Climate Ready O‘ahu
Risk Assessment Results

City & County of Honolulu
Climate Adaptation Strategy

December 30, 2020

Glossary

- **Climate hazard**: Climate change-related events or indicators, such as temperature or precipitation. Climate hazards include both shock and stress events.
    - **Shock:** An individual extreme event (e.g., storm) or disaster that occurs over a relatively short period of time (e.g., day(s) or weeks)
    - **Stress:** A gradual change in climate baseline that occurs over many years (e.g., sea level rise)
- **Likelihood:** The probability or expected frequency a climate hazard is expected to occur
- **Consequence:** A measure of the severity of impacts from a climate hazard
- **Risk:** The chance that a hazard will cause harm. Risk is a function of the likelihood of an adverse impact occurring and the severity of its consequences.

Contents

I. Risk Assessment Approach

The project team took an engagement-driven approach to the climate risk assessment, which consists of four components outlined in Figure 1. This risk assessment is a high-level overview of the likelihood that a climate hazard will occur and the magnitude of its consequences, at the island-scale.

Figure 1. Climate risk assessment process.

This approach emphasizes local knowledge and expertise and helps to inform high-level priorities, adaptation needs, and information gaps to support the development of a climate adaptation strategy for Oʻahu. Localized input on the prioritization of climate risks will help the City tailor Climate Ready Oʻahu to priority needs and adaptation strategies. The project team engaged City departments to select climate hazards, identify potential consequences, and vet the risk assessment results.

1. Understand the Context

The risk assessment identifies priorities for City departments and community plan areas to inform the development of adaptation strategies for Climate Ready Oʻahu. Although it was conducted at an island-wide scale, the project team used exposure mapping and case studies to also capture variable risks across the island. The assessment focused on near-term (2020-2050) risks to the City and County of Honolulu (City), to align with the time horizon considered in Climate Ready Oʻahu. The project team qualitatively evaluated longer-term risks beyond 2050 where possible.

Scope

Geography: City and County of Honolulu

Consequence Categories: Population, Economy, Environment

Climate Hazards:

- Hurricane
- "Rain bomb"
- Sea level rise and coastal erosion
- Decrease in precipitation
- Increase in temperature

Time frame: 2020-2050

1.1 Consequence categories

The project team and the City developed the following six key consequences, grouped into three categories, which represent key focus areas for the City:

- **Population** – measure of impacts to health and the community, specifically:

    - Physical health and safety
    - Mental health
    - Community cohesion and equity (e.g., differential impacts to daily life or identity)
- **Economy** – measure of impacts to economic activity, specifically:
    - Economic prosperity (e.g., impacts to specific industries or scale of economic losses)
    - Infrastructure (e.g., disruption to critical infrastructure and/or City services)
- **Environment and Culture** – measure of impacts to the natural environment and Native Hawaiian culture

1.2 Other considerations

For the purposes of this assessment, the project team focused on five hazards and seven distinct consequence types. In reality, certain hazards can have ripple effects on other hazards and consequences are interrelated. For example, increasing temperature, decreasing precipitation, wildfire incidences, and changes in trade winds all have compounding effects on each other that may increase the severity of consequences. Where appropriate, the project team commented on the interconnected nature of certain hazards and consequences in each climate risk profile in Section II.

To capture differential impacts across geographic locations or populations on the island, the project team engaged 15 City departments in one-on-one interviews to understand their climate challenges and potential consequences for the five hazards. The project team also used exposure mapping to identify specific geographic locations with higher exposure to each hazard. The project team then engaged City departments, the Community Advisory Hui, and the public to identify specific adaptation action areas (i.e., geographies, locations, and neighborhoods) for a more detailed case study of types of impacts and appropriate adaptations strategies to address the identified risks and consequences.

2. Identify Hazards and Risks

To focus the climate risk assessment, the project team and the City selected five key climate hazards that are likely to occur as a result of changing climate conditions by mid-century and would significantly affect the key consequence categories, with attention to, City infrastructure, assets, and the services provided to people around O‘ahu. The project team developed a list of key climate hazards from the City Climate Change Commission’s Climate Change Brief, including (Climate Change Commission, 2018a):

- Windward side of island becoming wetter (on trajectory of becoming up to 30% wetter by 2100)
- Leeward side of island becoming drier (on trajectory of becoming up to 60% drier by 2100)
- On trajectory of 3.2 feet of sea level rise by 2100 with impacts due to high tides and/or coastal hazard events decades in advance

- Tropical storm or hurricane, with storm surge, wind, and rain
- “Rain bomb” event (e.g., 4 inches/hour)
- Increase in average annual temperature of 2.7°F to 4.5°F by 2050
- Increase in average seasonal temperature
- Heat wave with temperatures in the high 80s/90s lasting at least 3 days
- Decreased trade winds
- Ocean acidification
- Ocean warming
- Coastal erosion
- Wildfire

To help identify priority hazards, City departments provided feedback via a survey form to rank their department’s hazards of concern. Based on this feedback, the project team worked with the City to narrow the set of hazards and to define plausible scenarios for each of the hazards to focus the risk assessment. The final list of climate hazards and scenarios is shown in Table 1.

What is a scenario?

To focus the risk assessment, the project team defined plausible scenarios of a specific severity for each climate hazard to evaluate the likelihood and consequences of that specific scenario. For stress events, the project team identified a critical threshold that is likely to occur by 2050 as part of the scenario to better evaluate likelihood.

Each scenario represents one permutation to illustrate the types of consequences associated with the hazard. The consequence ratings are specific to that scenario and could be more or less severe for other permutations of that hazard (e.g., O‘ahu could experience a hurricane that does not make landfall). Many hazards are also interconnected and may increase the severity of consequences (e.g., increasing temperatures and decreasing precipitation can lead to drought and wildfire). Defining a scenario helps to isolate the severity of consequences to a specific set of conditions and articulate how climate change influences the likelihood of each hazard for the purposes of identifying high-level priorities, adaptation needs, and information gaps.

Table 1. Selected climate hazards and scenarios

Climate Hazard	Scenario
Hurricane	Landfall of a major hurricane with storm surge, rainfall, and high winds
“Rain bomb”	Significant rain event with 4 inches of rain/hour
Sea level rise and coastal erosion	Sea level rise and associated coastal erosion on a trajectory to 3.2 feet by 2100 with impacts due to high tides and/or coastal hazard events decades in advance
Decrease in precipitation	Leeward side of island becomes up to 60% drier contributing to droughts
Increase in temperature	Increase in average annual temperature of 2.7°F to 4.5°F contributing to heat waves

3. Analyze Risks

To analyze risk, the project team mapped the hazards and evaluated the likelihood and consequences of each climate hazard scenario at an island-wide scale. The likelihood and consequence ratings are based on a combination of City department interviews and existing literature.

3.1 Map climate change exposure

The project team conducted an exposure screen with available geospatial data to better understand differential exposure across the island and to identify specific locations of at-risk infrastructure and people. While the risk ratings provide an island-wide overview of risks, in reality the risks will only manifest themselves in areas that are exposed to the hazard. Where possible, commentary on locations of greatest exposure is provided in the risk assessment results. Areas outside of the direct exposure area are still likely to experience indirect or cascading impacts.

In some cases, the current distribution of risks (e.g., average annual temperatures) provides a better understanding of differences in risk across the island than the forward-looking climate change data sets (e.g., temperatures are expected to rise relatively uniformly across the island). In these cases, the current hazard data was mapped rather than projected data. However, climate change projection information was used to inform the development of the likelihood and consequence ratings. The exposure maps and likelihood ratings for temperature and precipitation-related hazards draw primarily on available statistically downscaled climate projections for mid-century (Timm, Giambelluca, & Diaz, 2014), as dynamically downscaled projections (an alternative method) are only available for the end-of-century time period (Zhang, Wang, Hamilton, & Lauer, 2016); similarities or differences in trends identified with the dynamical method are briefly described in the Increase in Temperature and Decrease and Precipitation hazard sections below.

Table 2 provides a summary of the exposure mapping data and sources. The results of the mapping are included in Section II.

Table 2. Exposure mapping data and sources

Hazard	Mapped data	Source
Hurricane	Historical 500-year coastal and inland floodplain and modeled hurricane storm surge flooding Category 3 hurricane storm surge potential	FEMA Flood Insurance Rate Maps; NOAA SLOSH Model for Category 3 Hurricane
“Rain bomb”	Percent change in wet season precipitation under RCP 8.5 averaged over 2041-2071	Timm et al. 2014. *Statistical downscaling of rainfall changes in Hawaiʻi based on the CMIP5 global model projections.*

		https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014JD022059
Sea level rise and coastal erosion	The combined extent of 3.2 feet of sea level rise, with coastal erosion, and the annual high wave flooding event	Risk Assessment: Tetra Tech, Inc. combined hazard exposure data layers from the University of Hawaiʻi SOEST Coastal Geology Group. www.hawaiisealevelriseviewer.com. District Community Briefs: Building Footprint layer, roadway centerline layer, hospital and clinic layers, bridges, and dams from Honolulu and Hawaii GIS portals.
Decrease in precipitation	Percent change in dry season precipitation under RCP 8.5 averaged over 2041-2071	Timm et al. 2014. *Statistical downscaling of rainfall changes in Hawaiʻi based on the CMIP5 global model projections.* https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014JD022059
Increase in temperature	Historical average afternoon annual temperature	Geography Department at the University of Hawaiʻi. Climate of Hawaiʻi Interactive Map http://climate.geography.hawaii.edu/interactivemap.html

3.2 Rate likelihood

Likelihood ratings represent the degree of certainty that a climate hazard will occur in a given timeframe. Climate hazards can be either shock events (e.g., hurricane) or stress events (e.g., sea level rise). Evaluating the likelihood of these hazards is fundamentally different:

- **Shock events:** Likelihood is measured by the expected frequency of the hazard over a 30-year time period (e.g., 2020-2050).
- **Stress events:** Likelihood is measured by the probability that a critical threshold–a defined tipping point at which significant impacts occur–is exceeded by a given time period.

As such, the likelihood rating scale in Table 3 provides different rubrics for evaluating the likelihood of shock and stress events. The likelihood rating scale was applied to each climate hazard scenario for both a baseline historical time period and a mid-century time period (2020-2050). The project team primarily used climate data and information from the Climate Change Brief (Climate Change Commission, 2018a) and the Hawaiʻi and U.S.-Affiliated Pacific Islands chapter of the Fourth National Climate Assessment (USGCRP, 2018) to assess likelihood.

Table 3. Likelihood rating scale

Likelihood	Rating	Criteria for Climate-Related Shock Events	Criteria for Climate-Related Stress Events
Very Likely	5	Event is expected to happen about 15 or more times in a 30-year period.	Event is almost certain to cross critical threshold.
Likely	4	Event is expected to happen about 5 to 15 times in a 30-year period.	Event is expected to cross critical threshold. It would be surprising if this did not happen.
Possible	3	Event is expected to happen about 3 to 5 times in a 30-year period.	Event is just as likely to cross critical threshold as not.
Unlikely	2	Event is expected to happen about 1 to 3 times in a 30-year period.	Event is not anticipated to cross critical threshold.
Very Unlikely	1	Event is not expected to happen in a 30-year period.	Event is almost certain not to cross critical threshold.

3.3 Rate consequences

Consequence ratings represent the severity of impacts to a given consequence category. The metrics to define each category are intended to ensure consistency and comparability across climate hazard scenarios. Table 4 shows the consequence rating scale and metrics for each consequence category. Each consequence category is rated on a 1-5 scale based on cumulative island-wide impacts over the 2020-2050 time period. While the rating focuses on island-wide impacts, the hazard risk profiles note any relevant geographic differences in severity. The overall consequence score will be an average of the three consequence types: population, economy, and environment.

Differential Impacts

Although consequences are rated on an island-wide scale, consequences that are expected to have significant and severe differential impacts to particular populations or individuals are indicated with call-out boxes in the Risk Assessment Evidence Base of each hazard. For example, the elderly, young children, the homeless, and those living in poorly ventilated homes or homes without air conditioning may be disproportionately vulnerable to impacts from extreme heat.

The project team conducted interviews and held a working session with City and County department staff to gather information on the consequences of each climate hazard scenario and vet the consequence ratings and justifications.

The project team also held two series of virtual public meetings (two rounds of three meetings each for six meetings total) and two Community Advisory Hui meetings to investigate the climate hazard scenarios, identify areas of top concern, and discuss and assess the consequence categories.

Table 4. Consequence rating scale

	Population			Economy		Environment and Culture
	Physical Health and Safety	Mental Health	Community Cohesion and Equity	Economic Prosperity	Infrastructure	
Catastrophic – 5	1,000+ people affected	Widespread, severe mental health impacts lasting years	Widespread, severe impacts to daily life (e.g., inability to access employment, education) or identity (e.g., loss of home or sense of place), lasting months to years	Severe, long-term disruption to multiple industries with effects on employment Over $100 million in potential economic losses	Months-long disruption in infrastructure services Widespread disruption to critical infrastructure system	Irreversible damage or change to a broadly valued environmental and/or cultural area/resource
Major – 4	100-1,000 people affected	Widespread, severe mental health impacts lasting weeks to months	Widespread, severe impacts to daily life (e.g., inability to access employment, education) or identity (e.g., loss of home or sense of place), lasting days to weeks	Moderate, long-term disruption to multiple industries; or severe long-term impacts to one industry with effects on employment $10 million to $100 million in potential economic losses	Weeks-long disruption in infrastructure services Disruption to multiple critical infrastructure assets	Widespread, significant damage or change to a broadly valued environmental and/or cultural area/resource Recovery would take years to decades
Moderate – 3	10-100 people affected	Widespread, moderate mental health impacts lasting years	Widespread, moderate impacts to daily life (e.g., inability to access employment, education) or identity (e.g., loss of home or sense of place), lasting months to years	Severe, weeks- to months-long disruption to multiple industries; or moderate long-term impacts to one industry with effects on employment $1 million to $10 million in potential economic losses	Days-long disruption in infrastructure services Localized disruption to a singular critical infrastructure asset	Localized, significant damage or change to an environmental and/or cultural area/resource Recovery would take years to decades
Minor – 2	<10 people affected	Widespread, moderate, mental health impacts lasting weeks to months	Widespread, moderate impacts to daily life (e.g., inability to access employment, education) or identity (e.g., loss of home or sense of place), lasting days to weeks	Moderate, weeks- to months-long disruption to multiple industries; or severe short-term impacts to one industry with effects on employment $100,000 to $1 million in potential economic losses	Hours-long disruption in infrastructure services	Localized, moderate damage or change to an environmental and/or cultural area/resource Recovery would take months to years
Insignificant – 1	Extremely low possibility for physical health and safety impacts	Minimal expected mental health impacts	Minimal expected impacts to daily life or identity	Insignificant disruption to sector Less than $100,000 in potential economic losses	Temporary nuisance	Minimal damage or change to an environmental and/or cultural area/resource Recovery would take days to months

3.4 Confidence ratings

The consequence ratings are based largely on City Department interviews, augmented by readily available data and other information. Recognizing that certainty as well as the availability and quality of data can vary per climate hazard and consequence category, each likelihood and consequence rating was assigned a confidence rating using the scale in Table 5. The confidence rating indicates the strength, consistency, and makeup of the knowledge base used to inform the likelihood and consequence ratings.

Table 5. Confidence rating scale

High confidence	Medium confidence	Low confidence
Widespread agreement among multiple departments, or Multiple sources of independent evidence based on reliable analysis and methods	Some degree of agreement among departments, or Several sources of high quality independent evidence, with some degree of agreement	Varying amounts and quality of evidence

4. Evaluate Risks

To compute a total risk score and corresponding risk rating for each climate hazard scenario, the project team multiplied the likelihood score and overall consequence score:

Total risk = likelihood score x ((average population score + average economy score + environment score) / 3)

See Table 6 for the risk rating matrix and Table 7 for the corresponding score-to-rating rubric.

Table 6. Risk rating matrix

Likelihood	Consequences				
	Insignificant	**Minor**	**Moderate**	**Major**	**Catastrophic**
Almost Certain	Medium	Medium	High	Extreme	Extreme
Likely	Low	Medium	High	High	Extreme
Possible	Low	Medium	Medium	High	High
Unlikely	Negligible	Low	Medium	Medium	Medium
Rare	Negligible	Negligible	Low	Low	Medium

Table 7. Risk rating rubric

Risk Score	Rating	Risk Score	Rating
0 – 3	Negligible	**>11 – 18**	High
>3 – 5	Low	**18+**	Extreme
>5 – 11	Medium		

II. Risk Assessment Results

1. Overall Results

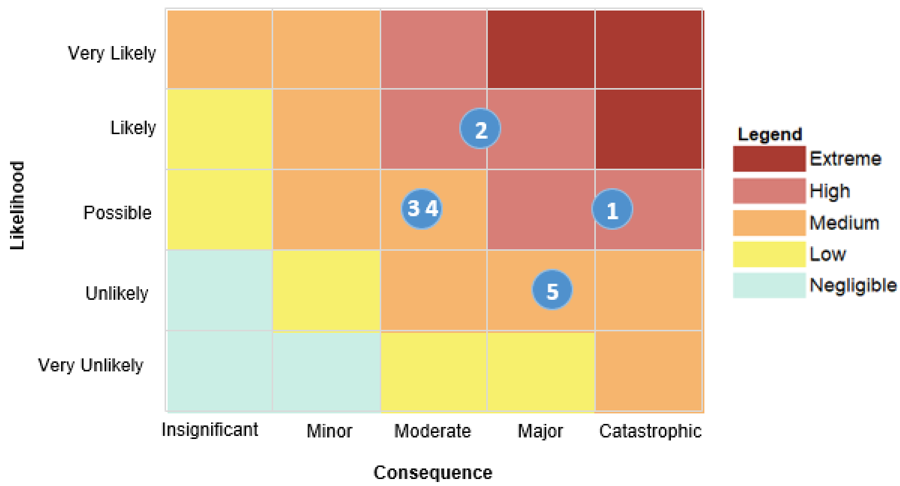

Figure 2. Risk matrix for all hazards. The numbers correspond to the ranking in the table below.

The risk assessment analyzed five priority climate risks to O‘ahu for 2020-2050 to inform the development of adaptation strategies for Climate Ready O‘ahu. Table 8 and Figure 2 summarize the overall results for 2050. The overall risk scores are a product of the likelihood and average consequence score. Sea level rise and coastal erosion, and increase in temperature emerged as the two greatest risks. Increase in temperature is estimated to have the greatest risk score increase of all hazards from present day to 2050. However, due to the gradual nature of sea level rise, increase in temperature, and decrease in precipitation, the City should be able to more easily mitigate risks and lower the severity of consequences through proactive actions.

Table 8. Overall risk assessment results

	Climate Hazard	Scenario	Current Rating (Score)	2050 Rating (Score)
1	**Sea level rise and coastal erosion**	Sea level rise and associated coastal erosion on a trajectory to 3.2 feet by 2100 with impacts due to high tides and/or coastal hazard events decades in advance	Medium (9.3)	High (14.0)
2	**Increase in temperature**	Increase in average annual temperature of 2.7°F to 4.5°F contributing to heat waves	Medium (6.9)	High (13.8)
3 (tie)	**“Rain bomb”**	Significant rain event with 4 inches of rain/hour	Medium (5.8)	Medium (8.7)
4 (tie)	**Decrease in precipitation**	Leeward side of island becomes up to 60% drier contributing to droughts	Medium (5.8)	Medium (8.7)
5	**Hurricane**	Landfall of a major hurricane with storm surge, rainfall, and high winds	Low (4.1)	Medium (8.2)

Table 8 provides the relative total consequence ratings for each of the hazards, which are presented from left to right by descending overall risk score. Figure 4 highlights the dominant consequences per hazard. Sea level rise and coastal erosion and hurricane are estimated to have the most significant consequences, but due to the low likelihood of a hurricane making landfall on O‘ahu, hurricane did not emerge as a top risk compared to the other hazards. Notably, the economic prosperity and infrastructure categories are rated at least a 3 (moderate consequences) across all hazards.

Multi-Hazard Pre-Disaster Mitigation Plan

The City’s Multi-Hazard Pre-Disaster Mitigation Plan (2019; HMP) also considers hazard risks, however, it uses a different methodology to evaluate Average Annualized Loss (AAL). Through that process, the HMP identifies the following order of hazard severity to the City (from most to least): hurricane winds; tsunami; floods; earthquakes; debris and rockfalls; coastal erosion; wildfire; dam failure; high surf; and hazardous materials. More information about this process and the City’s HMP is available at, resilientoahu.org/hazard-mitigation-plan.

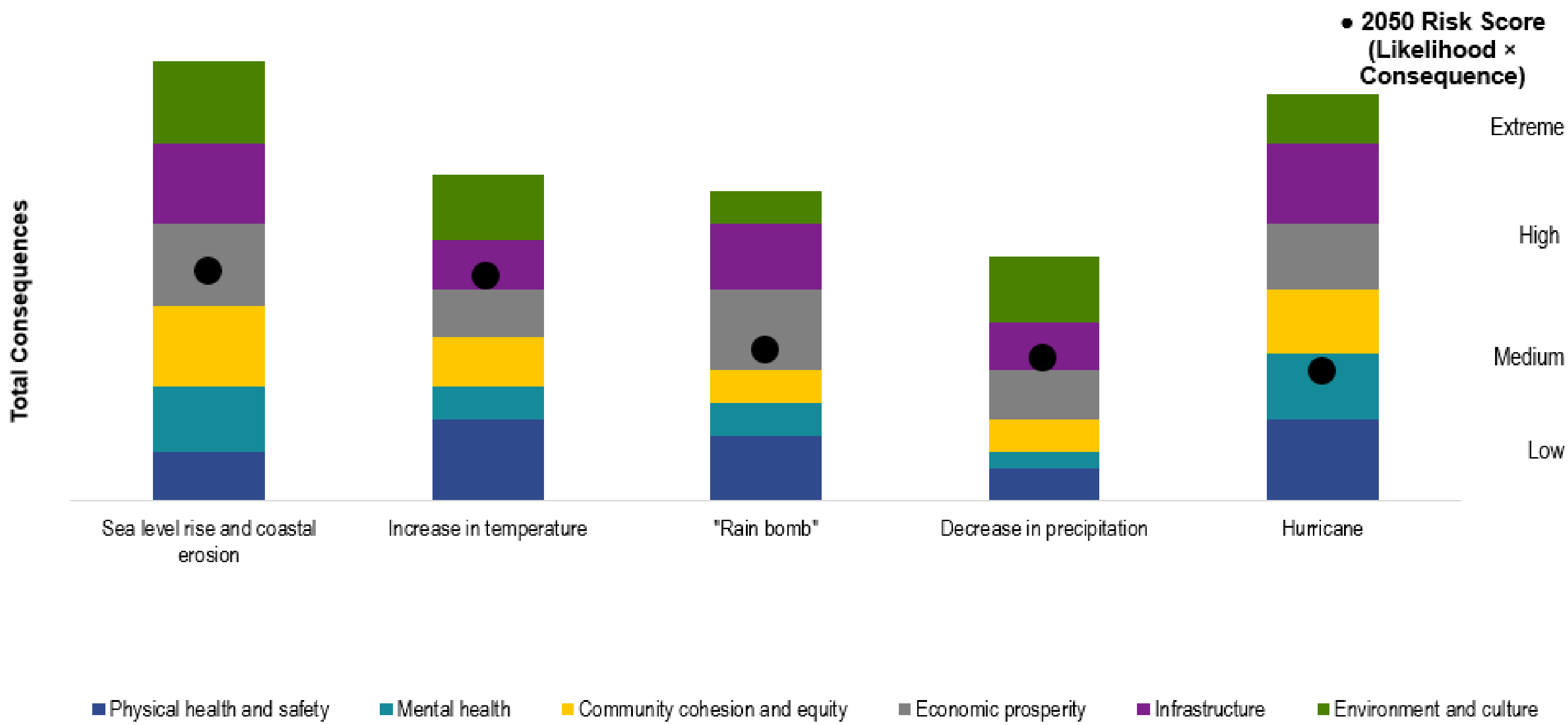

Figure 3. Consequence rating details by hazard.

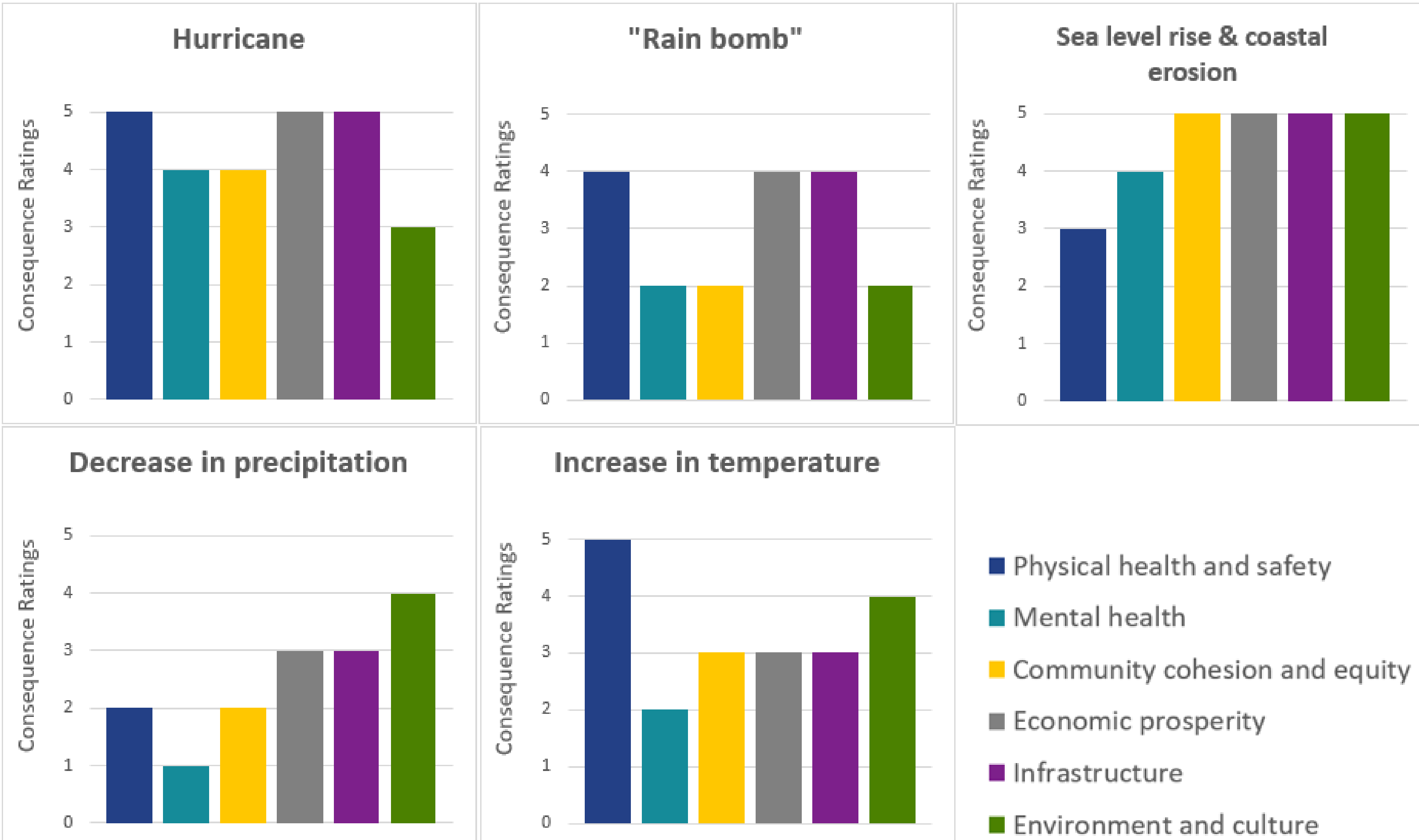

Figure 4. Consequences ratings per hazard.

2. Hurricane

SCENARIO: LANDFALL OF A MAJOR HURRICANE WITH STORM SURGE, RAINFALL, AND HIGH WINDS

2.1 Summary of Findings

Table 9. Risk assessment summary for hurricane

Likelihood		
Timeframe	**Rating** 1 2 3 4 5	**Confidence**
Current		High
2020-2050		Medium
Consequences		
Category	**Rating** 1 2 3 4 5	**Confidence**
Physical health and safety		High
Mental health		Medium
Community cohesion and equity		Medium
Economic prosperity		High
Infrastructure		High
Environment and culture		Low
Overall Risk		
Current	4.1 (Low)	High
2050	8.2 (Medium)	Medium

This assessment focuses on likelihood and consequences of a major hurricane, defined as a Category 3 storm with significant storm surge, making landfall on O‘ahu. Factors such as rate of precipitation, angle of incidence, and place of landfall will affect severity of impacts. Overall, the present-day risk of a severe storm scenario is **low** and the future risk is **medium**. This scenario can cause large scale power outages with cascading effects to local businesses; damage to transportation infrastructure, especially near the coast; and increased risk to physical health. The severity of impacts may vary based on the specific location of storm landfall.

Table 9 summarizes the risk assessment results for this hazard and Figure 5 shows the overall current and 2050 risk ratings on a risk matrix. The potential for compounding impacts from multiple severe storms in one season or subsequent seasons would increase the consequence of the events, especially in the economy, environment, and infrastructure categories, however, the ratings in this assessment focus on a single severe storm event.

2.2 Risk Assessment Evidence Base

2.2.1 Likelihood

The present-day likelihood rating for the hurricane scenario is **1** and the 2050 likelihood rating is **2.** The present-day likelihood rating is based on the lack of a major hurricane event ever making landfall on Oʻahu, while future likelihood is based on new storm path projections pushing storms closer to Oʻahu as well as the drivers of severe storms increasing.

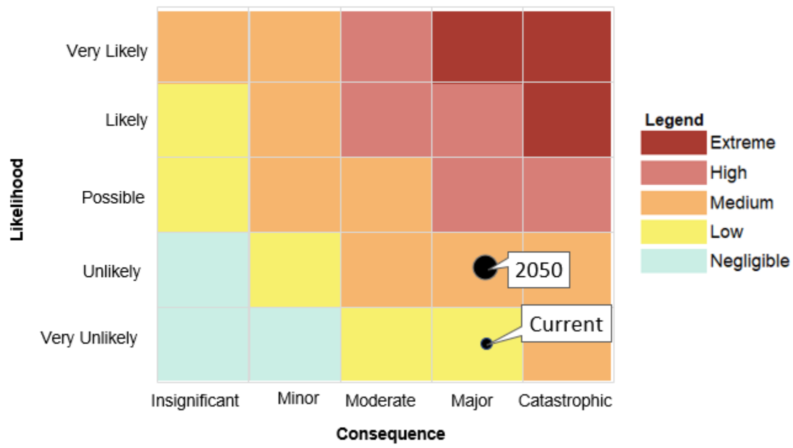

Figure 5. Risk matrix for hurricane.

Supporting evidence includes:

- The state of Hawaiʻi historically has had an equivalent annual 25.2% chance of severe storms of any magnitude (tropical storm up to category 4 hurricane) occurring annually (HI-EMA, 2018), although a storm of hurricane strength has never made landfall on Oʻahu.
- Hurricane strength storms making landfall across Hawaiʻi is an unlikely event for several reasons, including:
  - Hawaiʻi is a small patch of land, consisting of 10,931 square miles of land that sits in 6,246 million square miles of Pacific Ocean (Golembo, 2020).
  - During the central Pacific hurricane season, a high-pressure build north of Hawaiʻi results in stable and dry air pushed into the paths of hurricanes, inhibiting them from strengthening (Golembo, 2020).

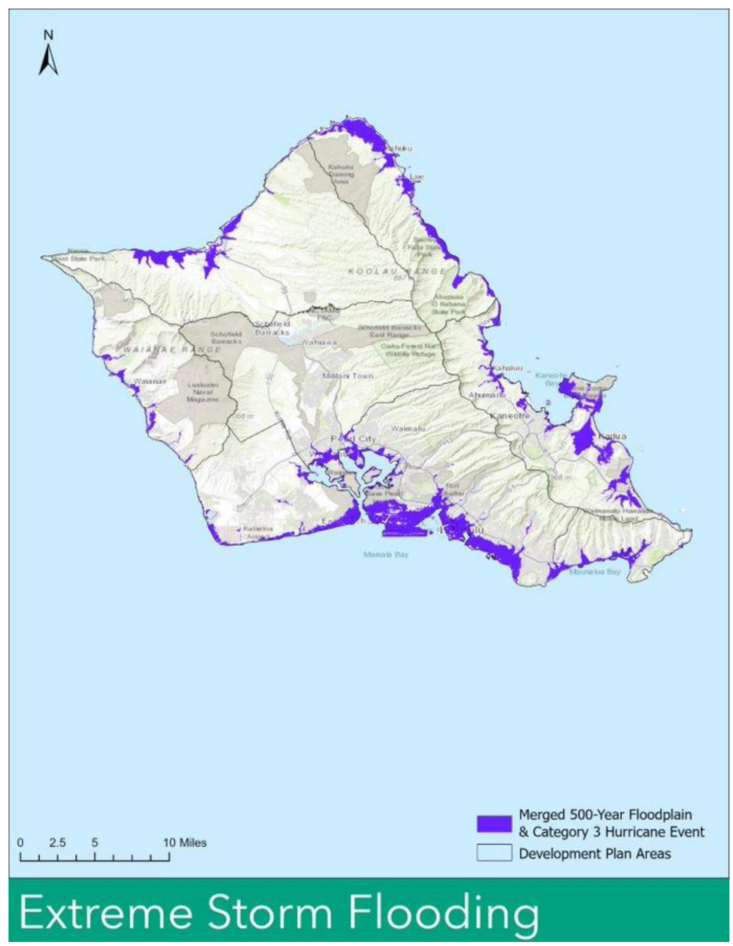

Figure 6. Exposure map of the flood zones from both FEMA Flood Insurance Rate Maps (FIRM) and NOAA-modeled storm surge from a Category 3 hurricane. Storm surge impacts are highly dependent on a storm's direction of approach.

    - Cooler sea-surface temperatures around 70°F east of Hawai‘i increase stability of the atmosphere, decreasing the likelihood that severe storms can form or maintain. Hurricanes generally require high 70s or warmer to strengthen (Golembo, 2020). However, recent Pacific marine heat waves in 2015 and 2019 have resulted in warmer than normal air temperatures (Cornwall, 2019; Climate Change Commission, 2018a). Marine heat waves are expected to increase in intensity and frequency due to climate change (Bindoff, et al., 2019).
- Severe storms are not expected to form more frequently in the future in the east Pacific; however, climate change is likely to alter the paths of storms so that landfall across Hawai‘i is more likely (Climate Change Commission, 2018a). Additionally, the frequency of El Niño events is expected to increase by about 36% by 2050, resulting in more active Pacific hurricane seasons (Climate Change Commission, 2018a).
- Figure 6 illustrates the flood zones from both FEMA Flood Insurance Rate Maps (FIRM) and NOAA-modeled storm surge from a Category 3 hurricane. Storm surge impacts are highly dependent on a storm's direction of approach. Areas near Honolulu and Kahuku are at high risk for flood damage (see Figure 6 for more detail on hazard zones). To reiterate, however, location of flood damage is highly dependent on a storm’s approach.

Confidence (Current): Medium

Current likelihood is only a medium based on the historical lack of a major hurricane making landfall on O‘ahu.

Confidence (2020-2050): Low

Future likelihood rating is based on multiple literature sources indicating increasing drivers of severe storms and changes in projected future storm tracks. Increasing sea-surface temperatures, changing storm paths, and increases in El Niño events are cited with moderate agreeance by the literature; however, estimates signaling these changes are not specific to O‘ahu, reducing confidence.

2.2.2 Consequences

The most severe consequences from a hurricane event are likely to affect infrastructure, economic prosperity, and physical health and safety on O‘ahu. All categories were ranked at least 3, with the least severe impacts expected to be realized in environment and culture.

Details on each individual consequence rating are provided below.

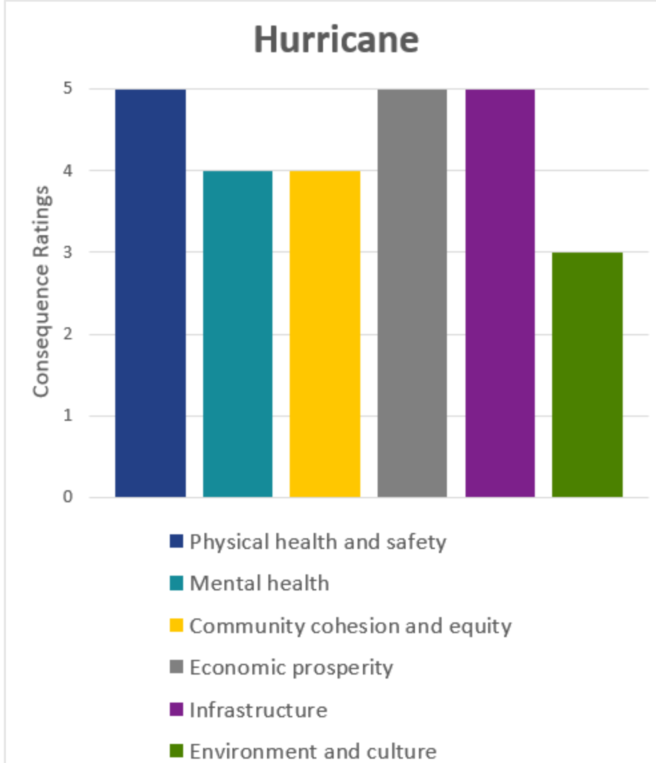

Figure 7. Consequence ratings for hurricane.

Population: Average score of 4.3

Physical health and safety: 5

A major hurricane event has potential to cause significantly higher risk of physical injury and disruption to health services on O‘ahu. Major potential impacts include lack of access to health services, increased risk of food insecurity, and disruptions to safe public water resources, among others. Disruptions may last for weeks after the hurricane event itself.

Supporting evidence includes:

- About 90% of deaths on Hawai‘i related to severe storm events have historically occurred as a result of storm surge (rather than wind). Storm surge is especially dangerous in combination with high tides. (HI-EMA, 2018)
- Damage to transportation infrastructure can disrupt emergency services and the supply chain of lifeline resources such as food, water, and other important deliveries (HI-EMA, 2018). Many communities are accessible by a single roadway and could be cut off if it is damaged or destroyed (Honolulu Office of Climate Change, Sustainability and Resiliency, 2019).
    - 88% of Hawai‘i’s food is imported; supply disruptions significantly impact food availability (HI-EMA, 2018). It is known to be difficult for many households on O’ahu to have and/or maintain the recommended 14-day food supply for disaster preparedness (Office of Economic Development, 2020).
    - The locations of some health centers may make them inaccessible. For example, several community health centers are very near the shoreline and have limited access roads that are at risk of flooding or damage from severe storms (Office of Economic Development, 2020).
- Floods resulting from hurricanes can cause contaminated drinking and washing water, poor sanitation, mold and mildew growth, carbon monoxide poisoning, as well as an increase in vector borne diseases from mosquitoes and other animals (HI-EMA, 2018).

- Downed or damaged power lines can cause loss of power from days to months depending upon severity of the event. As an example, over 25% of transmission poles failed after Hurricane Iniki hit Kauai (HI-EMA, 2018). This damage may affect emergency services (e.g., 911 system) and result in disruptions to public water supplies, water treatment, and sewage facilities as electric water pumps may be nonfunctional. Residents may be subject to boil-water notices in order to eliminate waterborne pathogens (HI-EMA, 2018; Personal communication, 2020).
    - Power outages may worsen health impacts of hurricanes by resulting in more limited access to health care, loss of light, increased potential for carbon monoxide poisoning, and decreased levels of food security (Klinger, Landeg, & Murray, 2014). The health of those who reside in climate-controlled environments may be particularly vulnerable to power outages in the wake of a disaster.
- Honolulu residents are at particular risk of displacement and economically disadvantaged populations may not have sufficient funds to evacuate. The elderly are also a more vulnerable risk group as they are more likely to need medical attention, extra time and a greater level of assistance during evacuation events (HI-EMA, 2018).
    - Since the population of Honolulu is aging, additional resources may be required in support of evacuation efforts prior to severe storm events. Additional emergency power support and medical equipment may be required in the future in order to maintain the current level of consequence as risk increases due to an aging population (HI-EMA, 2018).
    - Currently Oʻahu only has shelters that have holding capacity for a category 1 or less intense storm. This is a key vulnerability for storms of category 2 or greater intensity (Office of Housing, 2020).
    - Buses can be used to provide transportation to shelters during an evacuation event. If a storm of high severity occurs and a greater number of people require evacuation than during previous events, the bus system may not have enough capacity to accommodate an event of this type (Office of Housing, 2020).
    - The upper windward side of does not have a shelter in close proximity, which became apparent during preparations for Hurricane Douglas (July 2020), the closest passing Pacific Hurricane to the island of Oʻahu on record (Office of Housing, 2020).
- Many neighborhoods on Oʻahu were built in the 1950s and therefore are not designed to withstand hurricane-force winds. This may increase physical health risk for those residing in these neighborhoods (Office of Economic Development, 2020).
    - According to an assessment of Oʻahu single-family homes, 64.2% or more of the total single-family home inventory is considered deficient with respect to hurricane-force winds as of 2016 (Martin, 2019).
- After flooding in Kaʻaʻawa, flooded roadways were cleared of floodwaters and pumped into nearby streams. Occurrences such as these may pose public health risks as residents are more likely to come into contact with potentially hazardous waters. This risk is exacerbated if flooding damages septic tanks or other onsite sewage disposal systems (Department of Environmental Services, 2020).
- Health care disruption and high risk of physical injury may occur weeks after the hurricane event itself as power outages and other damaged infrastructure may be in a state of disrepair well after the event (Personal communication, 2020).

Confidence: High

Multiple City departments and external sources described similar risks based on impacts experienced so far. City departments reinforced multiple risks presented in reports and other litertature resulting in a high level of confidence.

Mental health: 4

Major hurricane events have the potential to cause widespread severe mental health impacts for months after the event such as higher stress levels and less access to public relaxation areas.

> **Differential Impacts**
>
> Vulnerable populations and those who are displaced or experience damages to personal property are more likely to experience severe impacts.

Supporting evidence includes:

- Key risk factors that may increase mental health vulnerability to disasters include age, low socioeconomic status, minority ethnic status, previous mental health issues, and level of social support (Goldmann & Galea, 2014).
    - On O‘ahu, the populations most vulnerable to mental health issues as a result of severe storms are those who are single, male, have previous mental health issues, or suffer from addiction (Office of Housing, 2020).
- Issues commonly reported after severe storm-related flooding events include behavioral problems in children; increased substance use and/or misuse; increased domestic violence; as well as exacerbating, precipitating or provoking people's existing problems with their mental health. Economic problems resulting from severe storm events may cause additional mental health stress. Severity of the storm event and level of exposure to the event are major factors that influence the severity of mental health issues realized as a result of the event (Stanke, et al., 2012).
- Flooding as a result of severe storms can be very stressful for residents and can continue for significant periods of time after the water has receded (Stanke, et al., 2012).
- Forced displacement, relocation, or land loss as a result of severe storms diminishes sense of place which causes further negative consequences (Ohl & Tapsell, 2000). Displacement also exacerbates mental health challenges and vulnerabilities (Office of Housing, 2020).
- The Honolulu Crisis Intervention Team may be able to provide mental health assistance in times of need, although mental health training is currently suspended due to the coronavirus pandemic (Office of Housing, 2020).
- If parks are severely damaged and closed as a result of a severe storm event there may be prolonged inability to use public spaces to relax, which may stress peoples' mental health. This stress has been demonstrated through the various coronavirus closures. Public parks may also be closed for recreation purposes if those spaces are required to serve as locations for supply pickups and as holding areas in the wake up a severe storm (Department of Parks and Recreation, 2020).
    - Facility reopening would be dependent upon the ability of the staff to maintain the area. For example, if comfort stations are nonfunctional, it may impact the decision to reopen a park. Legally, people are able to access the ocean whether or not a park is considered open or closed (Department of Parks and Recreation, 2020).

Confidence: Medium

Multiple City departments described similar or related risks. External sources, including literature reviews related to disasters and mental health impacts were also drawn from.

Community cohesion and equity: 4

A major hurricane on O‘ahu is likely to significantly disrupt community cohesion. Potential consequences include damage to historical or cultural resources, damage to neighborhoods not constructed to withstand high wind speeds, and population loss. Some impacts may be short-term and severe (business and transportation interruption), while some impacts are likely to be more moderate, but long-term (population loss).

Supporting evidence includes:

- After a major event like a severe storm, it is possible that O‘ahu will suffer from population loss as residents leave the island to stay with family or friends on the continental U.S. This may create challenges during rebuilding phases and result in impacts lasting years or decades. (Department of Emergency Management, 2020).
- O‘ahu’s existing level of community cohesion is negatively influenced by the large number of visitors the island receives. Permanent residents on the island are likely to have common resources and social ties that create a greater sense of community, while visitors lack these resources and sense of community (DEM, 2019).
- Some people, especially those living in low-lying coastal areas could lose their homes (Personal communication, 2020). Some neighborhoods, especially those built in the mid-20th century on O‘ahu, were not constructed to withstand hurricane force winds. Newer neighborhoods may fair better against strong winds (Department of Transportation Services, 2020).
- Many communities are accessible by a single roadway and could be cut off if it is damaged or destroyed during a hurricane event (Honolulu Office of Climate Change, Sustainability and Resiliency, 2019).
- O‘ahu is yet to have a major disaster that forces community members to build the partnerships and relationships necessary to organize around a rebuilding effort, unlike other regions within the state such as the County of Hawai‘i (Office of Economic Development, 2020).
- Historical and cultural resources near the shore may be vulnerable to damage from storm surge inundation, which may deplete communities of important meeting sites or culturally valuable places, thereby diminishing community cohesion (HI-EMA, 2018).
- Eroding beaches may impact local fishing and cultural practices as well as diminish portions of Hawaiian Home Lands, resulting in disruption to community cohesion, especially for Native Hawaiians (HI-EMA, 2018).
- A severe storm event may result in disruption to transportation services and other business interruption losses, which may hinder resident’s ability to reach their workplace, thereby negatively affecting community cohesion (Department of Transportation Services, 2020; HI-EMA, 2018).
- The homeless population may be particularly vulnerable to a loss of sense of community cohesion due to a hurricane. Homeless individuals may be more likely to experience loss of their belongings and a greater loss of sense of place than other residents (Office of Housing, 2020).

- Volunteer-reliant programs that support community cohesion during or after disaster events, such as the Red Cross, are suffering from severe decline in volunteers due to the coronavirus pandemic. Lower functioning of these groups may disrupt rebuilding efforts and therefore community cohesion and equity in the wake of a severe storm (Department of Facility Maintenance, 2020).

Confidence: Medium

Multiple City departments and external sources described similar risks, based on impacts experienced so far. City deparments had a high level of aggreance.

Economy: Average score of 5

Hazard: Tropical storm/hurricane, with storm surge, wind and rain

Key associated hazards:

- Storm surge
- Wind damage
- Rainfall

Key types of potential physical damages:

- Physical damages to *infrastructure including critical facilities* (e.g., airport, Port of Honolulu, state roads and buildings, utility and transportation infrastructure)
- *Long-term economic damages* (e.g., impacts to tourism industry or increased unemployment)

Coastal regions are at greater risk for tidal surge and high winds impacts, while *inland regions*, especially in 100-year and 500-year floodplains, are at significant risk to flooding from heavy rains.[1]

Extreme storms like tropical cyclones and hurricanes are likely to increase in frequency and intensity under climate change.

Though no high-intensity storms have directly hit Oʻahu as of 2020, a history of near-misses and increase in high-likelihood conditions are cause for concern and mitigation work.

Historical Events

From 2012 to 2017, four of the ten major tropical storm and hurricane events that impacted Hawaiʻi affected Oʻahu beyond necessitating risk monitoring: Tropical Storm Iselle (2014), Hurricane Kilo (2015), Hurricane Ignacio (2015), and Hurricane Olaf; the island also actively monitored Hurricane Jimena (2015), and Tropical Storms Niala and Oho (2015).[1] Additionally, in 2016, Hurricane Darby led to flash flooding and tropical-storm-strength winds on Oʻahu.[2]

Hurricane Iniki (1992)[3]

Strongest hurricane to hit Hawaiʻi in recorded history; $7.8B in direct damage

- *Human cost*: 4 fatalities, 25,000 people affected
- *Unemployment* rose at least 10% due to the storm, and took almost 7 years to return to pre-storm levels
- *Permanent losses*: Kauaʻi saw a permanent loss of ~12% of income and ~10% of its population
- *Infrastructure damages* including 14,400 homes damaged or destroyed, electric phone & power service lost by much of the island for over a month
- *Tourism industry* fell 70% following the storm, only returning to pre-storm levels ~8 years later
- *Agricultural industry* recovered post-storm, helped by government funding, though several plantations closed

Future events

The economic risk to Waikīkī alone from a Hurricane Iniki-strength (Category 4) storm striking Oʻahu's south shore is estimated at more than $30 Billion in direct economic losses and structural damage.[4]

Sources: 1. State of Hawaiʻi Hazard Mitigation Plan, 2018. 2. Star-Advertiser Staff, July 24, 2016. "Darby dumps rain on Oahu." 3. University of Hawaiʻi, 2014. *A Hurricane's Long-Term Economic Impact: the Case of Hawaiʻi's Iniki*. 4. *State of Hawaiʻi Multi-Hazard Mitigation Plan*, 2010. Hawaiʻi Coastal Hazard Mitigation Planning Project, Office of Planning, December 1993 as the original study with calculations updated by the University of Hawaiʻi, July 2010; Swiss Re Group, 2016.

Economic prosperity: 5

Severe storms have the potential to cause widespread impacts to all of Oʻahu's industries. Especially vulnerable are industries reliant on the Honolulu International Airport and the Port of Honolulu, such as local restaurants and small businesses. Livelihoods and employment may be impacted from nonfunctional roads causing disruption in residents' daily commute, airport/port shutdowns restricting supplies to the island, and small businesses lacking resources to rebuild quickly or at all.

Supporting evidence includes:

- A major storm could incur billions of dollars in industry damage, if other examples of impacts to the gulf coast and from Hurricane Maria are any indication. While the first hit will likely be quite catastrophic, buildings and communities will likely be built back stronger and subsequent impacts may be different (Personal communication, 2020).
- If a storm directly hit Honolulu Harbor, Waikīkī, and Kakaʻako – though any particular landfall location might be relatively unlikely – that hit could incur hundreds of millions if not billions of dollars in economic impacts (Personal communication, 2020).
- The Port of Honolulu is an integral supply site for the entire state of Hawaiʻi. Millions of tons of food and other supplies enter via the port each year and all petrol products arrive to Hawaiʻi by sea. Disruptions to the port, such as a power outage, are likely to have severe and cascading economics impacts to not only Oʻahu, but the state as a whole (HI-EMA, 2018).
- The interruption of critical services such as ports, airports, utility services, and other public services as a result of a hurricane are likely to disrupt virtually all forms of economic activity, including resident and visitor travel. Storm surge impacts on storage areas at the Port of Honolulu may severely disrupt supply chains, especially if there is little warning of disaster events (HI-EMA, 2018).
- International communities and investors rely on Hawaiʻi to be looked upon as a paradise for tourists. Severe storms, especially if increasing in frequency, may diminish this attitude, thereby impacting investment in tourism on Oʻahu (Office of Economic Development, 2020). Governments of other countries occasionally conduct safety inspections of potential travel destinations and suggest travel restrictions to their citizens based on the results. Thus, as safety is jeopardized by severe storm events, economic prosperity may be negatively impacted (Honolulu Emergency Services Department, 2020).
- The film industry (especially the foreign film industry) uses Oʻahu as a film location. The ability to continue to attract filmmakers to Oʻahu may be impacted by a higher potential for hurricanes, thereby impacting economic prosperity (Office of Economic Development, 2020).
- Many local food manufacturers (e.g., Hawaiʻi Chip Co, Honolulu Cookie Company, etc.) are highly reliant on tourism and are vulnerable to events that result in reduced tourism (Office of Economic Development, 2020).
- Recreation industries such as municipal golf courses and the Honolulu Zoo are likely to face financial disruptions in the wake of a hurricane. Recovery of these industries would likely take days to months depending upon severity. In order for golf courses to operate, debris must be cleared for golf carts to safely operate and there may be tolerance for a lack in other more aesthetic qualities of the courses (Department of Enterprise Services, 2020).
- Nonfunctional roads can have major implications for those who require transport to get to their places of employment or other daily activities. This is especially pertinent for coastal areas of Oʻahu as some workplaces have limited access roads and therefore limited detour options (DEM, 2019).
- The Daniel K. Inouye International Airport is located on a low-lying coastal plane, just 13 feet above sea level, with one runway built completely offshore, making it particularly vulnerable to storm surge events. The airport services more than 20 million visitors

annually and is a major source of imports to the island. Damage to the airport could cause devastating and long-term economic impact, especially for those whose jobs rely on a functioning airport. It is estimated that the airport could experience 1-2 week downtime for commercial flights as a result of a severe hurricane event, which may impact resident's ability to work, especially if they are directly employed by airport services. (HI-EMA, 2018).

- The agricultural industry and those employed by it are at risk in the wake of disaster events, including hurricanes and severe storms. Crops sensitive to wind damage and low-lying/coastal agricultural lands may be particularly vulnerable to high winds and flooding resulting from storms. Some smaller farms have fared better than larger farms during the coronavirus pandemic as they have quickly adjusted to sell directly to local residents. This may hold true in the wake of other disasters, such as hurricanes (Office of Economic Development, 2020).
    - According to an analysis conducted by the project team 5,816 acres of agricultural land are within the 500-year severe storm flood hazard zone and are thus vulnerable to flooding as a result of a hurricane event.
- Small businesses are likely to be less resilient after a severe storm event as many lack generators, operate out of buildings that are not constructed to withstand high winds, and lack recovery or continuity plans (Department of Emergency Management, 2020).

Confidence: High

Multiple reports and other high quality literature were drawn from. City departments had a moderate agreed that the extent of damage would be significant and provided high quality evidence in support.

Infrastructure: 5

Infrastructure on Oʻahu is very vulnerable to a major hurricane. Areas of potential major impact include critical infrastructure facilities such as the Daniel K. Inouye International Airport, the Port of Honolulu, water and energy utilities, and transportation infrastructure, among others. Disruptions may take weeks to months to fully recover from depending upon on the level of associated storm surge/flooding.

Supporting evidence includes:

- According to an analysis conducted by the project team, the following are within the 500-year severe storm flood hazard zone and are thus vulnerable to flooding as a result of a hurricane event: 23,739 buildings, 198 miles of roadway, 183 bridges, 3 fire stations, 5 hospitals, and 10,218 acres of urban land.
- The Daniel K. Inouye International Airport is located on a low-lying coastal plain, with one runway built completely offshore, making it particularly vulnerable to storm surge events. The airport services more than 20 million visitors annually and is a major source of imports to the island. Damage to the airport could cause devastating and long-term infrastructure impact (HI-EMA, 2018).
- The Port of Honolulu serves the entire state of Hawaiʻi. Millions of tons of food and other supplies enter via the port each year and all petrol products arrive to Hawaiʻi by sea (HI-EMA, 2018; Department of Emergency Management, 2020).

    - Piers and storage areas specifically are at risk of damage from a severe storm. Containers may fall into the water, potentially blocking ships from reaching their destination (HI-EMA, 2018).
- Honolulu's transportation system is extremely vulnerable to impacts from severe storms. Many roadways and bridges are located in coastal and flood prone areas. In many cases a flood or storm surge could impede travel and cut off communities due to a lack of detour options (Honolulu Office of Climate Change, Sustainability and Resiliency, 2019).
    - Bus and rail services are required to shut down during a major hurricane scenario. Additionally, the account-based revenue collection system on buses and future rail systems require power in order to function, so disruption to energy utilities may impact the ability of transportation services to run and collect revenue. Data warehouses that store transportation data may also be disrupted further complicating the restoration of transportation services on Oʻahu after a hurricane (Department of Transportation Services, 2020).
    - The Kalihi Transit Center may be particularly vulnerable to damage as it is located within a flood hazard area and has suffered impacts from previous storms (Department of Transportation Services, 2020; Department of Facility Maintenance, 2020).
    - Oʻahu's attempted transition to electric buses may be stifled by a severe storm event as power outages greater than 1-2 days may result in inability for electric buses to function (Department of Transportation Services, 2020).
- Up to 65% of the current residential housing stock is projected to be severely damaged or destroyed in a Category 1 hurricane (Honolulu Office of Climate Change, Sustainability and Resiliency, 2019).
- 60% of Oʻahu's critical infrastructure is located within a mile of the coast, making infrastructure highly vulnerable to wind and storm surge events, especially if a severe storm makes direct landfall (Honolulu Office of Climate Change, Sustainability and Resiliency, 2019). If a Category 2 hurricane was to make landfall on Oʻahu the estimated losses are $637 million to essential facilities (HI-EMA, 2018).
- During a severe storm event it is likely that energy utilities will be dramatically disrupted. Power lines may be badly damaged or destroyed from high winds and falling trees, resulting in loss of power from weeks to months, depending upon the severity of the storm. This can cause cascading impacts across island infrastructure. For example, water pumps require electricity to run (HI-EMA, 2018).
    - Although not on Oʻahu, electrical transmission and distribution lines on Kauaʻi have been susceptible to failure in previous storm events with over 25% of transmission poles failing during Hurricane Iniki (HI-EMA, 2018). On the Big Island of Hawaiʻi, Tropical Storm Iselle downed trees and utility wires, causing widespread power outages and resulting in over 100 reports of infrastructure issues (HI-EMA, 2018).
    - For a major hurricane event, Hawaiian Electric assume 3+ months without access to electricity, which would impact access to water, internet, and basic communication infrastructure (Personal communication, 2020).
- Storm surge has the potential to damage critical infrastructure such as roads and bridges. Coastal roads may be undermined or fully submerged, resulting in isolation of some communities. Storm surge could case road washouts, sinkholes, and bridge washouts on Oʻahu (HI-EMA, 2018).

    - If bridges fail, they can take a year or more to restore (Board of Water Supply, 2020).
- The option to purchase property insurance protection for hurricanes on Oʻahu may become more limited in the future. The City currently does not insure 100% of buildings for potential damages in a catastrophic event, instead the amount of insurance that is affordable is purchased. As climate change increases the frequency and intensity of severe storms, insurance prices may increase leading to the city having less coverage for the same cost, thus potentially disrupting rebuilding efforts. In catastrophic situations the US Federal Emergency Management Agency may assist in funding rebuilding efforts (Department of Budget and Fiscal Services, 2020).
- Communication infrastructure is at risk in the wake of a severe storm event on Oʻahu. If cell phone towers are downed, no satellite phone system exists as a backup to guide communication during immediate rebuilding efforts. Lack of communication may cause delays in restoration efforts as it could be challenging to determine areas of greatest need. Internet outages are also possible as broadband is limited on the island (Office of Housing, 2020; Department of Environmental Services, 2020).
- Water infrastructure is likely to face disruption in the event of a severe storm. Facilities at particular risk include the Sand Island Treatment Plant (particularly vulnerable to storm surge due to its coastal location), the Waiʻanae Treatment Plant, and the Kāhala pump station. Storm surge has the potential to damage or break pipelines which could result in significant water service disruptions lasting weeks. Some water facilities may be able to function for a period of days during a power outage with the use of backup generators, but extended power outages will likely result in nonfunctional facilities. A lack of spare parts may extend recovery time (Department of Environmental Services, 2020).
- Once wind speeds reach 50mph, lifeguard towers on beaches are closed and operations are shifted to be more easily mobile (Honolulu Emergency Services Department, 2020).

Confidence: High

Multiple high quality reports provided detailed information pertaining to infrastructure impacts, both projected and based on previous similar past experiences. City departments had a high level of aggreance with these reports and provided additional information.

Environment and Culture: 3

Hurricanes pose a moderate risk to some environmental resources, such as clean water, especially if pipelines fail resulting in hazardous spills. Coastal cultural resources may also be at risk as eroding beaches and changing natural environment disrupt usual practices, such as local fishing, and/or resources, such as ʻiwi. Recovery may take weeks to months or be unrecoverable.

Supporting evidence includes:

- According to an analysis conducted by the project team 1,464 acres of conservation land are within the 500-year severe storm flood hazard zone and are thus vulnerable to flooding as a result of a hurricane event.
- There is potential for multiple types of hazardous spills including fuel, industrial and sewage waste, household chemicals, among others. These contaminants may spill into land or marine environments on Oʻahu, causing damage to the natural environment.

Additionally, storm debris and material cleanup may result in a loss of landfill capacity (DEM, 2019).
    - A significant hurricane may damage ocean outfall pipes that release treated effluent into the deep ocean. There are four outfalls on O‘ahu which were recently assessed for damage potential. ENV determined that the Sand Island outfall requires further shoreline protection, which is now underway (Department of Environmental Services, 2020).
- Landfills may be unable to handle intense rainfall, resulting in hazardous untreated water and waste spills into public areas such as local beaches. Additionally, landfills may be forced to closed as a result of these events, hampering ability to process waste (Pacific Islands Regional Climate Assessment, 2016).
- Managing debris may be challenging after large scale destruction caused by a severe storm. Legislation was recently passed which limits the expansion of current landfills and creation of new landfills, potentially limiting areas to keep waste after a disaster (Department of Planning and Permitting, 2020).
- Eroding beaches may impact local fishing and cultural practices as well as diminish portions of Hawaiian Home Lands (HI-EMA, 2018). Significant beach restoration efforts may be needed to recover from a hurricane (Personal communication, 2020).
- Historical and cultural resources near the shore may be vulnerable to damage or destruction from storm surge inundation, which may deplete communities of important meeting sites or culturally valuable places that require decades to rebuild (HI-EMA, 2018; Personal communication, 2020).
- Fish living in golf course ponds on O‘ahu may be lost due to water overflow resulting from severe storm events. As ponds overflow, fish may swim outside of ponds areas into flooded waters and be unable to return to ponds when water recedes. (Department of Enterprise Services, 2020).

Confidence: Low

Few resources exist which comment on the envrionmental/cultural impacts of a major hurricane specfic to O’ahu. City departments provided little information to supplement reports.

3. “Rain Bomb”

Scenario: Significant rain event with 4 inches of rain/hour

3.1 Summary of Findings

Table 10. Risk assessment summary for “rain bomb”

Likelihood		
Timeframe	**Rating** **1 2 3 4 5**	**Confidence**
Current		Medium
2020-2050		Low
Consequences		
Category	**Rating** **1 2 3 4 5**	**Confidence**
Physical health and safety		Medium
Mental health		Medium
Community cohesion and equity		Low
Economic prosperity		Medium
Infrastructure		High
Environment and culture		Low
Overall Risk		
Current	5.8 (Medium)	Medium
2050	8.7 (Medium)	Low

As demonstrated by past events, a “rain bomb” featuring 4 inches of rain per hour can cause damage to transportation infrastructure, power outages, disruption to local agriculture operations and small business, with high overall consequences to economic prosperity and the infrastructure. Since “rain bombs” are usually localized events, the severity of impacts would be influenced by the specific location where the “rain bomb” event occurs and vary by population density and variation in land use. The areas most likely to receive precipitation during the wet season are illustrated in Figure 9, however, significant rain events can physically happen in any location (Pacific Islands Regional Climate Assessment, 2016).

Overall, a “rain bomb” event is a **medium** risk, both currently and in the future. Table 10 summarizes the risk assessment results for this hazard and Figure 8 shows the overall current and 2050 risk ratings on a risk matrix. While the below ratings assume a single event, compounding impacts of multiple “rain bombs” in one season, a prolonged wet period/series of rain events (Nash, Rydell, & Kodama, 2006) and saturated soils prior to a “rain bomb,” or a “rain bomb” during extreme high tide events, while unlikely, would increase consequences further, especially in the economy, environment, and infrastructure categories.

3.2 Risk Assessment Evidence Base

3.2.1 Likelihood

Historically O‘ahu has experienced 0-2 days annually of 99th percentile rain events, which is defined as 4+ inches of rainfall **over a 24-hour period**. Most occurrences of extreme heavy precipitation have been isolated to the eastern part of the island (Chu & Grubbs, 2009), which is consistent with where Figure 9 denotes the greatest change in precipitation. Occurrences of 4+ inches of rain in **one hour** have been reported at least four times on O‘ahu since 1974 (National Weather Service, 2020). According to the Fourth National Climate Assessment Hawai‘i has experienced increasing trends in extreme 30-day rainfall and the lengths of consecutive dry and wet days (USGCRP, 2018). Additionally, O‘ahu and Kaua‘i recently experienced a “rain bomb” event in April of 2018. The present-day likelihood rating for a “rain bomb” scenario on O‘ahu is **2.**

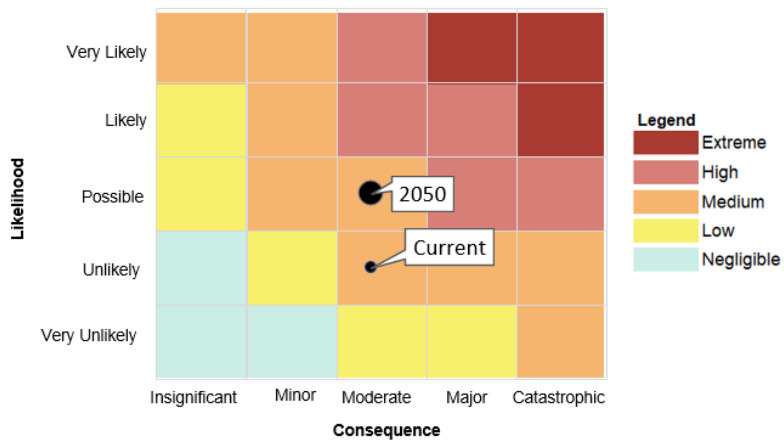

Figure 8. Risk matrix for "rain bomb."

Models show that 99th percentile extreme precipitation events are expected to become more common (Norton, Pao-Shin, & Schroeder, 2011), although little literature exists that predicts future frequency of events as intense as 4 inches of rain in one hour. However, because of warming ocean temperatures and an expected increase of El Niño and La Niña events, which bring more intense rains (Climate Change Commission, 2018a), “rain bomb” events can be expected to marginally increase in frequency by 2050. As such, the future likelihood rating is a **3.**

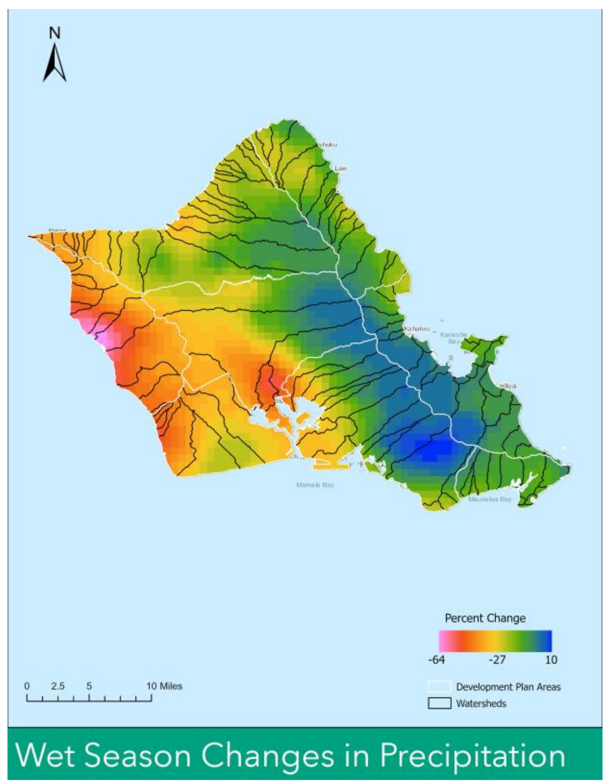

Figure 9. Map illustrating projected change in precipitation during the wet season.

Confidence (Current): Low

Determining historic hourly rainfall intensity on O’ahu is challenging as no readily available resources with this data exist. The current rating is based upon targeted searches for precipitation caused flood events on the island. It is posible an event was missed.

Confidence (2020-2050): Low

As literature and modeling that predict future likelihood of extreme intensity rainfall events of 4+ inches of rain over one hour are not available, the future rating relies on expected increases in 99th percentile rain events and literature that indicates the drivers of heavy precipitation events (such as El Niño and La Niña events) are increasing in frequency.

3.2.2 Consequences

The most severe potential consequences from a "rain bomb" event are to physical safety, infrastructure, and economic prosperity on Oʻahu. Those living in communities with higher potential to be isolated are most vulnerable.

Details on each individual consequence rating are provided below.

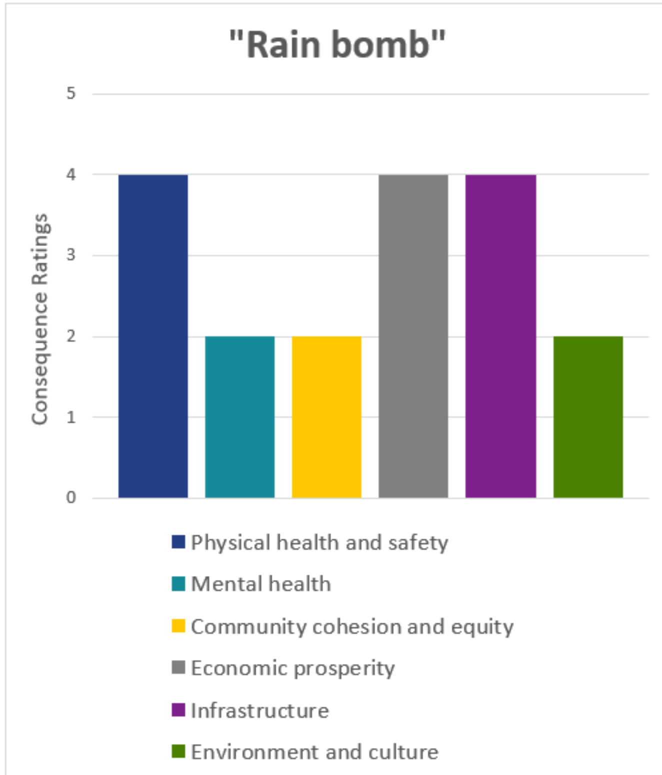

Figure 10. Consequence ratings for "rain bomb."

Population: Average score of 2.7

Physical health and safety: 4

A "rain bomb" event has the potential to cause disruption to health care services and injury. Potential impacts include disruption of access to health services, increased risk of temporary food insecurity, and disruptions to safe public water resources. Storms occurring in areas of high population density areas have greater potential to cause physical health and safety disruptions than those in more rural areas.

Supporting evidence includes:

- Roads have the potential to be flooded quickly which presents danger to the traveling public and may disrupt connections to isolated communities, especially if the supply chain of lifeline resources is disrupted (HI-EMA, 2018).
    - Oʻahu is at particular risk for transportation disruption as many communities are linked by a single roadway where there is potential for a severe storm event to cause damage to or cutoff the roadway (Honolulu Office of Climate Change, Sustainability and Resiliency, 2019).
- Because "rain bomb" events may be difficult to predict in both when and where they occur, health impacts and recovery may be uneven across the island (DEM, 2019).
- Floodwaters and runoff may result in mold and mildew growth, carbon monoxide poisoning, and, if contaminated, an increase in the potential for disease (Department of Environmental Services, 2020; HI-EMA, 2018).
    - For example, after flooding in Kaʻaʻawa, flooded roadways were cleared of floodwaters and pumped into nearby streams, thereby posing a public safety risk (Department of Environmental Services, 2020).

- Landfills may be unable to manage intense rainfall, resulting in hazardous untreated water and waste spills into public areas such as local beaches, posing public health risks (Pacific Islands Regional Climate Assessment, 2016).
- During a heavy precipitation event it is possible that energy utilities will be disrupted. Power lines may be badly damaged or destroyed from landslides or fastmoving water, resulting in loss of power from days to weeks, depending upon severity of the storm. Power outages may pose public health risks as water treatment and sewage facilities require electricity to run (HI-EMA, 2018).
    - Power outages may worsen health impacts of “rain bombs” by resulting in more limited access to health care, loss of light, increased potential for carbon monoxide poisoning, and decreased levels of food security (Klinger, Landeg, & Murray, 2014). The health of those who reside in climate-controlled environments may be particularly vulnerable to power outages in the wake of a disaster.
- Health care disruption and high risk of physical injury may occur weeks after the “rain bomb” event itself as power outages and other damaged infrastructure may be in a state of disrepair well after the event (Personal communication, 2020).
- Depending upon where rain bombs occur, communities may be isolated from health services for several weeks, as realized in the wake of the 2018 “rain bomb” impacting Kauaʻi (Personal communication, 2020).

Confidence: Medium

Multiple City departments and 1-2 external sources described similar risks based on impacts experienced so far. City departments reinforced some risks presented in reports.

Mental health: 2

“Rain bomb” events have the potential to cause localized impacts such as higher stress levels and less access to public relaxation areas. More severe impacts are likely to be witnessed for vulnerable populations and those who experienced damages to personal property.

Supporting evidence includes:

- Key risk factors that may increase mental health vulnerability to disasters include age, low socioeconomic status, minority ethnic status, previous mental health issues, and level of social support (Goldmann & Galea, 2014).
    - On Oʻahu, the populations most vulnerable to mental health issues as a result of flooding are those who are single, male, have previous mental health issues, or suffer from addiction (Office of Housing, 2020).
- Mental health issues commonly reported after heavy precipitation-related flooding events include behavioral problems in children; increased substance use and/or misuse; increased domestic violence; as well as exacerbating, precipitating or provoking people’s existing problems with their mental health. Economic problems resulting from flooding may cause additional mental health stress. Severity of the flooding event and level of exposure to the event are major factors that influence the severity of mental health issues realized as a result of the event (Stanke, et al., 2012).
- Flooding can be very stressful for residents. This stress may continue for significant periods of time after the water has receded (Stanke, et al., 2012).

- The Honolulu Crisis Intervention Team may be able to provide mental health assistance in times of need, although mental health training is currently suspended due to the coronavirus pandemic (Office of Housing, 2020).
- If parks are severely damaged and closed as a result of flooding there may be prolonged inability to use public spaces to relax, which may cause mental health disruption. This has been demonstrated through the various coronavirus closures. Public parks may also be closed for recreation purposes if those spaces are required to serve as locations for supply pickups and as holding areas in the wake of a disaster (Department of Parks and Recreation, 2020).
    - Facility reopening would be dependent upon the ability of the staff to maintain the area. For example, if comfort stations are nonfunctional, it may impact the decision to reopen a park. (Department of Parks and Recreation, 2020).

Confidence: Medium

Multiple City departments described similar or related risks. External sources, including literature reviews related to disasters and mental health impacts were also drawn from.

Community cohesion and equity: 2

A “rain bomb” event on Oʻahu is likely to cause localized impacts to community cohesion and equity, with consequences becoming more severe if the event occurs in a densely populated area. Consequences include loss of sense of place and inability to reach place of employment.

Supporting evidence includes:

- The homeless population may be particularly vulnerable to a loss of sense of community cohesion as a result of flooding. Homeless individuals may be more likely to experience loss of their belongings or loss of shelter (Office of Housing, 2020).
- A “rain bomb” event may result in disruption to transportation services and other business interruption losses, which may hinder resident’s ability to reach their workplace, school, or otherwise disrupt daily routine thereby negatively affecting community cohesion (Department of Transportation Services, 2020; HI-EMA, 2018).

Confidence: Low

Few resources exist which comment on the community cohesion and equity impacts of a “rain bomb” event specfic to O’ahu. City departments provided little information to supplement reports.

Economy: Average score of 4

Hazard: Rain Bomb

"Rain bombs" can cause both physical damages from flooding as well as loss of function damages from closed transportation infrastructure. Economic impacts can be estimated using historic events:

Historic 24-hour Rain Event: >49 In.

Between April 13 – 15 2018, an historic flash flood occurred over Kaua'i. 49 inches of rain fell in one 24-hour period, setting a new record for the United States. The "rain bomb" damaged or destroyed 532 homes, flooded business and vehicles, downed trees and power lines, and closed roadways and highways. The damage costs included $35M to highways and roads, $20M to public property, and $125M in flood-recovery efforts.

Landfill Flooding:

The storm drainage system and retention ponds at the PVT Land Company landfill in Nanakuli were upgraded to mitigate risks of a projected strong La Niña in 2010. When intense rain fell on the region in January 2011, the landfill recovered quickly, while other nearby landfills released hazardous materials and needed to close. PVT estimated they saved at least $1 Million from the upgrades, demonstrating the benefit of climate risk mitigation investments.

Landslides: Pali Highway Closure

"Rain bombs" can also cause damages through landslides. For example, overnight rain caused a mudslide on February 18, 2019 following heavy rains. The heavy rains resulted in landslides, mudslide, and rockfall which closed the Pali Highway. Repairs to the tunnel and attenuator system and to stabilize the slope cost over $20 million alone.

Damages extend beyond the repair costs, however, as the loss of function of the highway yields extra costs for travelers in terms of wait times. One way to estimate these costs is to assess the per person wait time (conservative estimate: 5 minutes) for the full length of the closure (260 days) and the average annual daily traffic. These costs can be monetized using the value of travel time from the Department of Transportation. Using conservative assumptions, the Pali Highway loss of function can be estimated to range from $10–26M.

Factoring in these non-physical loss of function costs can more than double the total impacts of the damages and represents a real threat to transportation systems as these events happen with more frequency.

Sources: Dingeman, 2019; DOT, 2015; EPA, 2017; EPA, 2018; Hawai'i Aloha Travel, 2019; HDOT, N.d.; State of Hawaii, 2019; NWS and NOAA, 2018; Keener et al., 2012.

Economic prosperity: 4

A "rain bomb" event has potential to cause significant impact to O'ahu's economy. Especially vulnerable are pre-Flood Insurance Rate Map (FIRM) structures, small businesses, agriculture, and the transportation industry, which may face severe impacts (occasionally permanent in extreme instances). Based on past events, total damages to the economy from flooding event may exceed $30 million.

Differential Impacts

Kalo and the cultivation of other traditional Hawaiian crops are at high risk of damage from heavy precipitation events. Agriculture farms have permanently closed as a result of heavy precipitation events in the past.

Supporting evidence includes:

- In 2008, severe flooding occurred (below the intensity required to be considered a "rain bomb" event) that damaged 4 dozen buildings and resulted in a FEMA disaster declaration that provided $1.1M in grant and loan assistance. This type of federal assistance may help ease the impacts of a "rain bomb" event.

- Agriculture and especially small farms are at particular risk. Localized flooding may destroy crops, and extended periods of flooding may result in long periods of waiting for resources to dry, resulting in reduced yields and further financial impact (Office of Economic Development, 2020).
    - Traditional farmers, such as kalo growers may be at particular risk since vulnerability is higher since the huli in a loʻi may be lost during a storm versus seeds that may survive underground. Nalo Farms in Waimānalo suffered damage from four heavy localized precipitation events resulting in the permanent closure of the farm. Difficulty to leverage crop insurance may have also contributed to the closure. (Office of Economic Development, 2020).
- Historic severe storm events on Oʻahu have led to millions of dollars in damages as a result of flooding, landslides, damage to stream drainage channels, boulder basins, and homes.
    - The New Year's Day flooding in 1988 led to $35 million dollars in damage to homes and infrastructure (DEM, 2019).
    - The April 2018 "rain bomb" caused flooding, mudslides, and rockslides that led to 410 properties and 104 residential structures damaged. Total costs exceed $20 million dollars for public property and infrastructure alone (DEM, 2019).
    - In 2004 a "rain bomb" in the Mānoa valley flooded large portions of the University of Hawaiʻi as well as Noelani Elementary School and other Mānoa residences. (DEM, 2019).
- Nonfunctional roads can have major implications for those who require transport to get to their places of employment or other daily activities. This is especially pertinent for workplaces that have limited access roads and therefore limited detour options (DEM, 2019).
- Small businesses are likely to be less resilient after a flooding event as many lack generators and recovery or continuity plans (Department of Emergency Management, 2020).
- Recovery resources may be more readily available in the wake of a "rain bomb" event than in a disaster event such as a hurricane because impacts are generally localized.
- "Rain bomb" impacts are relatively localized; depending on the location of a "rain bomb", its impacts could range from moderate to catastrophic. If a "rain bomb" hits Mānoa and Waikīkī, impacts could be on the scale of a hurricane hit. But, in other areas of the island the impacts would likely be damaging but not catastrophic for the island as a whole. For example, the "rain bomb" event in April 2018 mostly impacted residential properties (which can be catastrophic for an individual, household, or neighborhood), but had a catastrophic impact to the small agricultural sector in Waimānalo, where some farms went out of business. And a "rain bomb" event in the late 1980s in East Honolulu had significant localized cleanup and infrastructure rebuilding costs (e.g., damaged drainage channels) while infrastructure 10 or 15 miles away was relatively unscathed (Personal communication, 2020).

Confidence: Medium

Reports provided estimates of previous damages from "rain bomb" events. Multiple City departments provided anectodotal support of information presented in reports as well as unique information. Most departments provided information that was distinct from other departments.

Infrastructure: 4

Infrastructure on O‘ahu is fairly vulnerable to “rain bomb” impacts. Areas of potential major impact include water and energy utilities and transportation infrastructure.

Supporting evidence includes:

- During a heavy precipitation event it is possible that energy utilities will be disrupted. Power lines may be badly damaged or destroyed from landslides or fastmoving water, resulting in loss of power from days to weeks, depending upon severity of the stor m. This can have cascading effects across island infrastructure as water pumps require electricity to run (HI-EMA, 2018).
  - The account-based revenue collection system on buses and rail systems require power in order to function, so disruption to energy utilities may impact the ability of transportation services to run and collect revenue. Data warehouses that store transportation data are at particular risk of losing power during a “rain bomb” event (Department of Transportation Services, 2020).
  - Some water facilities may be able to function for a few days during a power outage with the use of backup generators, but extended power outages will likely result in nonfunctional facilities.
- Storm drains may be clogged with debris and require cleaning. Stormwater and wastewater lines are at risk of breaking due to substantial flow, inflow and infiltration, and large debris. An obstructed drainage system and a lack of spare parts may extend recovery time (Department of Environmental Services, 2020; Department of Emergency Management, 2020).
- Honolulu’s transportation infrastructure is vulnerable to impacts from flooding.
  - In many cases a flood could sever roadways and cut off communities due to a lack of detour options (Honolulu Office of Climate Change, Sustainability and Resiliency, 2019).
  - O‘ahu’s attempted transition to electric buses may be stifled by a heavy precipitation event as power outages greater than 1-2 days may limit the ability to charge them (Department of Transportation Services, 2020; Department of Facility Maintenance, 2020).
  - In the past, “rain bomb” events on O‘ahu have caused extensive transportation damage including street flooding, damage to stream flood mitigation channels, washed out roads and bridge damage. Consequences may be more severe than a tropical storm or hurricane due to lack of warning. (DEM, 2019; Department of Emergency Management, 2020).
  - Heavy precipitation events increase the likelihood for landslide events, which can damage roadways. 66 highways sites were identified as having high risk of rockfall. Bridges near Honolulu have also been damaged by landslide events in the past (HI-EMA, 2018).

Confidence: High

Multiple high quality reports provided detailed information pertaining to infrastructure impacts, based on similar heavy prcipitation experiences. City departments had a high level of aggreance with these reports and provided additional information.

Environment and Culture: 2

Some environmental resources, such as water quality, may be impacted by a “rain bomb” event. Cultural resources face little or unknown risk.

Supporting evidence includes:

- A “rain bomb” event has the potential to cause multiple types of hazardous spills including fuel, industrial and sewage waste, household chemicals, among others. These contaminants may spill into land or marine environments on Oʻahu, causing damage to the natural environment. Additionally, storm debris and material cleanup may result in loss of landfill capacity which may exacerbate contamination issues (DEM, 2019).
- Managing waste may be challenging after demolition caused by a landslide, rockslides, flooding, etc. Legislation was recently passed which limits expansion of current landfills and creation of new landfills, potentially limiting areas to keep waste after a disaster (Department of Planning and Permitting, 2020).
- Landfills may be unable to handle intense rainfall, resulting in hazardous untreated water and waste spills into the environment, such as local beaches (Pacific Islands Regional Climate Assessment, 2016).
- Fish living in golf course ponds on Oʻahu may be lost due to water overflow resulting from heavy precipitation events. As ponds overflow, fish may swim outside of ponds areas into flooded waters and be unable to return to ponds when water recedes. (Department of Enterprise Services, 2020).
- Streams may be blocked due to landslides or other felling or conveyance of debris during heavy precipitation events resulting in environmental disruption. This occurred in the 2004 Mānoa “rain bomb” (DEM, 2019)

Confidence: Low

Few resources exist which comment on the envrionmental/cultlrual impacts of a “rain bomb” event specfic to O’ahu. City departments had little information to supplement reports.

4. Sea Level Rise (SLR) and Coastal Erosion

SCENARIO: SEA LEVEL RISE AND ASSOCIATED COASTAL EROSION ON A TRAJECTORY TO 3.2 FEET BY 2100 WITH IMPACTS DUE TO HIGH TIDES AND/OR COASTAL HAZARD EVENTS DECADES IN ADVANCE

4.1 Summary of Findings

Table 11. Risk assessment summary for sea level rise and coastal erosion

Likelihood		
Timeframe	**Rating** **1 2 3 4 5**	**Confidence**
Current		High
2020-2050		High
Consequences		
Category	**Rating** **1 2 3 4 5**	**Confidence**
Physical health and safety		High
Mental health		Medium
Community cohesion and equity		Medium
Economic prosperity		Medium
Infrastructure		High
Environment and culture		Medium
Overall Risk		
Current	9.3 (Medium)	High
2050	14.0 (High)	High

This scenario focuses on 3.2 feet of global sea level rise and associated increases in coastal erosion. The Intergovernmental Panel on Climate Change and the Hawai‘i Climate Change Mitigation and Adaptation Commission established 3.2’ of SLR as a key risk threshold for exposure and planning purposes. 3.2’ of SLR is the upper end projection for 2100 under the RCP 8.5 scenario (Hawai‘i Climate Commission, 2017; Climate Change Commission, 2018a).

3.2’ SLR and accelerated coastal erosion will pose a **high** risk by 2050. Table 11 summarizes the likelihood, consequence, and overall risk ratings. Incremental impacts of these gradual hazards may significantly damage infrastructure and environmental resources, in turn impacting the economy, and force population displacement, with corresponding physical and mental health ramifications.

Infrastructure and natural resources in coastal locations and the low-lying urban center (particularly water and wastewater facilities, and assets and resources the tourism industry is reliant on) will generally be most vulnerable to physical damages and associated economic impacts. Impacts may be greater for communities in coastal and low-lying areas that are most exposed to sea level rise and coastal erosion as well as frontline communities (Climate Change Commission, 2018a; Hawai‘i Climate Commission, 2017).

4.2 Risk Assessment Evidence Base

4.2.1 Likelihood

The present-day likelihood rating for the sea level rise and coastal erosion scenario is **2** and the 2050 rating is **3**.

As shown in Figure 12, increasing levels of SLR are projected to occur over time. Further, 70% of sandy beaches on Kaua'i, O'ahu and Maui are eroding, driven in significant part by sea level rise, and erosion impacts are projected to double by mid-century (Hawai'i Climate Commission, 2017).

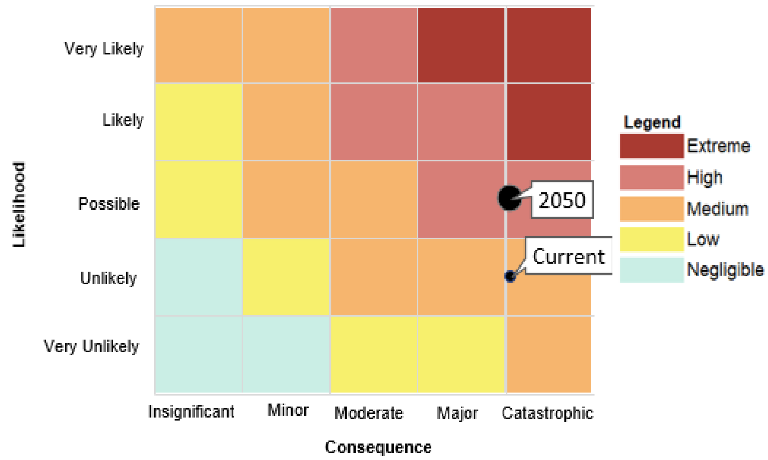

Figure 11. Risk matrix for sea level rise and coastal erosion.

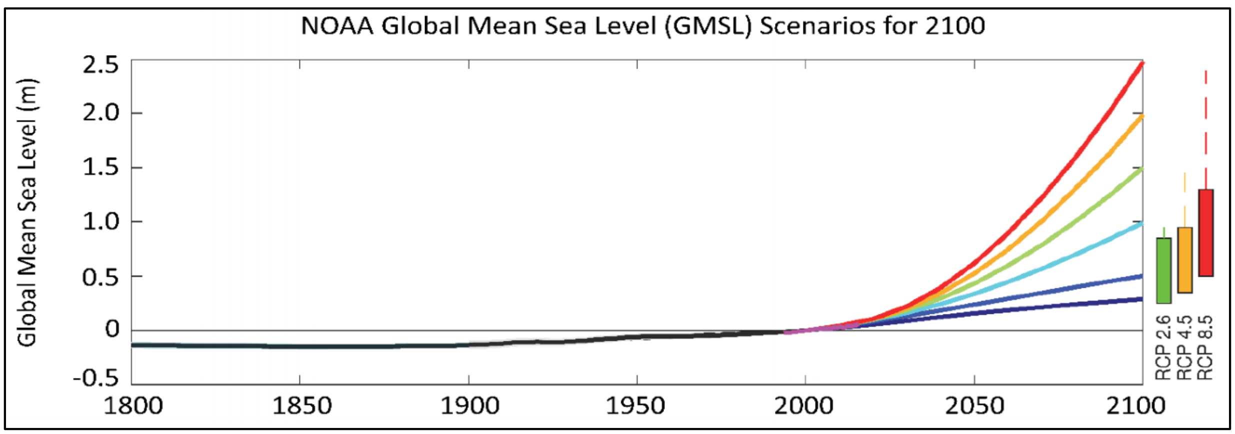

Figure 12. Projected rate of global sea level rise under different GMSL scenarios for 2100. Source: NOAA Global and Regional Sea Level Rise Scenarios for the United States, 2017.

Under RCP 8.5, climate models project that sea levels could rise by as much as 0.6 feet by 2030, 1.1 feet by 2050, and 3.2 feet by 2100 (The Water Research Foundation and BWS, 2019). Notably, estimates of future sea level rise for Hawai'i are approximately twenty to thirty percent higher than global average estimates because of gravitational effects.

Chronic or sunny-day flooding at or near this extent could occur before permanent flooding does (The Water Research Foundation and BWS, 2019). Observed sea level data from the Honolulu tide station indicates waters are already rising, and chronic coastal flooding is already occurring in Hawai'i. Over the last century, sea levels at this location rose approximately 0.50 feet (NOAA, 2020). Additionally, high tide flooding is becoming more frequent and having greater impacts, as captured in the University of Hawai'i Sea Grant College Program Hawai'i and Pacific Islands King Tides Project (Hawai'i Climate Commission, 2017). Models show there could be up to 58 days of minor flooding (20" above MHHW) per year by 2050 and permanent moderate flooding (32" above MHHW) by 2100 (NASA, 2020).

Incremental consequences of gradual SLR and erosion may begin with recurring floods at highest tides, and, depending on a location's elevation, build up to chronic flooding, permanent flooding, and finally land loss (Hawai‘i Climate Commission, 2017).

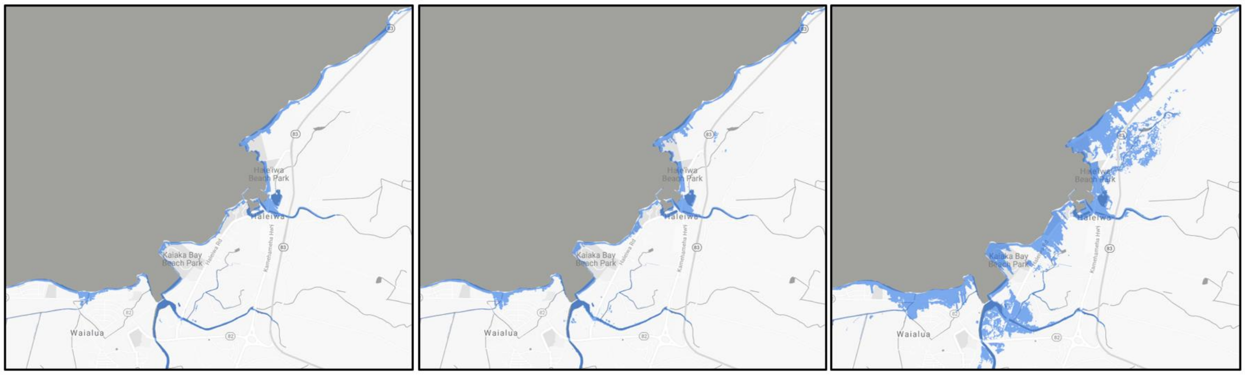

Figure 13. Projected sea level rise and coastal erosion exposure area along the North Shore at Waialua and Hale‘iwa: from left to right, 0.5 feet (2030 estimate), 1.1 feet (2050 estimate), and 3.2 feet (2100 estimate) of sea level rise. Images retrieved from Hawai‘i Sea Level Rise Viewer: www.hawaiisealevelriseviewer.com.

Confidence (Current): High

Many city departments' observations of recent coastal erosion, as well as historical data on sea level rise and associated impacts (e.g., as published by the USGCRP and University of Hawai‘i), indicate an observed increase in sea levels and coastal erosion.

Confidence (2020-2050): High

Sea level rise and coastal erosion analyses conducted by the Intergovernmental Panel on Climate Change (IPCC), U.S. Global Change Research Program (USGCRP), the University of Hawai‘i, City departments, and others provide a rigorous understanding of projections and future risks by mid- and end-of-century.

4.2.2 Consequences

Infrastructure damage and downstream impacts to the industries and livelihoods dependent on them could result in significant economic consequences (particularly for tourism and real estate). There could also be irreparable damage to O‘ahu’s coastal environment and culture. Forced migration due to coastal impacts may have significant consequences for community cohesion and equity. Additionally, physical and mental health risks associated with coastal flooding and forced relocation may be significant, particularly for communities in coastal and low-lying areas that are most exposed to sea level rise and coastal erosion, as well as frontline communities (Climate Change Commission, 2018a; Hawai‘i Climate Commission, 2017).

Details on each individual consequence rating are provided below.

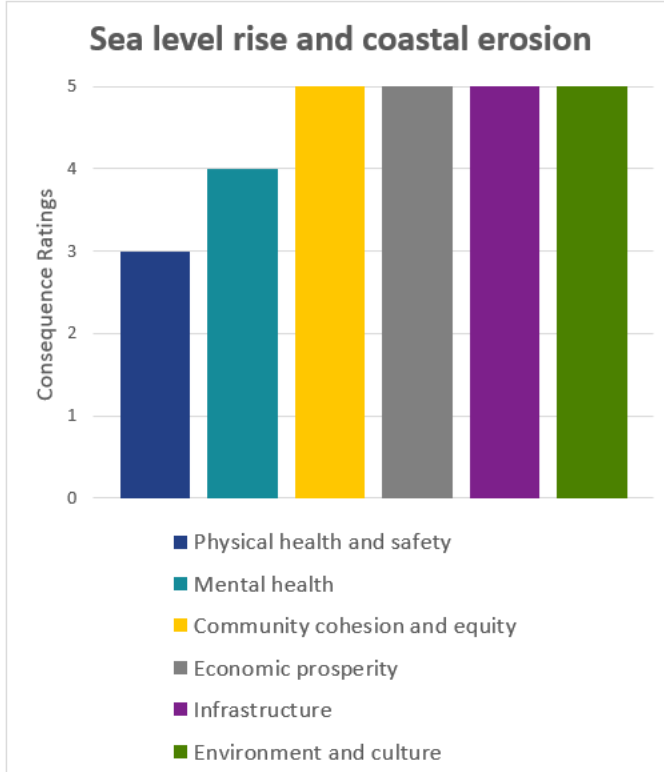

Figure 14. Consequence ratings for sea level rise and coastal erosion.

Population: Average score of 4

Physical health and safety: 3

Permanent and temporary flooding due to SLR could disrupt access to critical services or deliveries (e.g., medicine) if infrastructure is damaged; cause population displacement; and result in loss of public recreation areas that are critical to health and well-being.

Differential Impacts

Coastal, low-lying, and/or frontline communities may be disproportionately vulnerable to physical health risks.

Supporting evidence includes:

- Those living in homes right on the shoreline in areas with significant risks of intense flooding and erosion impacts (e.g., ‘Ewa Beach) or working in businesses in areas with significant groundwater and storm drain backflow flooding impacts (e.g., Māpunapuna) may be subject to health risks ranging from increased mold (e.g., due to chronic flooding) to loss of shelter (e.g., if a home slides into the ocean due to erosion) (HI-EMA, 2018; Hawai‘i Climate Commission, 2017). A key health risk associated with this hazard is that impacts occur gradually over time, leading to a lower perceived urgency than for “shock” events (e.g., hurricane) and less clarity around when or how to respond (Department of Emergency Management, 2020). Without adaptation, sea level rise is projected to displace approximately 13,300 people on Honolulu – a significant number, though <1% of the total population – including people across income levels, and both renters and homeowners (HI-EMA, 2018).

- Damages from erosion of coastal roads could impact public transportation – from temporary re-routing in the short-term to service changes and/or permanent route reconfiguration in the long-term. Disruptions of public transportation could have health implications if those particularly reliant on it (e.g., low-income workers, physically disabled persons) needed to resort to less safe modes of transportation (e.g., walking in extreme heat, or through flooded areas) (Department of Transportation Services, 2020; CCSR, 2020).
- Safety issues at beaches (e.g., unsafe comfort station facilities or beach accessways) related to coastal erosion could force beaches to close; the North Shore and Kāhala are key risk locations (Department of Parks and Recreation, 2020; Department of Design and Construction, 2020; Honolulu Emergency Services Department, 2020). Results of beach closure could include reduced recreation and relaxation, and those most likely to be impacted are those reliant on public areas for those purposes (e.g., low-income population and homeless population) (Department of Parks and Recreation, 2020).
- Loss or delayed receipt of key commodities such as medicine and food could cause a variety of health and safety impacts if erosion or higher sea levels disrupt the supply chain (e.g., closure of the Port of Honolulu) (Department of Emergency Management, 2020).
- Public health issues could arise if utility services (e.g., water, electricity) are disrupted due to sea level rise or coastal erosion impacting public utilities infrastructure located near the coast (University of Hawaiʻi, 2018).
- Greater potential prevalence of water-borne diseases or contaminated water, due to greater risks of impacts to water, wastewater, and sewer facilities and increased likelihood of temporary or chronic flooding in coastal and low-lying locations, may pose physical health and safety risks (Ebi, et al., 2018). Sea level rise could lead to inland flooding if tidal water backs up through the drainage system and spills out onto streets, particularly during king tide events (Department of Facility Maintenance, 2020). Further, public coastal wastewater treatment facilities and private on-site sewage disposal systems at risk of physical damage could pose health and safety risks if floodwaters become contaminated (Department of Parks and Recreation, 2020; Department of Budget and Fiscal Services, 2020; Department of Environmental Services, 2020).

Confidence: High

Multiple City departments and external sources described similar risks, based on both spatial risk analysis and impacts experienced so far.

Mental health: 4

Loss or degradation of ancestral coastal lands and resources, and public recreation spaces and associated economic risks will negatively impact mental health. Acute mental health impacts are expected as sea level rise threatens coastal homes and businesses.

Differential Impacts

Native Hawaiian populations, frontline populations, and individuals living along the coast may experience more severe mental health risks than the general population.

Supporting evidence includes:

- Stress and mental health impacts related to managing household flood damages (e.g., if costs pose a financial challenge) may increase in locations with greater flood risk due to sea level rise (Ebi, et al., 2018).
- Temporary or permanent flooding of park infrastructure could result in closures, which could limit people's ability to use those spaces for outdoor relaxation and/or recreation. These impacts will be felt most by those who rely the most on parks, such as low-income and homeless individuals (Department of Parks and Recreation, 2020).
- Economic impacts due to infrastructure damage or reduced tourism could be detrimental to affected individuals' mental health (e.g., loss of employment or real or perceived job insecurity).
- The projected displacement of over 13,000 residents could have significant mental health implications (Hawaiʻi Climate Commission, 2017; University of Hawaiʻi, 2018). Displacement is known to increase mental stress, affect ability to cope with other challenges, impact access to healthcare and public service, strain community ties and social bonds, and potentially create challenges around employment (Hess, Malilay, & Parkinson, 2008; Jackson & Devadason, 2019; Cianconi, Betrò, & Janiri, 2020; Ebi, et al., 2018).
- Mental health is a particularly critical concern for Native Hawaiian and Polynesian communities that may experience a loss of place, especially if individuals' identities are intrinsically tied to the ancestral places and resources that are projected to become inundated or unsafe (e.g., chronically flooded), or significantly change from traditional uses (CDC, 2020; Office of Housing, 2020).
- Since sea level rise and coastal erosion is not a disaster with designated recovery processes, mental health support may be limited relative to hazards such as hurricanes or "rain bombs" (Personal communication, 2020).

Confidence: Medium

Multiple external sources and departments described similar risks, though many (e.g., related to loss of infrastructure and environmental resources, and human displacement) lack community-based evidence as they have not yet been widely experienced on Oʻahu.

Community cohesion and equity: 5

A large percentage of the population of Oʻahu lives, works, or spends recreational time on the coast; loss of coastal land will impact the entire island community and the collective benefits derived from the coastal areas. Local communities that live, work, and play along the ocean, particularly in low-elevation locations, may be displaced and face severe community cohesion impacts, and communities further from the coast will be affected by the inland migration and/or disruption to travel, recreation, or commercial activities or employment. Native Hawaiian and Polynesian individuals with strong identity ties to the coast may be particularly impacted by the loss of land. And low-income communities, homeless individuals, and populations least represented in community planning may be least prepared for and most severely impacted by forced migration. Equity must be integrated into prioritization and decision-making to ensure that differential impacts and benefits are not overlooked or exacerbated.

Supporting evidence includes:

- Forced movement of people and businesses inland, and damages to culturally valued coastal land and resources such as Waimānalo Beach and the Māpunapuna area, may negatively impact community cohesion (Hawaiʻi Climate Commission, 2017; Office of Housing, 2020). With an estimated 4,000 homes and businesses on the shoreline at risk of inundation under 3.2' SLR, this inland movement and associated impacts are projected to be widespread (Hawaiʻi Climate Commission, 2017).
- Low-lying properties that provide housing to low-income or homeless populations (e.g., Hale Mauliola and Citron Street project) are at significant risk to flooding if they are not elevated (Department of Land Management, 2020; Office of Housing, 2020).
- Public spaces where people gather and recreate together (e.g., beaches, Ala Wai Golf Course, Honolulu Zoo, Waikīkī Shell) could be damaged and temporarily or permanently closed, thus decreasing community cohesion. These impacts will be felt most by people who rely most on public spaces (e.g., low-income population, homeless population, families with children) (Department of Enterprise Services, 2020; Office of Economic Development, 2020; Department of Parks and Recreation, 2020).
- Potential increased flooding risks (e.g., due to breaks in water transmission mains caused by erosion, or more sunny-day flooding caused by sea level rise and king tides) could reduce public confidence in the quality and maintenance of the water and drainage systems (Board of Water Supply, 2020; Department of Facility Maintenance, 2020).
- Those living at or near the poverty line with the least financial flexibility (e.g., ability to pay unexpected expenses) may be most affected by potential increases in water costs due to groundwater rise (Department of Environmental Services, 2020)
- Impacts to roads and other transportation infrastructure, ranging from nuisance flooding to rendering roads impassible, may be particularly detrimental to rural communities as they provide critical access for travel and transportation of goods, services, and support when needed (HI-EMA, 2018; Hawaiʻi Climate Commission, 2017).

Confidence: Medium

Multiple City departments described similar risks, though available detail on specific expected consequences (e.g., impacts to communities from loss of public spaces, or funding challenges associated with a slow-building risk) was limited.

Economy: Average score of 5

Hazard: 3.2' SLR + Erosion (projected to occur by end-of-century)

Statewide impacts may include:

- ~25.8k acres of land becoming "unusable"
- 6,500+ coastal structures "compromised or lost"
- Over $19 Billion in associated costs state-wide, with **Honolulu as a hotspot**, projected to experience over 66% of that loss (~$12.9B).

Projected impacts to O'ahu[1]

- **$12.9 Billion in economic costs** due to structure and land loss
- 3,880 structures flooded
- 9,400 acres of flooded land
- 17.7 miles of major road flooded with 3.2' SLR (5.5 miles with 1.1' SLR), including sections of Kamehameha Highway

Cost-benefit analyses of SLR adaptation & mitigation options for coastal highways[2] identified optimal measures at mileposts (MP) along approximately **62 miles of O'ahu coastal highways** (approx. 31 miles of State Route 83 along the North Shore and East Shore, MP 2–10 and 17–38; approx. 14 miles of State Route 72 along East O'ahu, MP 4–17; approx. 17 miles of State Route 93 along the Wai'anae Coast, MP 3–19).

The analyses found **optimal measures vary by location** and have a **wide range of costs**. Visual impacts also vary; more aesthetically pleasing measures may be preferred for beach locations if possible. MP locations were given different recommendations between the five categories of relocate (R), protect (P) Accommodate (A), monitor, no action (M) and a combination (C) of R, P and A.

3 combination categories: "Hard protection/Elevated road (H-E); Hard/Soft protection (H-SD); and Relocate/Add green space (R-G)."

Measure	Detail on Measure	Cost (USD/LF)
Road relocation – to new road	"Relocate is to move away from the water. Green spaces or wetlands can be restored to establish or maintain freshwater buffer areas. The road is also protected against long-term climate change impacts (e.g., sea level rise). However, obtaining development rights, where the land is privately owned, can be an issue."	$70,000
No Action / Monitor	Either "leave the road alone" or "monitor periodically" – this measure is used when there is "no road susceptibility and little to no ocean hazard"	$0
Combination – hard / soft protection	"Hard protection includes alternatives: hard protection–revetment/seawall (P-H) and combination-hard/soft protection (C-H-SD). Costs range greatly and are higher than soft protection but offer a more stable solution during high wave events. Alternative C-H-SD is recommended for popular beach areas for aesthetic purposes and when hardened protection is needed from high wave events."	$5,000
Combination – hard protection / elevate road	"Elevate includes alternatives: elevate road (A-E) and combination-hard protection/elevated road (C-H-E). The costs are high for these alternatives, given the cost and availability of gravel for building a pad. Both AE and C-H-E present the next best alternatives to mitigate against SLR and storm surge, if relocation cannot be done, where C-H-E is most often used in SLR and storm surge inundation areas."	$12,000

Sources: 1. Hawai'i Sea Level Rise Vulnerability and Adaptation Report, 2017. 2. State of Hawai'i Statewide Coastal Highway Program Report, 2019.

Economic prosperity: 5

The tourism and international investment industries that rely on the "untouched image of Hawai'i" would be negatively impacted by SLR and erosion damages to beaches and economically and culturally central locations.

Supporting evidence includes:

- Economic impacts of flooding may be disproportionately high in O‘ahu’s coastal and low-elevation urban center (Hawai‘i Climate Commission, 2017). Unlike a storm or rain bomb event, sea level rise impacts will be felt everywhere – in Hale‘iwa, Kualoa, Waikīkī, and the Harbor, to name a few – and will cause cumulative impacts (Personal communication, 2020). Different estimates find that impacts to property and buildings could generate costs of $7.3B (University of Hawai‘i, 2018), or $12.9B solely related to loss of structures and land (DEM, 2019). And, though not calculated, the relative economic impacts of damages to critical infrastructure, utilities and roads (University of Hawai‘i, 2018), as well as home value impacts, city revenue impacts, and cleanup costs when infrastructure falls into the ocean, may be much greater (Personal communication, 2020). Additionally, limited access to economic hubs due to flooding could be particularly detrimental to those who work there (University of Hawai‘i, 2018).
- Risks of direct and downstream impacts on the tourism industry may include:
  - Physical damages to locations key to the “image of Hawai‘i” that draws international tourism, film industry revenue and other investments. Impacts to the North Shore and Waikīkī (both the urban centers and the beaches), Chinatown, Wai‘anae, Waimānalo, and Kualoa Beach Park and Ranch are all of concern for this reason (Office of Economic Development, 2020).
  - Surfing competitions bring significant tourism to the island. Increased coastal erosion is already impacting these events (e.g., at the World Surf League Triple Crown, erosion impacted staging and watch locations and caused safety concerns, and seawalls affected wave breaks) (Office of Economic Development, 2020).
  - Flooding impacts on buildings (e.g., hotels) and public transportation used by visitors may reduce tourism revenue (Hawai‘i Climate Commission, 2017).
  - Individuals whose employment depends on the tourism industry, and large manufacturers dependent on tourism revenue (e.g., food manufacturers such as Hawai‘i Chip Co., Honolulu Cookie Company) are vulnerable to industry impacts (Office of Economic Development, 2020). Notably, impacts to the O‘ahu economy may also extend to other islands (Hawai‘i Climate Commission, 2017).
- ‘Ewa Beach and Pearl Harbor are both sites of concern for sea level rise and erosion impacts due to their use by the military, a significant component of the economy (Office of Economic Development, 2020).
- Particularly at-risk regions for economic impacts associated with flooding include Ala Moana, Waikīkī, Daniel K. Inouye International Airport, Joint Base Pearl Harbor-Hickam, the Pearl Harbor Historic Trail and adjacent areas, Māpunapuna, downtown Honolulu, Honolulu Harbor, Kaka‘ako makai, and makai portions of McCully-Mō‘ili‘ili (DEM, 2019).
- Real estate – traditionally a strong sector – could be impacted by SLR and erosion (University of Hawai‘i, 2018), especially without proper planning. This is particularly significant because homes are many peoples’ largest assets (Office of Economic Development, 2020).

Confidence: Medium

Detailed information on expected impacts was provided by many City departments, though the particular details provided by each varied and thus did not provide a high degree of agreement.

Infrastructure: 5

Significant infrastructure damages are already occurring, with increasing near-term risks to critical facilities (e.g., transportation and water and wastewater assets), key tourism infrastructure, and neighborhood roads and homes absent adaptation. Critical infrastructure on the coast and in low-lying areas will be at increasing risk to damages going forward (HI-EMA, 2018).

Supporting evidence includes:

- Infrastructure may be impacted by sea level rise hazards including direct marine inundation, wave flooding, groundwater inundation, and storm-drain backflow, as well as coastal erosion hazards (Habel, Fletcher, Anderson, & Thompson, 2020; Board of Water Supply, 2020).
- Locations where infrastructure may be particularly at risk to flooding include Ala Moana, Waikīkī, Daniel K. Inouye International Airport, Joint Base Pearl Harbor-Hickam, the Pearl Harbor Historic Trail and adjacent areas, Māpunapuna, downtown Honolulu, Honolulu Harbor, Kaka‘ako Makai, and Makai portions of McCully-Mō‘ili‘ili (University of Hawai‘i, 2018), as well as the Ala Wai Golf Course, the Honolulu Zoo, and the Waikīkī Shell (Department of Enterprise Services, 2020). Waikīkī and Māpunapuna, for example, are already seeing sea level rise impacts to drainage (Personal communication, 2020).

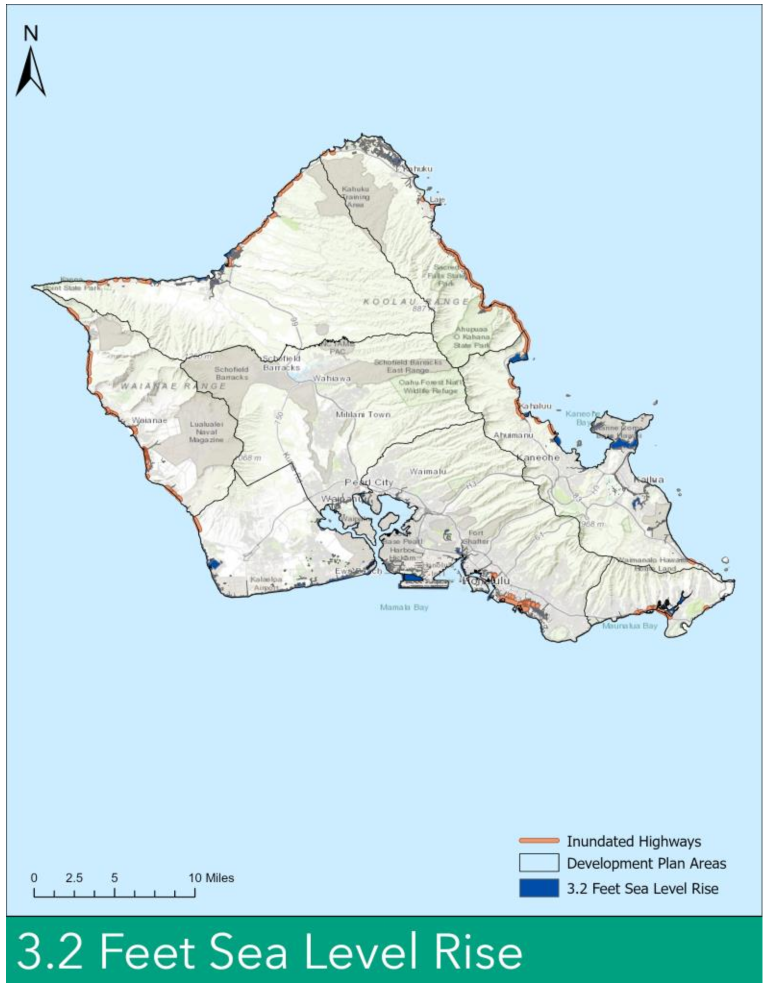

Figure 15: Exposure of coastal highways to 3.2 feet of sea level rise.

- Impacts of erosion on transportation infrastructure, particularly along the coast and in low-elevation regions, could be significant (Office of Housing, 2020; Office of Economic Development, 2020). Figure 15 displays in orange the major roadways that would be inundated when sea levels rise 3.2 feet and no adaptation actions are taken.
    - Coastal highways worth billions of dollars, as well as nearby infrastructure such as sewer lines, water lines, and utilities, may be impacted by flooding and erosion (DEM, 2019; University of Hawaiʻi, 2018). Coastal locations with infrastructure already experiencing erosion impacts include the windward coast (e.g., transmission main breaks along Kamehameha Highway), the leeward coast (e.g., outfall at Waiʻanae and lines to Waiʻanae), and the North Shore; these impacts are likely to continue or get worse in the future (Board of Water Supply, 2020; Department of Environmental Services, 2020; Department of Emergency Management, 2020; Department of Design and Construction, 2020; Department of Parks and Recreation, 2020).
    - Erosion along coastal roads will affect the City's ability to safely continue bus service along existing routes that use those roads (Department of Transportation Services, 2020).
    - Loss of access to major infrastructure or roads that serve as single access points to rural locations could limit the provision of City services (HI-EMA, 2018; Department of Environmental Services, 2020). 17.7 miles of major roads on Oʻahu are projected to be flooded by 3.2' SLR (Hawaiʻi Climate Commission, 2017).
    - This hazard will probably have the largest impact on State roads (though it will affect City roads as well) and the utility infrastructure below them; loss of power or access to highways could disrupt the City's ability to operate or provide services (Personal communication, 2020).

- Some areas already experience sunny-day flooding, especially during king tide events. When this occurs, tidal-driven water backs up through the drainage system onto streets and groundwater rises and breaches the land surface. In particular, simultaneous high tide and rainfall events are of key concern because water cannot drain (could last 2-8 hrs depending on severity or rain event and tide height) (Department of Facility Maintenance, 2020).
- Repaving to manage potholing and other impacts from SLR/erosion is already underway (Department of Design and Construction, 2020).

- Spatial analysis indicates that with 3.2' SLR, 7,749 buildings will be exposed, 68.98 miles of roadway exposed, 116 bridges exposed, and 4,613 acres of urban land exposed; no dams, police stations, or hospitals are projected to be exposed. However, anecdotal and observational evidence has indicated some impacts to police station infrastructure.
- Coastal comfort stations and on-site sewage disposal systems are already beginning to see impacts. Several comfort stations have the potential to be completely lost. Costs of moving or raising comfort stations will vary ($800,000 estimate). Impacts to comfort stations or other facilities key to health and safety could force the closure of parks. Sea level rise may pose a particular risk to parks on the windward side of the island (Department of Facility Maintenance, 2020; Department of Parks and Recreation, 2020).
- SLR could compromise coastal waste management facilities that are around ground level (e.g., septic tanks, wastewater and sewage treatment and disposal systems, storage and disposal sites for hazardous materials and waste), which could disrupt the systems and potentially release their contents into nearby waters and habitats (Department of Design and Construction, 2020; Department of Parks and Recreation, 2020; Department of Environmental Services, 2020; HI-EMA, 2018).
- Water and wastewater systems infrastructure may be degraded by corrosion and become slowly inundated and experience greater pressure and infiltration flows due to rising groundwater levels.
  - Increased marine inundation and groundwater inundation due to sea level rise could increase underground saltwater. This may corrode metal pipes and lead to metal water or sewer main breaks; BWS will be replacing pipes with plastic but a complete shift to plastic will likely take five or six decades. Repairing pipes is a challenge already because minimizing localized flooding requires waiting for low tides, and with higher sea levels, repairs could take longer (Board of Water Supply, 2020). Higher saltwater levels could also increase saltwater intrusion into the storm drain system, which could accelerate degradation of system infrastructure (e.g., pipes and catch basins) (Department of Facility Maintenance, 2020).
  - Groundwater table rise will slowly inundate below-grade infrastructure over time (Habel S. L., 2019). It may also increase the flow of infiltration into the sewers, introduce greater pressure on the outside of pipes, and affect infrastructure including storm-drain systems, roadways, waste disposal systems, and vented utility corridors (Department of Environmental Services, 2020; Habel S. L., 2019). Additionally, greater pressure will require greater pumping to get treated wastewater out at the ocean outfalls, increasing cost and energy usage (Department of Environmental Services, 2020).
- Beach infrastructure is at risk from SLR and erosion. HESD, supported by DPR and DFM have had to to relocate existing lifeguard stations (e.g., needed to 7 times at Kailua

Beach). For 22 lifeguard stations that were placed on concrete pads which have been undermined, the towers were moved and the concrete disassembled. Additionally, a Kualoa bath house notably fell into the ocean as a result of erosion and sea level rise (Honolulu Emergency Services Department, 2020).

Confidence: High

There is widespread agreement among City departments, outside literature, and exposure maps about consequences already being experienced and priority future risks.

Environment and Culture: 5

The coastal environment – from popular beaches and parks to various habitats, ecosystems, and natural resources (e.g., aquifer) – is likely to experience greater flooding and to some extent irreparable damage due to sea level rise and coastal erosion. Coastal communities will be disproportionately impacted by loss of coastal land and increased risks of living, working, and spending time by the oceans.

Supporting evidence includes:

- These hazards are already impacting customary and traditional practices such as salt cultivation, fishpond maintenance, and gathering from fisheries near the coast – for example, since 2014, sea level rise and flooding have been limiting access to land traditionally used for cultivating and harvesting salt (Climate Change Commission, 2018a). Different analyses of risk find differing levels of exposure. Statewide, approximately 550 Hawaiian cultural sites will be exposed to chronic flooding with 3.2’ of sea level rise (Climate Change Commission, 2018a). However, of the 10.9 square miles designated as Hawaiian home lands, only 0.6% of that area is vulnerable to 3.2’ sea level rise, and 1.8% is vulnerable to this scenario compounded by a 1% annual chance flood event (HI-EMA, 2018).
- A recent conservation easement agreement in Waikāne mandates that the land must be used to a) prioritize conservation, b) include public access and c) involve traditional agriculture education opportunities on the 2-acre portion of the land used for kalo farming. This piece of land is expected to be lost with +3 ft SLR; since there are no replacements or plans for adaptation, cultural and educational opportunities would be lost with it (Department of Land Management, 2020).
- Iconic beaches, parks, and coastal environments are at risk to impacts from sea level rise (HI-EMA, 2018; Office of Economic Development, 2020; Department of Facility Maintenance, 2020). 70% of beaches in Hawaiʻi already experience chronic erosion and land retreat. Over 13 miles of Oʻahu beaches fronting shoreline armoring (e.g., seawalls) have already been lost to coastal erosion, and this number could significantly grow especially if there is more widespread construction of seawalls and similar infrastructure (Hawaiʻi Climate Commission, 2017; HI-EMA, 2018). After an erosive episode, natural recovery can take months to years; beaches experiencing long-term chronic erosion may never fully recover, and be more exposed to future events. Beaches such as the iconic North Shore “Seven Mile Miracle” are expected to be reduced by coastal erosion in the future (HI-EMA, 2018).
- Near-shore and low-lying habitats and ecosystems will likely be affected by sea level rise, erosion, groundwater inundation, and the potential influx of saltwater into estuaries; many

such coastal habitats and ecosystems could be damaged or lost, though some (e.g., wetlands around Kahuku) may be expanded and improved (HI-EMA, 2018; Hawaiʻi Climate Commission, 2017; DEM, 2019). These impacts may make it increasingly challenging for the coast to “buffer” damages from storms (HI-EMA, 2018).

- If coastal waste management infrastructure is damaged such that it releases hazardous material or waste into coastal waters or habitats, those ecosystems and bodies of water could in turn be damaged (HI-EMA, 2018).
- Two parks (Kailua and Kualoa Beach) are already losing ground due to coastal erosion. Other beaches along the North Shore and Kāhala are at risks to impacts in Right-of-Ways that could necessitate future closures. Additionally, coastal erosion has already impacted trees at several beach parks (Department of Parks and Recreation, 2020).
- Spatial analysis indicates that with 3.2’ SLR, 1,282 acres of state designated agricultural land and 1,863 acres of conservation land are projected to be exposed.

Confidence: Medium

There is some degree of agreement among City departments about consequences already being experienced and priority future risks.

5. Decrease in Precipitation

SCENARIO: LEEWARD SIDE OF ISLAND BECOMES UP TO 60% DRIER CONTRIBUTING TO DROUGHTS

5.1 Summary of Findings

Table 12. Risk assessment summary for decrease in precipitation

Likelihood		
Timeframe	**Rating** **1 2 3 4 5**	**Confidence**
Current		High
2020-2050		Medium
Consequences		
Category	**Rating** **1 2 3 4 5**	**Confidence**
Physical health and safety		Low
Mental health		Low
Community cohesion and equity		Low
Economic prosperity		Medium
Infrastructure		High
Environment and culture		Medium
Overall Risk		
Current	5.8 (Medium)	Medium
2050	8.7 (Medium)	Medium

A progressive decrease in precipitation, particularly on the leeward side of the island will contribute to more frequent or severe drought conditions.

While these ratings are focused on precipitation-related impacts, a decrease in precipitation or prolonged drought can also contribute to wildfire. Some commentary on the compounding effects to wildfire are included in the evidence base below.

Decrease in precipitation of up to 60% on the leeward side of the island and associated droughts is a **medium** risk of incresing severity by 2050. Table 12 summarizes the likelihood, consequence, and overall risk ratings.

Figure 16 shows the overall current and 2050 risk ratings on a risk matrix. Decreasing precipitation and drought will have significant impacts on agricultural productivity, and environment and culture. If groundwater sources are not able to recharge, water availability could also become a chronic concern over time. However, groundwater levels are impacted far more by choices about land use than they are projected to be impacted by changes in climate (e.g., decrease in precipitation) (Brewington, Keener, & Mair, 2019).

5.2 Risk Assessment Evidence Base

5.2.1 Likelihood

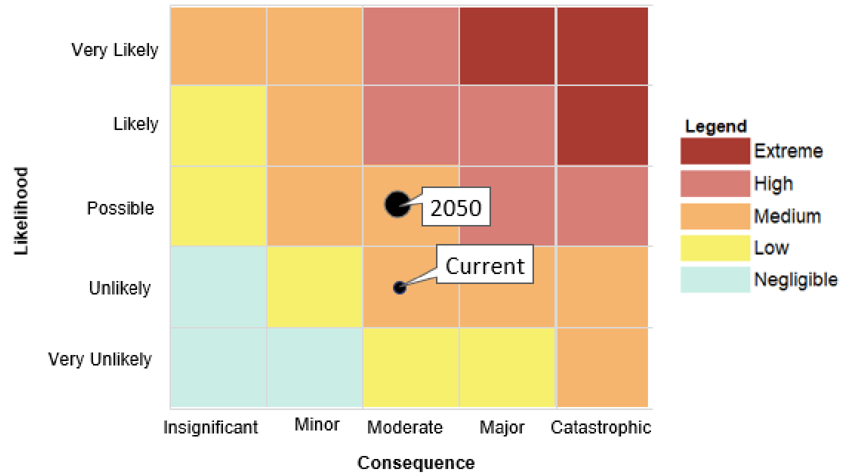

Figure 16. Risk matrix for decrease in precipitation.

The present-day likelihood rating for the decreasing precipitation scenario is **2** and the 2050 likelihood is **3**. Generally, statistically downscaled projections show the windward side of the island is getting wetter and the leeward side of the island is getting drier (Climate Change Commission, 2018a; HI-EMA, 2018). Drought events are also becoming more common (Climate Change Commission, 2018a). Mid-century projections indicate that a decrease in precipitation of up to 60% is likely for the leeward side of the island. However, most of the leeward side is projected to see a lesser decrease in the range of 35% to 50% (see Figure 17).

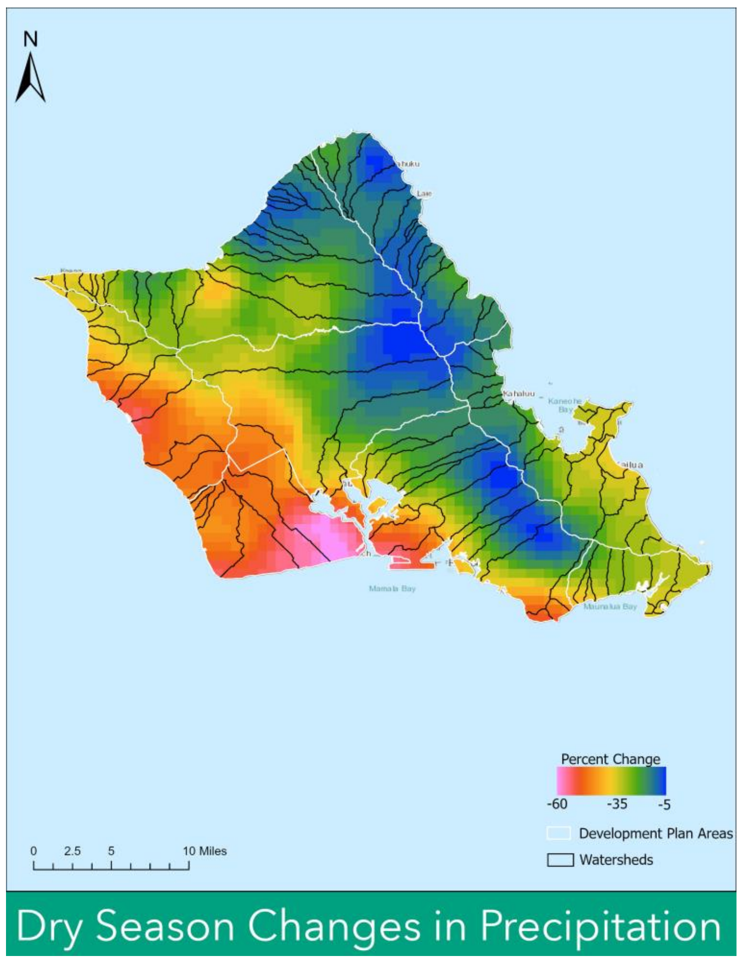

Figure 17. Dry season change in precipitation for mid-century.

For additional context, end-of-century projections based on higher-resolution dynamically downscaled data show O'ahu getting wetter overall, though the results also show a decrease in precipitation in smaller portions of the leeward side and in Haleiwa (Zhang, Wang, Hamilton, & Lauer, 2016). Differences in dynamically and statistically downscaled projections are shown in Figure 18.

Supporting evidence includes:

- Observed precipitation change for Honolulu indicates a declining trend from 1950 to 2015 compared to the 1951 to 1980 average (NOAA, n.d.).

- From 1901 to 2016, the State of Hawaiʻi experienced twenty-six severe droughts. Eleven of those droughts have occurred since 2000 (State of Hawai'i, 2017).
- Statistical downscaled modeling for RCP8.5 indicates that the leeward side of the island is expected to experience up to a 60% decrease in precipitation by mid-century (2041-2071) as shown in Figure 17. (Timm, Giambelluca, & Diaz, 2014). The area west of Māmala Bay such as ʻEwa is expected to experience the most significant decline.
- The project team conducted a spatial analysis of precipitation percent change during the dry season (shown in Figure 17) by land use type and found that 22% of urban acres, 2% of conservation acres, and 5% of agricultural acres are in the highest quartile range of -47% to -60% change in precipitation. The majority of urban acres (45%) and agricultural acres (40%) fall in the second lowest quartile of -19% to -33%. The majority of conservation acreas (61%) are in the lowest quartile of -5% to -19%.
- Trade winds are crucial to precipitation patterns across Oʻahu. The projected decrease in trade winds (Garza, Chu, Norton, & Shroeder, 2012) is expected to contribute to declining precipitation and more frequent drought conditions (HI-EMA, 2018).

Projected % Change in End-of-Century Rainfall

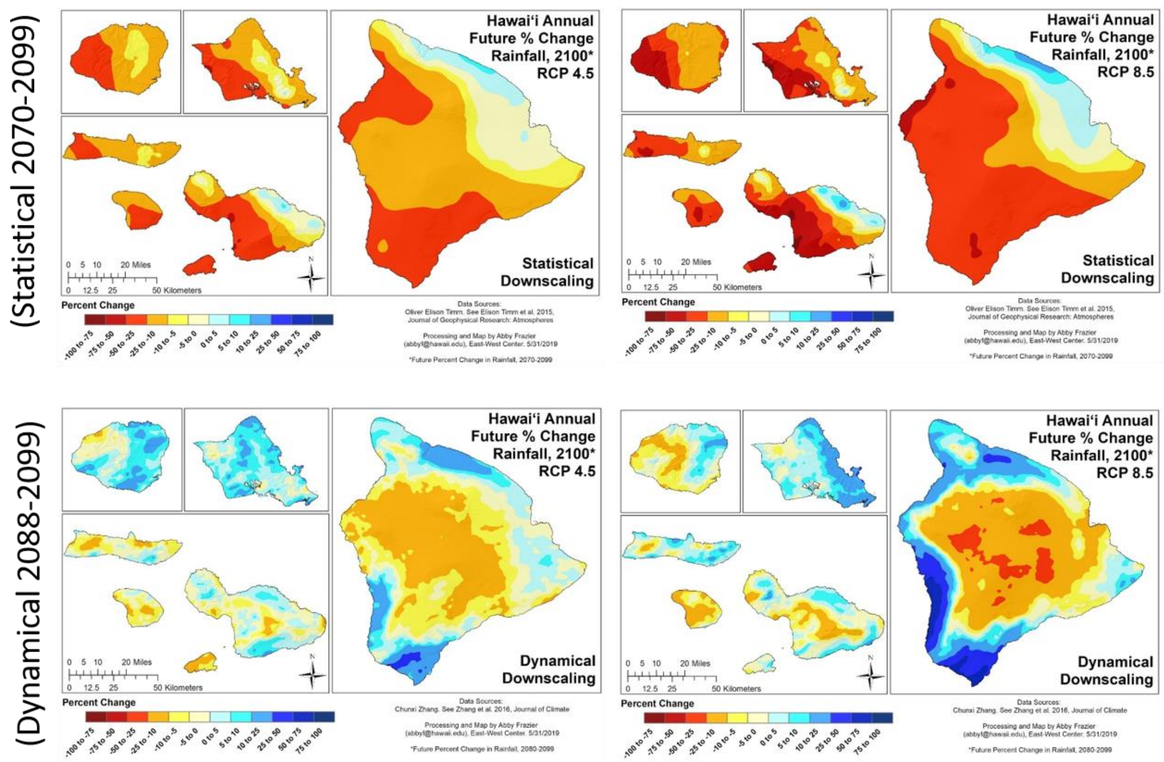

Figure 18. These maps visualize different high-resolution end-of-century precipitation projections generated from statistically and dynamically downscaled data. The greatest decrease in precipitation is shown in red, and the greatest increase is shown in dark blue. Both show an increase on the windward side (the dynamical map laso shows an increase on some of the leeward side) and a decrease in central O'ahu (the statistical map also shows a decrease on the full leeward side). Graphic from Keener, 2020.

Confidence (Current): High

Several data sources indicate an observed decline in precipitation as well as several instances of drought. Historic precipitation data also supports a pattern of less precipitation on the leeward side of the island.

Confidence (2020-2050): Medium

Several sources indicate a decreasing trend in precipitation, especially on the leeward side of the island. However, there is some disagreement (e.g., statistical vs. dynamical models) in the literature about how much precipitation will change by 2050 and how that will vary geographically.

5.2.2 Consequences

Decreasing precipitation on the leeward side of the island is expected to most significantly impact the environment and culture, economic prosperity, and infrastructure. A decline in water availability will have significant ripple effects on watershed health and agricultural productivity.

Details on each individual consequence rating are provided below.

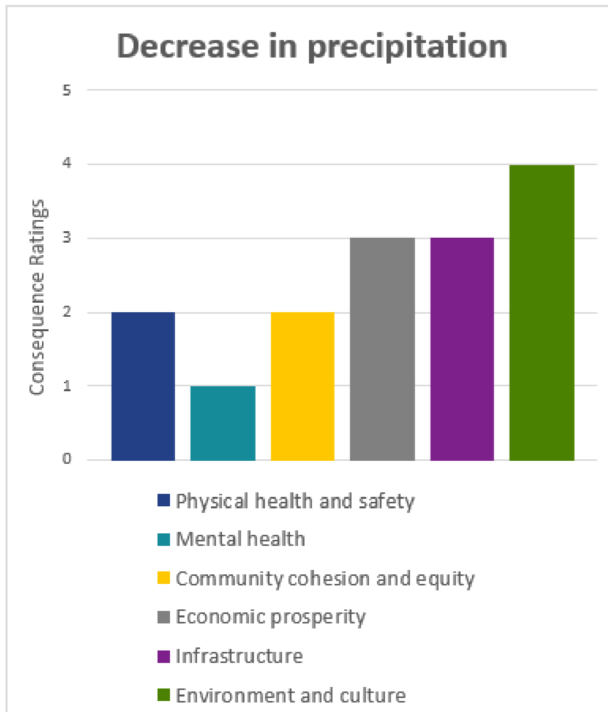

Figure 19. Consequence ratings for decrease in precipitation.

Population: Average score of 1.7

Physical health and safety: 2

There are limited physical health and safety risks from a decrease in precipitation or drought event. The ripple effects of these events on water quality and air quality could impact a limited number of people if directly exposed.

Supporting evidence includes:

- Potential health challenges related to decreased precipitation and drought include increased incidence of illness or disease related to decreased water quality and air quality (e.g., dust) (HI-EMA, 2018).
- Surface water reservoirs could experience high concentrations of toxic algal blooms, bacteria, and protozoa due to lower water levels, lower oxygen levels, and increased pollutant concentrations. If consumed, the contaminated water could cause illness (HI-EMA, 2018).
- If wildfires develop due to temperature and drought conditions, the fires could have more severe physical health and safety impacts (Personal communication, 2020).

Confidence: Low

There is limited information available for this consequence category.

Mental health: 1

Minimal mental health impacts are expected from a decrease in precipitation but could be greater for those reliant on farming as a business or food source. If a severe drought were to cause water availability challenges, mental health impacts like stress and anxiety could become more widespread.

Supporting evidence includes:

- Spending time in nature and parks has many mental health benefits. Decreasing precipitation may lead to less attractive and enjoyable nature experiences due to the aesthetics of browning and stressed vegetation (Department of Parks and Recreation, 2020; HI-EMA, 2018).
- Low-income, Native Hawaiian populations, and communities who grow food and live on the leeward coast could be disproportionately affected (Department of Planning and Permitting, 2020). A decrease in precipitation could cause increased stress and anxiety due to impacts to food and water availability.
- If a decrease in precipitation leads to severe drought, mental health impacts associated with drought may increase as well (e.g., farmers, ranchers, and service providers experiencing stress related to greater "burden of responsibility", reduced income, increased conflict, loss of educational opportunities and/or cultural traditions) (Finucane & Peterson, 2010).

Confidence: Low

There is limited information available for this consequence category.

Community cohesion and equity: 2

Although impacts to the general population are largely moderate such as limiting at-home water use, precipitation is expected to progressively decline by mid-century and beyond. Impacts to and stress on the community could increase over time as water availability is increasingly affected, affecting daily life.

Supporting evidence includes:

- Water rights and security are a contentious issue, especially on the leeward coast across communities of the Waiʻanae Coast (Office of Housing, 2020).
  - The leeward side is the fastest growing side of the island. This could add additional stress on water supply (Personal communication, 2020).
- Many low-income and Native Hawaiian populations live on the leeward coast (Department of Planning and Permitting, 2020). These populations could be disproportionately affected by decreasing precipitation and its ripple effects:
  - Many people have small farms or grow some of their own food (Department of Planning and Permitting, 2020).
  - Those that are more likely to travel by foot or bike will be more greatly impacted by drier conditions that lead to less vegetation and shade, increasing heat and sun exposure, and urban heat island effect (Department of Planning and Permitting, 2020).
- If water availability is limited, residents may be asked to make behavioral changes to reduce water use (Board of Water Supply, 2020; Personal communication, 2020).

Confidence: Low

There is limited information available for this consequence category.

Economy: Average score of 3

Hazard: Decrease in Precipitation

Decreased precipitation, particularly on the leeward side of the island, will impact the cattle and agricultural industries as well as increase wildfire damage and mitigation costs.

Wildfire Impacts

The drier leeward areas, where fires are more frequent, will see less rainfall, exacerbating drought conditions and increasing wildfire risk.

Grass-dominated landscapes allow wildfires to progress from areas of high ignition frequency to forested areas, placing watersheds and human safety at risk. Rugged terrain limits safe options for suppression efforts.[1]

Combined, wildfire consumed more than 30,000 acres of land across Hawaiʻi in 2018, up from 7,700 acres across the state in 2017.[2]

Drought Impacts

NOAA estimates that that the average drought causes more than $6.2B worth of damages per year in the US.[3]

In Hawaii, the 7-year drought from 2007-2014 resulted in about $44.5M in lost revenue to the ranching industry (including 20,000+ cattle) with full recovery expected to take 10 to 14 years and cost $4-6 million per year.[4]

Drought is the number one cause of loss for federal crop insurance payouts in Hawaiʻi ($10M since 1996).[5]

Non-insured crop disaster payments in the state totaled more than $23M between 2010 and 2018.[5]

Sources: 1. Traurnicht et al., 2015. 2. Ancheta, 2018. 3. NOAA, 2020. 4. Finnerty, N.d. 5. Frazier, 2019.

Economic prosperity: 3

Agriculture and tourism, specifically ecotourism, will be most affected by decreasing precipitation. Agricultural productivity is heavily dependent on water availability. A severe drought or repeated years of water stress could lead to significant economic losses. The aesthetics of popular parks and ecotourism destinations could also be affected.

Supporting evidence includes:

- Agriculture is dependent on springs and water from the mountains. Decreased precipitation, increased temperature, and changes in moisture could all affect agricultural productivity (Office of Economic Development, 2020; HI-EMA, 2018). For example, a drought from 1980-1981 caused over $1.4 million in agricultural and cattle losses (State of Hawai'i, 2017). Specific impacts could include (HI-EMA, 2018; State of Hawai'i, 2017):
  - Lower agricultural yields
  - Crop failures
  - Altered timelines for planting and harvesting
  - Limited groundwater pumping and water availability for irrigation
  - Increased erosion rates
  - Reduced livestock herd sizes due to reduced ground cover
  - Increased operational costs (e.g., needing to purchase feed or water for livestock)
- Long-term drought conditions could terminate golf course operations or create financial strains due to increased watering and maintenance costs (Department of Enterprise Services, 2020).
- Dry conditions will increase landscaping and maintenance costs and affect aesthetics. If public areas, parks, and other ecotourism-related attractions are not maintained,

vegetation will be stressed and may be less attractive to visitors, and there may be greater risk of the spread of invasive plant species affecting watershed health (Department of Parks and Recreation, 2020; HI-EMA, 2018).

- Cumulative impacts of decreased precipitation, particularly on water resources and agriculture, will be significant. Over time, the trend of lower rainfall will permanently reduce sustainable yields from the aquifer. This loss of water supply for new development will impact the economy, as desalinisation is very expensive. It is possible that, in response to decreased precipitation, more economical and efficient ways to reuse water or use ocean water to mitigate impacts will be developed (Personal communication, 2020).
- If brush fires develop due to temperature and drought conditions, the fires could:
  - Threaten park usage by residents and tourists, especially if park infrastructure and wildlife are significantly impacted (Department of Parks and Recreation, 2020).
  - Threaten golf courses. DES has experiened several manmade fires that spread through acres of brush on the courses (Department of Enterprise Services, 2020).

Confidence: Medium

Multiple City departments and external sources described similar risks, though there is limited information available on impacts to tourism or other sectors compared to impacts to agriculture.

Infrastructure: 3

O'ahu's freshwater supply is heavily dependent on rainfall and groundwater recharge. This is critical for drinking water and irrigation needs. Chronic water shortages are possible in the future if actions are not taken to cope with a reduced water supply.

Supporting evidence includes:

- Water costs are expected to rise if there is lower water availability because investments in new ways to attain, clean, and distribute water will be required. This can be a financial strain for departments as well as residents (Department of Parks and Recreation, 2020; Board of Water Supply, 2020). Options to cope with a reduced water supply could include:
  - Continuing existing research on technology to make desalination and water recycling processes more efficient, and working to diversify water resources (e.g., as described in the Wai'anae Watershed Management Plan) (Honolulu Board of Water Supply, 2009).
  - Expanding usage of recycled water (e.g., for irrigating parks) and conservation programs
  - Desalination from Kalaeloa
  - Behavioral and code changes to improve water efficiency
  - Transferring water supplies from the Pearl Harbor aquifer to the Wai'anae Coast
- Groundwater aquifers may not be able to recharge, which could affect irrigation and drinking water availability (Department of Planning and Permitting, 2020; HI-EMA, 2018).

- Chronic water shortages are possible if decreased precipitation coincides with higher temperatures, increased evaporation, decreased groundwater storage and recharge, and population growth (State of Hawai'i, 2017; HI-EMA, 2018).
    - The leeward side of the island is classified as medium water supply drought risk, meaning the area is either reliant on surface water sources or a vulnerable groundwater supply. The windward side of the island has low water supply drought risk (HI-EMA, 2018).
- Drought conditions could contribute to the development and spread of a wildfire, which would threaten critical infrastructure like utilities, roads, bridges, and personal property (HI-EMA, 2018).

Confidence: High

Multiple City departments and external sources describe freshwater supply as a major concern.

Environment and Culture: 4

Reduced stream flow and groundwater recharge will have ripple effects on the health of the watershed including habitat loss and degradation, water stress, and increased erosion and runoff. These impacts to the environment can also disrupt Native Hawaiian traditional and customary practices.

Supporting evidence includes:

- The overall health of the watershed will start to decrease as streams and vegetation dry out (Board of Water Supply, 2020; HI-EMA, 2018).
    - Streams will experience reduced flows and underground aquifers may not be able to recharge (Department of Planning and Permitting, 2020; Board of Water Supply, 2020; State of Hawai'i, 2017). Over the past century, Hawai‘i has observed reduced stream flow and declining groundwater levels (Climate Change Commission, 2018a).
    - Habitat loss or degradation could occur, which could decrease biodiversity on O‘ahu (HI-EMA, 2018; State of Hawai'i, 2017).
    - With the threat of intense floods between dry periods, forest health is critical for capturing rain and reducing runoff (Board of Water Supply, 2020). Reducing polluted runoff is especially important for protecting nearshore waters and reef ecosystems downstream (HI-EMA, 2018; State of Hawai'i, 2017).
    - Decreased precipitation could support certain invasive species (HI-EMA, 2018; Office of Economic Development, 2020).
- Drought conditions may “impair, diminish, or impede the exercise of traditional and customary practices” for Native Hawaiians. Practices such as the collection of plants, animals, and minerals rely on a healthy watershed and environment (HI-EMA, 2018; State of Hawai'i, 2017).
- Drought conditions could contribute to the development and spread of a wildfire, which would threaten vegetation, habitat, and critical species in the affected area (HI-EMA, 2018). For example, the 2016 drought contributed to wildfires at Diamond Head State Monument (HI-EMA, 2018).

Confidence: High

Multiple City departments and external sources describe similar risks to environment and culture.

6. Increase in Temperature

SCENARIO: INCREASE IN AVERAGE ANNUAL TEMPERATURE OF 2.7°F TO 4.5°F CONTRIBUTING TO HEAT WAVES

6.1 Summary of Findings

Table 13. Risk assessment summary for increase in temperature

Likelihood		
Timeframe	**Rating** **1 2 3 4 5**	**Confidence**
Current		High
2020-2050		High
Consequences		
Category	**Rating** **1 2 3 4 5**	**Confidence**
Physical health and safety		High
Mental health		Medium
Community cohesion and equity		High
Economic prosperity		High
Infrastructure		High
Environment and culture		Low
Overall Risk		
Current	6.9 (Medium)	High
2050	13.8 (High)	Medium

A progressive increase in average annual temperature will lead to ecosystem and habitat changes, as well as more frequent days of high temperatures and contribute to the frequency and severity of extreme heat events (e.g., five consecutive days above 90°F). The severity of this scenario will be further heightened if high temperatures or a heat wave coincides with a period of low trade winds. While this scenario is focused on heat impacts, an increase in average annual temperature can also contribute to drought and wildfire. Some commentary on the compounding effects to drought and wildfire are included in the evidence base below.

Statistically and dynamically downscaled data both project that the future climate on Oʻahu is highly likely to be significantly warmer. Notably, elevation may impact future projections of warming in higher-resolution analyses (Timm O. , 2017; Zhang, Wang, Hamilton, & Lauer, 2016).

Increase in average annual temperature of 2.7°F to 4.5°F and associated heat waves will increase from a **medium** to a **high** risk by 2050. Table 13 summarizes the likelihood, consequence, and overall risk ratings. Figure 20 shows the overall current and 2050 risk ratings on a risk matrix. A change in temperature of even a few degrees can have significant impacts on human health, air conditioning usage and energy demand, and the environment. The most vulnerable populations to heat-related death and illness are the elderly, young children, the homeless, outdoor workers, those living in homes without air conditioning, and those living in poorly ventilated, air conditioning-dependent homes. Generally, the valleys, urban center, and low-lying areas of Oʻahu experience the greatest heat exposure. Temperatures are expected to increase most rapidly in higher elevations, with additional resultant impacts to populations and the environment.

6.2 Risk Assessment Evidence Base

6.2.1 Likelihood

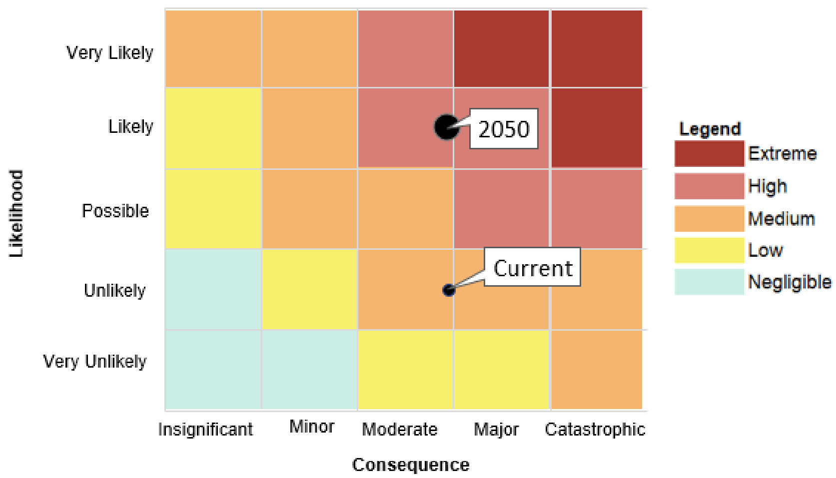

Figure 20. Risk matrix for increase in temperature.

The present-day likelihood rating for the increase in average annual temperature scenario is **2** and the 2050 likelihood is **4**. The present-day likelihood rating is based on historical warming rates of 0.3°F per decade. Global climate model projections indicate that an increase of 2.7°F to 4.5°F (1.5°C to 2.5°C) in Honolulu is likely by mid-century. This range encompasses the RCP 4.5 and RCP 8.5 emissions scenarios. Statistically and dynamically downscaled data both project that the future climate on Oʻahu is highly likely to be significantly warmer (Timm O. , 2017; Zhang, Wang, Hamilton, & Lauer, 2016). The likelihood of related temperature-driven hazards like drought, and wildfire are not included in this assessment. See the Decrease in Precipitation profile for additional insights on the likelihood and consequences of drought.

Supporting evidence includes:

- From 1916 to 2015, average annual temperature for the state of Hawaiʻi has risen 0.76°F compared to the 1944 to 1980 average (USGCRP, 2018; Climate Change Commission, 2018a). Currently air temperature is warming at a rate of 0.3°F per decade (Climate Change Commission, 2018a).
- In 2019, Hawaiʻi and Honolulu experienced its hottest summer to date. From August 10th to September 15th, Honolulu met or exceeded 90°F for 37 straight days, peaking at 95°F. Nightime temperatures also stayed above 80°F for 19 nights, compared to a historical average of 14 nights between 1950 and 2018 (Cappucci, 2019).
    - A heat mapping study was completed on August 31, 2019 for Oʻahu. Volunteers collected real time temperature and humidity readings in the morning, afternoon, and evening for 10 study traveses (CAPA Strategies, 2019). Figure 21 shows the mapped afternoon heat index for 3-4pm on August 31, 2019, which ranged from 85.1°F to 107.3°F (CCSR, 2019; CAPA Strategies, 2019). The urbanized lower elevation areas have a higher heat index.

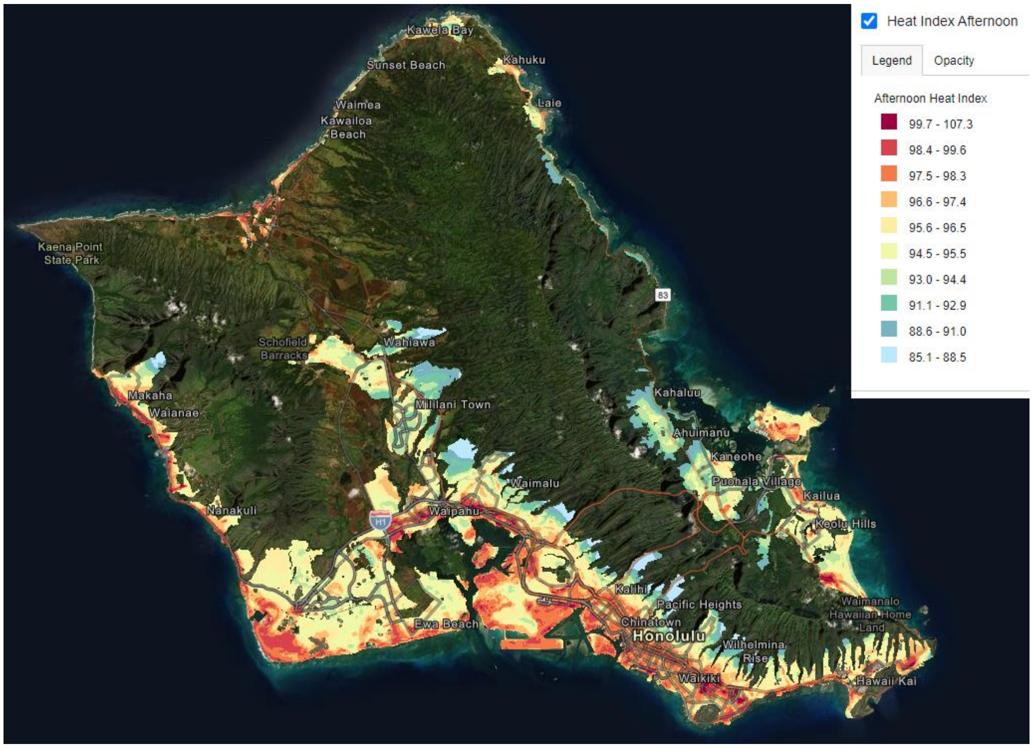

Figure 21. Oʻahu afternoon heat index on August 31, 2019 (CCSR, 2019).

- Figure 22 illustrates average annual afternoon temperature as a proxy for heat exposure. Generally, the valleys, urban centers, and low-lying areas of Oʻahu experience the greatest heat exposure. The project team conducted a spatial analysis of heat exposure by land use type and found that 99.5% of urban acres, 38.6% of conservation acres, and 93.7% of agricultural acres are in the highest quartile temperature range of 74.8°F to 78.8°F. An additional 40% of conservation acres are in the second highest quartile of 70.7°F to 74.8°F.
- Model projections indicate that mean surface temperatures will increase approximately 2.7°F to 4.5°F (1.5°C to 2.5°C) by mid-century and 3.6°F to 7.2°F (2°C to 4°C) by end of century under the RCP 4.5 and RCP 8.5 emissions scenarios. The greatest warming is

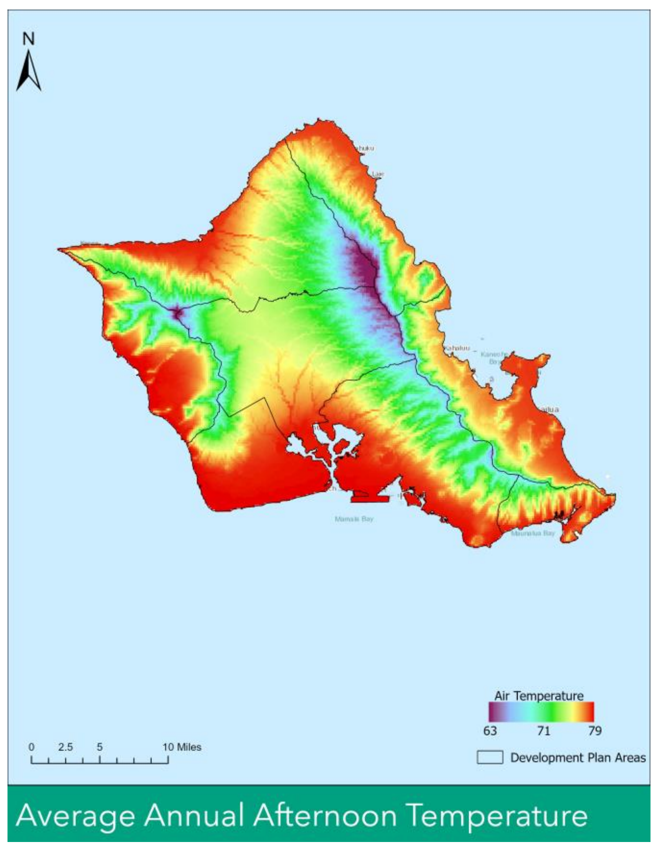

Figure 22. Average annual afternoon temperature for Oʻahu.

expected at higher elevations on O‘ahu (Timm O. , 2017).

- A decrease in trade winds could increase the severity of conseqeunces for increasing average annual temperature and heat waves. Daily average wind speeds are decreasing in Honolulu (Climate Change Commission, 2018a).
    - Trade winds affect wave height, cloud formation, temperature, and precipitation. A study of changes in trade winds from 1973 to 2009, found that northeast trade winds are decreasing. For example, at Daniel K. Inouye International Airport, northeast trade winds occured 291 days per year in 1973 compared to 210 days per year in 2009. In contrast, east trade winds increased in frequency from 1973 to 2009. East trade winds average 63 days per year for Honolulu. The study suggests a shift from notheast to east trade winds, which is indicative of a shift in large-scale pressure and wind patterns (Garza, Chu, Norton, & Shroeder, 2012).
- An increase in average annual temperature can have ripple effects on other climate-related hazards such as heat waves, increased evaporation, and decreased water availability (USGCRP, 2018; Climate Change Commission, 2018a). This can fuel drought conditions or wildfires (USGCRP, 2017; Climate Change Commission, 2018a).

Confidence (Current): High

Several data sources indicate an observed increase in average annual temperature.

Confidence (2020-2050): High

Several sources indicate an increasing trend in temperature, with the greatest warming expected at higher elevations. Mid-century and end of century temperature projections are for a range of emissions scenarios to better capture uncertainty.

6.2.2 Consequences

Increasing temperature is expected to most significantly impact physical health and safety and environment and culture. Certain subsets of the population are particularly vulnerable to heat-related health impacts including the elderly, young children, homeless populations, and populations with asthma, allergies, or other respiratory illnesses. Native flora and fauna, especially birds, are vulnerable to loss of habitat and increased prevalence of pests and disease.

Details on each individual consequence rating are provided below.

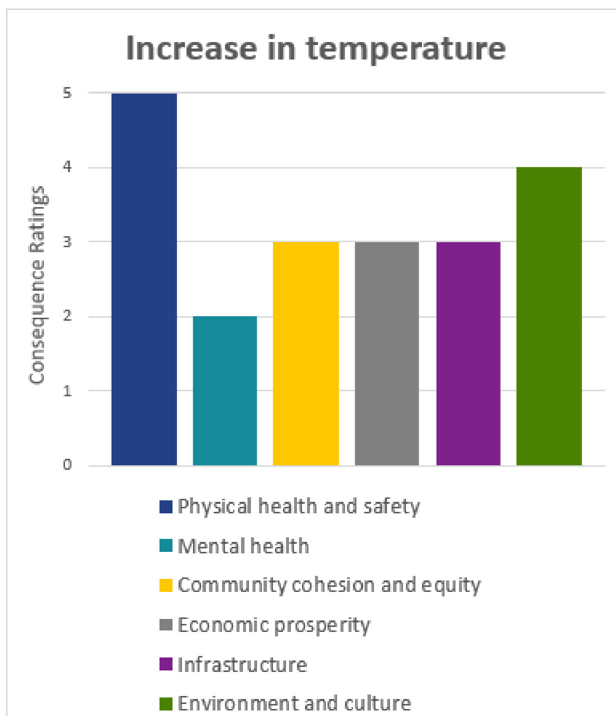

Figure 23. Consequence ratings for increase in temperature.

Population: Average score of 3.3

Physical health and safety: 5

> **Differential Impacts**
>
> Populations with respiratory illnesses or living in homes without air conditioning or poor ventilation are at greater risk of heat-related health impacts.

Heat exposure is associated with numerous health issues. A heat wave event paired with low trade winds could potentially affect thousands of people, particularly the elderly, young children, the homeless, those with asthma, allergies, or other respiratory illnesses, and those living in homes without air conditioning or with poor ventilation, and outdoor workers. If power is lost due to stress on the electrical system, that will increase the percent of population exposed to high temperatures.

Supporting evidence includes:

- Increasing temperatures and extreme heat events are associated with increased respiratory illnesses, heatstroke, cardiovascular disease, and kidney disease (HI-EMA, 2018). Increasing temperatures can also decrease air quality and disproportionately impact populations with asthma, allergies, and other respiratory illnesses (USGCRP, 2018; HI-EMA, 2018).
  - Extreme heat shock events can cause heat-related deaths and illnesses, particularly for children (<2 years old) and elderly (65+ years old) populations (HI-EMA, 2018). Unsheltered homeless populations are also at greater risk due to their exposure to extreme heat (Office of Housing, 2020). The life expectancy is already 20-30 years lower for the homeless population in Hawai‘i compared to national data on the homeless population (Office of Housing, 2020).
- Increasing temperatures can support higher insect survival and production, leading to an increase in the spread of vector-borne diseases (HI-EMA, 2018).
- The elderly population (65+ years old) on Hawai‘i is expected to increase from 17.1% (2016) to 23.8% (2045) of the total population (which is also growing), increasing the number of people vulnerable to heat-related health impacts over time (Honolulu Emergency Services Department, 2020; DBEDT, 2018).
- Many homes and buildings do not have air conditioning, increasing residents' and visitors' potential sensitivity to rising temperatures (Office of Housing, 2020). Health impacts will be exacerbated if high temperatures coincide with a period of low trade winds (Department of Planning and Permitting, 2020).
  - The recently developed Kumuwai affordable senior rental project, for example, has received complaints from residents related to heat. The facility does not have air conditioning and has limited operable windows per unit. Units do have mounted fans. This housing facility is for a high-risk group in regards to heat health and safety – elderly individuals (62+ years old) who are experiencing homelessness or are at risk of becoming homeless (Department of Land Management, 2020; DLM, 2019)
- If power is lost, residents or visitors staying in poorly ventilated buildings that are typically reliant on air conditioning for cooling such as multi-story high-rises will be particularly vulnerable to the heat. These buildings were not designed to function without air conditioning. Loss of power will also affect elevator service, hampering people's

ability to exit the building as well as emergency personnel's ability to quickly access upper floors. A widespread power outage could slow emergency medical services across the island. Response time is especially important for heat-related illnesses as these are typically progressive medical conditions (Honolulu Emergency Services Department, 2020).

Confidence: High

Multiple City departments and external sources described similar impacts to physical health and safety.

Mental health: 2

Increasing temperatures and heat waves can exacerbate existing mental health issues and be an added strain on mental health and wellbeing. This is particularly true for periods of uncomfortable extreme heat. A gradual increase in temperature may be less noticeable but is a chronic issue that will increase the number of uncomfortable days and nights per year.

> **Differential Impacts**
>
> More severe mental health impacts are possible for a small subset of the population. People with existing mental health conditions or dealing with homelessness are more vulnerable to severe impacts.

Supporting evidence includes:

- Homeless/verge of homeless populations tend to suffer from more mental health issues than the general population. They are also more vulnerable to heat living in crowded, poor-ventilated group housing or in unsheltered areas of the City. Approximately 15,000 people go through the homeless system in a given year (Honolulu Emergency Services Department, 2020; Office of Housing, 2020).
- Approximately 60,000 people live in poverty in O‘ahu and are less likely to be living in air conditioned or well-ventilated homes. Increasing temperatures can be an added strain on the mental health and wellbeing of these individuals (Office of Housing, 2020).
- A literature review systematically analyzed the relationship between heat and mental health, specifically suicide, bipolar disorder, mania and depression, schizophrenia, dementia, substance misuse, and mental health service usage. The literature review was not geographically or temporally constrained and ultimately focused on 35 studies that explicitly linked extreme heat and mental health. The strongest relationships were increased suicide risk as well as increased medical/emergency department visits during extreme heat events. The reviewed literature was less conclusive on extreme heat worsening other types of mental health impacts (Thompson, Hornigolda, Pageb, & Waitea, 2018).
- Because increases in temperature are likely to occur slowly over time, there may be greater opportunity to invest in mitigative measures and adapt to changes, thereby potentially limiting the mental health disruption that could be caused by temperature increases (Personal communication, 2020).

Confidence: Medium

Multiple City departments identified mental health challenges. However, the full extent of mental health impacts from climate-related events are not yet well understood or documented in existing literature. This remains an area for further research.

Community cohesion and equity: 3

Increasing temperature and heat waves will have widespread, moderate impacts to daily life, including creating uncomfortable living and working conditions, raising energy costs, and altering forms of travel and outdoor activity. As increased temperatures persist over time, people may need to alter their routines to adjust to the shift in average annual temperature. During a heat wave, more disruptive impacts are possible such as restricted energy use and more intense discomfort.

Supporting evidence includes:

- During record heat in 2015, Hawaiian Electric issued emergency public service announcements asking residents to restrict air conditioning use and reduce stress on the electrical system (Climate Change Commission, 2018a).
- Higher energy and air conditioning use will increase energy costs for residents, business owners, and the City (Department of Planning and Permitting, 2020; Honolulu Emergency Services Department, 2020). This may be a large financial burden for low income community members.
    - Energy costs in a recently developed affordable housing facility are two to three times higher than expected due to air conditioning flowing through the hallways as well as the units. This has been an unexpected financial burden for residents and an issue that an updated building code could prevent (Department of Planning and Permitting, 2020).
    - Building managers and homeowners may be resistant to installing air conditioning due to the high energy costs, but it may become a necessity for livability in the future. Habitable space insulation, ceiling fans and other building design elements can also be useful for increasing airflow and cooling (Department of Land Management, 2020; Department of Planning and Permitting, 2020).
- Commuting via walking or biking or waiting in open-air bus and rail facilities will become increasingly uncomfortable for residents and visitors as temperatures increase, thus requiring them to shift to more expensive modes of transportation (Department of Transportation Services, 2020; Department of Planning and Permitting, 2020). A shift in transportation mode to avoid the heat may also alter people's commute time, greenhouse gas emissions, and general satisfaction.
- Makeshift cooling centers are generally more available in wealthier communities than poorer communities (e.g., malls). There is also limited transportation access for homeless, verge of homeless, and poor populations to travel to these cooling centers to escape the heat. These populations are more often reliant on modes such as public transit, biking, and walking. However, some of these modes like buses can provide an air conditioned refuge itself (Office of Housing, 2020; Department of Transportation Services, 2020).
- Finding cool, conveniently located, and public transportation accessible housing that accepts Housing Choice Vouchers (HCV) will become increasing difficult for people reliant on the program (Office of Housing, 2020).
- Socializing and recreating outdoors may become increasingly challenging, especially for sensitive populations. For example:

- Community parades and outdoor events may pose a health risk for more vulnerable populations as temperatures increase. If temperatures are too hot, parades and other community events may need to be cancelled or rescheduled (Department of Transportation Services, 2020).
- Many DPR classes and services (e.g., Summer Fun), gyms, recreation rooms, and other indoor programming do not have air conditioning and may become uncomfortable to use or attend as temperatures increase (Department of Parks and Recreation, 2020).
- Public park equipment (e.g., play equipment, courts) may become too hot to use with increasing temperatures and during extreme heat events (Department of Parks and Recreation, 2020).

Confidence: High

Multiple City departments described similar impacts to daily life activities and energy costs.

Economy: Average score of 3

Hazard: Increase in Temperature

Increases in average annual temperature of 2.7 to 4.5°F will result in **impacts to vegetation and human health** across Hawai'i.

The Honolulu Department of Parks and Recreation estimates increasing need for **street tree replacements**, ranging in cost from $1k to $2.5k per tree. There are currently about 141,000 street trees,[1] for replacement value of around $20M.

Annually, Honolulu public street trees provide $3.9M in total benefits from runoff and CO_2 reductions, energy savings, air quality improvements, and social value.[2]

Urban vegetation plays a crucial role in lowering temperatures within cities and minimizing the urban heat island effect.[3]

Increasing temperatures will increase the need for **air conditioning** across the state.

Many homes in the state were built prior to 1950, where A/C was not common practice. Additionally, plantation style homes unique to the islands were built to be able to ventilate and cool naturally.[4]

As of 2019, 68% of O'ahu residential customers have A/C (compared to 53% for Maui and 32% for Hawaii). This number has significantly increased in the past 5 years, straining the grid and renewable energy goals.[5]

While there has been an uptick in classrooms with cooling systems, as of 2019, roughly 5,000 classrooms statewide lack A/C.[6]

Many newer homes are built with multiple ceiling fans, as it costs less than A/C. Installing central A/C for a 2,000 sq ft home can cost $3k - $4k, with additional electricity costs.[4]

Monthly electricity bills range based on the type of A/C unit (central air, window unit, split systems) but can range between $30 and $245 per month (assuming a 1,200 sq ft area).[7]

Each degree of thermostat is worth about 3% of your energy bill,[8] implying an annual electricity bill increase of $30-$400 based on potential temperature increases and energy usage.

Sources: 1. Honolulu Department of Parks and Recreation, 2019. 2. Honolulu DLNR, N.d. 3. Wang and Akbari, 2016. 4. Hawai'i Real Estate, 2017. 5. KITV Island News, 2019. 6. Lee, 2019. 7. Ketchum, 2018. 8. Energy Hub, 2012.

Economic prosperity: 3

Higher temperatures could encourage a shift from certain recreation and tourism activities with high heat exposure (e.g., golfing) to other activities with lower heat exposure (e.g., beaches and mountainous hiking trails). This shift is likely to be especially pronounced during a heat wave event. There will also be higher operational costs for certain City departments due to increased energy and water usage.

Supporting evidence includes:

- Certain recreation and tourism activities such as beaches, shaded parks, and mountain hiking trails may become more attractive to residents and visitors as a refuge from the heat (Department of Parks and Recreation, 2020).
- Other activities may become less attractive. Extreme hot days above 90°F can be particularly uncomfortable and unhealthy, especially in facilties where air conditioning is not available (Office of Economic Development, 2020).
  - Open air malls may experience decreased foot traffic (Department of Transportation Services, 2020).
  - Golf courses may experience lower turnout, especially among the elderly. Golf courses have not had to close due to extreme heat and safety concerns to date, but the occasional golfer does experience heat-related illness (Department of Enterprise Services, 2020).
  - Indoor recreation facilities may experience lower turnout. Indoor facilities have not had to close due to extreme heat and safety concerns to date (Department of Parks and Recreation, 2020).
  - Honolulu Zoo may experience decreased foot traffic and certain animals may also be at risk or face adverse health impacts in extreme heat (Department of Enterprise Services, 2020).
- Increasing temperatures could affect agricultural productivity (Department of Planning and Permitting, 2020).
- Many City departments will experience higher operational costs due to increased energy use (e.g., air conditioning) and water use (e.g., irrigation and landscaping). For example:
  - Golf course operations could be significantly affected by increasing temperature and drought conditions. Water usage and maintenance needs to maintain golf course grounds would create an unsustainable financial strain on operations. Staff may need to apply more chemicals and use more water to keep the grass green (Department of Enterprise Services, 2020).
  - DPR may need to increase irrigation and landscaping to maintain healthy trees and vegetation that provide critical shade to the community. There may also be added costs for removal of stressed trees and vegetation, and planting and maintenance of new trees (Department of Parks and Recreation, 2020).
- Worker safety considerations may increase under warmer temperatures. In hotter temperatures, for example, outdoor workers (e.g., parks staff, refuse collectors, construction workers) or staff working in a poorly ventilated indoor space may not be able to do their jobs as efficiently (Personal communication, 2020). Workers may need to restrict hours or add more breaks during periods of high heat to reduce the risk of heat-related health impacts.
- If brush fires were to develop due to temperature and drought conditions, the fires could threaten parks usage by residents and tourists, especially if park infrastructure and wildlife are significantly impacted (Department of Parks and Recreation, 2020).

Confidence: High

Multiple City departments described similar impacts to recreation and tourism activities and City operational costs.

Infrastructure: 3

Demand and strain on the electrical system is the most critical infrastructure impact. Loss of power during a heat wave would have numerous ripple effects on residents, businesses, and City operations. As temperatures increase, energy use and strain on the electrical system will increase. Transportation infrastructure and facilities could also be impacted, especially during periods of extreme heat.

Supporting evidence includes:

- Residents, tourists, businesses, and City staff are all likely to increase air conditioning use and thus demand on the electrical system during high temperatures. Blackouts are possible if actions are not taken to reduce demand (e.g., asking residents and businesses to reduce use) or increase system capacity (Honolulu Emergency Services Department, 2020; HI-EMA, 2018).
- City information technology (IT) systems are dependent on electricity and occasionally experience heat-related issues or outages (Office of Housing, 2020).
- Transportation assets could be damaged by hotter temperatures. For example:
    - Transportation pavement could experience increasing rutting and cracking under extreme heat conditions (FHWA, 2015).
    - Heat could lead to airport tarmacs failures (Personal communication, 2020)
    - Transportation infrastructure and facilities in open-air environments may be utilized less during periods of high temperatures (e.g., bike trails, rail stations, bus stops) (Department of Transportation Services, 2020).
- Higher temperatures could necessitate buildings being redesigned to function at the same comfort level (e.g., through energy efficiency improvements or larger heating, ventilation, and air conditioning (HVAC) systems) (Personal communication, 2020).
- If brush fires were to develop due to temperature and drought conditions, the fires could threaten critical infrastructure (Department of Parks and Recreation, 2020).

Confidence: High

Multiple City departments identified loss of power as a concern, especially as it related to ripple effects on other consequence categories.

Environment and Culture: 4

Increasing temperature creates a number of stresses to native flora and fauna such as shifts in habitat range and increased prevalence of pests, diseases, and invasive species. In particular, several native bird species are expected to be on the trajectory to lose a significant amount of their range or be at risk of extinction by end of century. Increased evaporation rates could also lead to a decline freshwater availability.

Supporting evidence includes:

- Increasing air temperatures are an added stress for native flora and fauna. This can lead to a shift in habitat and range (HI-EMA, 2018; Climate Change Commission, 2018a). Warmer temperatures can also support increased prevalence of pests, diseases, and invasive species (HI-EMA, 2018; Climate Change Commission, 2018a).

    - Native and endangered birds and plants are especially vulnerable to temperature stress, habitat shift, and pests and disease. Native birds like the ʻIwi (Hawaiian honeycreeper) are expected to decline as mosquito-borne disease and avian malaraia transmission increases in high-elevation forests (HI-EMA, 2018). A study of native forest bird species found that ten species are expected to lose greater than 50% of their range by end of century due to temperature-driven disease prevalence. Six of these species are at high risk of extinction and expected to lose 90-100% of their range by end of century (Fortini, 2015).
- Urban forestry and the urban tree canopy will also experience heat and water stress without irrigation and landscaping maintenance. It is important to maintain urban vegetation to decrease urban heat island effect (Department of Parks and Recreation, 2020). Trees can decrease ambient air temperatures by as much as 10°F (DPR DUF and CCSR, 2019). They provide a number of net benefits (see textbox in Economy section for details).
    - Irrigation regulations for landscaped areas may need to be revisited as temperatures increase (Department of Planning and Permitting, 2020).
    - The urban forest is already declining. A study of tree canopy change found a 3.1% net loss of tree canopy in the southern portion of Oʻahu from 2010 to 2013 due to both anthropogenic (e.g., landowner removal, development) and natural (e.g., extreme weather events, age) causes (MacFaden, Engel, & OʻNeil-Dunne, 2013).
- Warming temperatures and higher evaporation rates at high elevations can lead to a decrease in precipitation and freshwater supplies (Climate Change Commission, 2018a). In addition, if water use needs increase to maintain City landscaping and grounds, this could further stress water availability (Department of Parks and Recreation, 2020).
- If brush fires were to develop due to temperature and drought conditions, the fires could threaten park land and wildlife (Department of Parks and Recreation, 2020).

Confidence: Low

While the literature identifies clear connections between warming temperatures and environmental impacts, there is limited information and agreement on the expected severity of impacts by 2050.

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