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DISCLAIMER. This report is a tool to estimate the scale and cost of potential flooding and erosion with sea level rise. The exact location of flooding and economic costs from damages are estimates. Flood maps are in the range of 80 percent probability. Damage estimate costs are conservative. The data, maps, and recommendations provided should be used only as a screening-level resource to support management decisions to address sea level rise. As with all remotely sensed data, all features should be verified with a site visit. The risk associated with use of the results is assumed by the user. This report should be used strictly as a planning reference tool and not for permitting, or other legal purposes.

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Executive Summary

Shorelines are one of our planet's most dynamic physical features and Hawaii's are no exception. Communities along our shores have flourished for centuries in harmony with the ebb and flow of the tides, punctuated by the occasional devastating hurricane or tsunami event. However, rapid warming of the atmosphere and oceans, caused by two centuries of unabated carbon emissions, is causing increasing rates of sea level rise, unprecedented in human history, that threatens natural environments and development on low-lying coasts.

Sea level rise is an inevitable outcome of global warming that will continue through many centuries even if human-generated global greenhouse gas (GHG) emissions were stopped today. However, much of what happens with future sea level rise will depend on our ability, or inability, to implement aggressive global carbon emissions reduction programs envisioned through the 2016 Paris Climate Accord.

This Sea Level Rise Vulnerability and Adaptation Report (Report), initially mandated by Act 83 in 2014 (Hawaii Climate Change Adaptation Initiative) and expanded by Act 32 in 2017 (Hawai'i Climate Change Mitigation and Adaptation Initiative), provides the first state-wide assessment of Hawaii's vulnerability to sea level rise and recommendations to reduce our exposure and sensitivity to sea level rise and increase our capacity to adapt. This Report combines the best available science on climate change and sea level rise from sources such as the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (IPCC 2014), more recent scientific reports from the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA), as well as the best-available peer-reviewed scientific research articles. The Report also provides recommendations based on emerging good

practices and framed through extensive stakeholder consultations. The Report is considered a "living" output that will be updated as new information becomes available. The update process will be guided by learning questions crafted around the assumptions and limitations that need to be revisited over time as climate science evolves and new challenges appear on the horizon. While the Report focuses on sea level rise vulnerabilities and adaptation, it should also strengthen our State's resolve to do our part in reducing GHG emissions in line with Act 32 and the Paris Climate Accord. In addition, this report is intended to serve as a framework for identifying and managing other climate change threats facing Hawai'i.



Hawai'i Climate Adaptation Initiative Framework Applied to Sea Level Rise

Sea Level Rise Outlook

While the Earth's climate experiences natural change and variability over geologic time, the changes that have occurred over the last century due to human input of GHGs into the atmosphere are unprecedented. The rapid build-up of GHGs, including carbon dioxide, methane, nitrous oxide, and fluorinated gases, from humans, is causing global warming and climate disruption. The concentration of carbon dioxide in the atmosphere is well outside the range of natural variability and is now approaching 410 parts per million (Scripps Institution of Oceanography 2015); about 40 percent (%) higher than pre-industrial levels and the highest in at least 800,000 years and probably as long as 3 million years.

Sea level is rising at increasing rates due to global warming of the atmosphere and oceans and melting of the glaciers and ice sheets. Rising sea level and projections of stronger and more frequent El Niño events and tropical cyclones in waters surrounding Hawai'i all indicate a growing vulnerability to coastal flooding and erosion. While the IPCC's "business as usual" scenario, where GHG emissions continue at the current rate of increase, predicts up to 3.2 feet of global sea level rise by year 2100 (IPCC 2014), recent observations and projections suggest that this magnitude of sea level rise could occur as early as year 2060 under more recently published highest-end scenarios (Sweet et al. 2017). As such, questions remain

around the exact timing of that rise due largely to uncertainties around future behavior of Earth's cryosphere and global GHG emission trajectories. For this reason, it is vital that the magnitude and rate of sea level rise is tracked as new projections emerge, plan for 3.2 feet of sea level rise <u>now</u>, and be ready to adjust that projection upward. It is also important to recognize that global sea level rise will not stop at the year 2100, but will likely continue on for centuries.



Observed global mean sea level rise over the last century (Church and White 2011, Nerem et al. 2010, Yi et al. 2015, Hay et al. 2015, Hansen et al. 2016, Watson et al. 2015, Fasullo, Nerem, and Hamlington 2016)



Projected rate of global sea level rise under different GHG scenarios (IPCC 2014)

Methodology

Modeling, using the best available data and methods, was conducted to determine the potential future exposure of each island to multiple coastal hazards as a result of sea level rise. Three chronic flooding hazards were modeled: passive "bathtub" flooding, annual high wave flooding, and coastal erosion. The footprints of these three hazards were combined to define the projected extent of chronic flooding due to sea level rise, called the sea level rise exposure area (SLR-XA). Not all hazards were modeled for each island due to limited historical information and geospatial data. Each of these hazards were modeled for four future sea level rise scenarios: 0.5 feet, 1.1 feet, 2.0 feet and 3.2 feet based on the upper end of the IPCC, Assessment Report 5, representative concentration pathway 8.5, or "business as usual" sea level rise scenario.

Coverage of Hazard Modeling by Island			
	Sea Level Rise Exposure Area (SLR-XA; Chronic Flooding with Sea Level Rise)		
Island	Passive Flooding	Annual High Wave Flooding	Coastal Erosion
Kaua'i	v	V	V
Oʻahu	v	V	v
Maui	V	V	v
Moloka'i	V	-	-
Lāna'i	V	-	-
Hawaiʻi	√	-	-

Using the outputs of this coastal hazard modeling, vulnerability was assessed for the main Hawaiian Islands. Vulnerability is the result of exposure to a hazard, sensitivity or susceptibility to harm, and lack of capacity to cope and adapt. A vulnerability assessment estimates the potential social, cultural, economic, and environmental impacts of this exposure and provides important information needed to design appropriate strategies and use the right tools to adapt to sea level rise. This assessment determined the vulnerability of valued assets such as land, homes, beaches, cultural sites, roads, and other critical infrastructure to sea level rise.

Results Overview

Vulnerability is assessed in terms of potential impacts to land use, people, property, cultural and natural resources, and critical infrastructure. As the only U.S. state that is an island, Hawai'i is highly vulnerable to the effects of sea level rise. Vulnerability to sea level rise is based on modeling chronic coastal flooding with sea level rise due to passive flooding, annual high wave flooding, and coastal erosion in the SLR-XA.

Although this Report provides a range of sea level rise projections and vulnerability scenarios, the SLR-XA with 3.2 feet of sea level rise was chosen to depict hazards that may occur in the mid to latter half of this century. Vulnerability to 1.1 feet of sea level rise in the SLR-XA is used to approximate current or near-term exposure to coastal hazards and sea level rise. All sea level rise results from both the hazard modeling and vulnerability assessment are available to view on the <u>Hawai'i Sea Level Rise Viewer</u> (http://hawaiisealevelriseviewer.org/).

Summary of Key Terms, Assumptions, and Limitations in the Methodology Used to Assess Vulnerability in the Sea Level Rise Exposure Area (SLR-XA)

This summary is intended to help the reader become familiar with key terms, assumptions, and limitations in the modeling and vulnerability assessment methodology.

- The SLR-XA depicts the area exposed to potential chronic flooding and land loss based on modeling
 passive flooding, annual high wave flooding, and coastal erosion with sea level rise for the islands of
 Maui, O'ahu, and Kaua'i. The SLR-XA for the islands of Hawai'i, Molokai, and Lāna'i is based on
 modeling passive flooding only.
- Flooding in the SLR-XA is associated with long-term, chronic hazards punctuated by annual or more frequent flooding events. Over time, recurring flooding at the highest tides in low-lying areas leads to chronic flooding and then to permanent flooding, and permanent loss.
- Vulnerability in the SLR-XA is characterized as potential impacts to land use, people and property, critical infrastructure, Native Hawaiian communities, cultural resources, and coastal resources, including beaches.

Key assumptions and limitations of the vulnerability assessment include:

- Potential economic loss is based on present values of the land and structures from the county tax parcel database permanently lost in the SLR-XA.
- Economic (monetary) losses due to sea level rise on critical infrastructure (such as roads, airports, harbors, water, sewer and power, etc.) has not been considered, but many such structures or facilities that are located in the SLR-XA have been identified in this Report.
- A more detailed economic loss analysis of Oahu's critical infrastructure, including harbor facilities, airport facilities, sewage treatment plants, and roads is needed. State and County 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 in place over the next 30 to 70 years.
- Macro-economic impacts (such as on tourism or the real estate market) resulting from potential chronic flooding over time caused by sea level rise are not analyzed.

Potential Impacts in the Sea Level Rise Exposure Area (SLR-XA)

Chronic flooding in the SLR-XA with 3.2 feet of sea level rise would render over 25,800 acres of land in the State unusable. Some of that land will have eroded into the ocean, some will become submerged by inches or feet of standing water, and some areas will be dry most of the year, but repeatedly washed over by seasonal high waves. State-wide, about 34% of that potentially lost land is designated for urban use, 25% is designated for agricultural use, and 40% is designated for conservation. The loss of urban land could put pressure on development of inland areas, including those designated as agricultural and conservation lands.

Across the state, over 6,500 structures located near the shoreline would be compromised or lost in the SLR-XA with 3.2 feet of sea level rise. Some of these vulnerable structures include hotels, shopping malls, and small businesses. The loss of these structures may result in the interruption, relocation, or even closure of those businesses. Other types of structures which may be impacted are churches, schools, and community centers. In addition, houses and apartment buildings are also vulnerable and the loss of these structures would result in over 20,000 displaced residents in need of new homes. The value of projected flooded structures, combined with the land value of the 25,800 acres projected to be flooded, amounts to over \$19 billion across the State. Hotspots for potential economic loss across the State are centered in urban areas with the greatest potential loss in Honolulu on the Island of O'ahu, with 66% of the total statewide economic loss, due to the density and economic assets potentially exposed to sea level rise. As a result, the impacts of sea level rise on O'ahu could generate substantial social, infrastructure, and economic impacts with ripple effects throughout the State.

It should be noted that the \$19 billion in economic loss does not encompass the full loss potential in the State. Monetary losses that will occur from the chronic flooding of roads, utilities and other public infrastructure were not analyzed in this report and may amount to an order of magnitude greater than the potential economic losses from land and structures. For example, over 38 miles of major roads would be chronically flooded across the State with 3.2 feet of sea level rise, ranging from residential roads to sections of coastal highways such as Kūhiō Highway on Kaua'i, Kamehameha Highway on O'ahu, and Honoapi'ilani Highway on Maui. Utilities, such as water, wastewater and electrical systems often run parallel and underneath roadways, making lost road mileage a good indication of the extent of lost utilities. This chronically flooded infrastructure would have significant impacts on local communities as well as reverberating effects around each island through loss of commerce, loss of access to emergency services, and increased traffic on other roads and highways. Repair and relocation of vulnerable roadways are already costly efforts for the State and Counties, which will only worsen as sea level rises. In addition, many of our harbor and airport facilities are often located in low-lying coastal areas of the State and face the problem of chronic flooding. For this reason, the economic loss from land and structures.



Summary of potential impacts in the SLR-XA with 3.2 feet of sea level rise (chronic flooding) in Hawai'i

The loss of invaluable natural and cultural resources across all islands is even harder to quantify, yet their loss would cost the State dearly due to their intrinsic value. Beaches that provide for recreation, wildlife habitat, and cultural tradition will erode, from iconic sites such as Sunset Beach on O'ahu to neighborhood beach access points rarely visited by anyone except local residents. Some beaches could be lost entirely if their landward migration is blocked by roads, structures, shoreline armoring, or geology. The flooding of the over 2,000 on-site sewage disposal systems located in the SLR-XA with 3.2 feet of sea level rise could result in diminished water quality. The loss of and harm to native species and entire ecosystems will have implications for Hawaiian cultural traditions and practices, which are closely tied to the natural environment. Further, nearly 550 cultural sites in the State would be flooded and many Hawaiian Home Lands communities would be impacted by flooding. In some cases, these natural and cultural resources could be allowed to migrate inland or carefully relocated. In other cases, the resources are inextricably bound to place and would be permanently altered by flooding.

Opportunities and Challenges

Over the next 30 to 70 years, as sea level rises, homes and businesses located on or near the shoreline throughout the State will become exposed to chronic flooding. Portions of coastal roads may become flooded, eroded, impassible, and potentially irreparable, jeopardizing access to and from many communities. The flooding of hotels and transportation systems would impact the visitor economy and thus impact the people whose livelihoods depend on tourism. The impact of sea level rise on O'ahu is greater than all of the other islands combined due to the size of the population and extensive urbanization of vulnerable coastal areas. Even more troubling is the fact that impacts from chronic flooding with sea level rise on O'ahu can reverberate and translate into economic and social impacts for the other islands.

The added risk of coastal flooding from hurricanes and tropical cyclones from a warming planet poses a potential for loss of human life and property and for severe and long-term economic disruption. Tropical storms, hurricanes, and tsunamis create waves that flood low-lying coastal areas. This added risk from this "event-based" coastal flooding exacerbated by sea level rise is not included in this Report. It is important though that the reader understands that event-based coastal flooding with sea level rise would alter the extent of the area subject to flooding from such events.

The results of the vulnerability assessment highlight just a few of the very significant challenges the State faces under a scenario of 3.2 feet of sea level rise by the mid- to latter-part of the century. However, this may not be the worst of it. According to recent climate science, sea level rise greater than 6 feet is "physically plausible" by the end of the century (Le Bars, Drijfhout, and de Vries 2017, Sweet et al. 2017). While not modeled in this Report, additional feet of sea level rise would add thousands of acres to the SLR-XA on each island (Figure 2). A geographic information system (GIS) analysis using layers from the NOAA Sea Level Rise Viewer (NOAA 2017b), which only accounts for passive flooding, indicates that an additional 10,000 acres state-wide would be added to the SLR-XA with 5 feet of sea level rise. This would increase the total area exposed to chronic flooding State-wide to over 36,000 acres and the economic, environmental, cultural and societal impacts of which would be far greater than the results presented in this

Report. Each island's exposure to passive flooding with 5 feet of sea level varies due to its geomorphology with O'ahu having the highest additional exposure (36%) and Maui, the lowest additional exposure (15%) in terms of additional acres passively flooded with 5 feet of sea level rise.



Potential additional area of chronic flooding with 5 feet of sea level rise

The threat of 3 feet or more of sea level rise in this century is real and is not likely to diminish given the overall trend in scientific research toward higher and more rapid scenarios of sea level rise in this century. This state-wide vulnerability assessment provides a framework for considering sea level rise threats in planning decisions by illustrating spatial flooding in this century and providing a framework for adaption. Invariably, adaption to sea level rise will require difficult decisions regarding when, where, and how to act on this information.

Recommendations

Recommendations were developed to provide guidance for State and County agencies, communities, and other stakeholders for improving our capacity to adapt to sea level rise. These recommendations were compiled through a comprehensive literature review; interviews, workshops, and meetings with a wide range of stakeholders; and quarterly consultations with the Hawai'i Climate Commission. The recommendations are designed to support a multi-sectoral and holistic response to adaptation building on existing efforts and considering challenges and new opportunities.

Recommendation 1, support sustainable and resilient land use and community development, focuses on the central role that land use and community development planning play in adapting to sea level rise. A Recommended Action under Recommendation 1 is to recognize the SLR-XA with 3.2 feet of sea level rise as a state-wide vulnerability zone for planning at state, county, and community levels. It is further recommended that a land inventory be conducted in each county to identify urban areas that could support a managed retreat strategy.



Recommendations to improve Hawaii's capacity to adapt to sea level rise

Recommendations 2 and 3 support Recommendation 1, through prioritizing smart redevelopment in areas outside the SLR-XA, limiting exposure inside the SLR-XA, and incentivizing improved flood risk management. In prioritizing smart redevelopment in areas outside the SLR-XA, under Recommendation 2, each county is encouraged to identify priority target areas for smart redevelopment. The State should consider developing design standards as best management practices for building in the SLR-XA with 3.2 feet of sea level rise. Also under Recommendation 2, the potential impacts of sea level rise provide new opportunities to use land more sustainably by identifying and prioritizing areas for smart redevelopment within existing urban land boundaries and to minimize pressure on agriculture and conservation lands. Further, the identification of shoreline protection, conservation, and restoration priorities are needed to make decisions on shoreline armoring. Finally, Recommendation 3 seeks to incentivize improved flood risk

management through support to a state-wide Community Rating System program, encouraging property owners outside currently regulated flood zones to purchase flood insurance, and incorporate sea level rise in hazard mitigation plan updates and disaster recovery frameworks.

Recommendations 4, 5, and 6 address cultural and environmental vulnerabilities that underpin resilient and sustainable land use and community development. A state-wide assessment of legacy beach conservation priorities is suggested as a Recommended Action under Recommendation 4 for enabling beaches to persist with sea level rise. An inventory, protocols, and process are needed to preserve Native Hawaiian culture and communities with sea level rise as part of Recommendation 5. For Recommendation 6, a comprehensive review of environmental regulations that allow for the siting of environmental hazards, such as hazardous materials/waste storage facilities and onsite wastewater storage systems is needed to protect nearshore water quality with rising seas.

Finally, cross-cutting recommendations include developing funding sources and incentives for adaptation (Recommendation 7), supporting research, assessment, and monitoring of changing conditions (Recommendation 8), and promoting collaboration and accountability for adaptation (Recommendation 9). These cross-cutting recommendations highlight the need to engage diverse stakeholders in making complex decisions about addressing the impacts of sea level rise. Recommendation 7 highlights the very real need to address the cost of adaptation by exploring both funding sources and incentives while Recommendation 8 is fundamental to a learning approach to adaptation which involves conducting research, assessments, and monitoring needed to update the Report and other "living" outputs.

This Report should serve as a baseline for understanding the most probable impacts of sea level rise and should be used to as a tool by the decision makers of the State, the Counties, and community leaders. Recommendations to increase our capacity to adapt to sea level rise are described, but do not lay out a plan for implementation. The Hawai'i Climate Commission provides a collaborative multisectoral forum for furthering discussions on how, when, and where to implement many of these recommendations. Some recommendations were identified through stakeholder consultations as priorities to be fast-tracked for discussion and action. In addition, sequencing considerations and synergies among the recommendations need to be recognized and planned for. Overall, we have enough information now to take action to address the inevitable near and medium-term rise of sea level.