulu agencies through a coordinated framework • Expanded coordination with State, federal, and private-sector efforts	• Implementation of early/phased adaptation measures and strategies for priority/pilot areas	• Expansion of applicable and/or tested strategies to additional regions	• Intermediate scenario for nuisance flooding (24 times per year)
Water supply	• Advancement of research and monitoring • Increased water conservation • Adopt green plumbing code revisions • Supporting watershed management activities	• New source development • Expanded use of recycled water • Supply augmentation through stormwater capture and recharge	• Development of alternative potable and non-potable sources (e.g., desalination or indirect potable reuse and aquifer storage and recovery)	• Well water levels and chloride levels • Projected water demands within 90 percent of available supply during drought conditions • Projected reductions in sustainable yields or WUP allocations by CWRM
Water quality	• Develop triggerable actions for specific chloride concentrations • Implement additional monitoring wells • Investigate borehole flow in deep monitoring wells	• Well optimization (adjustment of pump settings) • Planning and design of brackish groundwater treatment options or other sources of supplies	• Abandonment and siting of new wells or other sources of water supply	• Chloride levels of 250 mg/L

CHAPTER 6

Proposed County Framework for Implementation of Adaptation Options

6.1 County Framework for Implementation of Climate Change Adaptation Strategies

This section identifies key organizations that are responsible for undertaking measures to plan for the effects of climate change. It does not attempt to catalogue all of the individual studies or activities undertaken by each agency to prepare for accelerated sea level rise and focuses on key measures that have been implemented as of August 2018. Other strategic adaptation measures may have been adopted between the time of completion of this study and its final publication.

Many organizations have undertaken planning studies in anticipation of sea level rise, but actual implementation of projects has not occurred nor have significant regulatory actions been mandated. Agencies that regulate land use for development purposes have generally not mandated implementation of adaptation options to address future climate change impacts. However, agencies are now beginning to consider the implications and options available to adapt to climate change impacts.

Successful implementation of climate change adaptation strategies will require significant coordination among multiple federal, State, and County agencies; the private sector; and other affected stakeholders. A major component of this coordination, particularly with respect to the protection of critical infrastructure on the island of Oahu, will need to involve specific agencies within the City and County of Honolulu.

The City and County of Honolulu Office of Climate Change, Sustainability, and Resiliency (OCCSR) was established in 2016. OCCSR is mandated by charter to seek local information from scientists and to track climate change science and potential impacts on City facilities, coordinate actions and policies of departments within the City to increase community preparedness, protect economic activity, protect the coastal areas and beaches, and develop resilient infrastructure in response to the effects of climate change. Additionally, OCCSR is tasked with integrating sustainable and environmental values into City plans, programs, and policies. As a member of the Rockefeller Foundation’s 100 Resilient Cities network, the OCCSR is responsible for developing Oahu’s Resilience Strategy, which will eventually include the City’s first-ever climate action and adaptation plan.

Other key City agencies having jurisdiction and responsibility for planning and implementation of adaptation measures include DPP, DFM, ENV, BWS, and the Department of Design and Construction (DDC). Additional coordination will also be required with the City Department of Transportation Services (DTS) and affected State agencies such as the State of Hawaii Department of Transportation (DOT), DLNR, and others. Though reference may be periodically made to the required coordination with DOT and/or other State agencies, the proposed County framework focuses chiefly on coordination requirements between the City agencies identified above.

6.1.1 Interagency Coordination

The successful planning and implementation of climate change adaptation strategies will require early and continuous interagency coordination starting at the County level. Synchronization of agency plans, particularly infrastructure-related adaptation strategies, will be a key element to the successful execution and accomplishment of agency goals and objectives.

Climate data suggest an accelerated pace of change over the planning horizon of this climate change study (2015 to 2100). Accordingly, future impacts will have important significance for near-, mid-, and long-term (30- to 50-year) planning, and agencies should make informed decisions and take proactive steps based on probable conditions that are not immediately observable.

DFM and ENV will be independently undertaking their own agency-specific evaluations of potential climate change impacts, which may mirror the approach of the BWS assessment and include but not be limited to (1) a vulnerabilities assessment, (2) identification of risks, (3) evaluation and ranking of risks, and (4) identification of adaptation options in anticipation of future climate change impacts. Several initial meetings were held with staff from OCCSR, DPP, DFM, and ENV to inform them about the scope and objectives of this study with the goal of securing early commitment and agreement to develop an interagency framework for collaboration and coordination of climate change adaptation strategies. In addition to these individual agency meetings, the project team presented an overview of the study approach to the City and County of Honolulu Climate Change Resiliency Team (CCCRT) that was recently established by OCCSR. The CCCRT currently comprises OCCSR, BWS, ENV, DFM, DPP, DDC, DTS, and other key City agencies.

Following the discussions with these City agencies, the City Climate Change Commission was formally established in early 2018. The City Climate Change Commission was created by amendment to the City Charter in the 2016 general election, which also mandated the creation of the OCCSR. Its role is to gather the latest science and information on climate change impacts to Hawaii and provide advice and recommendations to the Mayor, City Council, and executive departments as they look to draft policy and engage in planning for future climate scenarios. The City Climate Change Commission consists of five members with expertise in climate change in Hawaii (two of whom currently serve as TAC members on this project).

Following the formal establishment of the Commission, BWS provided an informational presentation to the Commission. The Commission was similarly informed of the current planning approach being used by BWS to identify infrastructure and water supply vulnerabilities and strategies. The goals and objectives of the WRF/BWS project were shared highlighting again the need for collaboration and interagency coordination to ensure successful implementation of climate change adaptation strategies.

6.1.2 Framework for Implementation of Climate Change Adaptation Strategies

In June 2018, the City Climate Change Commission adopted sea level rise guidance and recommendations for Oahu that built upon the State's 2017 *Hawaii Sea Level Rise Vulnerability and Adaptation Report* and other scientific and federal research. Following this guidance, the Mayor issued Directive 18-01 on July 16, 2018 to all City department and agency heads, which set forth the following key directives (Directive 18-01 2018):

- Departments and agencies shall:
  - Align programs wherever possible to help protect and prepare infrastructure, assets, and the public for the physical and economic impacts of climate change
  - Work cooperatively to develop and implement land use policies, hazard mitigation actions, and design and construction standards that mitigate and adapt to the impacts of climate change and sea level rise

- Use the City Climate Change Commission's guidance in their plans, programs, and capital improvement decisions, to mitigate impacts to infrastructure and facilities subject to sea level rise exposure, which may include elevation or relocation of infrastructure and critical facilities, the elevating of surfaces, structures, and utilities, and/or other adaptation measures

Following the issuance of the Mayor's Directive, a State-level Executive Order was drafted and is currently being circulated for review and comments by the Hawaii Climate Change Mitigation and Adaptation Commission. The Governor's Executive Order upon its effect (and as may be amended) sets forth the following similar provisions:

- All executive departments of the State shall assess a range of options for mitigating impacts of sea level rise to infrastructure, critical facilities, natural and cultural resources, and environments including relocation of infrastructure and critical facilities, especially in locations where conservation of beaches and coastal environments is desired
- Directs officials at all levels of government to regard climate change and the need for climate adaptation as pressing matters, to take a proactive approach in mitigating impacts caused by sea level rise, and to develop programs to protect the state for future generations
- Directs officials at all levels of State and County government to work in a coordinated, interagency manner, including through the Hawaii Climate Change Mitigation and Adaptation Commission, to address climate change and sea level rise impacts on natural resources, communities, and land uses in a comprehensive manner

6.1.3 Proposed County Framework for Implementation of Climate Change Adaptation Strategies

It is envisioned that in carrying out the Mayor's Directive (and future Governor's Directive), a County interagency framework will be needed to identify and set forth the following planning information and recommended implementation criteria.

6.1.3.1 Framework Objectives

- To achieve initial integration of stormwater, wastewater, and drinking water planning efforts (by DFM, ENV, and BWS) and corresponding land use planning efforts (by DPP) undertaken in response to potential climate change impacts as guided by the efforts of OCCSR and the City Climate Change Commission

6.1.3.2 Planning Context

- The County framework and its component parts are intended to serve as coordination "guidelines" for implementation of climate change adaptation strategies, which can more effectively inform State and other agencies and the general public

6.1.3.3 Current Operational and Infrastructure Relationships between DFM, ENV, and BWS

- Identification of common operational issues and/or infrastructure assets that may be vulnerable to climate change impacts
- Delineation of prospective climate change relationships between DFM, ENV, BWS, DPP, and OCCSR to initially define the roles and responsibilities of five key City and County agencies with respect to the development of climate change adaptation strategies that may lead to broader and more effective coordination with other County (e.g., DDC, DTS, etc.) and State agencies
- Consideration of legal mandates and specific statutory, ordinance, or other regulatory requirements
- Coordination of recommended plans and climate change adaptation strategies developed by each agency

6.1.3.4 Framework Implementation Plan

- To develop a dynamic planning process that results in a “living document” that can provide County and State decision makers with well formulated options and strategies for addressing future infrastructure, water resource management, and land use development issues
- An initial Implementation Plan for near-term and long-term actions, which describes and outlines a planning approach for effective integration of recommended adaptation strategies between DFM, ENV, BWS, DPP, and other agencies

Figure 6-1 shows a proposed County framework for implementation of climate change adaptation strategies, which lays out the recommended internal coordination between OCCSR, DPP, BWS, ENV, and DFM, and related external coordination with State agencies. The County framework suggests that a parallel and concurrent approach be taken by DFM, ENV, BWS, and other County agencies such as DDC and DTS to identify vulnerabilities and rank risks associated with climate change impacts on stormwater, wastewater, drinking water, and other critical infrastructure, assets, and operations. The identification of adaptation options and mitigation of impacts to critical infrastructure assets should be planned, designed, and ultimately constructed in coordination with each affected agency. CIP projects should be appropriately sequenced and funded in alignment with the integrated objectives of each agency, leading to more effective and cohesive implementation of selected adaptation strategies, CIP project scheduling, and financing.

The coordinated efforts of CIP project identification, financing, and implementation by DFM, ENV, BWS, and other County agencies should be supported in parallel by the planning and policy setting efforts of DPP and OCCSR. Approval of development projects such as TOD should be similarly guided by the policies and directives established by DPP. As envisioned by the Charter amendment, OCCSR should lead and champion the coordination of City adaptation efforts at all levels of the County in coordination with the State and other entities. Adopting and implementing this proposed County Framework for Implementation of Climate Change Adaptation Strategies appropriately responds to and comports with the Mayor’s Directive 18-01 and recommended guidance of the City Climate Change Commission.

Accelerated sea level rise will only heighten the need to address current vulnerabilities and examine the costs and benefits of taking adaptive actions in a coordinated and effective manner. Determining where, what, and when to implement specific actions and justifying the cumulative expenditure of resources needed can best be accomplished under a coordinated framework. Agencies working in concert with each other, as opposed to independently, will be better informed and able to address the uncertainty, timing, and magnitude of future climate change impacts.

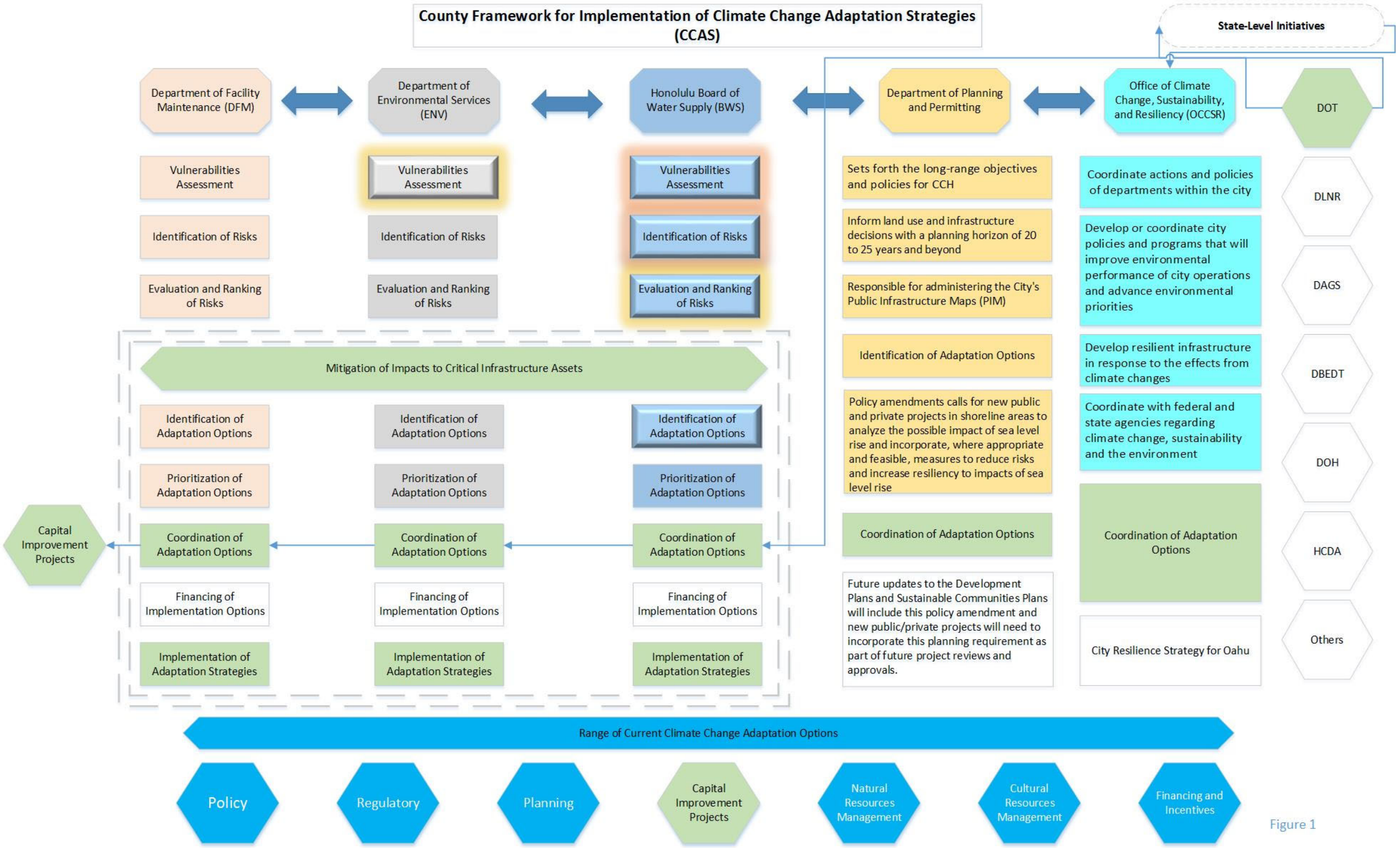


Figure 6-1. County Framework for Implementation of Climate Change Adaptation Strategies.

6.2 Road Map to Climate Change Resiliency

OCCSR conducted a Resilient Oahu Workshop with stakeholders across Oahu to share information and develop initial recommendations to help shape a resilience strategy for Oahu. More than 140 stakeholders from 19 sectors and representing 117 organizations participated in this workshop.

In diagnosing and prioritizing resilience issues on Oahu, infrastructure failure was identified as one of the "Top Shocks," defined as sudden, sharp events that threaten a city in a short time frame, and rising sea level was identified as one of the "Top Stresses," defined as having the ability to weaken the fabric of a city on a daily or cyclical basis. Providing for and enhancing natural and man-made assets, which included the sub-categories of "safeguards for critical infrastructure" and "redundant diverse infrastructure," was identified as one of the top weaknesses by the workshop participants.

Discussions with OCCSR led to the development of a draft Road Map to Climate Change Resiliency (Road Map) incorporating the planning scope of the WRF/BWS project, the proposed County framework for implementation of climate change adaptation strategies, and the current goals and mandates of the OCCSR. The draft Road Map integrates OCCSR's vision and objectives for Oahu's Resilience Strategy, the goals of the CCCRT, and the guidance of the City Climate Change Commission and Mayor's Directive 18-01.

Successful implementation of climate change adaptation strategies will require coordination and integration of both public- and private-sector efforts. With respect to protection of infrastructure alone, coordination with multiple private-sector utilities, such as Hawaiian Electric Company, Hawaii Gas, Hawaiian Telcom, Spectrum, and others will be needed along with the required interagency coordination between affected State and County agencies proposed in the County framework.

6.2.1 Government and Public Utilities Task Force

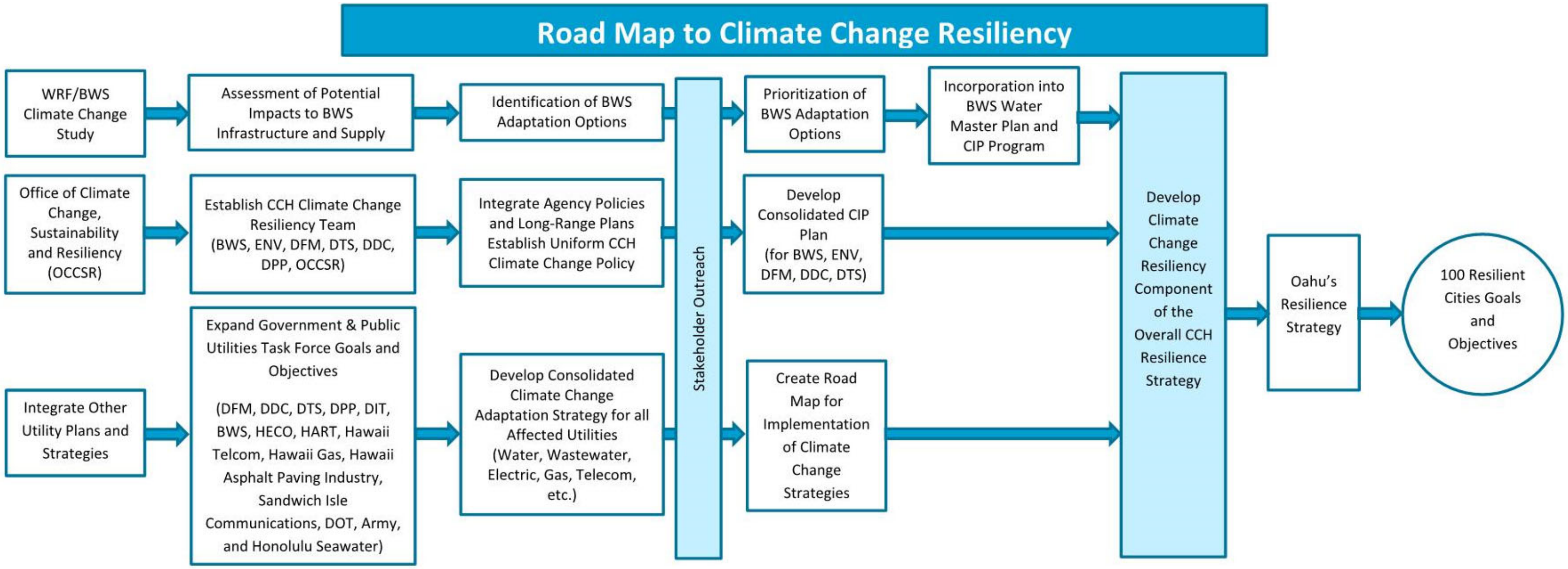
Existing intergovernmental and private-sector working groups or ad hoc committees should be used to carry forth the discussion and preparations for climate change adaptation rather than establishing new or duplicative committees for this purpose. One example of this is the Government and Public Utilities Task Force, which meets monthly and currently includes the following members:

- DFM
- DDC
- DTS
- DPP
- Department of Information Technology
- BWS
- Honolulu Authority for Rapid Transit
- Staff representing the City Council
- Oahu Metropolitan Planning Organization
- Hawaiian Electric Company
- Hawaii Gas
- Hawaii Asphalt Paving Industry
- Sandwich Isle Communication
- Honolulu Seawater Air Conditioning, LLC
- DOT
- State Department of Commerce and Consumer Affairs
- DOH, Hazard Evaluation and Emergency Response Office
- Staff representing the Public Utilities Commission

- U.S. Army

The proposed Road Map shown in Figure 6-2 incorporates the proposed County framework and the integration of agency policies and long-range plans to establish a consolidated implementation plan leading to the desired development of an overall Oahu Resilience Strategy. The draft Road Map envisions integration of other utility plans and strategies, expansion of the current goals/objectives of the existing Government and Public Utilities Task Force, and development of a consolidated climate change adaptation strategy for all affected utilities (e.g., water, wastewater, electric, gas, telecom, etc.). The suggested parallel planning process also identifies a strategic direction, the means for establishing collaborative partnerships, and mechanisms for addressing financial viability for implementation of adaptation strategies.

Preparing for sea level rise, however, has been the exception rather than the rule, and efforts to plan for sea level rise have been impeded by many obstacles including institutional barriers, government policies including flood insurance maps that do not consider sea level rise, and lack of plans delineating which areas should be protected or not as sea level rises. The proposed Road Map, which would need to be adopted by the identified agencies, is intended to stimulate focused discussion starting with the Government and Public Utilities Task Force and other affected agencies, private-sector parties, and key stakeholders who share the common goal of achieving climate change resilience.



Strategic Direction	SET GOALS
	• Climate change adaptation goals and key performance indicators established for water, wastewater, stormwater, and planning policies.
		GATHER SUPPORT
		• BWS, ENV, DFM, DPP, DDC incorporate climate change goals and key performance indicators into collaborative strategic plan.
		• OCCSR established as the CCH lead for coordinating agency strategies and policy development.
			PRIORITIZE AND IMPLEMENT
			• Climate change initiatives are prioritized using tools such as:
			  • Strategic Business Planning
			  • Effective Utility Management (EUM)
			  • Environmental Management Systems (EMS)
			• Utilize "triple bottom line" approach for climate change decision-making.

Collaborative Partnerships	EVALUATE OPPORTUNITIES • Identify and analyze opportunities for collaboration on climate change adaptation projects (e.g., joint venture, state/county, public/private partnerships).	ESTABLISH CONNECTIONS • Formalize agreements (MOUs, MOAs, contracts, etc.) with partners to facilitate data exchange and planning with water, wastewater, stormwater, and other applicable utilities/agencies. • Climate change planning efforts are integrated with other agencies regarding implementation of adaptation projects and coordination of resources.	LEVERAGE RESOURCES • Establish partnerships to maximize available funding to implement strategic projects/programs. • Pursue interagency and partnership opportunities to reduce carbon footprint/greenhouse gas (GHG).
Financial Viability	IDENTIFY FUNDING OPTIONS • Financial strategy developed to support climate change impact assessments and to fund adaptation strategies and projects.	BUSINESS CASE EVALUATION • Lifecyle analysis used for decision-making on climate change projects. • Sea level rise impacts considered on all capital project design and in operating budgeting decisions and standard operating practices.	INVEST IN THE FUTURE • Utilities/agencies generate sufficient revenue to invest in long-range adaptation priorities/projects. • Pursue private-public partnerships to fund strategic initiatives.

Figure 6-2. Road Map to Climate Change Resiliency.

6.3 Identification of Recommended Sea Level Rise Action Items for a Selected Pilot Area

Current policies are now being revised/adopted to include the effects of climate change, particularly related to the effects of sea level rise on coastal environments and infrastructure. Responding to sea level rise will require careful consideration as to where and how particular areas will be protected by structures, raised or elevated above projected flood levels, relocated landward, or simply left as is to be potentially abandoned as sea level rises. The ability to quantitatively evaluate the many physical, environmental, social, economic, and institutional considerations that may be encountered will affect when and how some decisions will or should be made.

Predicting, understanding, and responding to the effects of sea level rise will require integration of ongoing research and monitoring and continued evaluation of environmental and socioeconomic impacts. Improved data collection and understanding of vulnerabilities and risks of sea level rise, and integrating assessments of physical vulnerability, economic analyses, and planning options will be critical to decision making, selecting, and prioritizing implementation of sea level rise adaptation options. Stakeholder involvement throughout this process will be equally important in making well-informed choices and understanding the consequences of each decision and actions taken.

The implications of climate change will bring forth physical, environmental, societal, and economic challenges for the island of Oahu. Institutional barriers will need to be addressed and near-term decisions should be made to implement targeted opportunities for adaptation. This section addresses some of the available options and actions that can be taken in response to sea level rise.

6.3.1 Sea Level Rise Adaptation Measures

A set of sea level rise adaptation measures was identified and recommended for implementation. Adaptation options were categorized into the following implementation categories: Research and Monitoring, Policy/Regulatory, Financing, Planning and Engineering Feasibility Studies, Public Outreach and Communication, Design, and Construction, as shown in Table 6-1.

Table 6-1. Recommended Sea Level Rise Adaptation Measures.

Sea Level Rise Adaptation Categories	Sea Level Rise Adaptation Measures	Planning, Design, and Construction Considerations
Research and Monitoring	• Continue environmental baseline data collection. • Refine research on SLREA that will be impacted. • Continue updates of island-wide SLREA forecasting/modeling as new data become available. • Expand and continuously monitor tidal and groundwater well network.	• Continue required environmental baseline data collection related to proposed adaptation strategies (e.g., ecological, species habitat, water quality, etc.). • Fund and advance SLREA forecasting/modeling research and identify/refine projected SLREA that will be impacted. • Expand sea level rise-related monitoring programs to validate sea level rise rates island-wide (e.g., additional tide gauges, monitor wells, etc.).
Policy/Regulatory	• City Climate Change Commission *Sea Level Rise Guidance and Recommendations*. • Mayor's Sea Level Rise Directive establishing sea level rise targets, City agency policies, and responsibilities for implementation. • Governor's Sea Level Rise Executive Order establishing sea level rise targets, State agency policies, and responsibilities for implementation. • Amend land use plans to include sea level rise policies. • Establish SLREA Resiliency Districts/Zoning. • Update Flood Insurance Rate Maps (FIRMs) for sea level rise. • Add Land Use Ordinance sea level rise building codes and design criteria for new developments. • Add sea level rise requirements to long-range infrastructure facilities plans and CIP. • Adopt county framework for interagency coordination. • Consolidate and streamline SLREA environmental and permit review process.	• Implement the City Climate Change Commission's guidance, Mayor's Directive 18-01, and forthcoming Governor's Executive Order setting forth City and County of Honolulu Actions to Address Climate Change and Sea Level Rise. • Establish Sea Level Rise Flood Protection/Resiliency Districts/Zoning to facilitate permitting of sea level rise adaptation projects within projected SLREA • Review/approval processes should require incorporation of specific sea level rise design/mitigation for new developments and CIP projects. • Update utility and roadway improvement plans. Establish requirements for planned flood protection and sea level rise adaptation measures for all new development proposals in the area (requirements should be tied to applicable permits and development approvals). • Implement County framework for interagency coordination for implementation of climate change adaptation strategies (i.e., CIP). • Develop a consolidated environmental and permit review process to streamline implementation of sea level rise adaptation options (e.g., consolidated public hearings, concurrent agency reviews, etc.).
Financing	• Authorize CIP appropriations for sea level rise adaptation measures. • Develop alternative funding strategies to supplement CIP appropriations. • Establish an SLREA assessment/fee to implement sea level rise adaptation measures. • Authorization and appropriation of federal matching funding. • Develop tax incentive programs for private development to implement sea level rise improvements. • Establish sea level rise improvement districts to fund site-specific sea level rise adaptation measures.	• Seek federal funding and State/City matching funding for sea level rise adaptation projects. • Create financial funding incentives and/or tax incentive programs for implementation of sea level rise adaptation measures particularly for existing facilities, as opposed to new developments (e.g., hotels, commercial centers, etc.). • Establish sea level rise improvement districts (i.e., special tax districts) within projected SLREAs to help fund sea level rise adaptation projects (e.g., assessments for infrastructure improvements associated with elevating streets, utility relocations, constructing seawalls, stormwater pump stations, etc.).

(continued)

Table 6-1. Continued.

Sea Level Rise Adaptation Categories	Sea Level Rise Adaptation Measures	Planning, Design, and Construction Considerations
Planning and Engineering Feasibility Studies	• Initiate implementation of the long-range infrastructure facilities plans and CIP. • Utilize the SLREA research to identify key infrastructure impacts. • Conduct vulnerability and risk assessments of SLREA impacted infrastructure. • Develop criteria for selection of priority areas for inundation and coastal erosion. • Develop adaptive strategies for hardening/elevating or retreating/redevelopment. • Develop drainage master plans for 100-year storm with target sea level rise (elevating and stormwater pumping). • Create a GIS elevation contour map for site-specific grading and drainage. • Install interim flood mitigation measures (one-way drainage valves, onsite stormwater pumps, berms). • Conform/elevate new development consistent with the drainage master plans. • Conform/elevate existing development consistent with the drainage master plans. • Initiate planning and engineering to elevate roadways and utilities once nuisance flooding exceeds 24 times/year. • Mitigate coastal erosion impact areas, hardening coastal roadways, seawalls, and bridge improvements. • Initiate district area Environmental Impact Statement (EIS) and long-lead permitting/approvals. • Revise and adjust CIP sequencing for site-specific drainage, roadway elevation, pumping, bridge hardening, etc. • Incorporate sea level rise CIP design and construction improvements in annual budgets.	• Develop criteria for selection of priority areas for implementation of climate change adaptation options (identifying areas that will not be protected can avoid misallocation of both financial and other resources). • Develop drainage and flood prevention measures that incorporate projected sea level rise impacts. Install interim flood mitigation measures at selected locations, prioritizing those that face the greatest risk. • Evaluate existing drainage systems for current discharge and storage capacity, pipe elevation inverts, and present points of discharge, etc. Elevate roadways and utilities once nuisance flooding exceeds 24 times per year. • Assess potential sea level rise impacts within priority areas, such as Waikiki, including required improvements for bridges (e.g., the Ala Moana Blvd. bridge and McCully Street bridge along Ala Wai Canal). • Initiate long-lead permitting/approvals (e.g., from USACE, State DOH Clean Water permits, federal and State EIS, etc.).
Public Outreach and Communication	• Continuous engagement of the community through the sea level rise adaptation planning process. • Develop communication materials and outreach strategies for specific CIP projects. • Conduct project-specific stakeholder and community meetings.	• Develop and update information on community-level risk mapping and assessments every 5 years to increase community awareness (and acceptance of proposed sea level rise initiatives). • Convene quarterly meetings with targeted stakeholder groups (such as the Hawaii Tourism Authority (HTA), Hawaii Hotel and Lodging Association, Waikiki Improvement Association, and other affected stakeholders within the Waikiki district).

(continued)

Table 6-1. Continued.

Sea Level Rise Adaptation Categories	Sea Level Rise Adaptation Measures	Planning, Design, and Construction Considerations
Design	• Design of highest-priority adaptation projects by district (such as Waikiki, Iwilei, Kakaako, Mapunapuna, etc.) — Phase 1 design — Phase 2 design — Phase 3 design	• Design and construct prioritized adaptation measures, which as examples may include but may not be limited to: — Design/construct new or upgraded drainage systems with suitable conveyance (e.g., larger pipes) and other improvements (e.g., backflow prevention) to address future sea level rise — Design/construct new or modify existing pump stations as part of a regional drainage system for intermittent or continuous dewatering — Design/construct elevated roadways in conjunction with utility relocation and planned drainage improvements (such as along Ala Wai Blvd. between Kalakaua Ave. and Ala Moana Blvd.; Hobron Ln.; and Ena Rd.) — Design/construct retrofit of bridges, culverts, canals that are significantly limiting, or are expecting to limit, conveyance in the future
Construction	• Construct highest-priority adaptation projects by district (such as Waikiki, Iwilei, Kakaako, Mapunapuna, etc.) — Phase 1 construction — Phase 2 construction — Phase 3 construction	

Implementation of adaptation strategies will ultimately depend upon the lead time associated with a given response option and the costs/benefits of acting now versus acting later. In some cases, the expected impacts are far enough in the future that people may view the situation as having ample time to respond. In other cases, the adverse impacts of sea level rise may be more effectively addressed now rather than taking action later.

The City Climate Change Commission in its Guidance notes the following:

> A more detailed economic loss analysis is needed of Oahu's critical infrastructure, including harbor facilities, airport facilities, sewage treatment plants, and roads. State and City agencies should consider potential long-term cost savings from implementing sea level rise adaptation measures as early as possible (e.g., relocating infrastructure sooner than later) compared to the cost of maintaining and repairing chronically threatened public infrastructure (Climate Change Commission 2018).

The principles of economics and risk management provide useful guidance for decision making associated with sea level rise adaptation. It may be far cheaper to plan for sea level rise in the design of a new (or rebuilt) road or drainage system than to modify it later when costs will be higher and when the time frame for implementation will be shorter.

In coastal areas where major investments have already been made, it is unlikely that existing development and infrastructure would be abandoned. Eventual retreat or abandonment may ultimately become the reality if adaptive measures are not implemented or are unsuccessful in addressing future climate change impacts. With respect to shoreline protection, feasibility studies should be undertaken to identify designs that can accommodate a range of future scenarios, and strategies that address a range of uncertainty should be prioritized for implementation. Incentives may be needed for property owners to address sea level rise. Alternatively, regulatory or zoning provisions may need to be mandated requiring more restrictive or adaptive measures, such as the construction of higher floor elevations.

The lack of floodplain mapping that takes into account sea level rise also does not help facilitate these actions. Incorporating sea level rise into floodplain maps would appear to be a low-regrets activity, because it is relatively inexpensive and would enable agencies to modify requirements where appropriate. However, while incorporating SLR into floodplain mapping may not appear to be technically challenging, it does raise potential administrative and political challenges. Possible ripple effects upon property owners may include reduced property values and/or increased construction costs. Additionally, it is unclear which SLR projection and timeframe should be incorporated within the updated flood maps.

6.3.2 Selection of Pilot Area

BWS has long considered how best to protect and manage its water resources and assets and, in conjunction with this study, how best to adapt and modify infrastructure as sea level rises. Because of the projected vulnerability of Oahu's coastline to marine inundation and groundwater inundation, BWS has advocated for pilot implementation of select strategies within priority areas that may be significantly impacted by sea level rise. As noted earlier, while other agencies may be actively planning for climate change, they have not as a coordinated effort initiated any actionable plans in anticipation of sea level rise.

To address projected impacts, BWS has recommended early implementation of no-regrets options based upon the requisite lead time for planning, design, and construction of select projects in relationship to specific triggers or events associated with future sea level rise. Like other cities such as New York City and Boston, and Miami-Dade County in Florida, BWS is proactively considering the implications of climate change and the impacts of rising sea level on infrastructure, roads, and floodplain management. Strategies proposed and/or implemented by other cities have included building flood walls, dewatering, raising roadways, and constructing tidal flood gates to decrease the impacts of sea level rise.

The inter-relationships and dependence of decisions between federal, State, County, and property owners poses challenges and potential barriers to selecting specific areas for targeted implementation of sea level rise strategies. No single agency or entity is in charge or solely responsible for developing and implementing response strategies to sea level rise, which ultimately cross multiple agency jurisdictions. The actions of one agency can be hindered by others who have not decided upon or who may not be ready for implementation because of factors such as availability of funding, and uncertainty of the timing and magnitude of the projected impacts.

The long-term strategies and options to adapt to sea level rise can be generally categorized into three approaches: protection and mitigation, elevation, and retreat. Each individual strategy or combination of options may be applicable to certain locations and unacceptable for others. The degree of protection, elevation, or retreat may not be easily determined or simply based upon a cost/benefit analysis and may need to take into consideration environmental or other socioeconomic sensitivities associated with the proposed actions. Identification of a pilot location for early implementation of adaptation options and the justification of costs and the timing for implementation of such strategies may be equally, if not more, challenging.

Reaching agreement and selection of the best area for early implementation of sea level rise adaptation measures may prove to be challenging. However, potential pilot areas can be initially identified based upon several qualitative criteria, which include but are not limited to:

- Potential for accommodation of adaptation options or opportunities for retreat
- Projected vulnerability to sea level rise impacts
- Potential severity of social, economic, or environmental impacts
- Opportunity for implementation of adaptation measures in alignment with proposed or planned improvements in the area
- Potential for integration of multiple adaptation strategies (versus a single limited strategy)
- Suitability of existing infrastructure or assets for future utilization, modification, or expansion in support of climate change mitigation/adaptation actions (e.g., repurposing decommissioned wastewater pump stations for dewatering purposes)
- A sequential and logical plan of action can be developed for the delineated area of probable impacts for implementation of “no-regrets” options

A focused dialogue should be immediately started and sustained between the State and County to decide upon a coordinated plan of what will be protected, abandoned, or relocated. OCCSR is recommended as the lead agency to undertake this leadership role for the City. Certain assumptions can be made regarding the potential economic and environmental benefits/consequences associated with the selection of a pilot area chosen for implementation of climate change strategies. However, applicable scientific data (which are constantly evolving), and input from policymakers and stakeholders, will need to be included as part of the decision-making process.

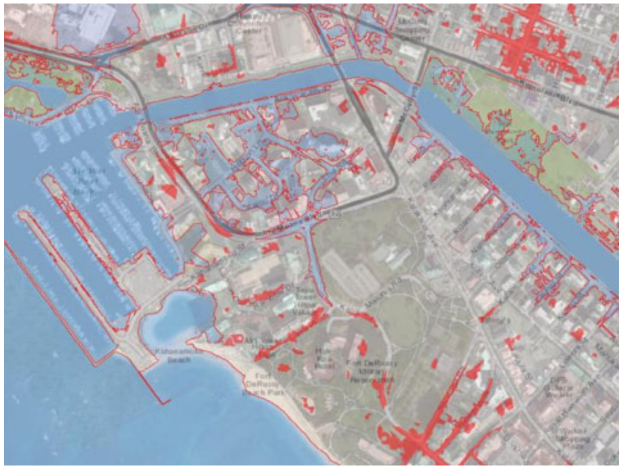
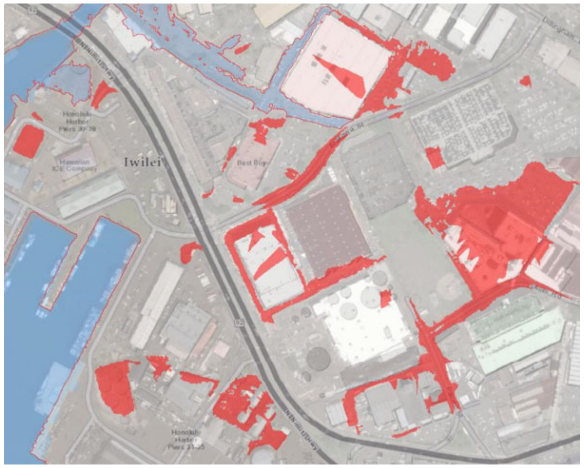
Recent research from UH has identified major portions of Honolulu and Waikiki that are vulnerable to flooding as groundwater rises because of sea level rise. The UH Department of Geology and Geophysics, School of Ocean and Earth Science and Technology (UH SOEST) has developed a computer model that combines ground elevation, groundwater location, monitoring data, estimates of tidal influence, and numerical groundwater-flow modeling to simulate future flood scenarios in urban Honolulu using 3 feet of sea level rise, as projected under certain climate change scenarios (UH SOEST 2017).

Shellie Habel, lead author of the study, notes “This flooding will threaten $5 billion of taxable real estate; flood nearly 30 miles of roadway; and impact pedestrians, commercial and recreation activities, tourism, transportation, and infrastructure. The flooding will occur regardless of seawall construction, and thus will require innovative planning and intensive engineering efforts to accommodate standing water in the streets.” The water table in many locations is already near the existing ground surface, in some cases within 2 feet at high tide conditions. Construction projects and main break repairs need to dewater excavations before construction or pipeline repairs can begin (UH News 2017).

As the water table rises, there will be increasing drainage problems in these areas when it rains. Seawater will fill existing drainage systems (except at low tide levels) and standing ponds of water will persist within the area without the ability or location to drain. Street access will be affected and/or limited, wetland conditions may become the norm, and certain areas may be permanently flooded with standing water. Limited options may be available regarding investment and infrastructure repairs that can be done to address these conditions. “Groundwater inundation will require entirely unique adaptation methods if we are to continue to live in and develop the coastal zone. Coastal planners and community stakeholders will need to work with architects, engineers, geologists, ecologists, economists, hydrologists and other innovative thinkers in order to manage these problems.” (UH News 2017)

Current mapping of projected marine inundation and groundwater inundation from sea level rise suggests several potential areas for pilot implementation of climate change adaptation strategies. Private and public entities should begin to implement short- and mid-term preparedness and adaptation plans for sea level rise starting with flooding and drainage issues in selected parts of Honolulu. West Waikiki and Iwilei represent two candidate areas for consideration. Table 6-2 compares these two candidate pilot areas.

Table 6-2. Two Candidate Pilot Areas for Sea Level Rise Adaptation and Initial Climate Change Adaptation Strategy Implementation.

Selection Criteria	West Waikiki	Iwilei
Projected vulnerability to sea level rise impacts	Projected groundwater inundation and marine inundation at 3.2 ft sea level rise. 	Projected groundwater inundation and marine inundation at 3.2 ft sea level rise. 
Potential severity of social, economic, or environmental impacts	• Tourism is the top industry in the state of Hawaii. The island of Oahu, also home to Waikiki Beach, is considered the main tourist area with high economic impact and value. In 2016, 4,803,345 visitors stayed exclusively in hotels. The average length of stay was 7.18 days and total visitor expenditures for 2016 was close to $16 billion (HTA 2016). • Waikiki accounts for nearly half of tourism statewide, supplying more than 72,000 jobs and providing 8% of the gross state product (DBEDT 2003).	• Because of the low-density character of existing development, proximity to downtown Honolulu, and consolidated landownership, Iwilei-Kapalama is expected to see the highest levels of TOD in the entire rail corridor. Based on land and entitlement capacity, market demand, and landowner input, this study has anticipated that more than 13,000 new housing units may be constructed (City and County of Honolulu 2017).
Opportunity for implementation of adaptation measures in alignment with proposed or planned improvements in the area	• Potential integration and coordination opportunity with the Ala Wai Canal Flood Risk Management Study, Oahu, Hawaii (USACE 2017). • Given the extent of development within the watershed (particularly in the Waikiki district), there are potentially significant benefits associated with implementing flood risk management measures (USACE 2017).	• Improvements associated with TOD and other planned improvements provide significant opportunities for incorporation of adaptation strategies in this area. • The TOD planning team has engaged public and private property owners and infrastructure agencies to identify critical investments needed.

Selection Criteria	West Waikiki	Iwilei
Potential for integration of multiple adaptation strategies (versus a single limited strategy)	• West Waikiki provides an opportunity to combine drainage improvements, utility relocation, and roadway elevation in conjunction with planned Ala Wai Canal improvements. • The infrastructure projects recommended by this study will need to be implemented by the City, the State, private utilities, and private developers. • The HTA, Hawaii Lodging and Tourism Association, Waikiki Improvement Association, and others are actively working with State and City officials to identify and implement mitigation options.	• To accommodate anticipated growth, with a high priority on supporting affordable housing development. The assessment includes high-level cost estimates for infrastructure improvements, a phasing strategy, and other recommendations to support TOD. • An associated study is exploring innovative financial tools to help fund the necessary improvements. • Given the degree of needed upgrades, and the scale of expected development, it is impractical for landowners to make these improvements on a project-by-project basis (City and County of Honolulu 2017).
Existing infrastructure or assets may be suitable for future utilization, modification, or expansion in support of climate change mitigation/adaptation actions	• Upgrading of the current drainage system and use of Ala Wai Canal as a conveyance system in combination with future dewatering, including “repurposing” of ENV’s Beachwalk pump station, can be potentially combined and implemented within an integrated adaptation strategy.	• The area has poor roadway connectivity, which negatively impacts pedestrian, transit, bicycle, and vehicular access. There are also significant deficiencies in the drainage, electrical, sewer, and water systems that limit development potential.
A sequential plan of action can be developed for the delineated area of probable impacts for implementation of “no-regrets” options	• Coastal erosion will likely increase as sea level rises at rates higher than previously observed. Rising sea level also increases the vulnerability of existing development along the coastline, increasing the risk of flooding during rainstorms. • Vulnerable areas of Waikiki can be strategically targeted for incremental implementation of climate change adaptation options.	• Planned efforts are complemented by several other City-led projects to support TOD: the creation of a linear park along Kapalama Canal, the Iwilei Drainage Study, implementation of the City’s Affordable Housing Strategy, and technical assistance from the U.S. Environmental Protection Agency related to contaminated land and sea level rise. State agency partners are actively participating in these projects and planning for affordable housing and mixed-use developments.

Recognizing the magnitude of costs associated with the implementation of adaptation strategies, coordination with other agency efforts/projects should be one of the highest priorities and criteria for selection of a pilot area. Opportunities for integration with other planned projects or improvements should also be identified and weighed for consideration.

The Waikiki area may be viewed by many as one of the highest-priority areas for protection and adaptation to sea level rise. Abandonment of hotel properties is unlikely and options for elevation are not readily available options for Waikiki. As a major economic driver for the State and County, the Waikiki corridor may be an appropriate area for pilot implementation of no-regrets strategies.

Perhaps more importantly, the Waikiki area may provide actionable opportunities for integration with other ongoing planning and mitigation efforts, specifically the planned improvements to the Ala Wai Canal, which bounds the Waikiki area to the north. The Waikiki area has been flooded several times during previous storms when the Ala Wai Canal was overtopped. The 2017 Ala Wai Canal Flood Risk Management Study done by the U.S. Army Corps of Engineers (USACE) reported an estimated flood damage of more than $85 million associated with the October 2004 storm event. Other historical flood events within the past century have resulted in significant property damages and other health and safety risks. The affected population within the 1 percent floodplain was estimated at approximately 54,000 residents plus an additional estimated 79,000 visitors in Waikiki (USACE 2017).

Herein lies an opportunity and synergy for proactive implementation of climate change adaptation strategies within the Waikiki district area. Opportunities to reduce groundwater inundation and marine inundation (i.e., flooding) in the Waikiki area closely correspond to those identified in the USACE 2017 study. The USACE study recommended improving channel and bridge conveyance capacities, enhancing education and communication of flood risks, improving the storm drainage system, and addressing landownership boundaries and maintenance responsibilities. Based on the flood risk management goal of the study, specific flood-related problems were defined for the Ala Wai watershed, including flooding that may be exacerbated by climate change and associated projected increases in sea level rise (USACE 2017).

The following Sea Level Rise Action Strategy incorporates a qualitative approach for identifying and assembling planning, design, and construction measures into an adaptive plan based upon existing data and available information, collaborative professional judgment, and risk-informed assumptions. The process involved an initial grouping of conceptual sea level rise management measures based on the identified problems within the Waikiki area, which forms the basis for a combination of specific actions and timelines for implementation. As noted in Chapter 4, the West Waikiki area, centered around Hobron Lane and bounded by Ala Moana Boulevard, Ala Wai Boulevard, and Kalakaua Avenue, would be a viable candidate site for pilot implementation of sea level rise adaptation strategies and options.

The proximity of this area to the existing Ala Wai Canal poses an opportunity for implementation of adaptation measures in alignment with proposed or planned improvements within the Ala Wai watershed area. Taking this pilot area as an example, specific adaptation measures can be identified for implementation using the City Climate Change Commission's intermediate scenario of 1.7 feet of flooding based on an occurrence of nuisance flooding of 24 times per year as a milestone/trigger (Climate Change Commission 2018), and proposed adaptation measures can be sequentially implemented in accordance with the necessary lead time for planning, design, and construction of these adaptation options.

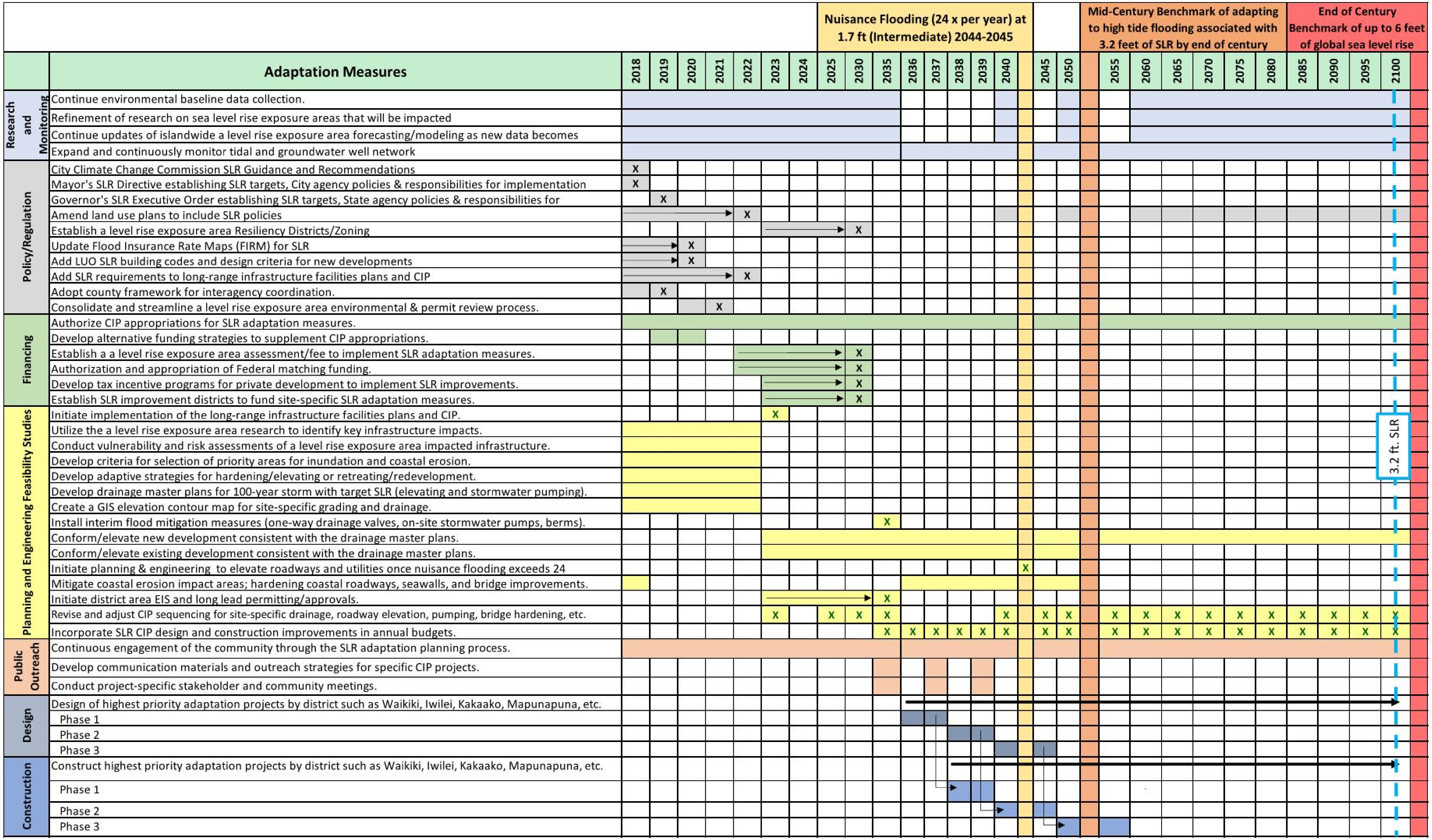
The proposed actions identified in Figure 6-3 were derived from the list of Recommended Sea Level Rise Adaptation Measures described in Table 6-2 and serve as a "template" for implementation of adaptation options for West Waikiki, as well as other priority areas such as Iwilei. Certain actions should be implemented concurrently, while others may be incrementally undertaken, or in the case of planning, design, and construction, will need to be sequentially phased over time for implementation. Each proposed action item is tied to a specific time frame for initiation and completion, and/or to a recommended trigger or milestone for implementation, such as the City Climate Change Commission's intermediate scenario for nuisance flooding of 24 times per year by the projected time frame of 2044–45. Other action items, such as financing and public outreach and communication, will need to be conducted on a continuous basis throughout the planning horizon.

Further discussion and steps should be taken to assess and validate the feasibility of these options for implementation, including evaluation of the positive or negative effects of these actions in preparing for future climate change. The final site-specific locations and design of these sea level rise adaptation options, together with pilot implementation of such measures, will ultimately determine their success (or failure) and can offer lessons learned that can be applied elsewhere across the island.

Many flood protection and other adaptation options may need to span more than one location or one type of design. Physical connections within a neighborhood, access and potential impacts to privately owned land, connecting areas of elevated roadways to lower elevations, visual impacts, etc. will need to be evaluated and addressed.

The City should develop "local" climate resilience plans for areas that face the highest risk from sea level rise in the near term. For these areas and subsequent climate resilience plans, potential hazards should be addressed and all adaptation efforts within a district should be coordinated and integrated wherever possible. This coordination will provide for partnership opportunities, optimize the use of resources, and avoid duplication of investments.

In the end, joint capital project planning, design, and construction will maximize climate change readiness and minimize project costs associated with planning, pre-construction engineering and design, and construction (including mitigation activities for impacts to aquatic habitat and cultural resources). Land acquisitions, easements, rights-of-way, relocations, disposal, and planning for contingencies will also be facilitated through these efforts. Opportunities for joint financing of adaptation options can be coordinated with implementation of other community benefits or priorities such as open space, and safe and efficient mobility within the district. Climate change readiness efforts at the district scale, starting with pilot areas like West Waikiki, can lead to integration of locally specific initiatives to advance multiple goals at the same time, thereby minimizing project risk and uncertainties.



Nuisance Flooding (24 x per year) at 1.7 ft (Intermediate) 2044-2045

Mid-Century Benchmark of adapting to high tide flooding associated with 3.2 feet of SLR by end of century

End of Century Benchmark of up to 6 feet of global sea level rise

	Adaptation Measures	2018	2019	2020	2021	2022	2023	2024	2025	2030	2035	2036	2037	2038	2039	2040		2045	2050		2055	2060	2065	2070	2075	2080	2085	2090	2095	2100	
Research and Monitoring	Continue environmental baseline data collection.	■	■	■	■	■	■	■	■	■	■					■			■			■	■	■	■	■	■	■	■	■	
	Refinement of research on sea level rise exposure areas that will be impacted	■	■	■	■	■	■	■	■	■	■					■			■			■	■	■	■	■	■	■	■	■	
	Continue updates of islandwide a level rise exposure area forecasting/modeling as new data becomes	■	■	■	■	■	■	■	■	■	■					■			■			■	■	■	■	■	■	■	■	■	
	Expand and continuously monitor tidal and groundwater well network	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■		■	■	■	■	■	■	■	■	■	■	
Policy/Regulation	City Climate Change Commission SLR Guidance and Recommendations	X																													
	Mayor's SLR Directive establishing SLR targets, City agency policies & responsibilities for implementation	X																													
	Governor's SLR Executive Order establishing SLR targets, State agency policies & responsibilities for		X																												
	Amend land use plans to include SLR policies	→	→	→	→	X										■			■			■	■	■	■	■	■	■	■		
	Establish a level rise exposure area Resiliency Districts/Zoning						→	→	→	X																					
	Update Flood Insurance Rate Maps (FIRM) for SLR	→	→	X																											
	Add LUO SLR building codes and design criteria for new developments	→	→	X																											
	Add SLR requirements to long-range infrastructure facilities plans and CIP	→	→	→	→	X																									
	Adopt county framework for interagency coordination.	■	X																												
	Consolidate and streamline a level rise exposure area environmental & permit review process.			■	X																										
Financing	Authorize CIP appropriations for SLR adaptation measures.	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■		■	■	■	■	■	■	■	■	■	■	
	Develop alternative funding strategies to supplement CIP appropriations.		■	■																											
	Establish a a level rise exposure area assessment/fee to implement SLR adaptation measures.					→	→	→	→	X																					
	Authorization and appropriation of Federal matching funding.					■	■	■	■	X																					
	Develop tax incentive programs for private development to implement SLR improvements.						→	→	→	X																					
	Establish SLR improvement districts to fund site-specific SLR adaptation measures.						→	→	→	X																					
Planning and Engineering Feasibility Studies	Initiate implementation of the long-range infrastructure facilities plans and CIP.						X																								
	Utilize the a level rise exposure area research to identify key infrastructure impacts.	■	■	■	■	■																									
	Conduct vulnerability and risk assessments of a level rise exposure area impacted infrastructure.	■	■	■	■	■																									
	Develop criteria for selection of priority areas for inundation and coastal erosion.	■	■	■	■	■																									
	Develop adaptive strategies for hardening/elevating or retreating/redevelopment.	■	■	■	■	■																									
	Develop drainage master plans for 100-year storm with target SLR (elevating and stormwater pumping).	■	■	■	■	■																									
	Create a GIS elevation contour map for site-specific grading and drainage.	■	■	■	■	■																									
	Install interim flood mitigation measures (one-way drainage valves, on-site stormwater pumps, berms).										X																				
	Conform/elevate new development consistent with the drainage master plans.						■	■	■	■	■	■	■	■	■	■		■	■		■	■	■	■	■	■	■	■	■	■	
	Conform/elevate existing development consistent with the drainage master plans.						■	■	■	■	■	■	■	■	■	■		■	■												
	Initiate planning & engineering to elevate roadways and utilities once nuisance flooding exceeds 24																X														
	Mitigate coastal erosion impact areas; hardening coastal roadways, seawalls, and bridge improvements.	■										■	■	■	■	■		■	■												
	Initiate district area EIS and long lead permitting/approvals.						→	→	→	→	X																				
	Revise and adjust CIP sequencing for site-specific drainage, roadway elevation, pumping, bridge hardening, etc.						X		X	X	X					X		X	X		X	X	X	X	X	X	X	X	X	X	
	Incorporate SLR CIP design and construction improvements in annual budgets.										X	X	X	X	X	X		X	X		X	X	X	X	X	X	X	X	X	X	
Public Outreach	Continuous engagement of the community through the SLR adaptation planning process.	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■		■	■	■	■	■	■	■	■	■	■	
	Develop communication materials and outreach strategies for specific CIP projects.										■		■		■																
	Conduct project-specific stakeholder and community meetings.										■		■		■																
Design	Design of highest priority adaptation projects by district such as Waikiki, Iwilei, Kakaako, Mapunapuna, etc.											→	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→	
	Phase 1											■	■																		
	Phase 2													■	■																
	Phase 3															■		■													
Construction	Construct highest priority adaptation projects by district such as Waikiki, Iwilei, Kakaako, Mapunapuna, etc.												→	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→	
	Phase 1													■	■																
	Phase 2															■		■													
	Phase 3																		■		■										

Figure 6-3. Sea Level Rise Action Strategy .

CHAPTER 7

Conclusions and Next Steps

Impacts of climate change on the BWS infrastructure and the effects on groundwater sustainable yield (i.e., water availability/reliability) were the primary focus of this study. An important outcome of this effort was the development of a proposed County framework for coordination of agency efforts associated with climate change mitigation and adaptation. When embarking on new collaborations or new approaches, it is beneficial to start small and build on successes by first setting a coordinated framework that can be practically implemented and which will be long-lasting. This proposed framework is intended to support and lead to identification of selected pilot areas for which adaptive options can be prioritized and strategically implemented.

The study began with the goal of addressing existing vulnerabilities and identifying strategies to assist the BWS in the preparation and adaptation to climate change. Various mitigation and adaptation measures were identified to address potential impacts to water supply, water quality, and the protection of existing BWS infrastructure. There was also early recognition of the need to coordinate and integrate the efforts of other affected agencies and private sector utilities who share common goals and objectives associated with the impacts of future climate change.

Many companion planning initiatives and studies are currently ongoing, and these efforts should seek to avoid duplication and instead capitalize on the findings and recommendations of each successive study. At the same time, some important and essential studies and analyses, including planning and policy considerations, are lagging and in need of immediate execution. As an example, regional drainage plans should be updated to incorporate sea level rise implications and financing mechanisms for funding of near- and long-term adaptation measures should be identified and/or developed to support these initiatives.

The uncertainty of the magnitude and timing of future climate change impacts, along with continuing research and changing projections, present additional challenges in prioritizing and evaluating available options. Many studies have appropriately recognized the need for flexibility and robustness of plans, and the need for an iterative process to successfully implement mitigation and adaptation options. However, at the same time many efforts fall short of establishing specific triggers or milestones for when such actions should occur.

In addition to establishing triggers, which will need to be constantly updated and refined based on new information, target areas will need to be selected for priority application of adaptation measures. These “pilot” areas and the “lessons learned” through the early implementation of recommended actions will help guide future government and private sector efforts. These efforts will need to be integrated and effectively coordinated to maximize use of resources, minimize duplication of efforts, and to streamline and overcome existing obstacles or impediments to implementation. The “who, what, where, and when” questions associated with climate change will need to be collaboratively answered, and more importantly undertaken together under an agreed upon framework for implementation.

This study provides a recommended starting point for focused discussions beginning with the proposed County Framework for Implementation of Climate Change Adaptation Strategies (starting initially with the affected County agencies), a draft Road Map to Climate Change Resiliency (involving both government agencies, private sector entities, and stakeholders), and a proposed Sea Level Rise Action

Strategy (that prioritizes recommended actions in alignment with specific triggers and time frames for execution). The study also suggests consideration of West Waikiki as the first pilot area for implementation of adaptive options given that Waikiki is a major economic driver for the State and County and provides actionable opportunities for integration with other ongoing planning and mitigation efforts, specifically the planned improvements to the Ala Wai Canal, which bounds the Waikiki area to the north. The assessment methodology and proposed framework identified for development of adaptive management strategies, and the “template” for implementation of adaptation options (e.g., the SLR Action Strategy) represents a viable approach to evaluating and planning for the impact of climate change on water quantity, quality, and infrastructure that can hopefully serve as a potential model for other utilities.

A deliberate approach should be taken for accomplishment of long lead time options requiring planning, design, and construction in advance of anticipated impacts. The projected consequences of climate change will require continued vigilance and monitoring of climate trends and ongoing evaluation of projected impacts. This study used the best information that was available to assess climate change vulnerabilities and develop adaptive strategies. As additional climate change projections and modeling results become available, this study should be updated periodically (every 5 to 10 years) to reflect the latest data and scientific knowledge and lessons learned from collaboration with other agencies and adaptive strategy implementation.

APPENDIX A

Sea Level Rise Hazard Projections

Figures provided in Appendix A have been created by Brown and Caldwell based on information provided by UH Professor Chip Fletcher and his research group.

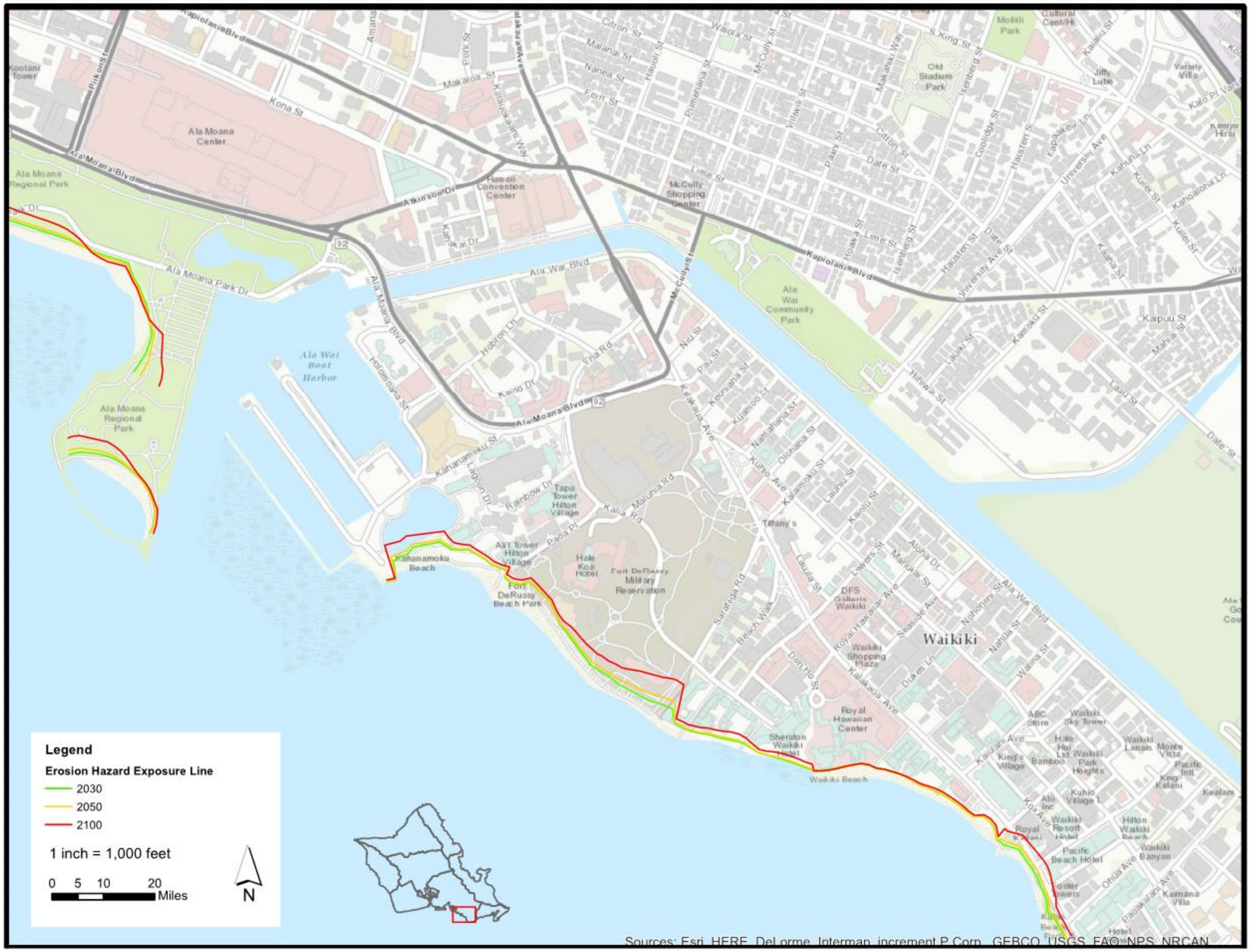


Figure A-1. Erosion Hazard Exposure with Sea Level Rise in 2030, 2050, and 2100 in Waikiki.

Source: Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

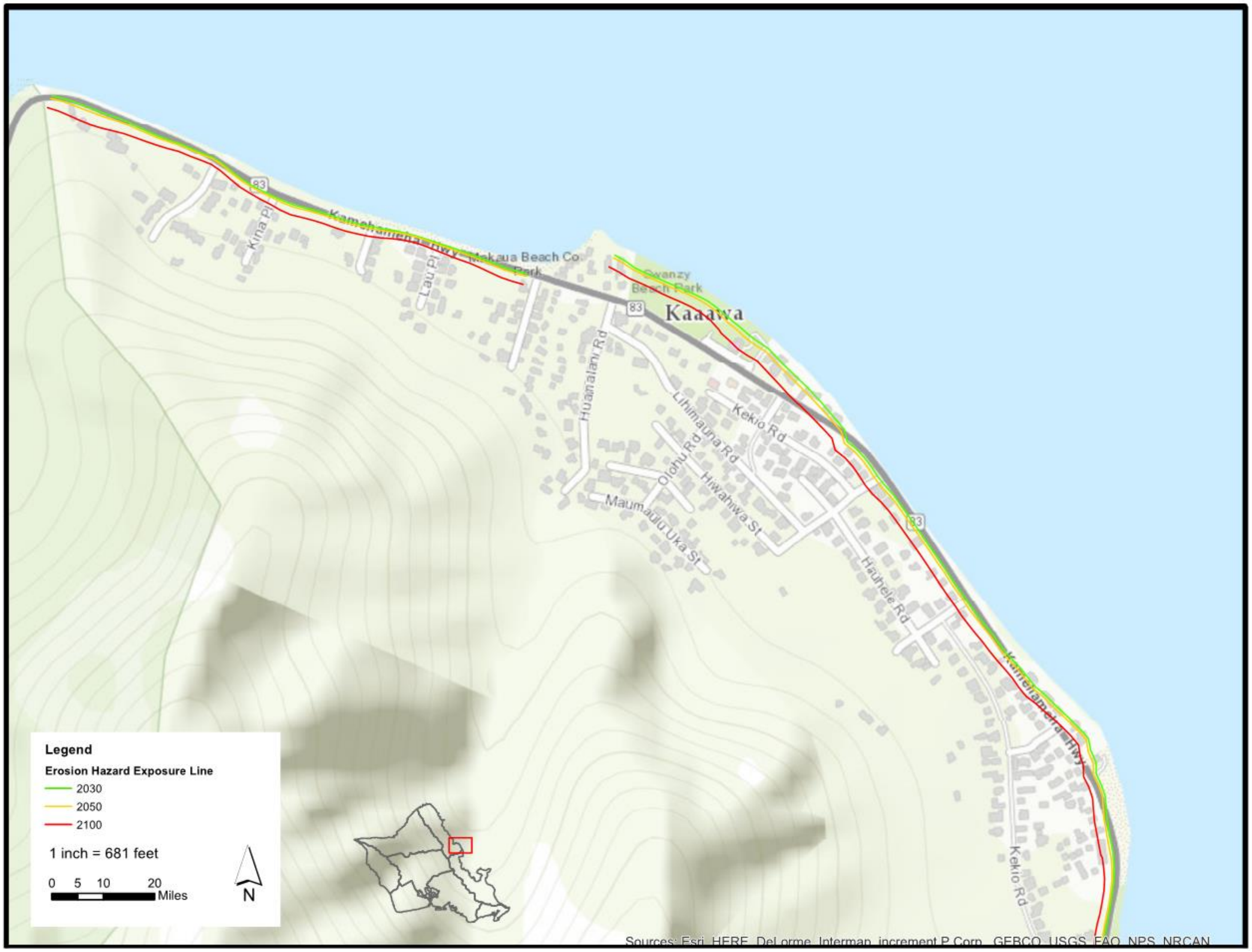


Figure A-2. Erosion Hazard Exposure with Sea Level Rise in 2030, 2050, and 2100 in Kaaawa.

Source: Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

Figure A-3. Erosion Hazard Exposure with Sea Level Rise in 2030, 2050, and 2100 in Maili.

Source: Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

Figure A-4. Erosion Hazard Exposure with Sea Level Rise in 2030, 2050, and 2100 in Ewa Beach.

Source: Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

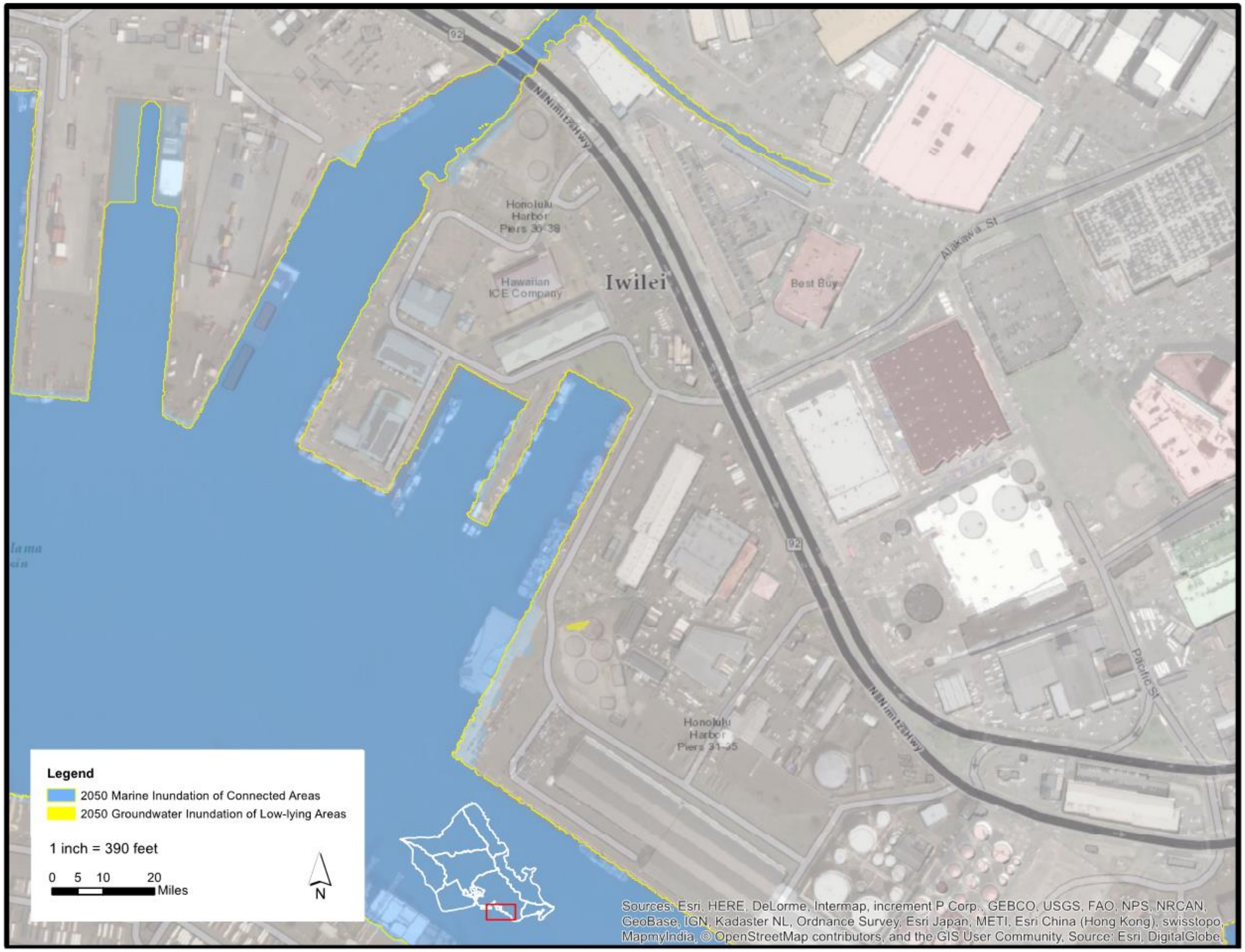


Figure A-5. Marine and Groundwater Inundation in 2050 in Iwilei.

Source: Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

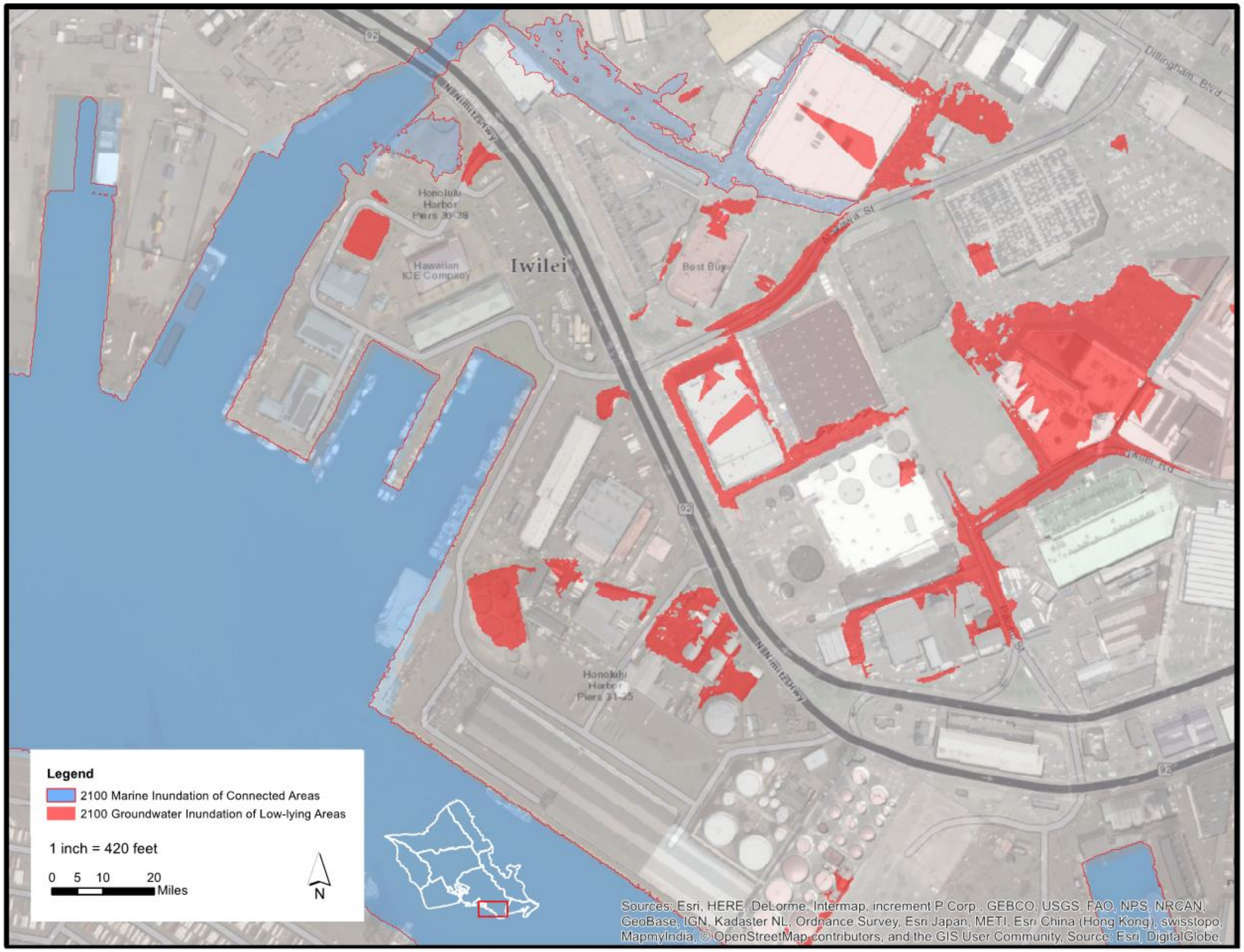


Figure A-6. Marine and Groundwater Inundation in 2100 in Iwilei.

Source: Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

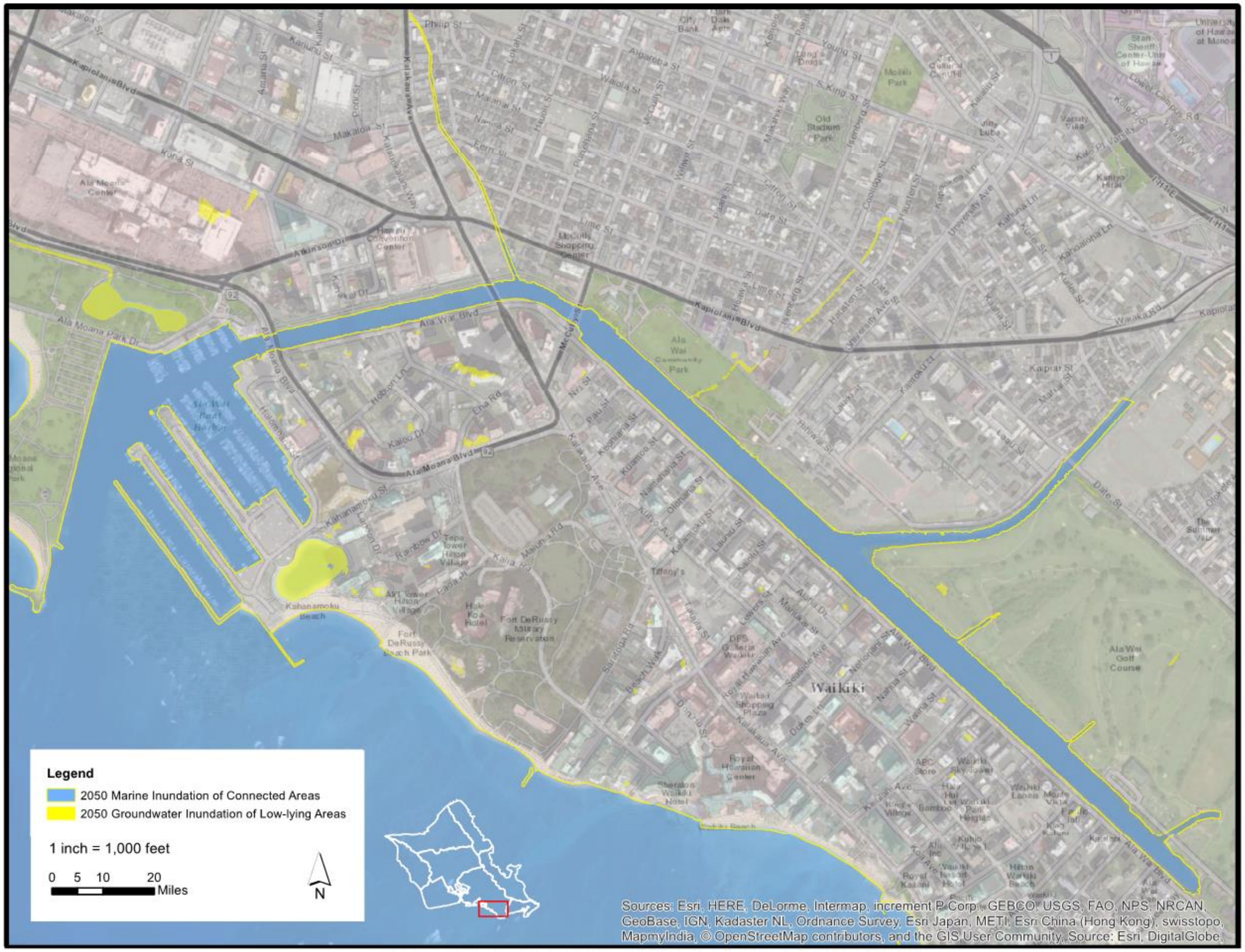


Figure A-7. Marine and Groundwater Inundation in 2050 in Waikiki.

Source: Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

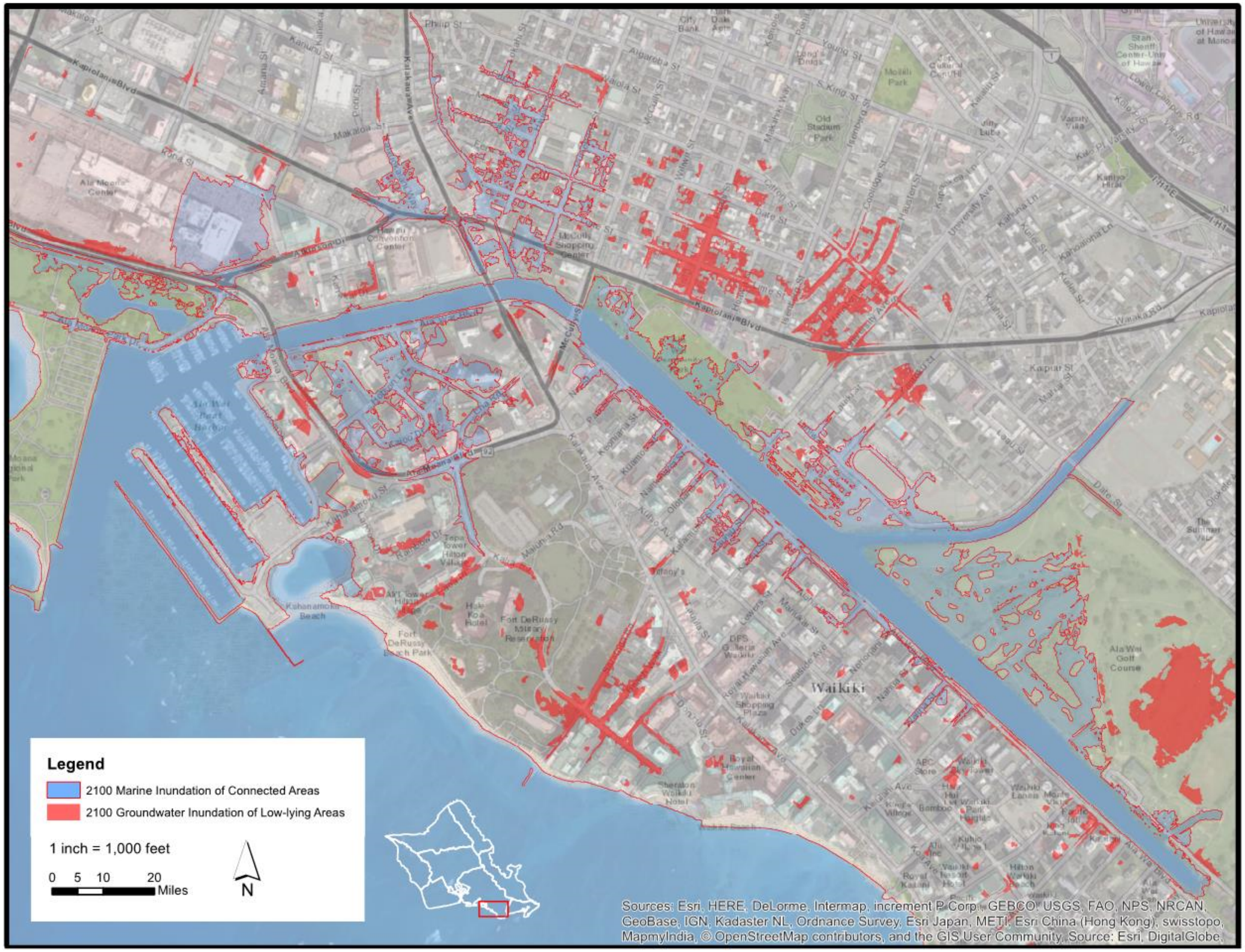


Figure A-8. Marine and Groundwater Inundation in 2100 in Waikiki.

Source: Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

Figure A-9. Marine and Groundwater Inundation in 2050 in Hawaii Kai.

Source: Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

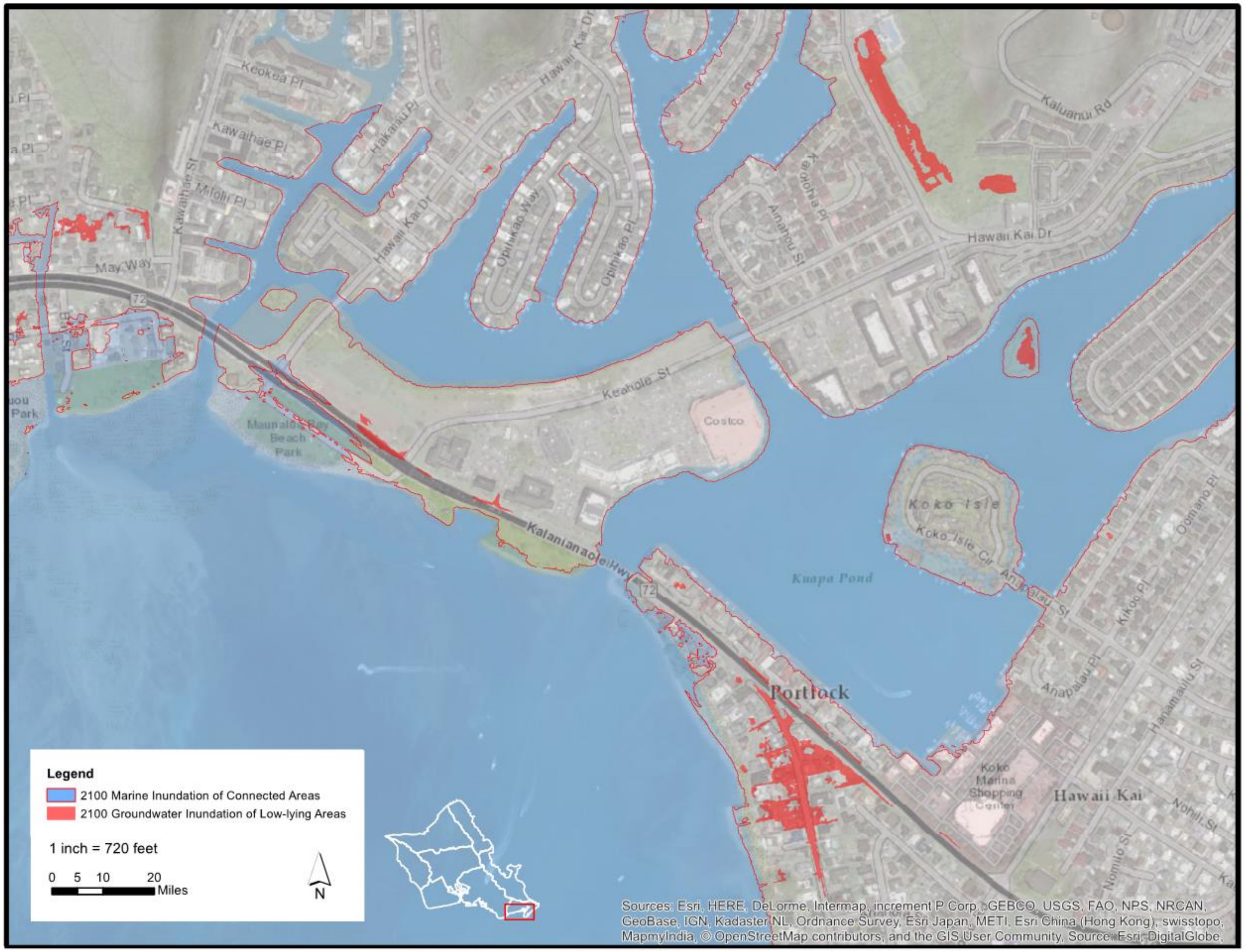


Figure A-10. Marine and Groundwater Inundation in 2100 in Hawaii Kai.

Source: Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

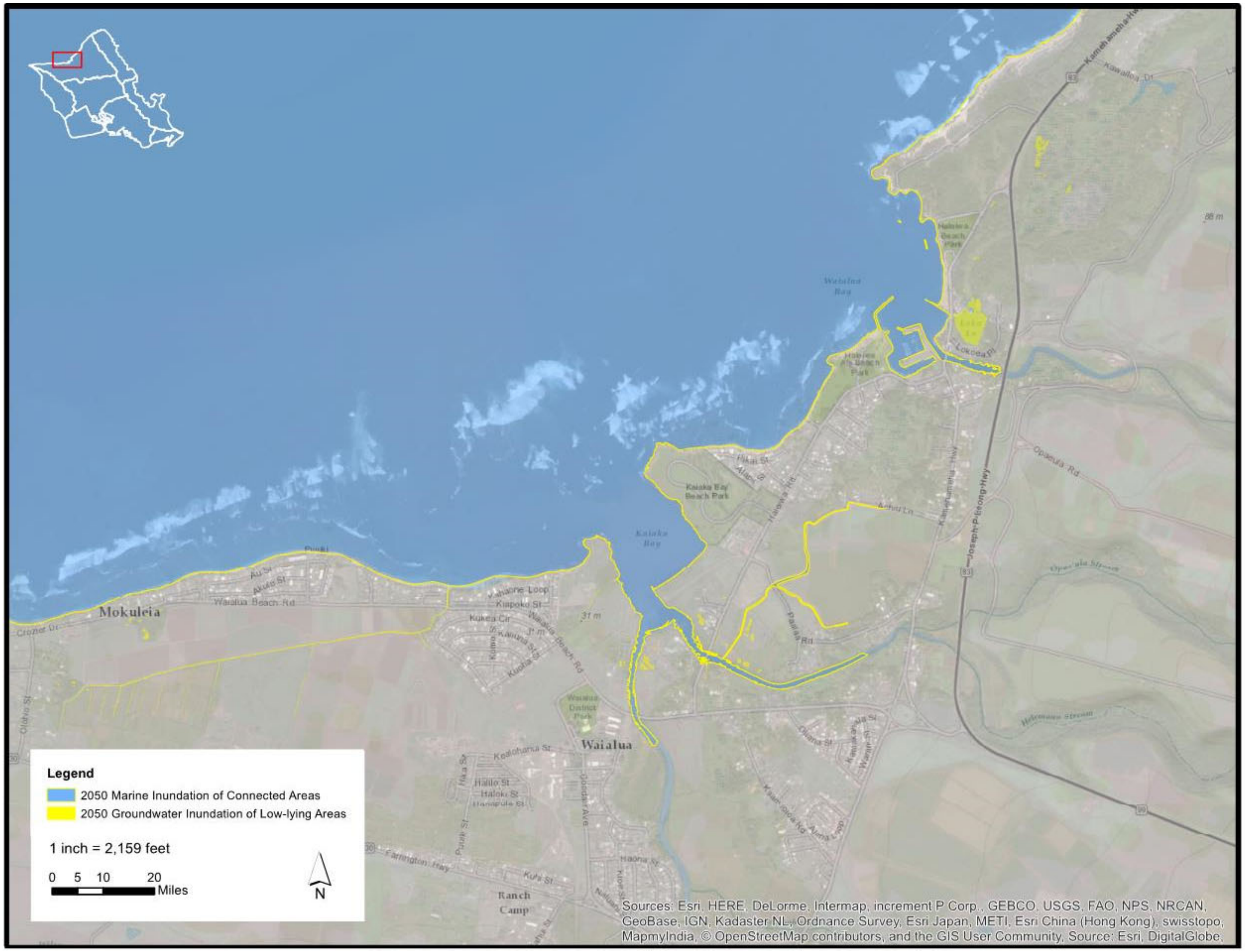


Figure A-11. Marine and Groundwater Inundation in 2050 in North Shore.

Source: Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

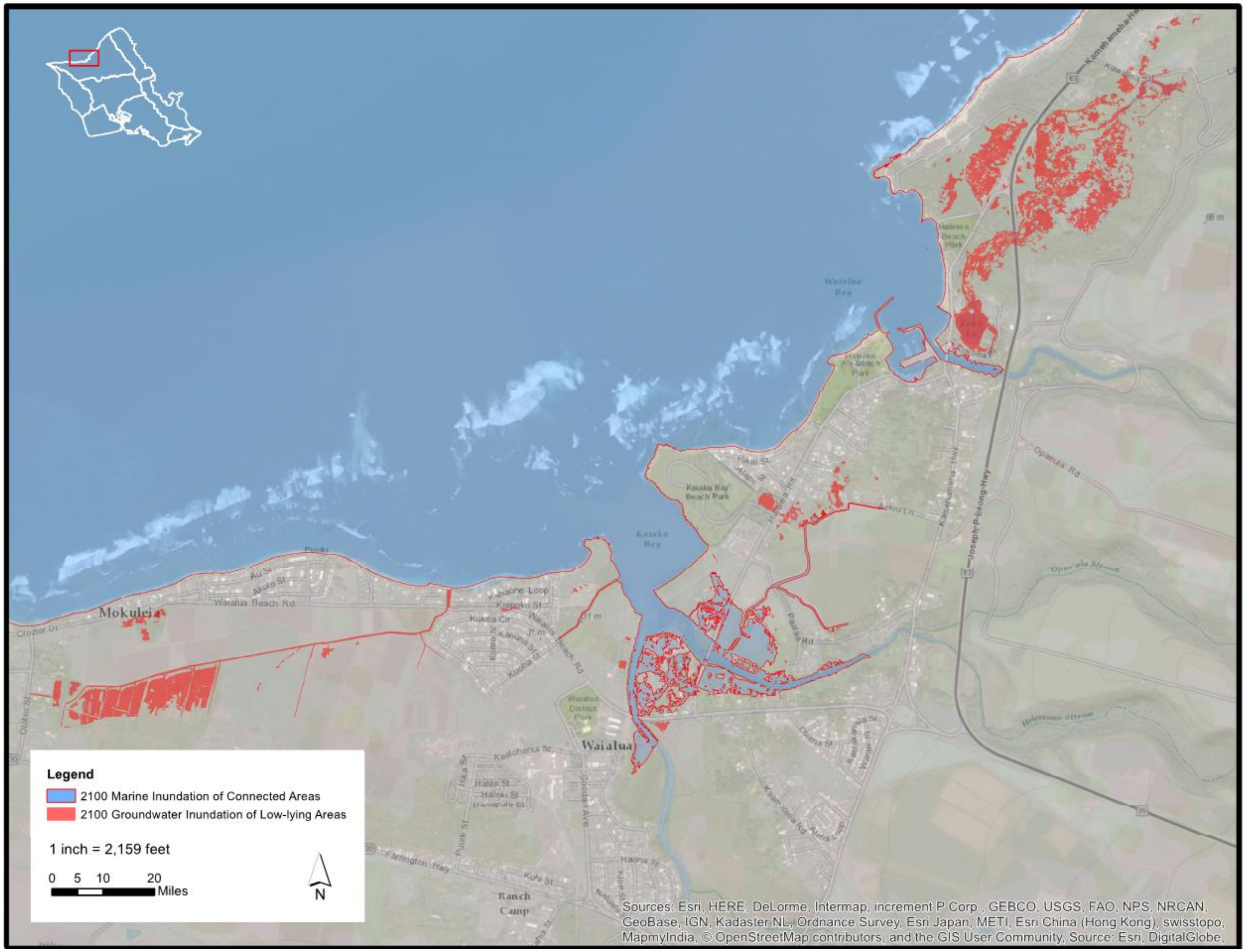


Figure A-12. Marine and Groundwater Inundation in 2100 in North Shore.

Source: Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

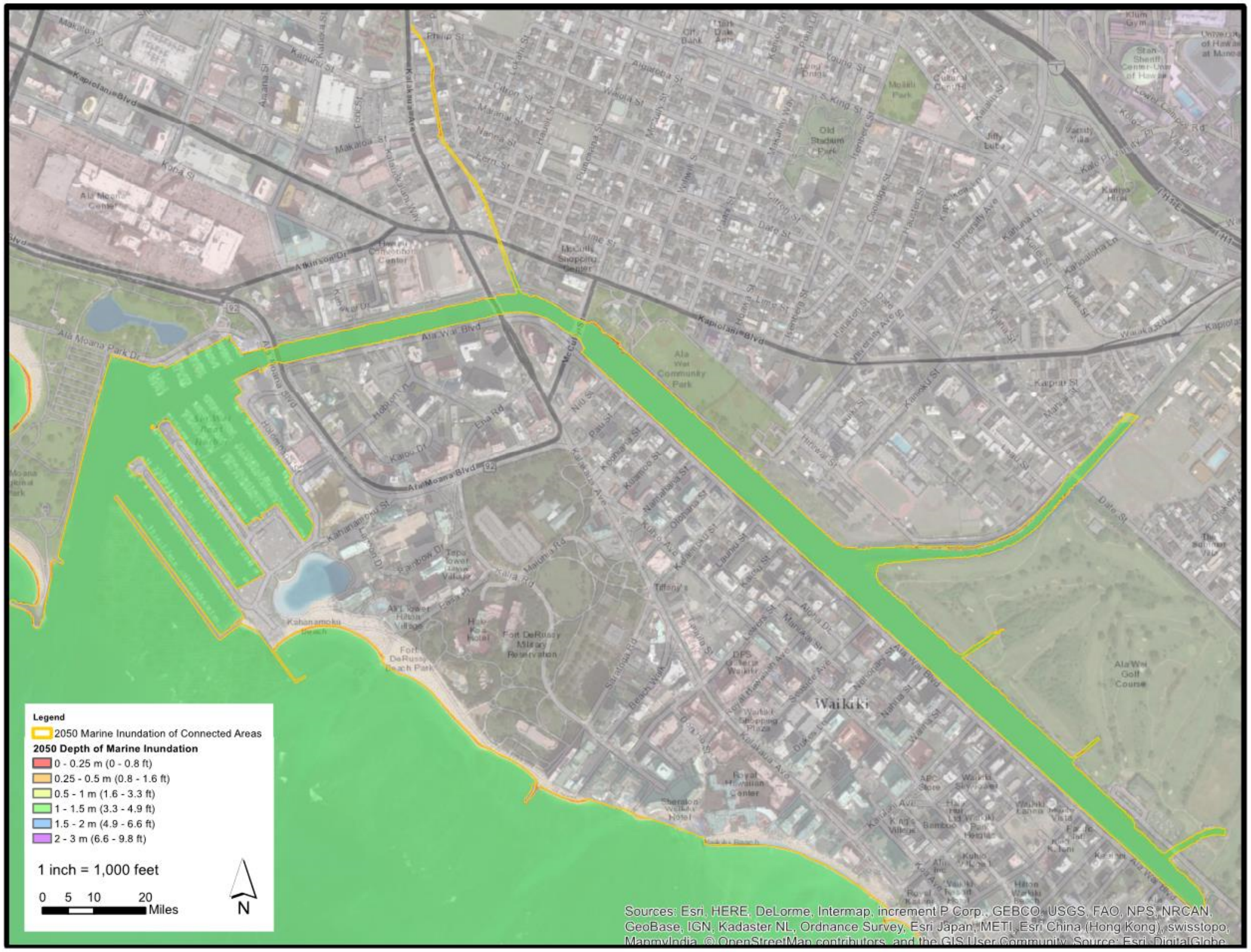


Figure A-13. Depth of Marine Inundation in 2050 in Waikiki.

Source: Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

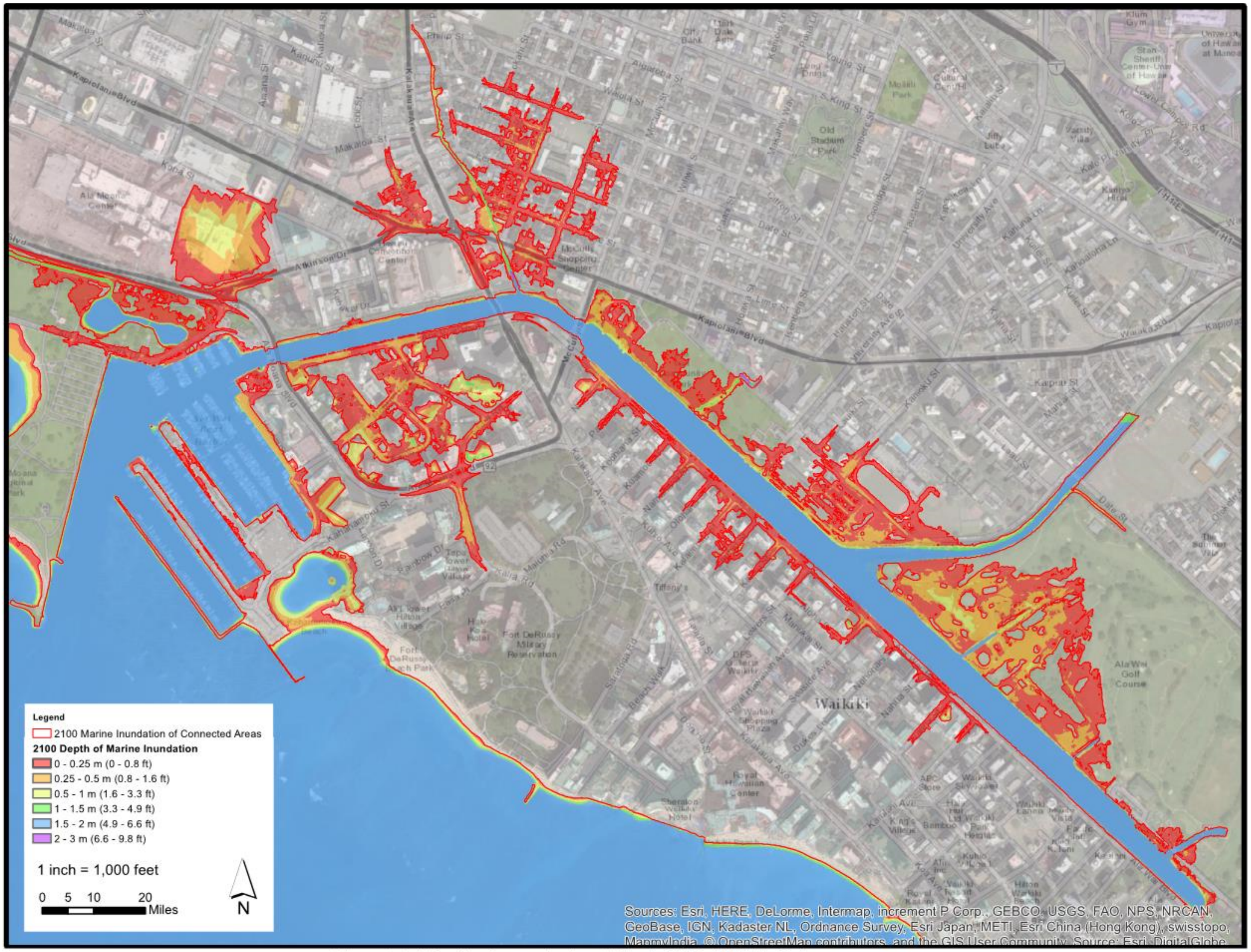


Figure A-14. Depth of Marine Inundation in 2100 in Waikiki.

Source: Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

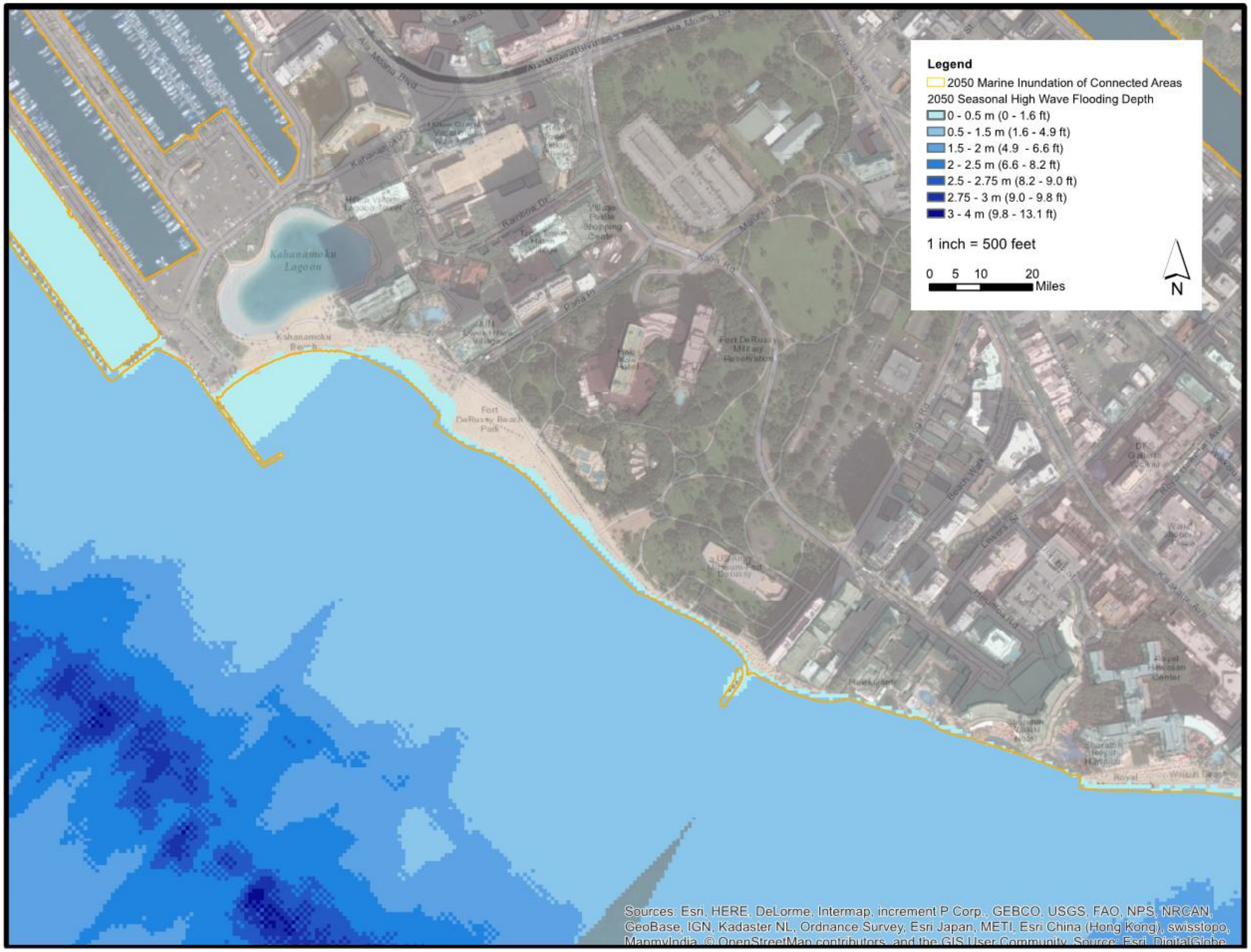


Figure A-15. Seasonal High Wave Flooding in 2050 in Waikiki.

Source: Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

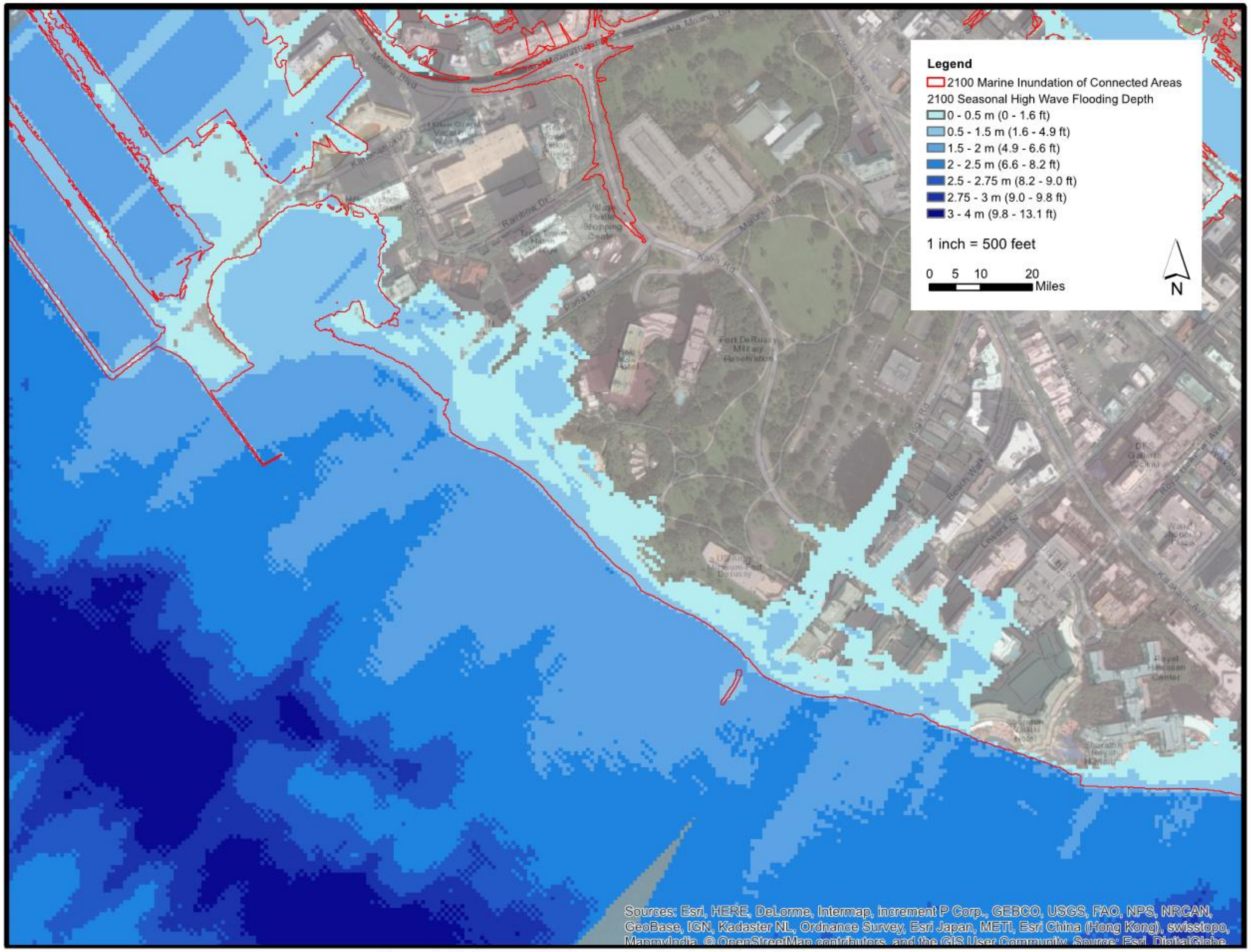


Figure A-16. Seasonal High Wave Flooding in 2100 in Waikiki.

Source: Data from Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community.

APPENDIX B

Infrastructure Vulnerability Assessment

For the evaluation, the full BWS pipe infrastructure database was clipped by the marine inundation and groundwater inundation boundaries to create a database of the impacted infrastructure using ArcGIS geospatial tools, and this area is referred to as the sea level rise exposure area (SLREA). The data were then merged with the eight planning regions so future data could be sorted by region.

BWS provided the relevant pipe attributes including:

- Pipe asset code
- Pipe length
- Pipe diameter
- Pipe material
- Pipe coating type
- Installation year
- Pipe cover (e.g., soil, hanging from bridge, etc.)
- CapPlan outputs: consequence of failure, probability of failure, and risk score

The clipped data were then exported to an Excel database and combined to eliminate overlapping pipe segments. For example, pipe segments impacted by marine inundation in 2050 were merged with the same segment impacted in 2100, so there is only one entry per unique pipe segment. Two new attributes were created in the database to indicate the hazard in 2050 and the hazard in 2100. The possible hazard combinations between the planning horizons were then ranked in order of risk based on an understanding of the hierarchy of vulnerabilities from seawater intrusion versus groundwater inundation. Additionally, a pipe segment impacted in both planning horizons was prioritized over a pipe segment that is not impacted until 2100.

The possible hazard combinations were ranked as follows in the database:

- Marine inundation 2050/marine inundation 2100
- Groundwater inundation 2050/marine inundation 2100
- Groundwater inundation 2050/groundwater inundation 2100
- None/marine inundation 2100
- None/groundwater inundation 2100

Chapter 4 of the report discusses the analysis of the infrastructure hazards for two sea level rise scenarios including all pipe diameters ranging from 1.25-inches to 42-inches. The length of pipeline affected by marine inundation increased five-fold with an increase in sea level rise from 1.1 feet to 3.2 feet (Figure B-1). The increase in pipe length influenced by groundwater inundation is even more dramatic over the 50-year planning horizon, increasing from approximately 700 feet of pipe to 52,000 feet from 2050 to 2100 (Figure B-2). As sea level rises, the water table is assumed to rise proportionally, resulting in a significant increase in low-lying areas that will be inundated by groundwater in addition to those impacted by sea level rise.

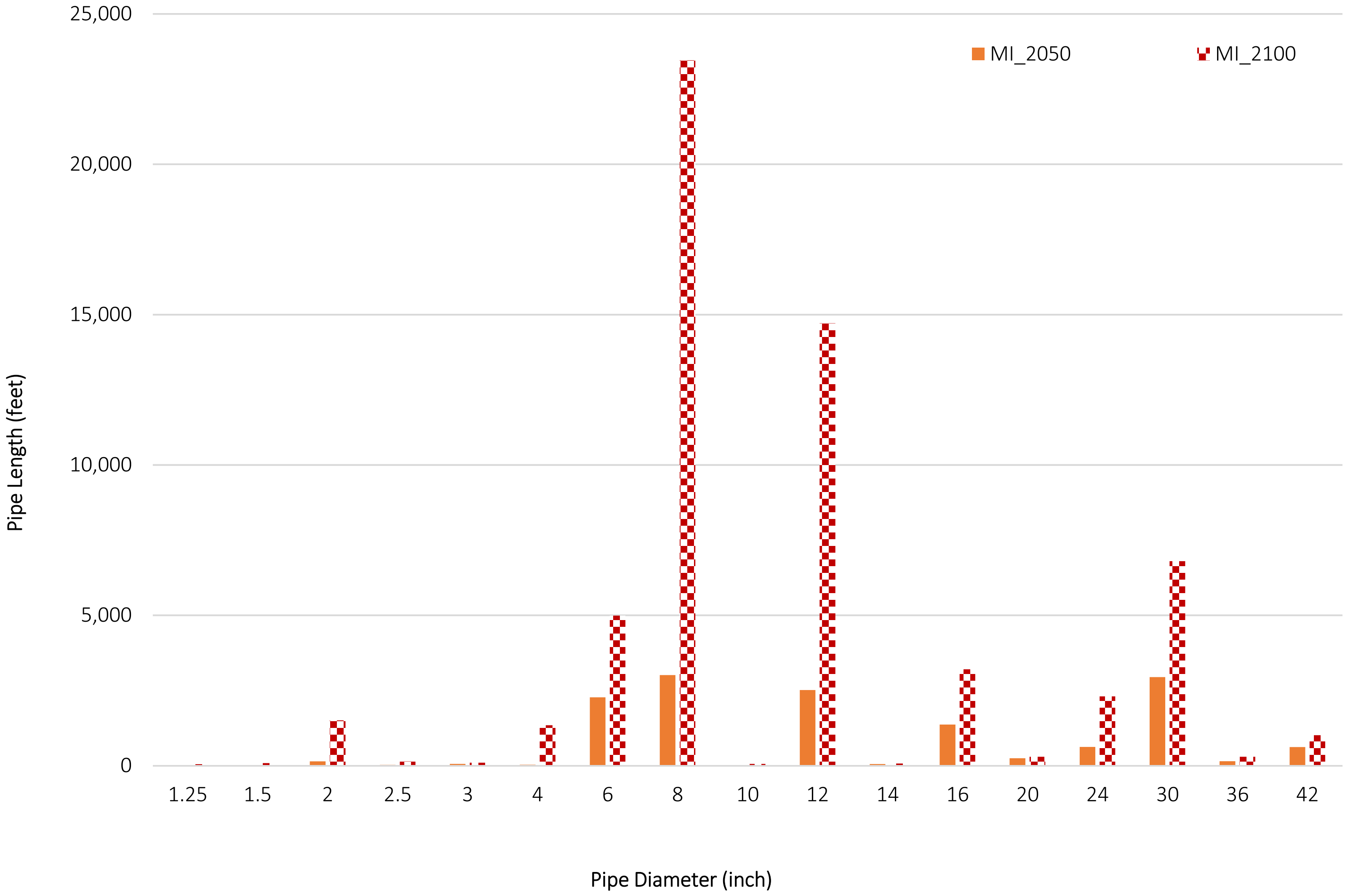


Figure B-1. Pipe Lengths Impacted by Marine Inundation in 2050 (1.1 ft Sea Level Rise) and 2100 (3.2 ft Sea Level Rise).

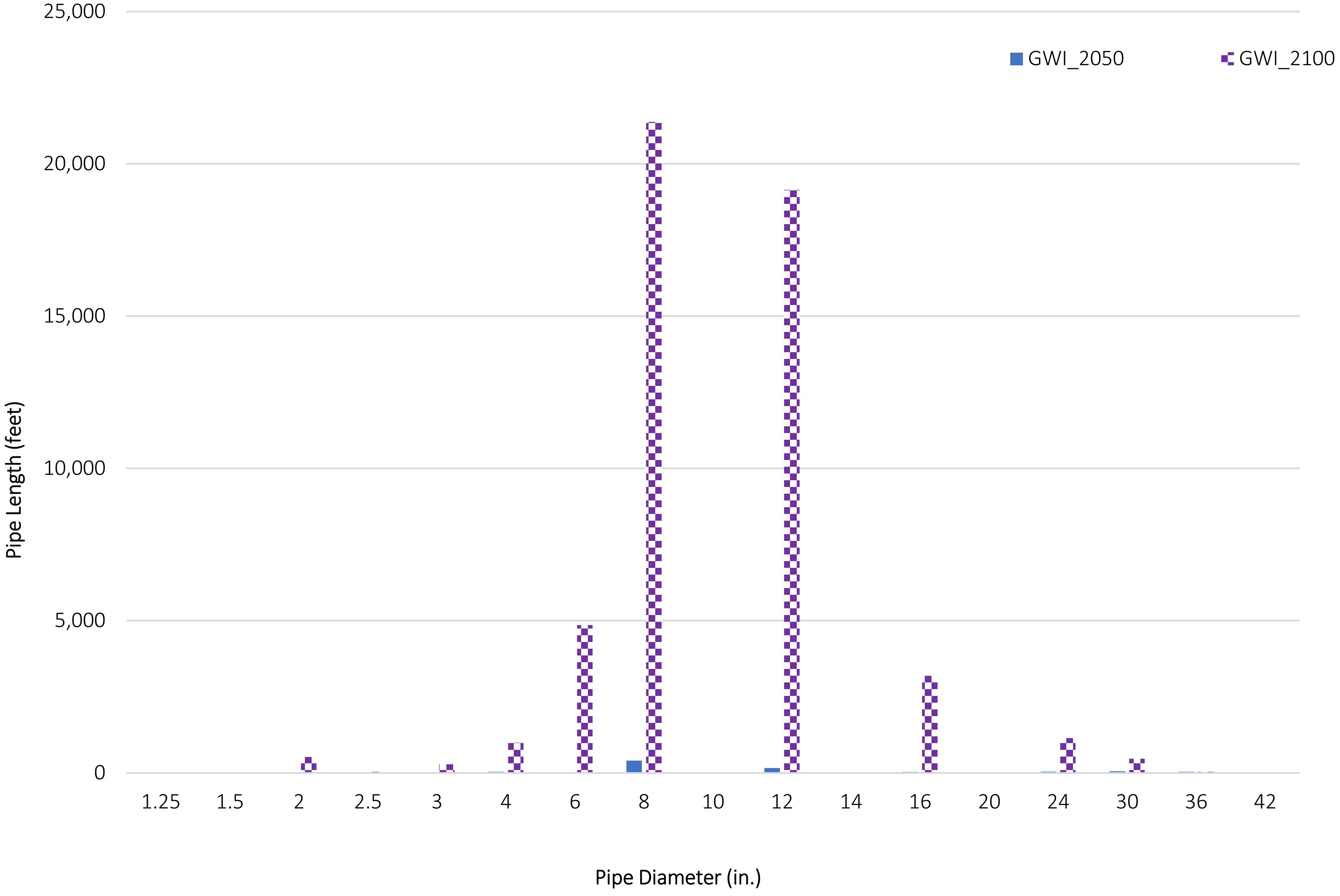


Figure B-2. Pipe Lengths Impacted by Groundwater Inundation in 2050 (1.1 ft Sea Level Rise) and 2100 (3.2 ft Sea Level Rise).

APPENDIX C

Groundwater Recharge Approach

The calculations and figures provided in Appendix C have been created by Brown and Caldwell based on information provided by UH Professor Tom Giambelluca, Abby Frazier of the East-West Center, and the University of Hawaii research team.

C.1 Linear-Regression Modeling Approach

The study completed by Izuka, Oki, and Engott titled "Simple Method for Estimating Groundwater Recharge on Tropical Islands" and published in the Journal of Hydrology was the basis for the linear-regression modeling approach. Izuka et al. (2010) developed and tested linear-regression models relating recharge to rainfall (and other water-budget inflows/outflows). The linear-regression models were developed using water-budget data sets for western Maui and the Lihue Basin of Kauai. The regression models were tested by comparing regression model-projected recharge to recharge estimated by additional water-budget data sets for (1) western Maui; (2) the Lihue Basin, but for a different water-budget scenario from the one used to develop the regression model; and (3) other tropical-island areas in southern Oahu and western Tutuila (Izuka et al. 2010).

Izuka et al. examined two different types of linear regression: a single-segment simple linear regression and a multiple-segment linear regression. For each recharge versus explanatory variable relationship tested, the optimal regression model was identified using a least-squares approach by finding the regression line(s) that minimized the sum of the squared errors between the regression line(s) and the recharge values (Izuka et al. 2010).

C.1.1 Selection of Data Set

The USGS water-budget model for Oahu (Engott et al. 2017) was used as the source of rainfall and recharge data for the linear-regression model-fitting process. Prior to fitting linear-regression models to the Oahu water-budget data set, the data set was processed to exclude data points that were heavily influenced by anthropogenic inflows/outflows. Similar data reduction was performed by Izuka et al. (2010). Data points with 2010 land uses representing developed and managed lands, specific forms of agriculture, wetlands and water bodies, and sparse vegetation were excluded from the analysis. Retained land uses were native forest, alien forest, shrubland, grassland, and kiawe/phreatophytes. From the retained land uses, an additional data reduction step was applied, representing less than 10.5 percent of the total recharge for Oahu, by removal of any data points with non-zero values of direct recharge and/or septic leakage. Thus, the retained data set represents a simplified water budget free of anthropogenic factor bias.

The retained data set included approximately 138,000 of the roughly 400,000 original data points (i.e., less than half of the original data points). However, each data point is associated with an area and recharge value, and the data points in the retained land uses represent 63 percent of the area and 82 percent of the volumetric recharge for Oahu, as shown in Table C-1 and on Figure C-1 (Engott et al. 2017). Data reduction of anthropogenic factors forces the statistical projections to be based on natural systems conditions. Developed and highly managed land receives supplemental irrigation when natural conditions do not meet the local irrigation demands and may also include areas of zero recharge (impervious areas) or elevated recharge (induced infiltration systems). Island-wide, anthropogenic sources of water (i.e., irrigation, direct recharge, and septic leakage) account for 7 percent of the total inflow to the water budget (rainfall and fog drip account for the remaining 93 percent, though fog drip accounts for only approximately 0.5 percent). A bivariate plot of recharge versus rainfall from the retained data set is shown on Figure C-2 (data obtained from Engott et al. 2017). Figure C-3 shows the locations of the data points in the retained data set.

Table C-1. Oahu Recharge Budget by Land Use (1978–2007).

Source: Data from Engott et al. 2017.

Land Use	Retained for Linear Regression	Total Area (ac)	Percentage of Area		Total Recharge (ac-ft)	Percentage of Recharge Budget	
Native forest	Retained for linear regression (except for a small number of data points with anthropogenic recharge representing less than 0.5% of island-wide recharge)	61,525	16.08%	63%	364,812	49.31%	82%
Alien forest		92,705	24.24%		156,720	21.18%	
Shrubland		49,632	12.98%		60,151	8.13%	
Grassland		31,331	8.19%		20,773	2.81%	
Kiawe/phreatophytes		4,436	1.16%		1,084	0.15%	
Developed, low intensity	Excluded from linear regression	56,840	14.86%	37%	60,051	8.12%	18%
Developed, medium intensity		28,219	7.38%		12,840	1.74%	
Golf course		5,193	1.36%		12,777	1.73%	
Tree plantation		7,902	2.07%		10,049	1.36%	
Reservoir		224	0.06%		9,841	1.33%	
Diversified agriculture		10,805	2.82%		8,809	1.19%	
Water body		854	0.22%		4,554	0.62%	
Pineapple		2,699	0.71%		4,504	0.61%	
Corn		3,278	0.86%		4,344	0.59%	
Developed, high intensity		21,337	5.58%		3,699	0.50%	
Sparsely vegetated		2,472	0.65%		2,287	0.31%	
Taro		46	0.01%		1,739	0.24%	
Coffee		345	0.09%		469	0.06%	
Wetland		985	0.26%		349	0.05%	
Near-coastal or estuarine water body		1,679	0.44%		0	0.00%	
Total		382,507	100%		739,851	100%	100%

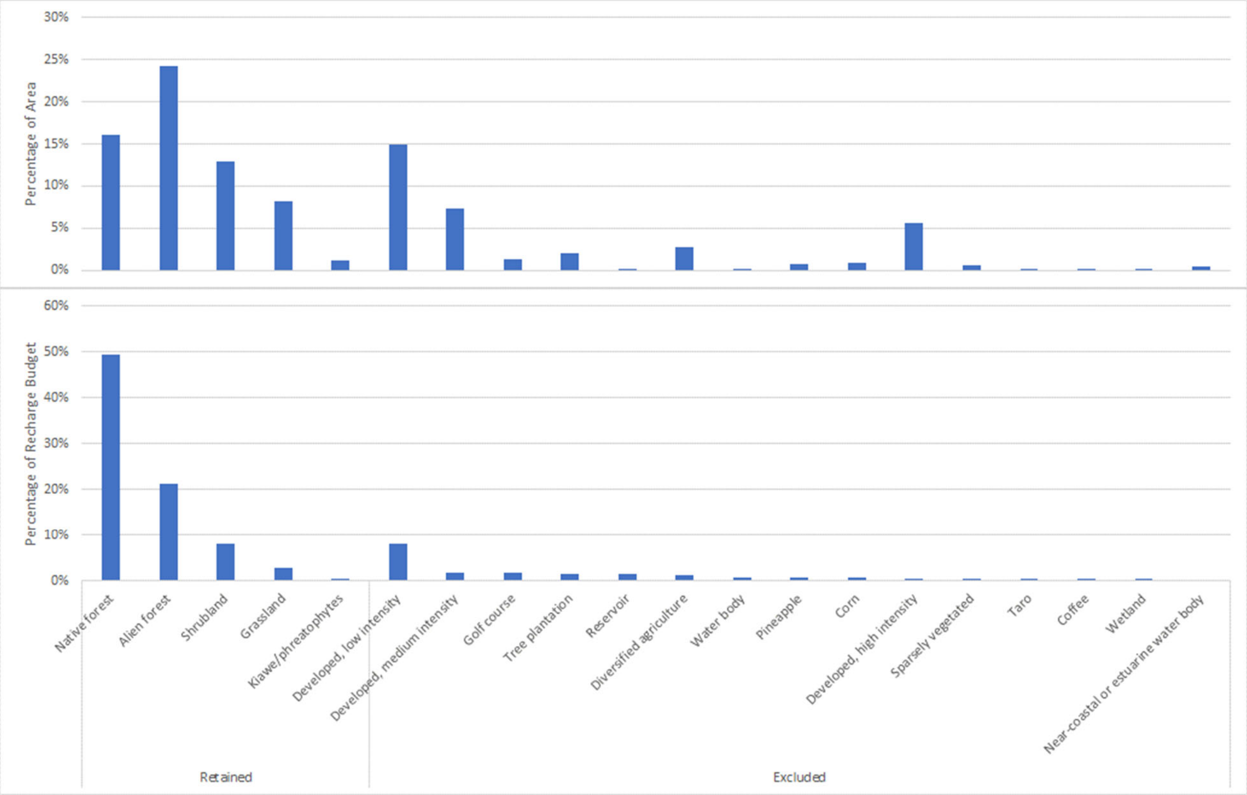


Figure C-1. Oahu Area and Recharge Budget by Land Use (1978–2007).

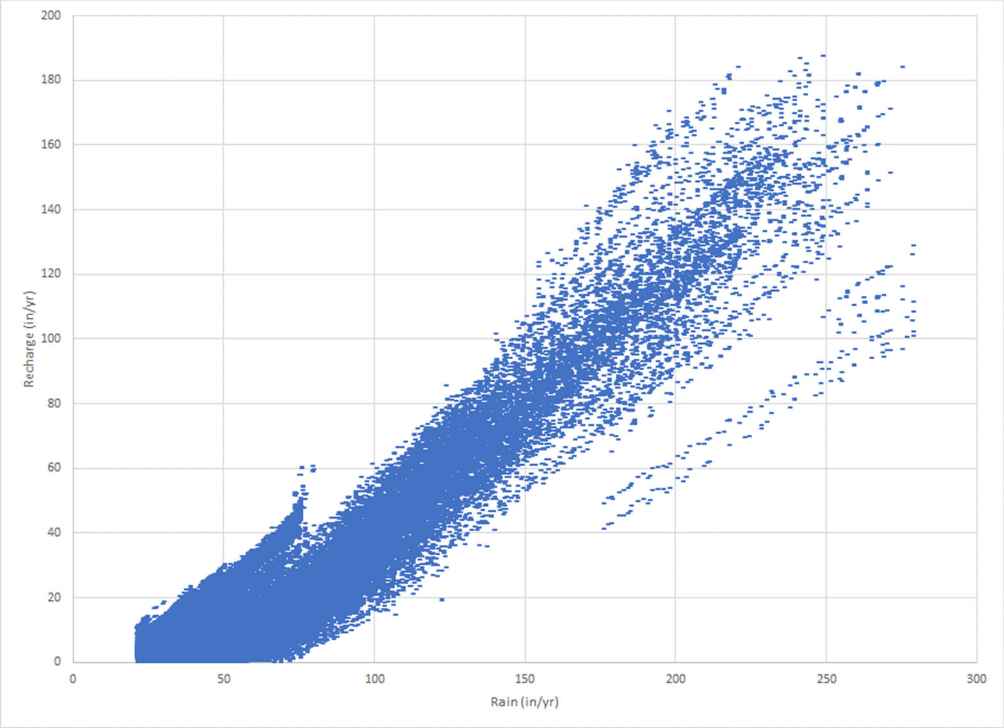


Figure C-2. Recharge vs. Rainfall from the Retained Correlation Data Set.

Source: Data from Engott et al. 2017.

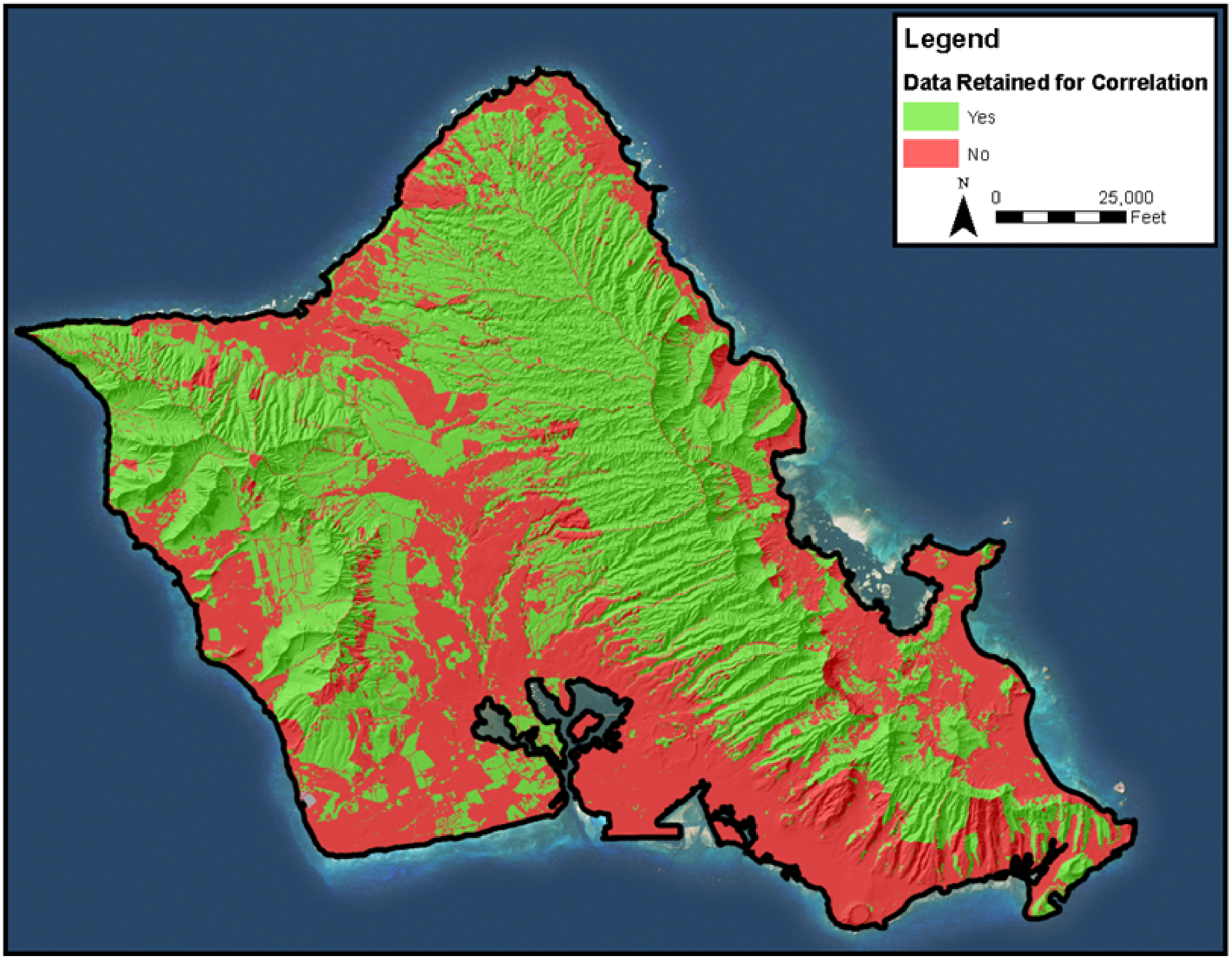


Figure C-3. Data Locations Retained for Correlation.

C.1.2 Linear-Regression Methods

Several different linear-regression forms were assessed to determine the best fit to the recharge versus rainfall data set. These forms included (1) a single-segment simple linear regression, (2) a single-segment linear regression with the y-intercept fixed at zero, and (3) several different forms of two-segment and three-segment linear regressions.

Orographic features and the direction of prevailing winds influence the recharge versus rainfall relationship geographically across Oahu. Areas in and around the Koolau Mountains on the windward side of Oahu follow one recharge-rainfall relationship while areas in and around the Waianae Mountains on the leeward (western) side of Oahu follow another. The Koolau Mountains are characterized by having much higher rainfall compared to the Waianae Mountains. Rainfall in the Koolau Mountains encompasses the full range of rainfall values from the 1978–2007 data set shown on Figure C-4 (i.e., 20 to 278 inches per year [in./yr]), while rainfall in the Waianae Mountains does not exceed 80 in./yr.

To account for differences between the Koolau and Waianae mountains, linear-regression models were also fit for two subsets of the data set, referred to as the Koolau Mountain Zone data set and the Waianae Mountain Zone data set. Data were assigned to each mountain zone using the boundaries shown on Figure C-4. The zones were delineated by drawing a polyline passing between the two mountain ranges, roughly from Haleiwa in the north to the Pearl Harbor inlet in the south. Between the two endpoints, the polyline was drawn by roughly bisecting the areas of higher rainfall occurring over each mountain range.

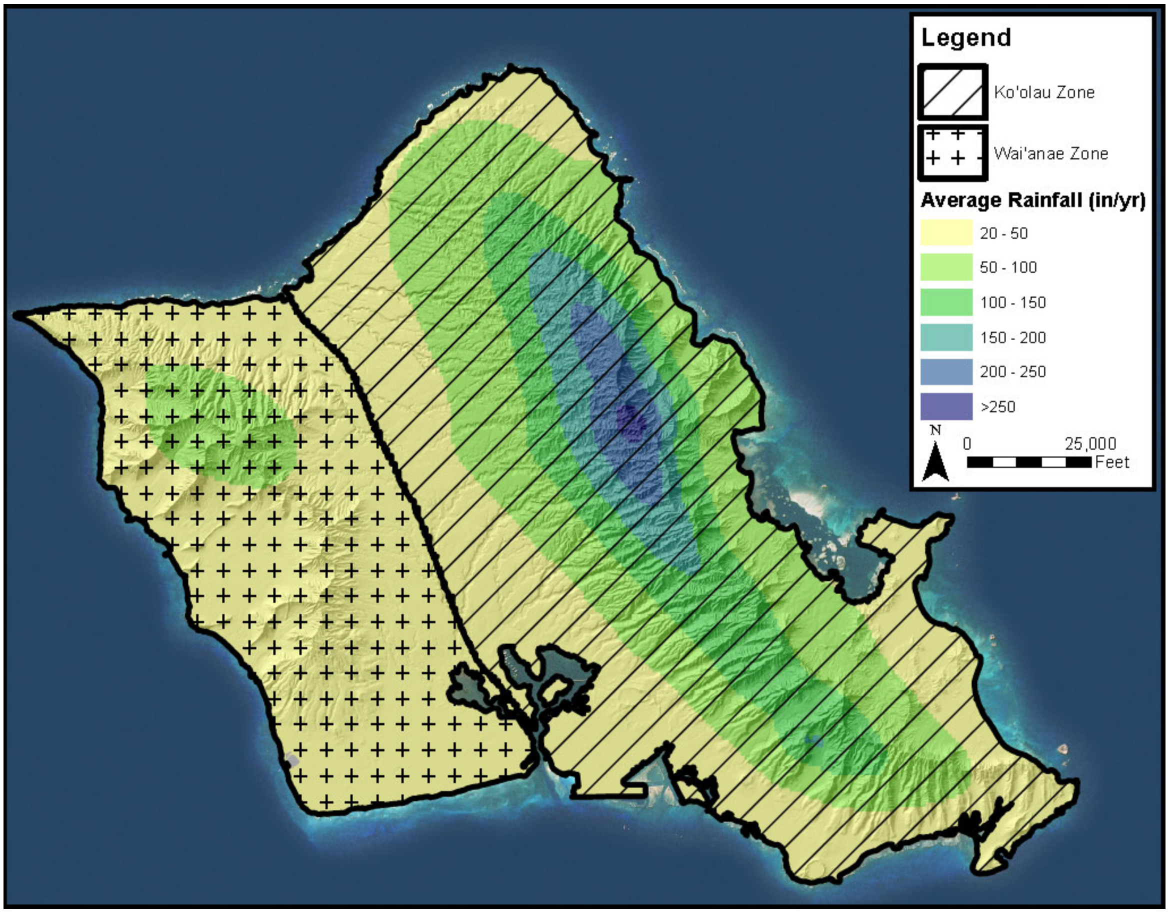


Figure C-4. Delineation of Mountain Zones.
Source: Data from Engott et al. 2017.

Linear regressions were performed using weighted linear-regression methods where each individual data point was weighted by the area it represents. Weighting by area was selected because the USGS water-budget data set (Engott et al. 2017) does not exist on a uniform grid over Oahu. Using unweighted linear regression would allow data points that represent small areas to exercise undue influence on the regressions. Weighting by area removes this potential bias.

Regardless of the form of the linear-regression model being fit, minimization of the weighted root mean square error (WRMSE) provides the fit that most closely reflects individual measurements. Minimizing WRMSE involves finding the linear-regression model that minimizes the following equation:

$$WRMSE = \sqrt{\frac{\sum_{i=1}^{N} w_i (y_i - \hat{y}_i)^2}{\sum_{i=1}^{N} w_i}}$$

where: y_i is the value of recharge for the ith data point from the USGS data set [Engott et al. 2017]

$\hat{y}_i$ is the value for recharge estimated by the linear-regression model for the ith data point

w_i is the weight assigned to the ith data point

N is the total number of data points in the data set

For multiple-segment linear regressions, the data were partitioned into subsets of data for each linear segment based on specified breakpoints between the segments (breakpoint refers to the value of rainfall at which one linear segment ends and the next begins). A linear regression was fit within each segment subject to the constraint that the linear-regression models in each segment are continuous at the breakpoints (i.e., the line segments connect to each other at the breakpoints). The overall performance of the multiple-segment regression model was then evaluated using the equation for WRMSE across all segments. This process was repeated for all possible values for the breakpoints in increments of 1 in./yr. The breakpoints that produced the smallest WRMSE were selected as the optimal breakpoints for the given multiple-segment form. All linear regressions, regardless of form, were implemented with a code written in the R Statistical Programming Language (R Core Team 2016) using calls to the "lm" function with appropriate data inputs and constraints for the given form of the regression model.

C.1.3 Linear-Regression Modeling Results

Regardless of the data set (i.e., Koolau, Waianae, or both zones combined), a two-segment linear regression of the following form was selected to model the rainfall-recharge relationship. The general form of this regression model is shown on Figure C-5. A single breakpoint was used to divide the data set into two segments. The regression line in the first segment was determined using simple linear regression with the constraint that the line pass through the axis origin. The regression line in the second segment was determined using linear regression subject to continuity with the first segment at the breakpoint.

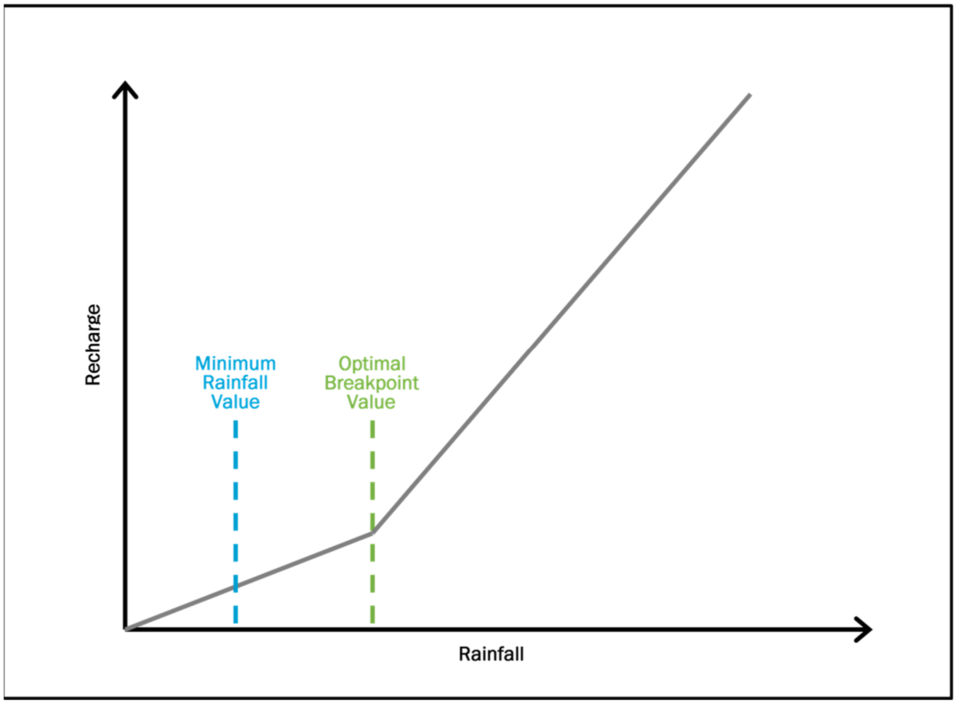


Figure C-5. General Form of Selected Linear-Regression Model.

The form of the linear-regression model described above was selected based on three primary factors. First, regardless of data set, the regression model produced the second lowest value of WRMSE among all regression models. The only regression model that produced a lower WRMSE was one that allowed a change in slope at the minimum rainfall value. Second, the form of the regression model was relatively simple compared to models with additional segments. Models with additional segments, while potentially producing lower values of RMSE, run the risk of “overfitting” the USGS data set (Engott et al. 2017) and inferring rainfall-recharge relationships that are heavily influenced by the “noise” in the data rather than the dominant “signal.” Third, the form of the regression model allows for the estimation of recharge at rainfall values below the minimum rainfall value in the USGS data set (Engott et al. 2017). If, for example, recharge were set equal to zero below the minimum rainfall value, then the regression model would project zero recharge in areas where future rainfall decreases below the current minimum rainfall value. While it is likely true that there is some threshold rainfall value below which no recharge will occur, arbitrarily setting this threshold at the current minimum rainfall value would be inappropriate. Thus, a regression model in which recharge varies linearly below the minimum rainfall value was viewed as more appropriate for this analysis.

Because each data set (i.e., Koolau, Waianae, or both zones combined) was evaluated using the regression method described above, final model selection was based not on the form of the linear model but instead on the ability of the single-zone versus two-zone methods to approximate the volumetric water budget across Oahu and within the two mountain zones. Figure C-6 plots the performance of the single-zone and two-zone models. The performance metric evaluated on the plot is the percent discrepancy (i.e., residual) in volumetric recharge estimated using the linear-regression model compared to the volumetric recharge reported by the USGS (Engott et al. 2017) water-budget model. For each model, the volumetric recharge residual is shown for (1) all of Oahu, (2) the Koolau Mountain Zone, and (3) the Waianae Mountain Zone. Negative residuals indicate that the linear-regression model underpredicts volumetric recharge. Positive residuals indicate an overprediction.

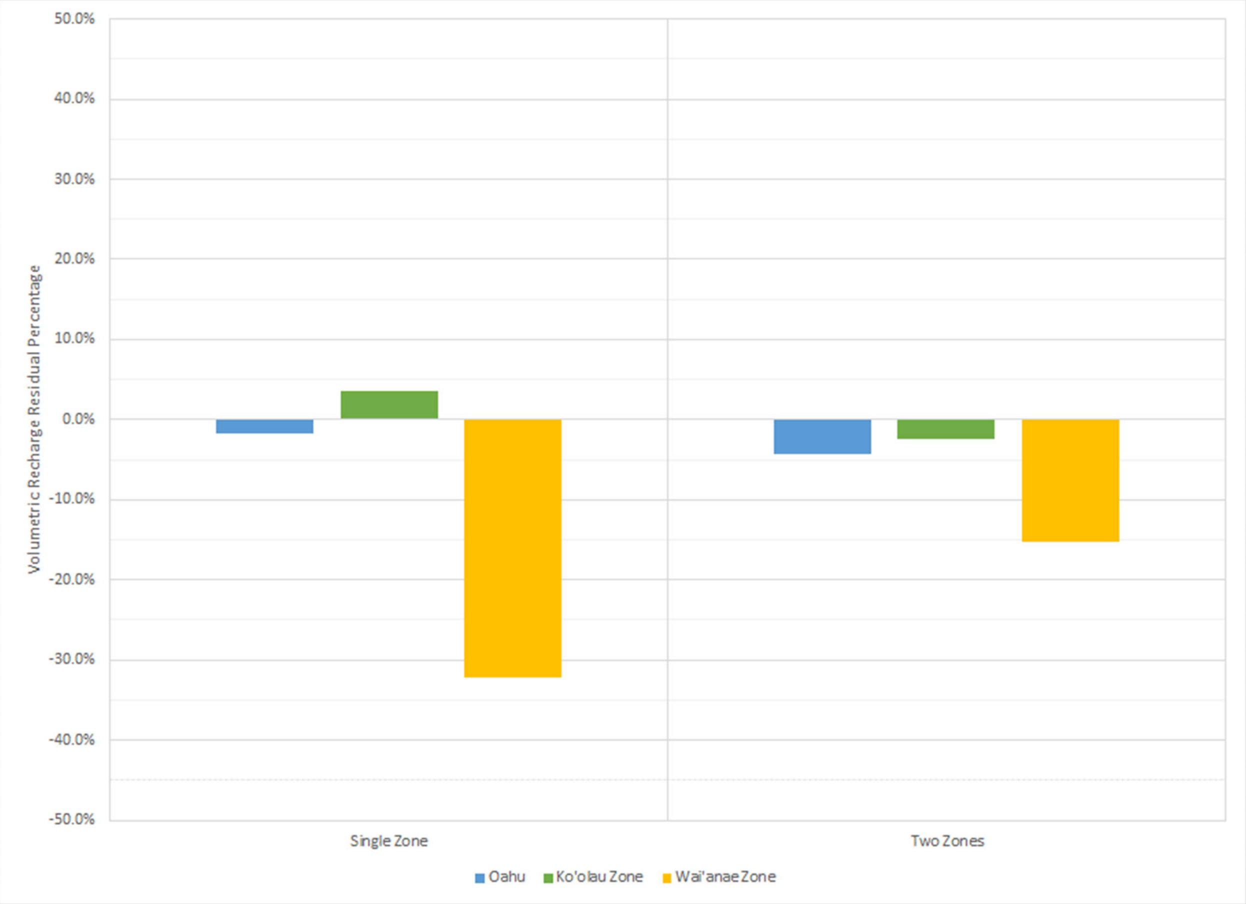


Figure C-6. Linear-Regression Model Comparison Based on Volumetric Recharge Residual Percentage. Volumetric recharge residual percentage is the percentage difference between recharge estimated using the linear-regression model and the recharge reported by the USGS water-budget model (Engott et al. 2017).

Figure C-7 indicates that both models perform reasonably well when results are aggregated over all of Oahu. The single-zone model produces a volumetric recharge residual of -1.7 percent while the volumetric recharge residual of the two-zone model is -4.3 percent. However, the two-zone model provides lower volumetric recharge residuals within the individual mountain zones, and thus is the model selected as the better fit. The two-zone model achieves a volumetric recharge residual of -2.4 percent in the Koolau Mountain Zone and -15.2 percent in the Waianae Mountain Zone. The model fit is shown on Figure C-7. Model parameters and statistics for the single zone and two-zone (best-fit) linear-regression models are provided in Table C-2.

The larger underprediction of recharge in the Waianae Mountain Zone by both linear-regression models occurs because the regression data set excluded data points with anthropogenic sources of inflow to the water budget. Because the Waianae Mountain Zone experiences less rainfall than the Koolau Mountain Zone, anthropogenic sources of water compose a larger percentage of the water budget in the Waianae Mountain Zone. While anthropogenic sources of water account for 7 percent of the total inflow to the island-wide water budget, they account for 15 percent of the total inflow in the Waianae Mountain Zone and just 5 percent in the Koolau Mountain Zone.

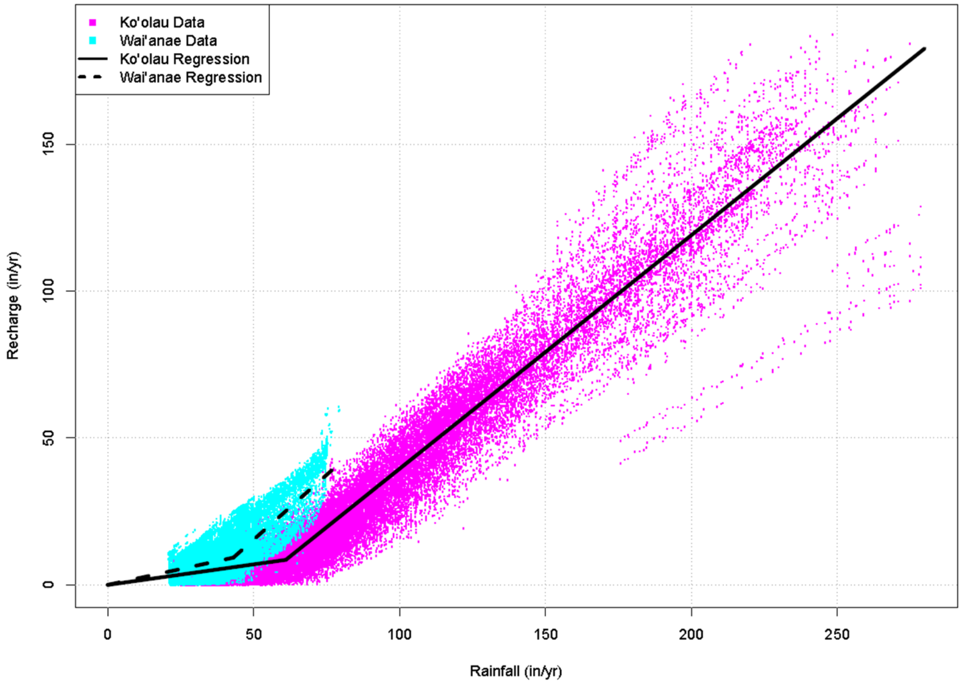


Figure C-7. Best-Fit Recharge-Rainfall Model.
Source: Data from Engott et al. 2017.

Table C-2. Model Parameters and Statistics.

Source: Data from Engott et al. 2017.

				Model Parameters				Volumetric Recharge Residual Percentage[b]		
Model Description	**Zone**	**WRMSE (in./yr)**	**Breakpoint Between Lower and Upper Segments (in./yr)**	**Lower Segment Slope (in./yr / in./yr)**	**Lower Segment Y-Intercept (in./yr)**	**Upper Segment Slope (in./yr / in./yr)**	**Upper Segment Y-Intercept (in./yr)**	**Oahu**	**Koolau**	**Waianae**
Single-zone	**N/A**	**9.31**	**65**	**0.204**	**0**	**0.779**	**-37.4**	**-1.7%**	**+3.6%**	**-32.2%**
Two-zone[a]	**Koolau**	**10.0**	**61**	**0.140**	**0**	**0.795**	**-40.0**	**-4.3%**	**-2.4%**	**-15.2%**
	Waianae	**5.10**	**43**	**0.215**	**0**	**0.881**	**-28.6**			

a. Best-fit model results.

b. Volumetric recharge residual percentage is the percentage difference between recharge estimated using the linear-regression model and the recharge reported by the USGS water-budget model

A map of the volumetric recharge residual percentage between the USGS water-budget model (Engott et al. 2017) and the best-fit linear-regression model is provided as Figure C-8. In both the Koolau and Waianae mountain zones, recharge is generally underpredicted at high elevations and overpredicted at the base of the mountains. Recharge in developed coastal areas is generally overpredicted in the Koolau Mountain Zone while it is generally underpredicted in the Waianae Mountain Zone. Irrigated areas generally experience the strongest underprediction of recharge by the linear-regression model, as expected due to the exclusion of data points with anthropogenic factor bias from the regression data set.

A map of the volumetric recharge residual percentage between the USGS water-budget model (Engott et al. 2017) and the best-fit model aggregated within DLNR aquifer boundaries (State of Hawaii Office of Planning 2006) is provided as Figure C-9. At this scale, model performance is generally within -15 to +25 percent, with a few exceptions at relatively small scales. Similar performance was achieved at regional scales by the recharge versus rainfall models presented by Izuka et al. (2010) within the regions evaluated in that study.

Although the linear-regression model does not perfectly project recharge at every point on Oahu, these discrepancies were mitigated to some extent when the model was used to project future recharge. The linear-regression model was used to project recharge using both the present and future rainfall data sets. Thus, any spatial bias in the performance of the regression model appeared in both the present and future estimates of recharge. The change in future recharge was calculated by computing the difference between present recharge and future recharge, and thus the spatial bias canceled out to some extent. Because the largest spatial biases in the performance of the regression model are due to anthropogenic recharge, the model is interpreted to reasonably approximate future changes in natural recharge free of anthropogenic factors (e.g., changes in land use, development, water management, etc.).

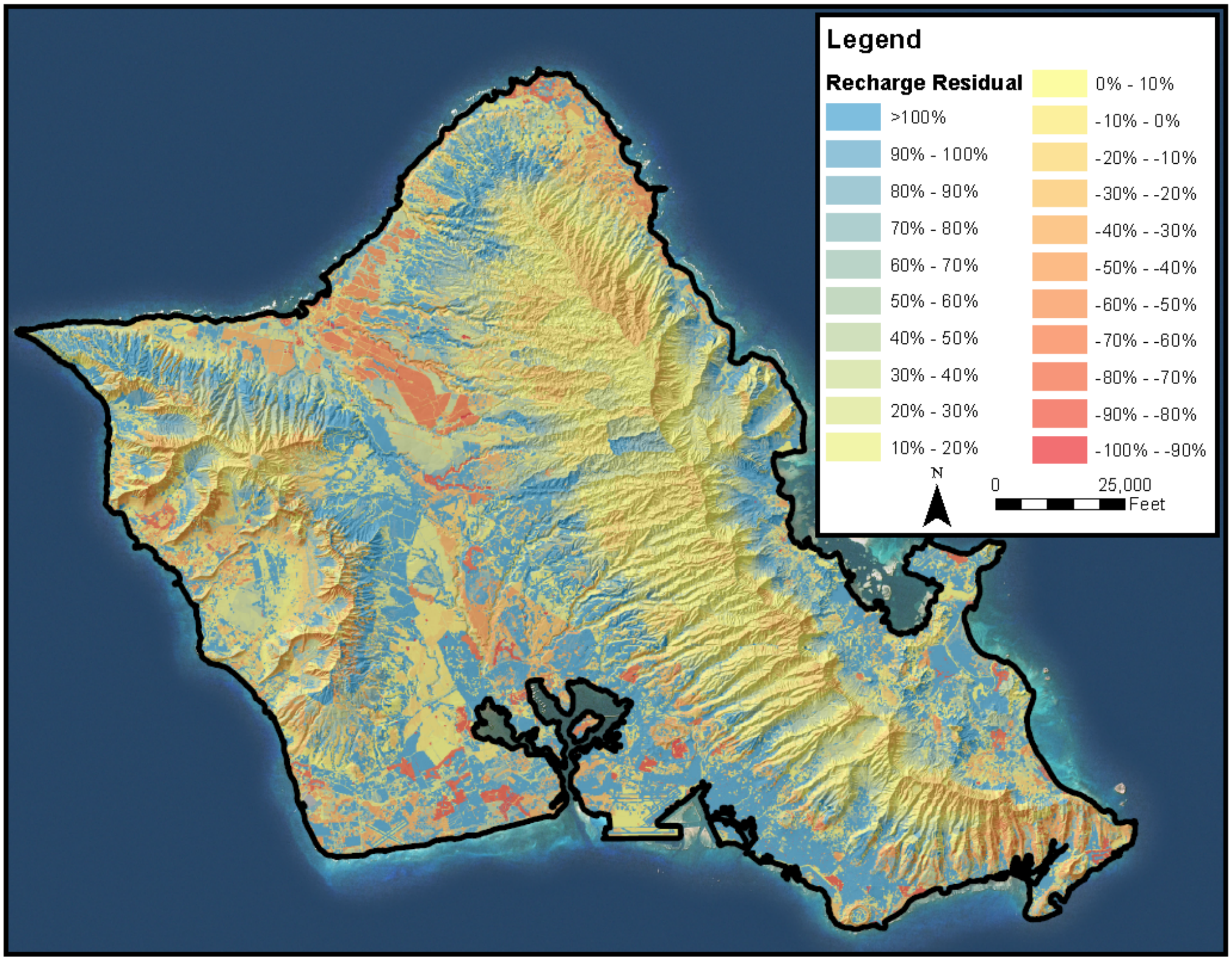


Figure C-8. Best-Fit Model Volumetric Recharge Residual.
Volumetric recharge residual is the percentage difference between recharge estimated using the linear-regression model and the recharge reported by the USGS water-budget model (Engott et al. 2017).

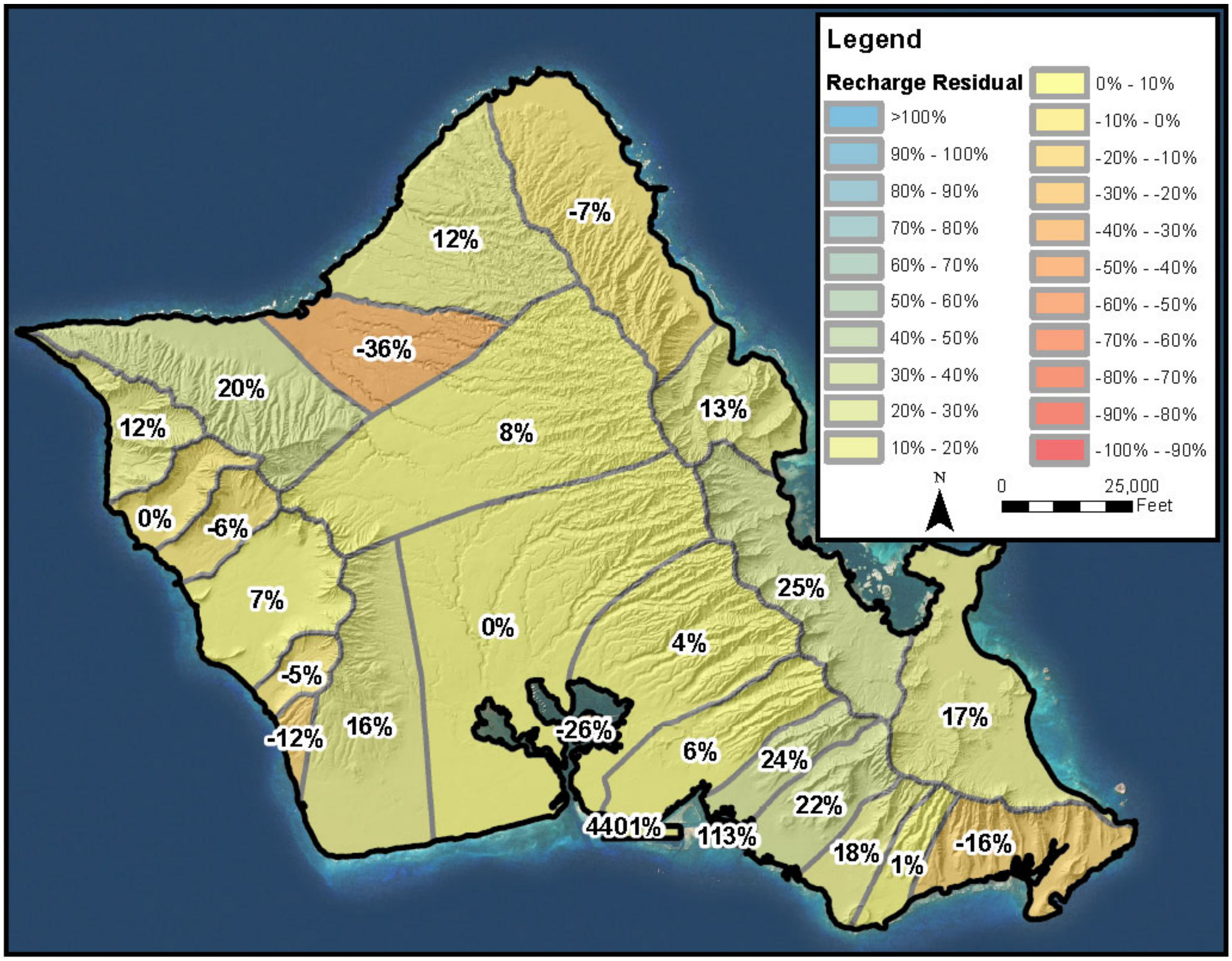


Figure C-9. Best-Fit Model Volumetric Recharge Residual (by Aquifer).

Volumetric recharge residual is the percentage difference between recharge estimated by the linear-regression model and the recharge reported by the USGS water-budget model (Engott et al. 2017).Projected Recharge Under Climate Change Scenarios

Changes in recharge were estimated using three data sets for projected rainfall developed using different climate downscaling methodologies and periods. The first data set represents dynamically downscaled rainfall projections for the period 2080–2099 (Zhang et al. 2016). The second and third data sets represent statistically downscaled rainfall projections for the periods 2041–2070 (mid-century) and 2071–2100 (late-century) (Timm et al. 2015). Each of the three data sets contains rainfall projections based on two GHG RCPs: RCP 4.5 and RCP 8.5, for a total of six climate change scenarios.

Recharge estimates were developed following the process flow diagram shown in Figure C-10. All calculation steps were implemented digitally using ArcGIS ModelBuilder as follows:

1. Raster files were obtained from the referenced data sources depicting the projected changes in Oahu rainfall. A total of 12 rasters were obtained, including wet season (November–April) and dry season (May–October) projections under the six scenarios previously described.
2. For each scenario, the wet and dry season rasters were added together to obtain rasters of projected annual changes in rainfall.

3. The annual projected change in rainfall rasters was added to the present (1978–2007) annual rainfall raster from the Rainfall Atlas of Hawaii (Giambelluca et al. 2013) to create rasters of projected rainfall under the 12 climate change scenarios.
4. All rainfall rasters (present and projected) were split into separate rasters for the Koolau Mountain Zone and the Waianae Mountain Zone.
5. Recharge rasters were created by applying the best-fit recharge versus rainfall linear-regression models to the rainfall rasters in each mountain zone.
6. For each scenario (present and projected), the recharge rasters in each mountain zone were combined into a single island-wide raster.
7. The changes in recharge under the climate change scenarios were calculated by subtracting the present (1978–2007) estimated recharge raster from the projected recharge rasters.

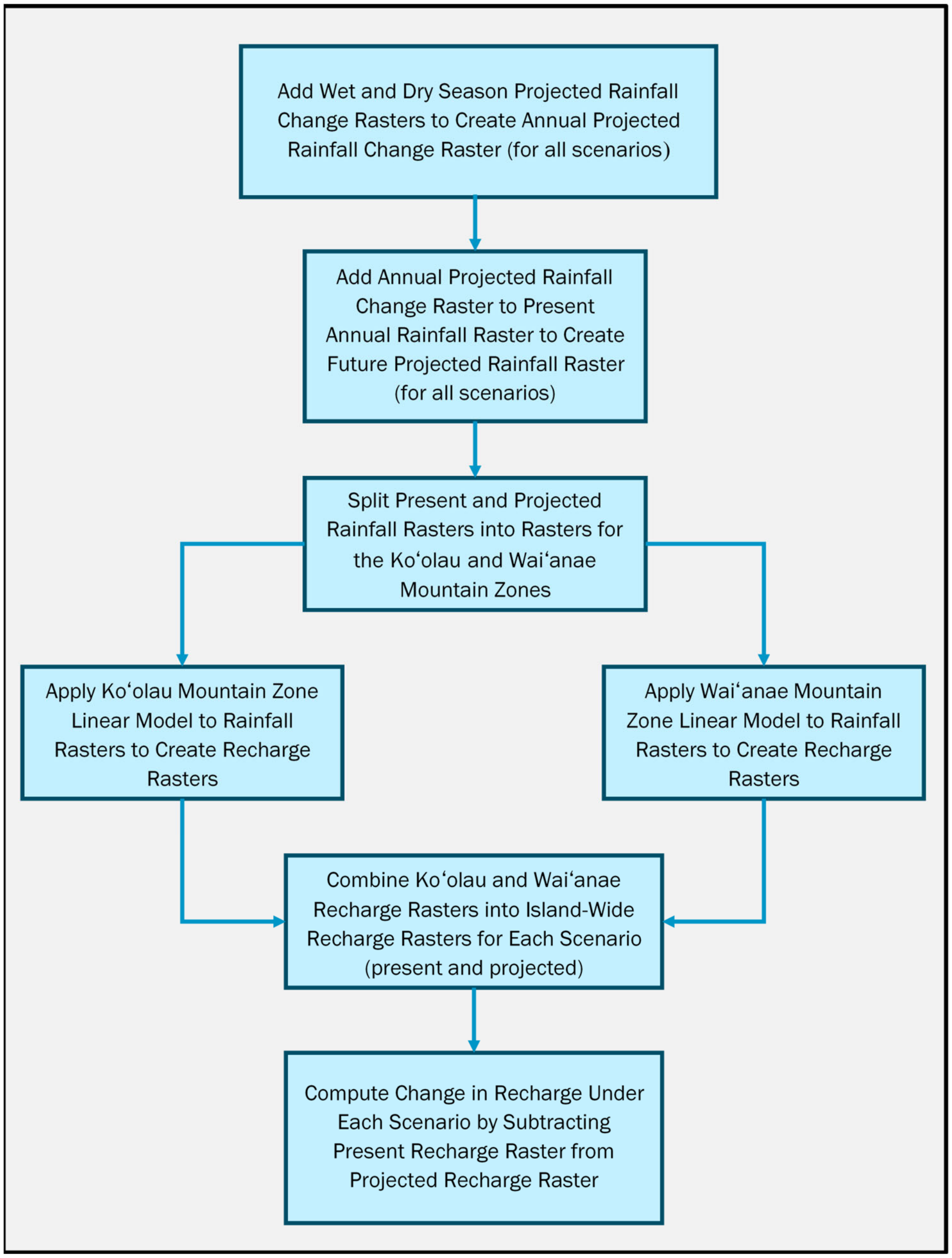


Figure C-10. Recharge Calculation Flow Diagram.

As previously discussed, the linear-regression model was used to calculate recharge in both the present and future periods to attempt to minimize the effects of spatial bias in the performance of the model. The alternative would have been to compare the projected future recharge to the estimates of recharge presented by the USGS water-budget model (Engott et al. 2017), which would have introduced significant spatial bias into the estimates of future changes in recharge.

Figure C-11 provides maps of the projected changes in rainfall for the dynamically downscaled data set. Positive values indicate more rainfall and negative values indicate less rainfall. The changes in rainfall are also aggregated within DLNR aquifer boundaries. Figure C-12 provides analogous maps of the projected changes in recharge. Figures C-13 through C-16 provide the projected rainfall and recharge changes for the two statistically downscaled data sets.

Table C-3 provides a summary of present and projected recharge as calculated by the linear regression model. The projected recharge is presented for each of the six climate change scenarios. Within each scenario, projected recharge is calculated for each aquifer. The results in Table C-3 indicate a range of possible outcomes for projected recharge, with the potential for both increases and decreases in recharge.

The two dynamical downscaling scenarios project increased recharge island-wide in the 2080 - 2099 time period, which is consistent with the increased precipitation under these scenarios. The RCP 8.5 scenario indicates slightly more recharge (+6.6 percent) compared to the RCP 4.5 scenario (+4.8 percent). Almost all aquifers are projected to experience increased recharge, with increases ranging between 0.3 percent and 21.5 percent. Aquifers that experience decreases are largely concentrated in the northwest corner of Oahu (Figure C-12), although projected decreases are relatively small (-0.3 percent to -5.1 percent).

In contrast to the dynamically-downscaled scenario, the four statistical downscaling scenarios project decreased recharge both island-wide and within every aquifer due to decreased precipitation. Island-wide, projected decreases in recharge range from -15.7 percent to -24.2 percent. Decreases in recharge are generally more pronounced in the 2071 - 2100 time period compared to the 2041 - 2070 time period. Decreases in recharge are also more pronounced under the RCP 8.5 scenario compared to the RCP 4.5 scenario. Within the aquifers, projected decreases in recharge range between -2.8 percent and -72.1 percent. Figures C-14 and C-16 indicate that, regardless of scenario, the aquifers that experience the largest decreases in recharge are located on the leeward (western) side of Oahu.

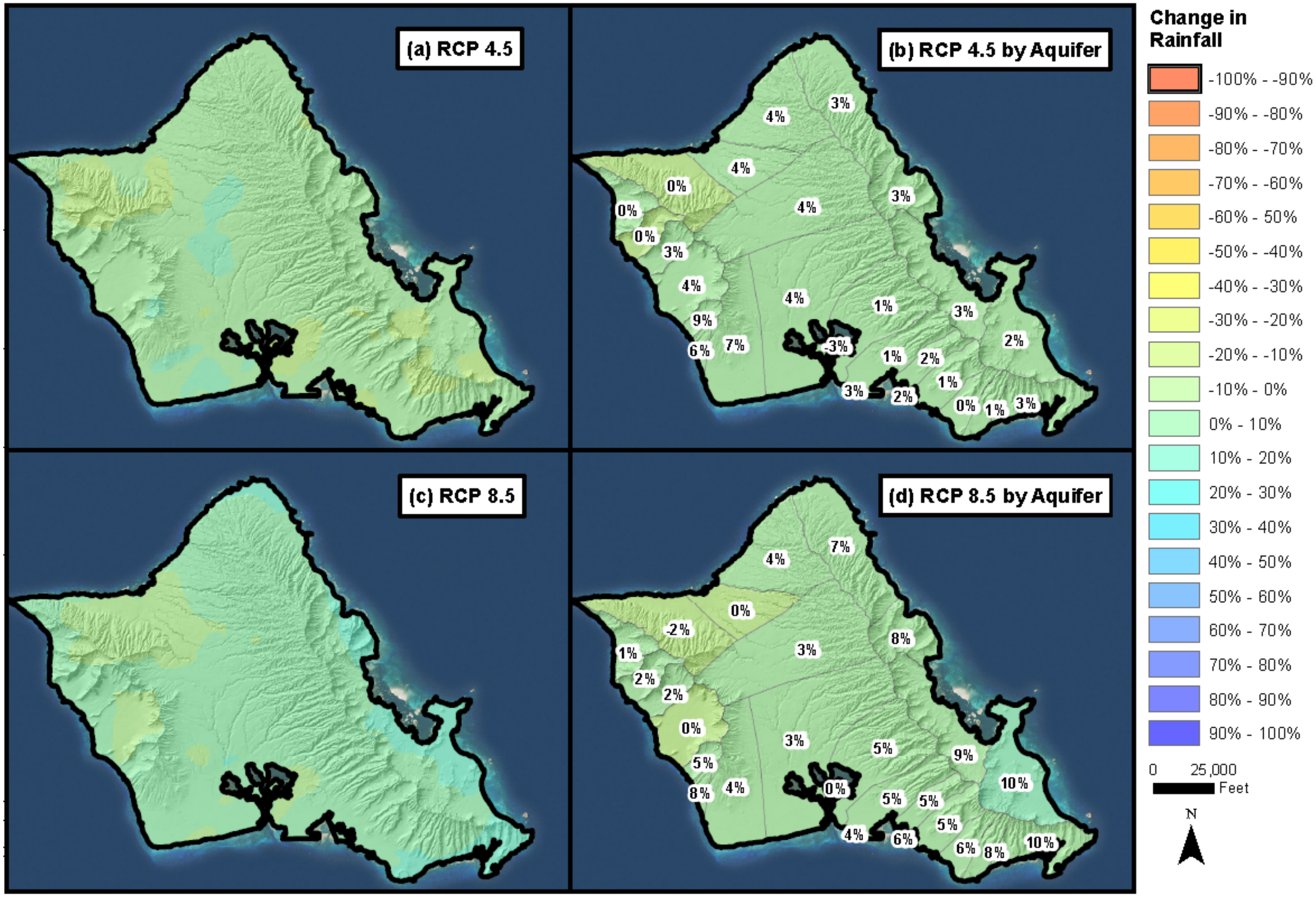


Figure C-11. Projected Changes in Rainfall: Dynamic Downscaling (2080–2099) Minus Present (1978–2007).
Source: Data from Zhang et al. 2016 and Giambelluca et al. 2013.

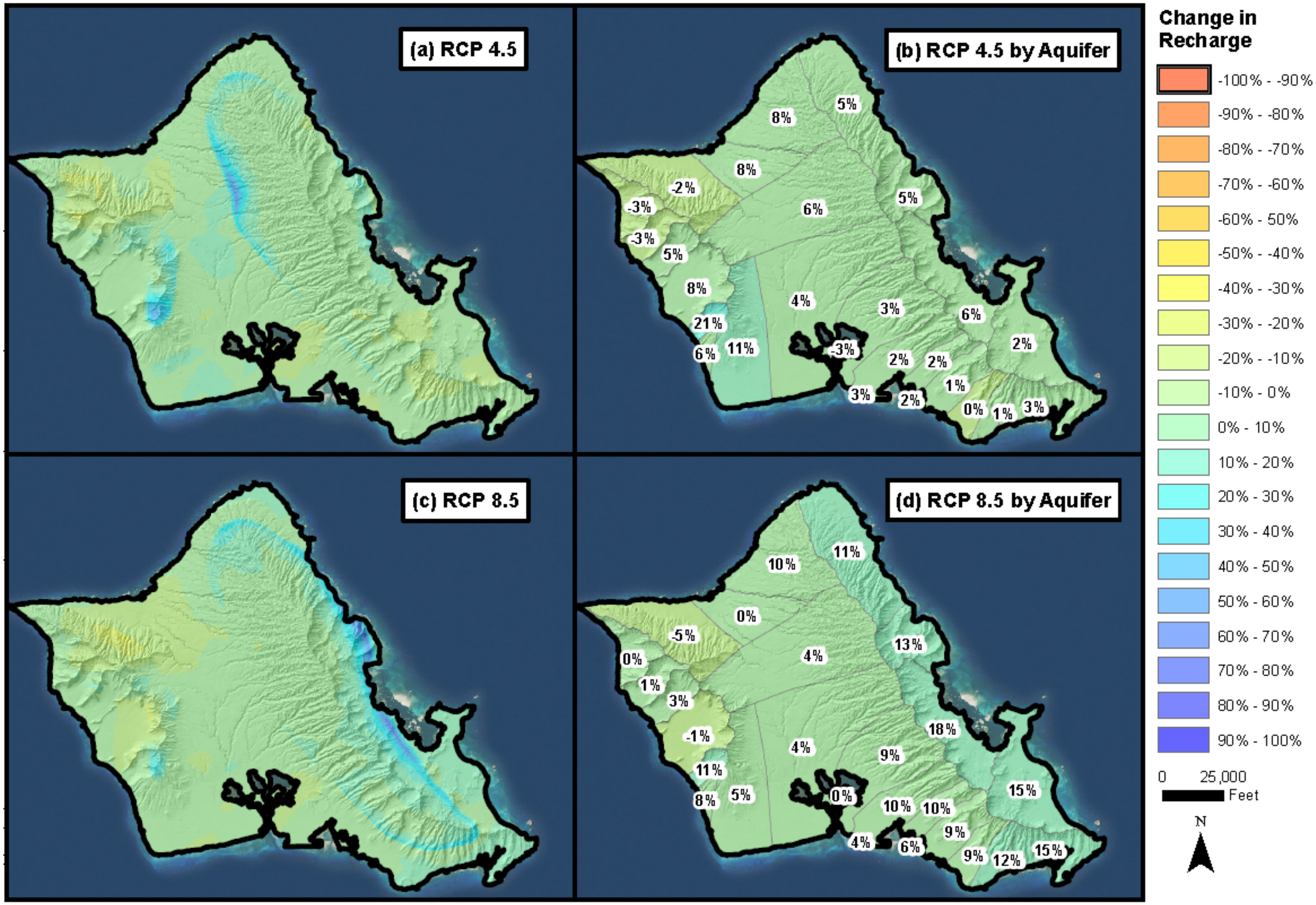


Figure C-12. Projected Changes in Recharge from Regression Model: Dynamic Downscaling (2080–2099) Minus Present (1978–2007).

Source: Data from Zhang et al. 2016 and Giambelluca et al. 2013.

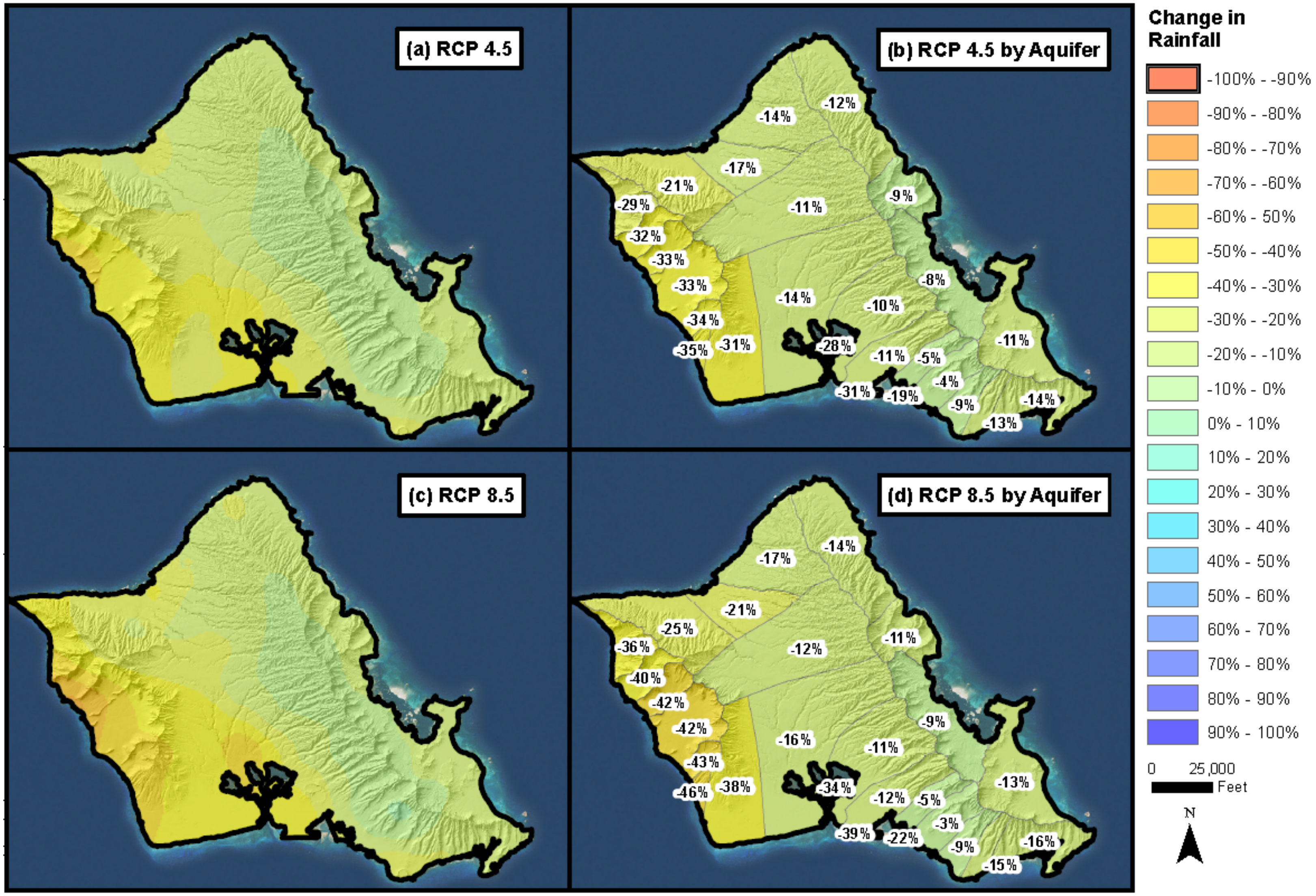


Figure C-13. Projected Changes in Rainfall: Statistical Downscaling (2041–2070) Minus Present (1978–2007).

Source: Data from Timm et al. 2015 and Giambelluca et al. 2013.

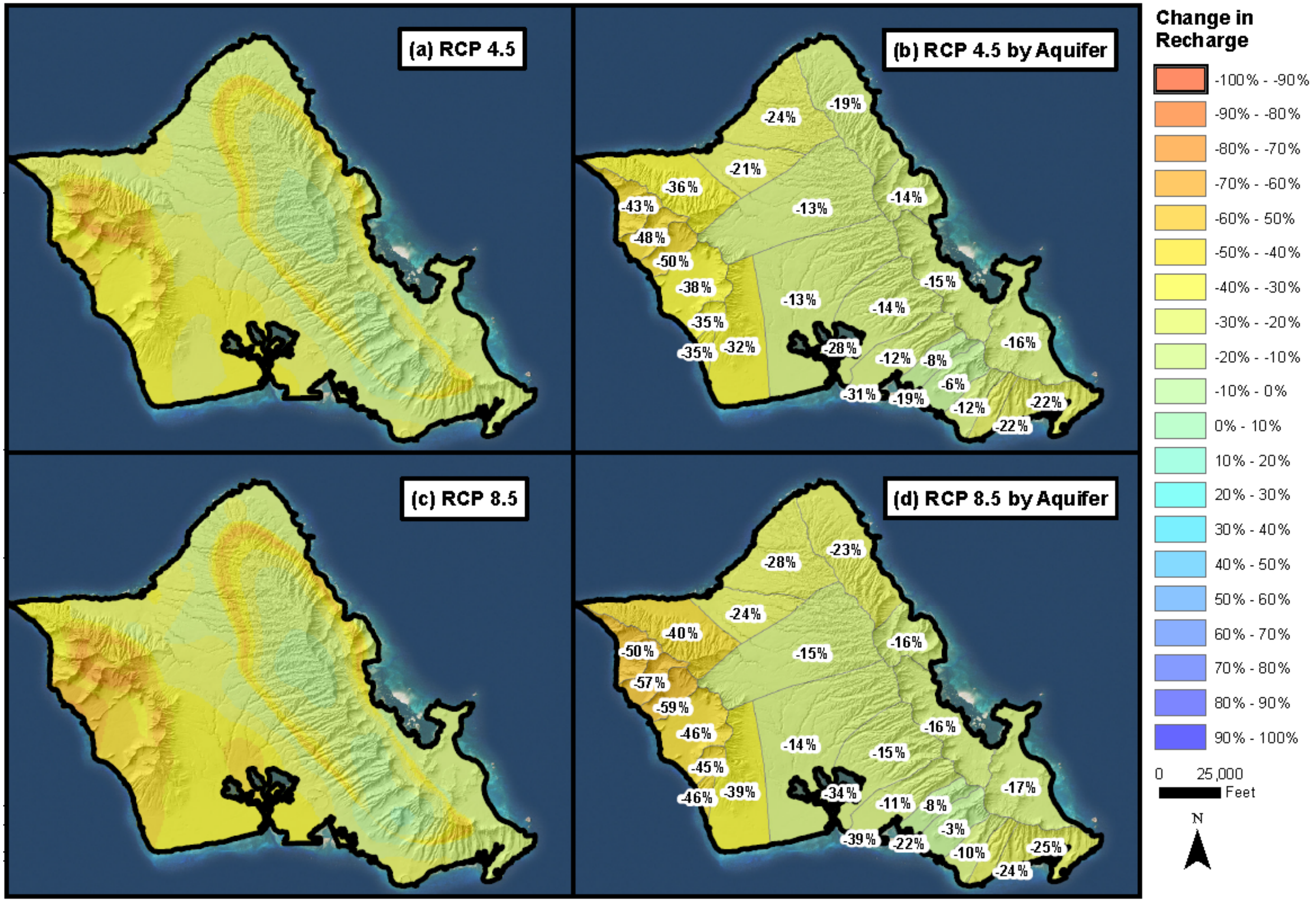


Figure C-14. Projected Changes in Recharge from Regression Model: Statistical Downscaling (2041–2070) Minus Present (1978–2007).
Source: Data from Timm et al. 2015 and Giambelluca et al. 2013.

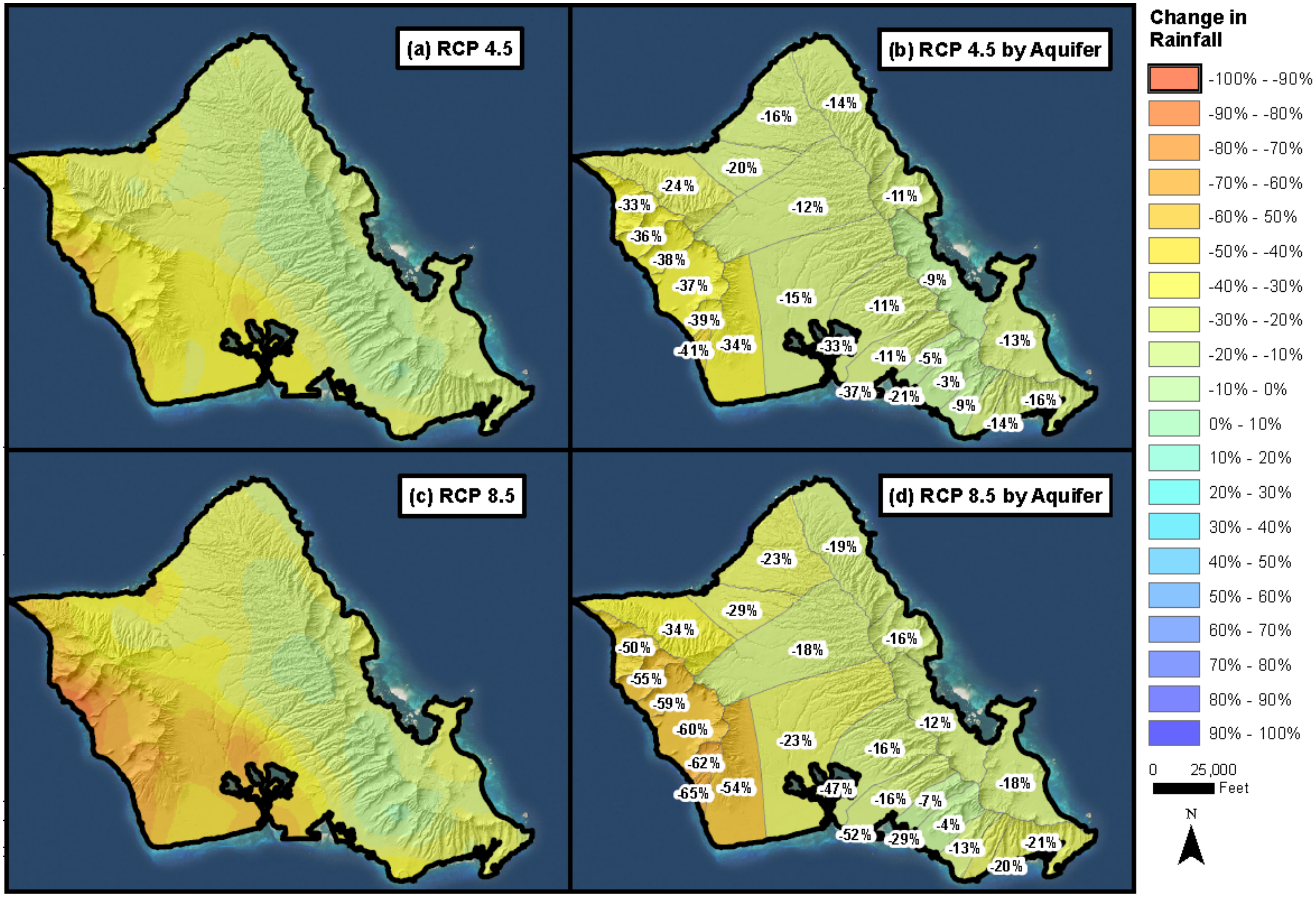


Figure C-15. Projected Changes in Rainfall: Statistical Downscaling (2071–2100) Minus Present (1978–2007).
Source: Data from Timm et al. 2015 and Giambelluca et al. 2013.

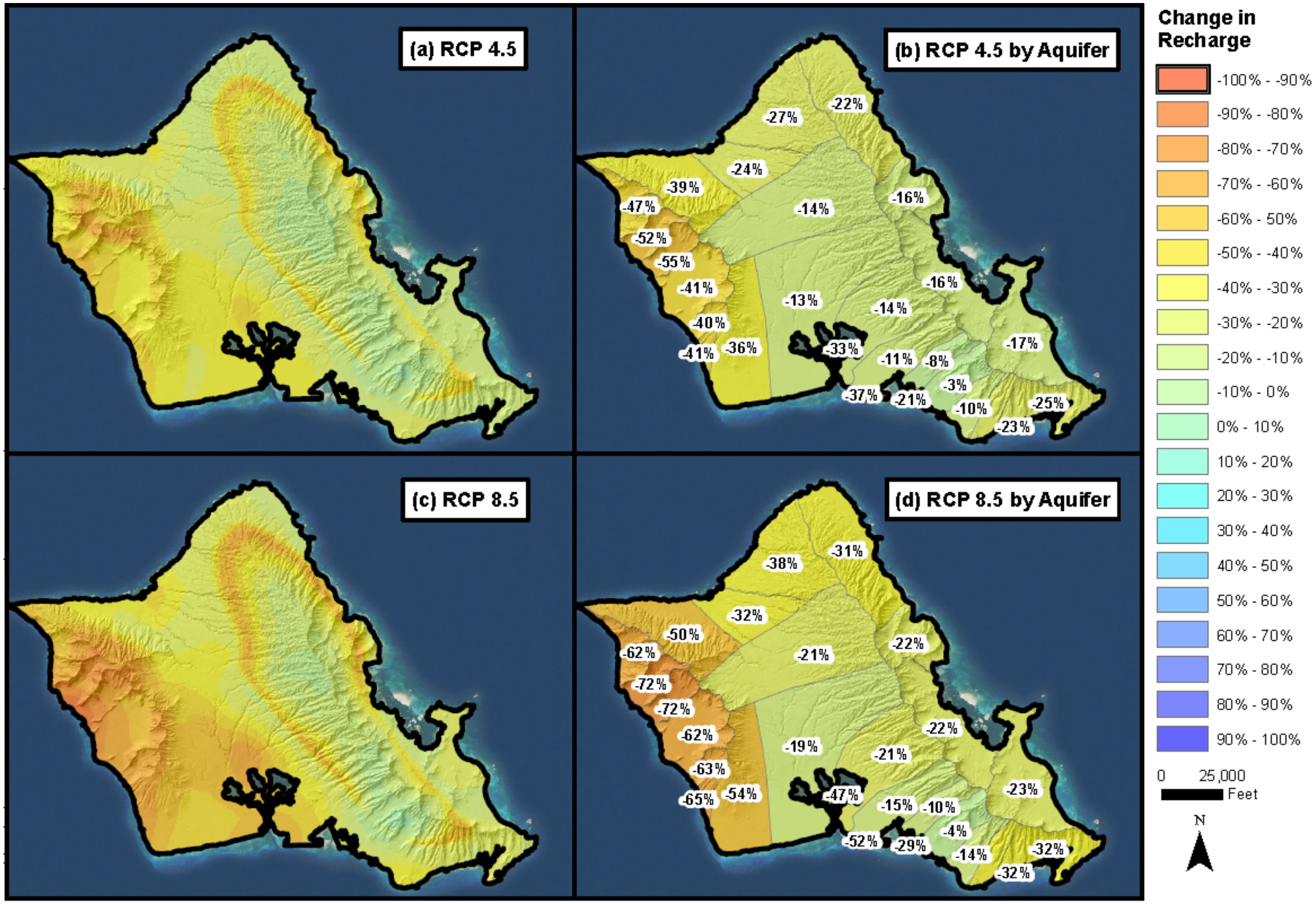


Figure C-16. Projected Changes in Recharge from Regression Model: Statistical Downscaling (2071–2100) Minus Present (1978–2007).

Source: Data from Timm et al. 2015 and Giambelluca et al. 2013.

Table C-3. Summary of Present and Projected Recharge as Calculated by the Linear-Regression Model.

DLNR Aquifer System Name	DLNR Aquifer Code	Present Recharge (1978–2007) (ac-ft)	Dynamical Downscaling (2080–2099) RCP 4.5			Dynamical Downscaling (2080–2099) RCP 8.5			Statistical Downscaling (2041–2070) RCP 4.5			Statistical Downscaling (2041–2070) RCP 8.5			Statistical Downscaling (2071–2100) RCP 4.5			Statistical Downscaling (2071–2100) RCP 8.5		
			Projected Recharge (ac-ft)	Change in Recharge (ac-ft)	Change in Recharge (percent)	Projected Recharge (ac-ft)	Change in Recharge (ac-ft)	Change in Recharge (percent)	Projected Recharge (ac-ft)	Change in Recharge (ac-ft)	Change in Recharge (percent)	Projected Recharge (ac-ft)	Change in Recharge (ac-ft)	Change in Recharge (percent)	Projected Recharge (ac-ft)	Change in Recharge (ac-ft)	Change in Recharge (percent)	Projected Recharge (ac-ft)	Change in Recharge (ac-ft)	Change in Recharge (percent)
Palolo	30101	10,095	10,062	-33	-0.3%	11,043	948	9.4%	8,885	-1,210	-12.0%	9,068	-1,027	-10.2%	9,050	-1,045	-10.4%	8,675	-1,420	-14.1%
Nuuanu	30102	23,957	24,270	313	1.3%	26,154	2,197	9.2%	22,608	-1,349	-5.6%	23,282	-675	-2.8%	23,167	-790	-3.3%	23,059	-898	-3.7%
Kalihi	30103	13,660	13,959	299	2.2%	14,993	1,334	9.8%	12,503	-1,157	-8.5%	12,612	-1,048	-7.7%	12,591	-1,069	-7.8%	12,262	-1,398	-10.2%
Moanalua	30104	22,627	23,046	419	1.9%	24,858	2,231	9.9%	19,988	-2,639	-11.7%	20,056	-2,571	-11.4%	20,136	-2,491	-11.0%	19,187	-3,440	-15.2%
Waialae-West	30105	5,520	5,550	31	0.6%	6,194	675	12.2%	4,310	-1,210	-21.9%	4,210	-1,310	-23.7%	4,236	-1,284	-23.3%	3,774	-1,746	-31.6%
Waialae-East	30106	7,315	7,513	197	2.7%	8,431	1,116	15.3%	5,692	-1,624	-22.2%	5,457	-1,859	-25.4%	5,487	-1,828	-25.0%	4,988	-2,328	-31.8%
Waimalu	30201	69,496	71,242	1,746	2.5%	75,784	6,288	9.0%	59,480	-10,015	-14.4%	59,046	-10,450	-15.0%	59,526	-9,969	-14.3%	55,076	-14,420	-20.7%
Waipahu-Waiawa	30203	101,562	105,812	4,250	4.2%	106,126	4,564	4.5%	88,634	-12,928	-12.7%	87,678	-13,884	-13.7%	88,194	-13,368	-13.2%	82,129	-19,433	-19.1%
Ewa-Kunia	30204	13,590	15,082	1,492	11.0%	14,295	705	5.2%	9,263	-4,327	-31.8%	8,298	-5,292	-38.9%	8,764	-4,826	-35.5%	6,197	-7,393	-54.4%
Makaiwa	30205	1,023	1,086	63	6.1%	1,105	82	8.0%	664	-359	-35.1%	555	-468	-45.8%	602	-421	-41.1%	360	-663	-64.8%
Nanakuli	30301	2,316	2,813	497	21.5%	2,562	247	10.7%	1,496	-819	-35.4%	1,281	-1,035	-44.7%	1,389	-926	-40.0%	850	-1,465	-63.3%
Lualualei	30302	9,757	10,515	758	7.8%	9,657	-100	-1.0%	6,085	-3,672	-37.6%	5,296	-4,461	-45.7%	5,715	-4,042	-41.4%	3,676	-6,081	-62.3%
Waianae	30303	6,637	6,950	312	4.7%	6,866	229	3.4%	3,336	-3,302	-49.7%	2,736	-3,902	-58.8%	3,013	-3,625	-54.6%	1,850	-4,788	-72.1%
Makaha	30304	8,572	8,294	-279	-3.3%	8,639	67	0.8%	4,452	-4,120	-48.1%	3,719	-4,853	-56.6%	4,082	-4,490	-52.4%	2,405	-6,167	-71.9%
Keaau	30305	8,330	8,105	-226	-2.7%	8,371	40	0.5%	4,708	-3,622	-43.5%	4,155	-4,175	-50.1%	4,383	-3,947	-47.4%	3,179	-5,151	-61.8%
Mokuleia	30401	23,884	23,472	-413	-1.7%	22,668	-1,216	-5.1%	15,339	-8,545	-35.8%	14,245	-9,639	-40.4%	14,513	-9,371	-39.2%	11,823	-12,061	-50.5%
Waialua	30402	7,383	7,978	595	8.1%	7,408	25	0.3%	5,862	-1,521	-20.6%	5,593	-1,790	-24.2%	5,648	-1,735	-23.5%	4,999	-2,384	-32.3%
Kawailoa	30403	38,271	41,386	3,115	8.1%	41,950	3,679	9.6%	28,972	-9,299	-24.3%	27,385	-10,886	-28.4%	27,966	-10,305	-26.9%	23,768	-14,502	-37.9%
Wahiawa	30501	149,962	158,779	8,817	5.9%	156,536	6,574	4.4%	129,887	-20,075	-13.4%	127,449	-22,513	-15.0%	128,781	-21,181	-14.1%	117,832	-32,130	-21.4%
Koolauloa	30601	70,566	74,275	3,709	5.3%	78,325	7,759	11.0%	57,023	-13,543	-19.2%	54,633	-15,933	-22.6%	54,883	-15,683	-22.2%	48,707	-21,860	-31.0%
Kahana	30602	49,831	52,539	2,708	5.4%	56,159	6,328	12.7%	42,994	-6,837	-13.7%	41,779	-8,052	-16.2%	41,908	-7,924	-15.9%	38,713	-11,118	-22.3%
Koolaupoko	30603	46,657	49,298	2,641	5.7%	55,161	8,504	18.2%	39,741	-6,916	-14.8%	39,063	-7,594	-16.3%	39,052	-7,605	-16.3%	36,363	-10,294	-22.1%
Waimanalo	30604	17,523	17,834	311	1.8%	20,131	2,608	14.9%	14,691	-2,832	-16.2%	14,579	-2,944	-16.8%	14,540	-2,983	-17.0%	13,501	-4,022	-23.0%
Unnamed (Ford Island)	NA	128	124	-3	-2.5%	127	0	-0.3%	92	-36	-28.3%	84	-43	-34.0%	86	-42	-32.6%	67	-60	-47.3%
Unnamed (Kumumau Pt)	NA	56	57	1	2.6%	58	2	3.6%	39	-17	-30.9%	34	-22	-38.7%	35	-21	-37.1%	27	-29	-52.4%
Unnamed (Sand Island)	NA	151	155	4	2.5%	160	9	6.1%	123	-28	-18.5%	118	-33	-21.6%	119	-32	-21.4%	108	-44	-28.8%
Total		708,869	740,194	31,325	4.4%	763,762	54,894	7.7%	586,868	-122,001	-17.2%	572,410	-136,459	-19.3%	577,864	-131,004	-18.5%	523,573	-185,295	-26.1%

C.2 Climate Resiliency and Aquifer Sustainable Yield

The sustainable yields of Oahu's aquifers are summarized in the June 2008 WRPP for the State of Hawaii CWRM. Aquifer sustainable yields are determined by CWRM and updated periodically with new data and planning horizons. In general, CWRM utilized a systematic approach to evaluating the lowest projected sustainable yield from a range of modeling output, following precautionary principals of managing water resources (CWRM 2008).

Groundwater resources throughout Oahu and other parts of Hawaii, are generalized as either high-level dike-impounded aquifers, or basal aquifer systems, based on aquifer boundary conditions. High-level or dike-impounded aquifers, as the names suggest, are generally interior to the islands and higher elevation. This juxtaposition results in dike-impounded systems in high recharge areas that can also provide seepage recharge into under or lower-lying basal aquifers. The level and coastal terrain of the basal systems supports urbanization, with basal systems supplying most of the groundwater use. Oahu's groundwater resources are characterized by 23 aquifer units in 6 aquifer sectors.

Estimations of future groundwater recharge and sustainable yields for the Oahu aquifers are provided for comparative analyses and planning purposes. The range of potential impacts to sustainable yield at the aquifer level may be used to assess infrastructure and water resources constraints as a function of changing climate conditions. As previously described, the estimation of sustainable yield for regulatory purposes is defined using the RAM model. Extrapolated sustainable yield estimates are based only on the ratio of current recharge and sustainable yield extrapolated to the future recharge projections. This simple process overlooks the interflows between aquifers and other source and sink terms that may change in the future but provides an approximate range of conditions to support future planning work. While providing insight to the possible range of impacts to sustainable yield throughout Oahu's aquifer systems, additional recharge analyses and RAM modeling should be completed to assess long-range impacts from climate change following CWRM's framework and approach for sustainable yield updates. This additional effort may provide additional certainty in the modeling of sustainable yield to produce results suitable for regulatory purposes, improving on the planning-level results provided herein.

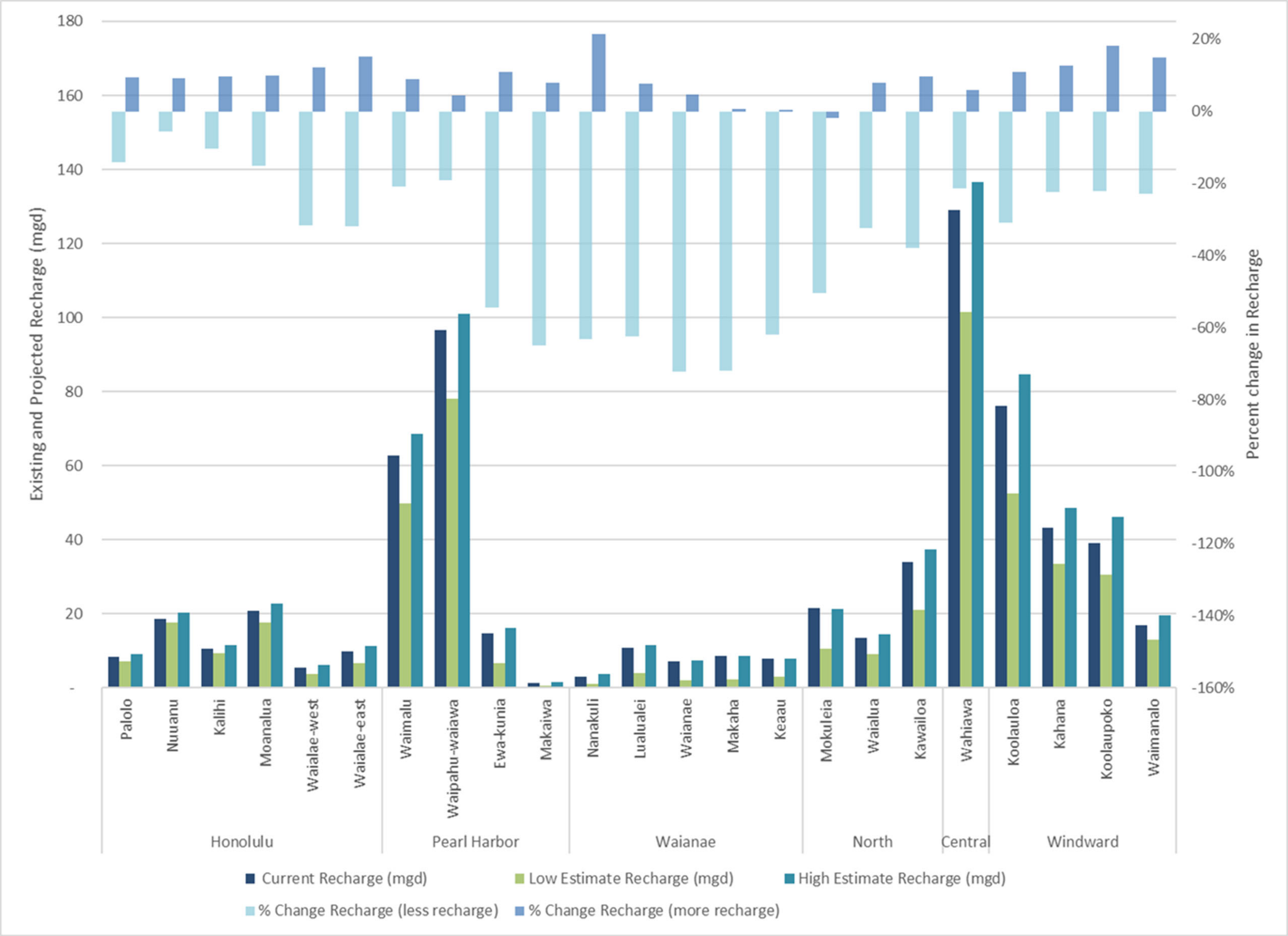


Figure C-17. Potential Impacts to Groundwater Recharge.

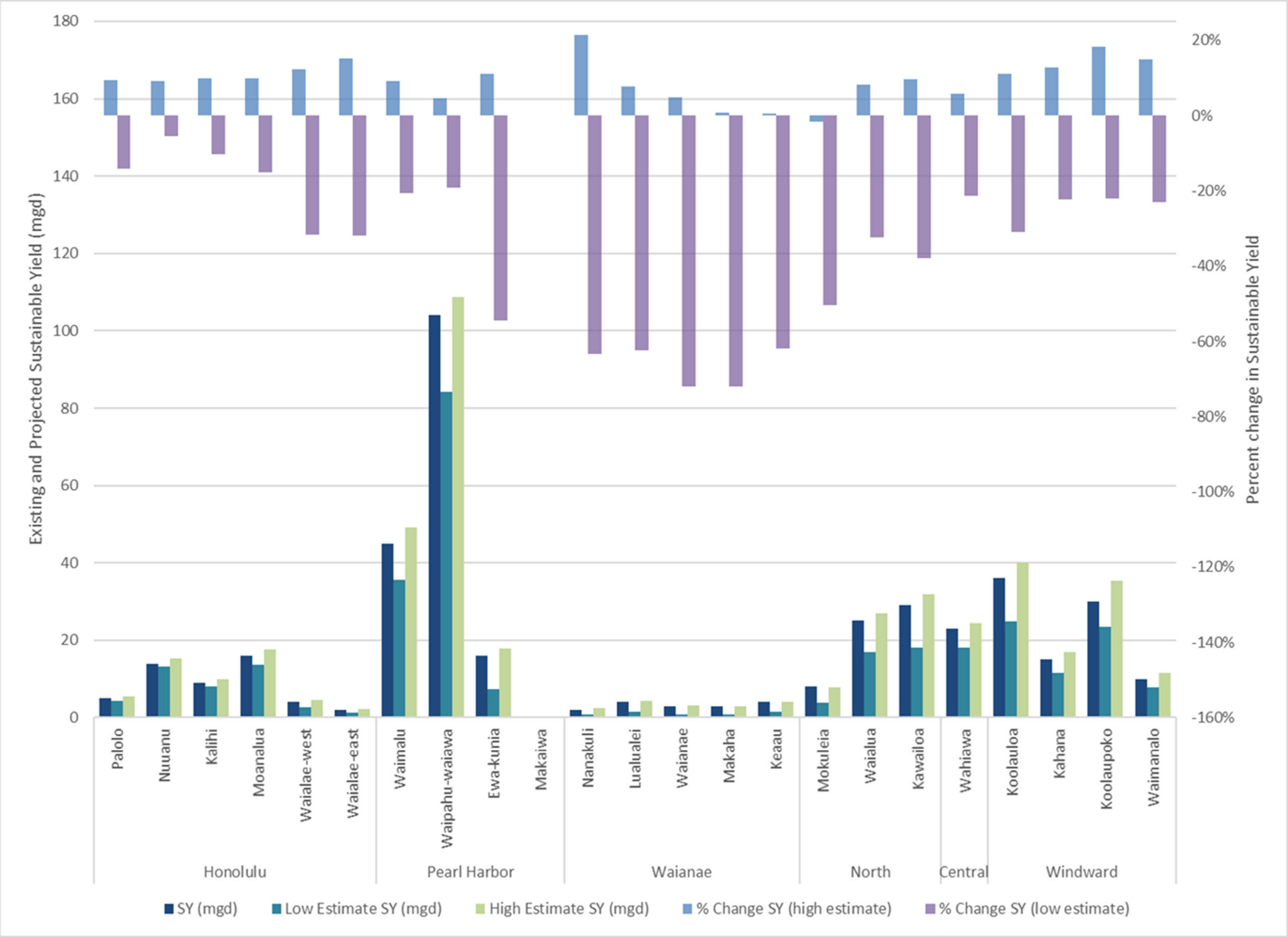


Figure C-18. Potential Impacts to Sustainable Yield.

C.3 Limitations

The limitations of the recharge/sustainable yield analysis undertaken as part of this study are discussed below and included seven primary factors:

- Uncertainty associated with the USGS water-budget model (Engott et al. 2017);
- Reduction of the USGS water-budget dataset (Engott et al. 2017) to a subset prior to performing the linear regression;
- The temporal and spatial scales of the analysis;
- The linear-regression method;
- Uncertainty in future climate modeling;
- Uncertainty in future water and climate policies and practices; and
- Simplifying assumptions used in the sustainable yield analysis.

The linear-regression equations in this study were developed using rainfall and recharge values from a USGS water-budget model (Engott et al. 2017) rather than actual measurements of rainfall and recharge. Thus, the accuracy of the regression analysis is subject to the degree to which the USGS model (Engott et al. 2017) represents the true water - budget on Oahu.

The linear -regression model in this study was produced using only a subset of the data from the USGS water- budget model (Engott et al. 2017). Data were excluded that represent developed and irrigated areas, and thus the retained data set represents a simplified water-budget free of anthropogenic factor bias. This data reduction step, while necessary, likely introduced a spatial bias into the linear regression results, as discussed below.

Data reduction likely affected the linear-regression model in three ways. First, developed and irrigated areas on Oahu tend to be located in areas that are flat and low in elevation. Slope and elevation are two factors that influence rainfall and recharge, and thus the linear-regression model may not be well calibrated for flat and low-lying areas. Second, data reduction eliminated anthropogenic sources of recharge from the analysis. As previously discussed, anthropogenic sources of recharge comprise compose 7 percent of the recharge on Oahu. Thus, the linear -regression model likely underpredicts recharge in areas where anthropogenic recharge is significant. Third, developed areas tend to contain impervious surfaces that restrict recharge, and thus the linear-regression model likely overpredicts recharge in areas where impervious surfaces have been constructed. Despite the limitations introduced by data reduction, the retained dataset represents 82 percent of the recharge budget on Oahu, and thus the linear -regression model is expected to be a good approximation of the overall water - budget on Oahu.

The linear-regression analysis was performed on data representing long-term climate conditions over a 30-year period. The future projected climate change scenarios were also developed for long-term climate conditions over periods of 20 to 30 years, and thus the linear-regression model is appropriate for those scenarios. However, the regression equations in this study may not be as accurate if applied to shorter-duration (e.g., monthly or yearly) datasets. The same principle applies to the spatial scale of the regression analysis. The regression equations were developed over large regions of Oahu but are unlikely to achieve the same level of accuracy if applied to smaller spatial scales.

The linear-regression method itself introduced uncertainty into the analysis. The linear-regression equations effectively provide an estimate of average recharge for a given value of rainfall. As shown on Figure C-7, though, recharge varies above and below the regression line by up to ±50 percent. The variability in recharge for a given value in rainfall is caused by differences in the other water-budget variables (e.g., runoff, evapotranspiration ET, fog drip, etc.) that are were not considered in this analysis. Thus, the linear-regression model represents a simplified water-budget that approximates the average rainfall-recharge relationship of Oahu. The regression model would not achieve the same level of accuracy if applied to areas where the unaccounted-for water-budget variables vary significantly from the average values on Oahu.

The projections of future recharge in this analysis were based on projections of future rainfall developed by downscaling global climate change models to the local area of Hawaii. The projections of future recharge are subject to any uncertainties that exist in the climate modeling and downscaling analyses. Further, the projections of future recharge do not account for potential changes in future evapotranspiration ET that may be correlated with changes in future precipitation.

The projections in this study do not account for potential changes in land and water use on Oahu that may result from increased development, changes in irrigation practices, or changes in water management policies. The projections are intended to provide an estimate of changes in natural recharge under current land uses given the projected changes in rainfall. The projections also do not account for potential global climate policies that could determine which RCP scenario is most likely to occur. The selected RCP scenarios were chosen to provide a range of possible outcomes.

Finally, the extrapolation of projected recharge to sustainable yield is subject to the simplifying assumption that the current ratio of sustainable yield to recharge will remain constant as future recharge varies. Groundwater recharge is a dominant term in the estimation of sustainable yield, and thus this simplifying assumption may be reasonable. However, sustainable yield is also affected by the specifics of groundwater flow, distribution, discharge, and freshwater-saltwater interaction, which are not evaluated in this study.

APPENDIX D

Mayor’s Directive 18-01

OFFICE OF THE MAYOR
CITY AND COUNTY OF HONOLULU
530 SOUTH KING STREET, Room 300 • HONOLULU, HAWAII 96813
PHONE: (808) 768-4141 • FAX: (808) 768-4242 • INTERNET: www.honolulu.gov

KIRK CALDWELL
MAYOR

ROY K. AMEMIYA, JR.
MANAGING DIRECTOR

GEORGETTE T. DEEMER
DEPUTY MANAGING DIRECTOR

DIRECTIVE NO. 18-01
July 16, 2018

MEMORANDUM

TO: ALL DEPARTMENT AND AGENCY HEADS

FROM: KIRK CALDWELL, MAYOR

SUBJECT: CITY AND COUNTY OF HONOLULU ACTIONS TO ADDRESS CLIMATE CHANGE AND SEA LEVEL RISE

I. PURPOSE

To establish policies to address, minimize risks from, and adapt to the impacts of climate change and sea level rise in accordance with the findings and recommendations of the City and County of Honolulu ("City") Climate Change Commission ("Commission") *Sea Level Rise Guidance* ("Guidance"), and accompanying *Climate Change Brief* ("Brief"), both adopted on June 5, 2018, and the State of Hawai'i *Sea Level Rise Vulnerability and Adaptation Report (2017)* ("Report").

II. SUMMARY

The Report finds that for O'ahu specifically, with no actions, 3.2 feet of sea level rise and its associated erosion, flooding, and waves will chronically impact, displace, and/or permanently inundate:

- 9,400 acres of land (over half of which is designated for urban land uses);
- $12.9 billion in building and land values, which does not account for public infrastructure and other utilities;
- 13,300 residents;
- 3,880 structures; and
- 17.7 miles of major roadway.

The Commission also stresses that impacts from high tide flooding will be observed decades before permanent inundation by sea level rise. Tidal flooding will become more frequent and more damaging as ocean levels rise. Even smaller tide heights, when convergent with rainfall, will impede drainage leading to flooded roads and properties, and disrupt traffic. Furthermore, the Commission finds that, because of continued high levels of global carbon emissions, it is reasonable to set as a planning benchmark up to 6 feet of sea level rise in the latter decades of this century.

III. SCOPE

These guidelines shall apply to all executive branch departments and agencies.

IV. POLICY

Each City department and agency shall, consistent with the Paris Agreement and Chicago Climate Charter, consider the need for both climate change mitigation and adaptation as pressing and urgent matters, to take a proactive approach in both reducing greenhouse gas emissions and adapting to impacts caused by sea level rise, and to align programs wherever possible to help protect and prepare the infrastructure, assets, and citizens of the City for the physical and economic impacts of climate change.

V. PROCEDURES

All City departments and agencies are required to:

1. Use the most current versions of the Commission's Guidance and accompanying Brief, and the Report and associated Hawai'i Sea Level Rise Viewer as resources for managing assets, reviewing permitting requests, and assessing project proposals; and

2. Consider how sea level rise and associated climate change risks will impact the City's residents and visitors, infrastructure, communities, policies and programs, investments, natural resources, cultural and recreational sites, and fiscal security; and

3. Use the Guidance, Brief, and Report in their plans, programs, and capital improvement decisions, to mitigate impacts to infrastructure and facilities subject to sea level rise exposure, which may include the elevation or relocation of infrastructure and critical facilities, the elevating of surfaces, structures, and utilities, and/or other adaptation measures; and

4. Develop place-specific guidance for shoreline policy changes based on additional policy guidance from the Climate Change Commission regarding: new regulations; management procedures for affected coastal assets; and, additional sea level rise projections that are as specific as possible, regularly updated, and delineate associated impacts; and

5. Work cooperatively to develop and implement land use policies, hazard mitigation actions, and design and construction standards that mitigate and adapt to the impacts of climate change and sea level rise; and

6. Work cooperatively to propose revisions to amend shoreline rules and regulations to incorporate sea level rise into the determination of shoreline setbacks and Special Management Area considerations for the safety and welfare of people and structures, provision of municipal services, as well as the protection of open space, the environment, public access to and along the shoreline, public trust resources including beaches, and public use and enjoyment of these resources; and

7. Work cooperatively to develop a process to review applications for new development in shoreline areas in conjunction with other agencies and entities with expertise in shoreline hazards and erosion in order to protect and enhance open space, the environment especially beaches, public access to and along the shoreline, public safety, and public resources; and

8. Work to conserve and enhance a natural, dynamic shoreline wherever possible. Temporary emergency measures may be utilized to address acute erosion events, especially on sandy beaches, where consistent with these guidelines and in alignment with other agencies. Permitting permanent shoreline armoring is generally inconsistent with this directive and should only be considered as a last resort where it supports significant public benefits and will result in insignificant negative impacts to coastal resources and natural shoreline processes.

VI. RESPONSIBILITIES

All City departments and agencies under the Mayor's jurisdiction shall work cooperatively to ensure the success of the missions outlined above. Independent agencies, City-affiliated entities, and City-related institutions are also strongly encouraged to work to help advance these efforts and adopt similar initiatives, where applicable. All actions and outcomes shall be in accordance with applicable local, state, and federal laws.

VII. GENERAL

This Directive shall take effect immediately and remain in effect until amended or rescinded in writing by the Mayor. The applicable procedures are delineated in Administrative Directives Manual ("ADM") Subject No. 920, a copy of which is attached hereto.

Attachments:
Sea Level Rise Guidance
Climate Change Brief
ADM Subject No. 920

Subject No. 920 Effective Date: 07/16/18

Subject
ACTIONS TO ADDRESS CLIMATE CHANGE AND SEA LEVEL RISE

Subject Matter Expert
CCSR

Reference
Mayor's Directive No. 18-01

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sea level rise exposure, which may include the elevation or relocation of infrastructure and critical facilities, the elevating of surfaces, structures, and utilities, and/or other adaptation measures; and

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APPENDIX E

City Climate Change Commission's Guidance Document

PURPOSE

Pursuant to the Revised Charter of Honolulu ("RCH") Section 6-107(h), the City and County of Honolulu ("City") Climate Change Commission is charged with gathering the latest science and information on climate change impacts to Hawaiʻi and providing advice and recommendations to the mayor, City Council, and executive departments as they look to draft policy and engage in planning for future climate scenarios and reducing Honolulu's contribution to global greenhouse gas emissions. This report provides a description of findings and recommendations with regard to adapting to sea level rise.

INTRODUCTION

There has been considerable detailed research on the global and local implications of accelerating sea level rise. This report by the City Climate Change Commission builds on findings in the Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report (2017), Sweet et al. (2017), USGCRP (2017), Sweet et al. (2018), and other scientific literature to provide specific policy and planning guidance on responding to sea level rise by the City.

SUMMARY OF KEY FINDINGS

1. The projected median global temperature increase this century is 5.8°F (3.2°C).[1]
    a. The likely range of global temperature increase is 3.6 to 8.8°F (2.0 to 4.9°C), with a 5% chance that it will be less than 3.6°F (2°C) and a 1% chance that it will be less than 2.7°F (1.5°C) by the end of this century.[2]
2. Relative to the year 2000, the projected rise of global mean sea level (GMSL) by the end of this century is 1.0 to 4.3 ft (0.3 to 1.3 m).[3]
    a. Relative to the year 2000, GMSL is very likely (90 to 100% confidence) to rise 0.3 to 0.6 ft (0.09 to 0.18 m) by 2030, 0.5 to 1.2 ft (0.15 to 0.36 m) by 2050, and 1.0 to 4.3 ft (0.3 to 1.3 m) by 2100.[4]
3. High tide flooding will arrive decades ahead of any GMSL rise scenario.[5]
    a. Table 1 (supplementary information) provides estimates of when minor high tide flooding will arrive in Honolulu 6, 12, and 24 days per year.
    b. Based on the location of the Honolulu Tide Station,[6] high tide flooding will occur by mid-century, and as early as 2028, at least two dozen times per year, at certain locations in the 3.2SLR-XA.[a]
4. Modeling results, as mapped in the Hawaiʻi Sea Level Rise Viewer,[b] reveal a critical elevation in GMSL rise between 2.0 and 3.2 ft (0.6 to 1 m) relative to mean higher high water.[c]
    a. This is a critical range of rising sea level where there is a rapid increase in the amount of land exposed to hazards on low-lying coastal plains, such as characterize the urbanized south shore of Oʻahu.
    b. This is a dangerous elevation range, where reacting after the fact to establish adaptation strategies is likely to be less successful and costlier than taking proactive measures.
5. Globally, energy-related carbon dioxide emissions are projected to grow an average 0.6% per year between 2015 and 2040, 1.3% per year below the level from 1990 to 2015.[7]
6. Future emission pathways have little effect on projected GMSL rise in the first half of the century, but significantly affect projections for the second half of the century.[8]
    a. Table 2 (supplementary information) provides estimates of projected GMSL under NOAA scenarios.[9]
7. Regardless of emissions pathway, it is extremely likely (95 to 100% confidence) that GMSL rise will continue beyond 2100.[10]
8. The world's major ice systems including Antarctica and Greenland,[11] and the mountain glaciers[12] of the world are all in a state of decline.

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[a] "SLR-XA" is an acronym that stands for *sea level rise-exposure area*. The Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report (2017) recommends (p. 217) that the SLR-XA at 3.2 ft (0.98 m) of sea level rise be recognized as a state-wide vulnerability zone and that it be employed by agencies to formulate comprehensive adaptation strategies. 3.2 ft (0.98 m) of sea level rise is modeled by Church et al. (2013) as the worst case scenario at the end of the century. However, the scenario does not take into account potential instability in marine-based sectors of the Antarctic ice sheet.

[b] The online Hawaiʻi Sea Level Rise Viewer is served by the Pacific Islands Ocean Observing System at the School of Ocean and Earth Science and Technology, University of Hawaiʻi at Mānoa: http://www.pacioos.hawaii.edu/shoreline/slr-hawaii/

[c] Mean higher high water (MHHW) is the average of the higher high water height of each tidal day observed over the National Tidal Datum Epoch, a 19 year period determined by the National Oceanic and Atmospheric Administration.

   a. Research indicates that on multiple occasions over the past three million years, when global temperatures increased 1.8 to 5.4°F (1 to 3°C), melting polar ice sheets caused global sea levels to rise at least 20 ft (6 m) above present levels.[13]
   b. If atmospheric warming exceeds 2.7 to 3.6°F (1.5 to 2°C) above present (ca. 2015), collapse of the major Antarctic ice shelves triggers a centennial- to millennial-scale response of the Antarctic ice sheet that produces a long-term commitment (an unstoppable contribution) to sea-level rise.[14] Substantial Antarctic ice loss can be prevented only by limiting greenhouse gas emissions to RCP2.6[d] levels. Higher-emissions scenarios lead to ice loss from Antarctica that will raise sea level by 1.9 to 9.8 ft (0.6 to 3 m) by the year 2300.[15]
   c. Antarctica has the potential to contribute more than 3.28 ft (1 m) of sea-level rise by 2100 and more than 49.2 ft (15 m) by 2500, if emissions continue unabated. In this case atmospheric warming will soon become the dominant driver of ice loss, but prolonged ocean warming will delay its recovery for thousands of years.[16]
   d. Emerging science regarding Antarctic ice sheet stability suggests that under high emission pathways, a GMSL rise exceeding 8 ft (2.4 m) by 2100 is physically possible.[17]
   e. The Greenland ice sheet is more sensitive to long-term climate change than previously thought. Studies[18] estimate that the warming threshold leading to an essentially ice-free state is in the range of 1.4 to 5.8°F (0.8 to 3.2°C), with a best estimate of 2.9°F (1.6°C) above preindustrial levels. The Arctic is on track to double this amount of warming before mid-century.[19]
   f. Further melting of mountain glaciers cannot be prevented in the current century - even if all emissions were stopped now.[20] Around 36% of the ice still stored in mountain glaciers today will melt even without further emissions of greenhouse gases. That means: more than one-third of the glacier ice that still exists today in mountain glaciers can no longer be saved even with the most ambitious measures.

9. Rising seas threaten human communities and natural ecosystems in multiple ways.
   a. Urbanized coastal areas become increasingly vulnerable to four types of flooding during high water and high wave events:
      1) Flooding across the shoreline due to wave run-up.
      2) Saltwater intrusion of engineered drainage systems.
      3) Groundwater inundation.[21]
         a) Intrusion of buried infrastructure and other buried assets that are not sealed.
         b) Formation of new wetlands, initially concurrent with high tide.
      4) Rainstorms, especially concurrent with high tide.
   b. Land loss and coastal erosion.
      1) If the back-beach area is composed of sand-rich dunes, sandy paleo shoreline deposits, or high wave sand berms, the released sand nourishes the retreating beach.
      2) If the back-beach area is hardened, a beach is prevented from retreating. This leads to beach erosion, beach narrowing, and beach loss. Hardening has caused at least 5.4 mi (8.7 km) of beach loss on O‘ahu.[22]
   c. Saltwater will intrude streams and coastal wetlands, increasing the salinity of the environment and threatening low-lying agriculture (e.g., kalo farming) and wildlife sanctuaries.
   d. Wave, and eventually still water overtopping of Loko i‘a kuapā (fishpond walls) will increase.
      1) Interior circulation will change (including at mākāhā).
      2) Upland discharge into the pond will change.
      3) Fishpond connections to the shore will become unstable.
   e. Wave energy at the shore will increase.
      1) Muddy shore deposits may be released.
   f. Damaging flooding will increase when hurricanes, tsunamis, and seasonal high waves strike.
   g. Annual high waves, which arrive in Hawai‘i seasonally, will flood further landward and cause more damage, as sea level continues to rise.

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[d] To provide guidance for developing mitigation and adaptation strategies, scientists have defined four different 21st century pathways of greenhouse gas emissions called “RCP’s” for Representative Concentration Pathways. The RCP’s include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and one scenario with very high greenhouse gas emissions (RCP8.5).

RECOMMENDATIONS

Given the tools available to planners, stakeholders and policy-makers with the Hawaiʻi Sea Level Rise Viewer, the NOAA SLR Viewer, and the Climate Central–Surging Seas Risk Finder,[e] the City Climate Change Commission, pursuant to RCH Section 6-107(h), recommends that:

1. The mayor, City Council, and executive departments of the City utilize the 2017 Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report (hereafter "Report") and online Viewer, for baseline planning activity and infrastructure assessment and development with regard to sea level rise.
2. The research finds that it is reasonable to set as a planning benchmark up to 3.2 ft (~1 m; 3.2SLR-XA) of GMSL rise by mid-century as it will be an area experiencing chronic high tide flooding.
3. The research finds that it is reasonable to set as a planning benchmark up to 6 ft (1.8 m; 6SLR) of GMSL rise in the later decades of the century, especially for critical infrastructure with long expected lifespans and low risk tolerance, as it will be an area experiencing chronic high tide flooding.
4. The Special Management Area (SMA) boundary be revised to include parts of the 3.2SLR-XA that are not currently in the SMA.
5. Disclosure of all lands be required in the 3.2SLR-XA and 6SLR.
    a. Disclosure on all real estate sales, City Property Information Sheets, and all other real estate transactions.
6. The 3.2SLR-XA and 6SLR be adopted as a vulnerability zone (hazard overlay) for planning by the City.
    a. The hazard overlays should be used for planning purposes, for example in the general plan, all development plans, and sustainable community plans.
7. That all City departments and agencies be directed to use the Report, the 3.2SLR-XA, and the 6SLR in their plans, programs, policies, and capital improvement decisions, to mitigate impacts to infrastructure and critical facilities related to sea level rise.
8. All ordinances related to land development, such as policy plans and regulations should be reviewed and updated, as necessary.
9. Relevant City departments and agencies be supported with adequate resources and capacity to implement these recommendations and proactively plan for sea level rise, as it will rapidly become a major challenge to City functions.

The City Climate Change Commission adopts the precautionary principle and a scenario-based planning approach and supports these recommendations as planning targets informed by the best available science. This set of recommendations are important each and in their own right and are designed to complement each other and be implemented together. Implementing one does not eliminate the need to adopt the others. The City Climate Change Commission fully acknowledges that there is uncertainty in the timing and magnitude of sea level rise projections globally and for Hawaiʻi. This is a living document that will be updated as additional information becomes available.

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[e] Surging Seas Viewer: https://riskfinder.climatecentral.org/county/honolulu-county.hi.us?comparisonType=postal-code&forecastType=NOAA2017_int_p50&level=3&unit=ft

SUPPLEMENTARY INFORMATION

NOAA has published a model of high tide flooding for the Honolulu Tide Station (Sweet et al., 2018). Relative to MHHW, the threshold for minor high tide flooding is 1.7 ft (0.52 m), for moderate high tide flooding is 2.6 ft (0.8 m), and for major high tide flooding is 3.8 ft (1.17 m). High tide flooding will arrive decades ahead of global mean sea level rise.

High tide flooding, as defined by NOAA, has never occurred at the Honolulu Tide Station as none of these thresholds has ever been crossed. Table 1 provides estimates of when minor high tide flooding will arrive in Honolulu 6, 12, and 24 days per year using the NOAA model.

Table 1 - When will minor (0.52 m) high tide flooding occur in Honolulu?

Scenario	6 x per year	12 x per year	24 x per year
Intermediate Scenario	2038	2041-2042	2044-2045
Intermediate High Scenario	2030	2033	2035-2036
High Scenario	2025-2026	2028-2029	2030-2031
Extreme Scenario	2024	2026	2028-2029

Because of the exponential nature of the NOAA sea level scenarios, the doubling time of high tide flooding is rapid in all scenarios. High tide flooding events are likely to cluster around the summer and winter solstices. High tide flooding will occur first at certain locations in the 3.2SLR-XA as defined in the Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report (2017).

High tide flooding can take several forms. Beach erosion will be pronounced during high tide flooding events. Storm drain flooding will occur where marine water blocks drainage and spills out onto the street, or where runoff cannot drain and causes flooding around storm drain sites. Groundwater inundation will develop where the water table rises to break the ground surface and creates a wetland.

At first this flooding will be most common when high tide and precipitation occur simultaneously, but eventually will occur without precipitation at high tide. Rainfall that occurs at high tide when storm drains are blocked and the ground is saturated will lead to widespread flooding. Marine flooding will occur at high tide when seawater flows across the shoreline. Wave flooding will occur at high tide during typical seasonal swell events as waves run-up past the shoreline and into the backshore. Tsunami and storm surge occurring at high tide will cause greater flood damage than historically.

Global mean sea level will rise 3.2 ft (~1 m) relative to the year 2000. NOAA (Sweet et al., 2017) has published scenarios that provide estimates, by decade, of when GMSL will hit this benchmark (Table 2).

Table 2 - When will global mean sea level rise 3.2 feet (~1 m)?	
Intermediate Scenario	end of the century
Intermediate High Scenario	decade of the 2080's
High Scenario	decade of the 2070's
Extreme Scenario	decade of the 2060's

Gravitational forces will cause regional sea level in the North Central Pacific to rise above the global mean (Spada et al., 2015). NOAA suggests planners use higher scenarios for large projects with low risk tolerance. This recommendation is also made by the U.S. Army Corps of Engineers.

Modeling of sea level rise impacts on Oʻahu (Report) reveals the following:

1. Homes and businesses on Oʻahu's shorelines will be severely impacted by sea level rise. Nearly 4,000 structures will be chronically flooded with 3.2 ft (~1 m) of sea level rise (**Figure 1**).
2. Of the 9,400 acres of land located within the 3.2SLR-XA, over half is designated for urban land uses, making Oʻahu the most vulnerable of all the islands.

3. With 3.2 ft (~1 m) of sea level rise, almost 18 mi (30 km) of O‘ahu’s coastal roads will become impassible, jeopardizing access to and from many communities.
4. O‘ahu has lost more than 5 mi (8 km) of beaches to coastal erosion fronting seawalls and other shoreline armoring. Many more miles of beach will be lost with sea level rise if widespread armoring is allowed. In the Report, Chapter 5 (Recommendations) explores opportunities to reduce beach loss by improving beach protection policies.
5. A more detailed economic loss analysis is needed of O‘ahu’s critical infrastructure, including harbor facilities, airport facilities, sewage treatment plants, and roads. State and City agencies should consider potential long-term cost savings from implementing sea level rise adaption measures as early as possible (e.g., relocating infrastructure sooner than later) compared to the cost of maintaining and repairing chronically threatened public infrastructure.

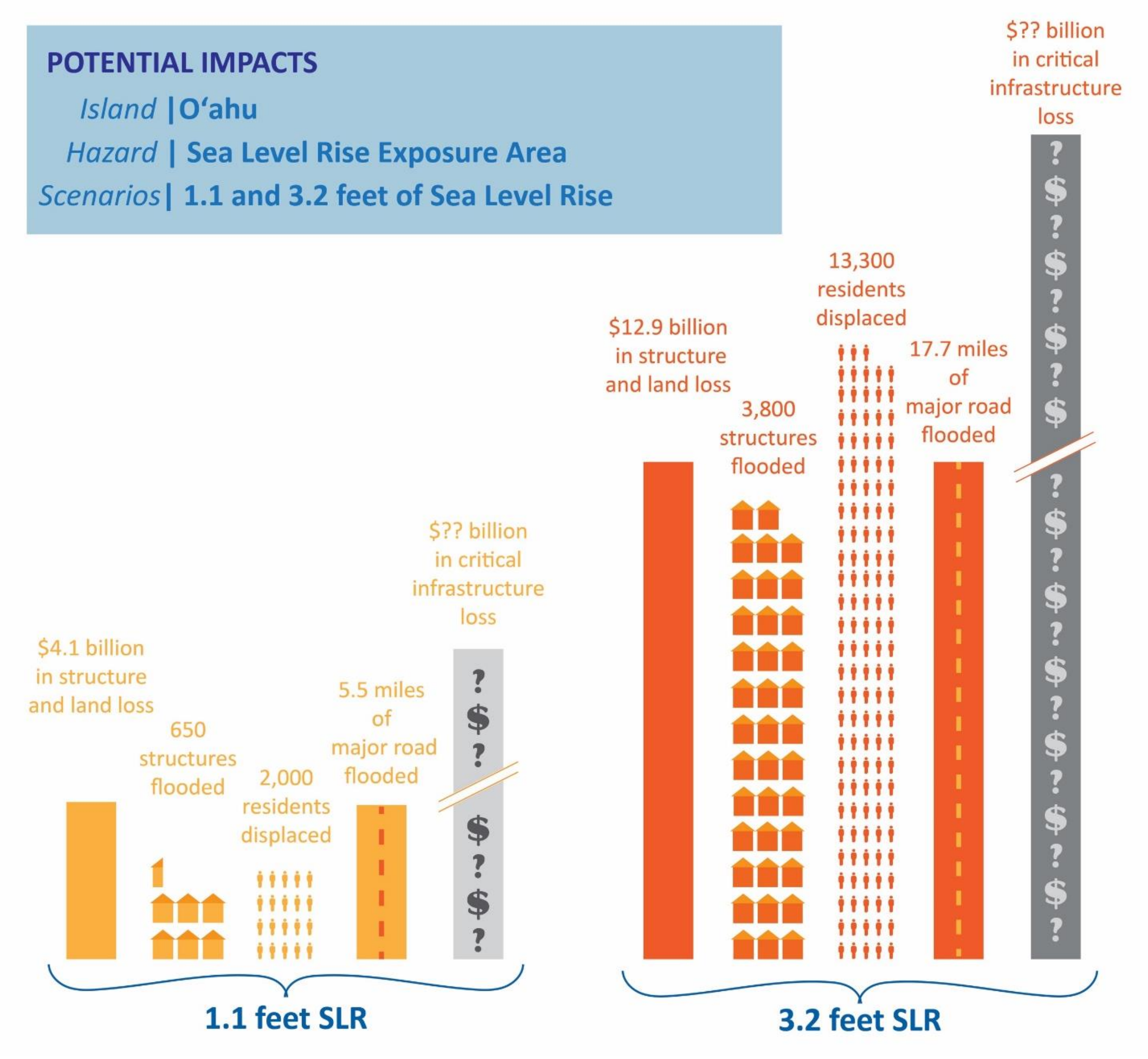

Figure 1. Sea level rise impacts on O‘ahu.

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