Anchialine Pools

Climate Change Vulnerability Assessment Synthesis for Maui, Lāna‘i, and Kaho‘olawe

An Important Note About this Document: This document represents an initial evaluation of vulnerability for anchialine pools on Maui Nui¹ based on expert input and existing information. Specifically, the information presented below comprises vulnerability factors selected and scored by habitat experts,² relevant references from the literature, and peer-review comments and revisions (see end of document for methods and defining terms). The aim of this document is to expand understanding of habitat vulnerability to changing climate conditions, and to provide a foundation for developing appropriate adaptation responses.

Habitat Description

Anchialine pools are landlocked pools found on limestone or lava flows. They are characterized by subsurface hydrological connectivity, but lacking surface connection to the ocean (Pacific Coast Joint Venture Hawai‘i 2006; The Nature Conservancy 2012). Pools vary in salinity, dissolved oxygen levels, and water level depending on distance to the sea, tidal fluctuations, groundwater input, and rainfall (Pacific Coast Joint Venture Hawai‘i 2006; The Nature Conservancy 2012). The Hawaiian Islands have the largest concentration of anchialine pools in the world (Brock et al. 1987). The island of Maui has many anchialine pools, while Kaho‘olawe has one pool with very high salinity (Hawai‘i Department of Land and Natural Resources 2015).

Habitat Vulnerability

Anchialine pool habitats were evaluated to have moderate-high vulnerability to climate change due to high sensitivity to climate and non-climate stressors, high exposure to projected future climate changes, and low-moderate adaptive capacity.

<table>
<thead>
<tr>
<th>Anchialine Pools</th>
<th>Rank</th>
<th>Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Future Exposure</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Adaptive Capacity</td>
<td>Low-Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Vulnerability</td>
<td>Moderate-High</td>
<td>High</td>
</tr>
</tbody>
</table>

Anchialine pools are sensitive to climate-driven changes in pool salinity or water depth caused by precipitation changes, storm surge, or saltwater intrusion; salinity and depth changes can be exacerbated by development and water diversions that alter groundwater recharge and

¹ Moloka‘i is considered separately from this assessment. The vulnerability assessment workshop approach was not applied to Moloka‘i as the PICCC funded Ka Honua Momona between 2014-2016 to host a workshop series to identify climate-related risks and vulnerabilities, and brainstorm potential solutions and partnerships. EcoAdapt and PICCC were invited to participate in a one-day workshop with the Moloka‘i Climate Change Network in April 2017 to discuss adaptation options.

² This information was gathered during a vulnerability assessment and scenario planning workshop in August 2016 (http://ecoadapt.org/workshops/mauivulnerabilityworkshop). Further information and citations can be found in the Hawaiian Islands Climate Vulnerability and Adaptation Synthesis and other products available online at www.bit.ly/HawaiiClimate.
withdrawal. Additionally, anchialine pools are sensitive to sea level rise, which may increase pool vulnerability to invasive species, as well as pool distribution, particularly if development blocks landward migration. Anchialine pool shrimp are also sensitive to pollutants and water temperature.

The adaptive capacity of anchialine pools may be bolstered by subsurface connectivity, protection through natural area reserves, and knowledge gained through successful restoration efforts on other islands. However, anchialine pools are less valued by the public than other aquatic systems, and face competing interests with development and upstream water uses. Additionally, a lack of knowledge about individual pool aquatic assemblages and hydrodynamics make it difficult to know how each pool will respond to or recover from changes.
Sensitivity and Exposure

Climatic Factors and Disturbance Regimes

Changes in precipitation amount and timing, storm surge, and saltwater intrusion affect anchialine pool salinity and depth, although it is unknown how salinity changes may affect unique anchialine pool ecological communities (Table 1). Shifts in large-scale patterns of atmospheric circulation will likely affect Hawaiian anchialine pools by influencing precipitation; however, the impact of these changes are uncertain, especially because water management influences groundwater contributions to pool systems (Bassiouni & Oki 2013). Temperature increases may stress pool biota. Sea level rise may cause shifts in pool distribution, and combined with storm surge, may increase surface connectivity between pools, increasing the likelihood of invasive species establishment.
Table 1. Current and projected future trends in climatic factors and disturbance regimes, as well as their potential impacts on anchialine pool habitats. This habitat is sensitive to the climatic factors and disturbance regimes listed below, and will likely be exposed to projected future changes in them. Factors presented are those ranked as having a moderate or higher impact on the habitat; additional factors that may influence the habitat to a lesser degree include soil moisture.

<table>
<thead>
<tr>
<th>Climatic factors and disturbance regimes</th>
<th>Historical and current trends</th>
<th>Potential impacts on habitat</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Precipitation (amount &amp; timing)</strong></td>
<td><strong>High impact (high confidence)</strong></td>
<td><strong>Reduced rainfall may restrict pool distribution and water level by reducing groundwater recharge and direct runoff (Pacific Coast Joint Venture Hawai‘i 2006); studies on Hawai‘i have found pool size to affect community composition (Sakihara 2012)</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Historical and current trends</strong></td>
<td><strong>Reduced rainfall may alter pool community structure by increasing salinity; exact impacts are unknown (Marrack 2014), but salinity does influence anchialine pool shrimp distribution (Sakihara 2012) and larval survivorship (Havird et al. 2015)</strong></td>
</tr>
<tr>
<td></td>
<td>• Since 1920, precipitation has decreased across the Hawaiian Islands, with the strongest drying trends occurring over the last 30 years (Frazier et al. 2016; Frazier &amp; Giambelluca 2017)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• From 1920 to 2012, dry season (May–Oct.) precipitation declined 1% to 5% per decade for most areas on Maui and Lāna‘i, particularly in leeward areas; Kaho‘olawe experienced more modest drying of up to 1.2% per decade (Frazier &amp; Giambelluca 2017)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• From 1920–2012, Maui experienced the largest wet-season (Nov.–April) precipitation declines of any island in the state, decreasing 27.6 mm per decade, which ranged from 2% to 5% per decade in East Maui (Frazier &amp; Giambelluca 2017)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• The frequency of trade wind inversion (TWI) occurrence increased an average of 20% since 1990, resulting in a 31% reduction in wet season rainfall and a 16% reduction in dry-season rainfall at nine high-elevation sites on Maui (over 1,900 m [6,234 ft]; Longman et al. 2015)</td>
<td></td>
</tr>
<tr>
<td><strong>Projected future trends</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Precipitation projections are highly uncertain because they vary in projected direction and magnitude, and will be affected by shifts in the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), as well as the amount of future greenhouse gas emissions. Possible future scenarios include:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Little to no change in average precipitation by 2100 (Keener et</td>
<td></td>
</tr>
</tbody>
</table>
Maui, Lāna‘i, and Kahoʻolawe Climate Change Vulnerability Assessment for the Hawaiian Islands Climate Synthesis Project
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<table>
<thead>
<tr>
<th>Water temperature</th>
<th><strong>Historical and current trends</strong></th>
<th><strong>Projected future trends</strong></th>
<th><strong>Potential impacts on habitat</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• No anchialine pool temperature trends are available</td>
<td>• No anchialine pool temperature projections are available</td>
<td>• Two species of anchialine pool shrimp (<em>Halocaridina rubra</em> and <em>Metabetaeus lohena</em>) appear tolerant of variable and high water temperatures (Vaught et al. 2014; Marrack et al. 2015); for example, they are often found in water temperatures above 20°C (68°F; Hawai‘i Department of Land and Natural Resources 2015) and have been recorded in areas with water temperatures up to 35°C (95°F; Chan &amp; Fujii 1986)</td>
</tr>
</tbody>
</table>

- Significant decreases in precipitation across all seasons by 2100, particularly in leeward areas (30% to 80% decrease in wet-season leeward precipitation and -20% to +20% change in wet-season windward precipitation; 10% to 90% decrease in dry-season precipitation; Elison Timm et al. 2015)
- By 2100, increased rainfall on windward slopes of Maui (up to 30% in the dry season), and decreased rainfall on Lānaʻi and leeward slopes of Maui in both seasons (Zhang et al. 2016)

<table>
<thead>
<tr>
<th>Tropical storms/hurricanes</th>
<th><strong>Historical and current trends</strong></th>
<th><strong>Potential impacts on habitat</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Tropical storm frequency was particularly high from 1982–1995, but then decreased slightly from 1995–2000 (Chu 2002)</td>
<td>• Storm surge can introduce marine fauna to pools (Brock &amp; Bailey-Brock 1998)</td>
</tr>
<tr>
<td></td>
<td>• Overall, tropical storm frequency increased slightly since 1966–1981 (Chu 2002)</td>
<td>• Extreme wave events may temporarily increase pool salinity and sedimentation, but groundwater typically flushes the system (Marrack 2014)</td>
</tr>
</tbody>
</table>
### Projected future trends

Tropical storm projections are highly uncertain because they are influenced by large-scale patterns within the ocean and atmosphere (Murakami et al. 2013). Possible future scenarios include:

- Increased frequency and strength of tropical storm activity around the Hawaiian Islands due to a northwest shift in storm track and increased strength because of large-scale changes in environmental conditions (Murakami et al. 2013).

### Historical and current trends

- At Kahului station, sea levels rose an average of 2.1 mm/year (0.08 in) from 1947–2016 (equivalent to a change of 0.21 m [0.69 ft] in 100 years; NOAA/National Ocean Service 2017)
- No historical/current trends are available for Lāna‘i and Kaho‘olawe
- Saltwater intrusion has increased in north Maui, due primarily to groundwater withdrawals (Gingerich & Engott 2012):
  - The freshwater lens became thinner between 1985 and 1999, as indicated by data from the Waiehu Deep Monitor Well
  - There was no change in the width of the freshwater lens in west Maui, as indicated by data from the Māhinahina Deep Monitor Well

### Projected future trends

There is high certainty that sea levels will continue to rise at increasing rates, but the magnitude and timing of change is less certain. Possible future scenarios include:

- By 2100, global sea level will likely rise between 0.3 to 2.5 m (0.98 to 8.2 ft); relative sea level may be higher in the Hawaiian Islands compared to global levels, ranging from 0.4 to 3.3 m (1.3 to 10.8 ft; Sweet et al. 2017); no regional sea level rise projections are available
- There are no projections available for saltwater intrusion, but it

### Potential impacts on habitat

- Sea level rise may expand pool size via increased flooding, cause pool loss to inundation, or create new pools if the land behind pool areas remains undeveloped and the substrate is appropriate (Marrack & O’Grady 2014)
- Sea level rise may increase surface connectivity between invaded pools, fishponds, and manmade resort water features, increasing the potential for invasive fish introductions (Marrack 2014, 2016)
- Saltwater intrusion will likely increase subsurface pool salinity, particularly if groundwater levels decline as a result of withdrawals and reduced precipitation; the consequences of increased salinity on anchialine pool species are unknown (Marrack 2014, 2016), but salinity is known to influence shrimp distribution (Sakihara 2012) and larval survivorship (Havird et al. 2015)

### Potential refugia

is likely to increase due to sea level rise, drought, and groundwater withdrawals (Rotzoll et al. 2010; Ferguson & Gleeson 2012)
Non-Climate Stressors

Sensitivity of the habitat to climate change impacts may be highly influenced by the existence and extent of, and current exposure to, non-climate stressors (Table 2). Climate-driven changes in pool characteristics may be exacerbated by non-climate stressors. For example, development may contribute to pool loss through fill or by preventing landward migration. Both development and water diversions can exacerbate pool hydrological shifts by affecting groundwater flow, and pollution and poisons may create more stressful conditions for pool biota.

Table 2. Key non-climate stressors that affect the overall sensitivity of anchialine pool habitats to climate change. All factors were ranked as having a moderate or higher impact on the habitat.

<table>
<thead>
<tr>
<th>Non-climate stressors</th>
<th>High impact (high confidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Residential &amp; commercial development</strong></td>
<td></td>
</tr>
<tr>
<td>Potential impacts on habitat</td>
<td></td>
</tr>
<tr>
<td>Development can:</td>
<td></td>
</tr>
<tr>
<td>o Eliminate pools (Pacific Coast Joint Venture Hawai‘i 2006; Hawai‘i Department of Land and Natural Resources 2015)</td>
<td></td>
</tr>
<tr>
<td>o Alter pool hydrology (e.g., through increased groundwater withdrawals) and geomorphology (e.g., through fill; Pacific Coast Joint Venture Hawai‘i 2006; Conservation Council for Hawai‘i 2011; Hawai‘i Department of Land and Natural Resources 2015)</td>
<td></td>
</tr>
<tr>
<td>o Prevent landward pool migration/new pool formation in response to sea level rise (Marrack 2016)</td>
<td></td>
</tr>
<tr>
<td>o Increase pool nutrient and pollutant loading through groundwater contamination (Marrack et al. 2015), which can alter pool community structure and function, particularly in pools with invasive fish (Dalton et al. 2013)</td>
<td></td>
</tr>
<tr>
<td>Pattern of exposure: Highly localized</td>
<td></td>
</tr>
<tr>
<td><strong>Water diversions</strong></td>
<td></td>
</tr>
<tr>
<td>Potential impacts on habitat</td>
<td></td>
</tr>
<tr>
<td>Inland water diversions and groundwater withdrawals may affect pool community structure by increasing salinity and reducing subsurface habitat connectivity (Marrack 2014)</td>
<td></td>
</tr>
<tr>
<td>Pattern of exposure: Highly localized</td>
<td></td>
</tr>
<tr>
<td><strong>Pollutions &amp; poisons</strong></td>
<td></td>
</tr>
<tr>
<td>Potential impacts on habitat</td>
<td></td>
</tr>
<tr>
<td>‘Ōpae (native shrimps) are sensitive to pollution from human pool use (e.g., soaps, shampoos, litter) and human and pet refuse (Mitchell et al. 2005; Conservation Council for Hawai‘i 2011)</td>
<td></td>
</tr>
<tr>
<td>Fertilizers can alter natural pool chemical balance (Conservation Council for Hawai‘i 2011)</td>
<td></td>
</tr>
<tr>
<td>Elevated nutrient levels (e.g., nitrogen, phosphorus) can increase primary producer biomass (particularly if shrimp abundance is low due to other factors) and alter pool structure and function (Marrack et al. 2015 and citations therein)</td>
<td></td>
</tr>
<tr>
<td>Pattern of exposure: Consistent across habitat</td>
<td></td>
</tr>
</tbody>
</table>
**Agriculture & aquaculture**

**Potential impacts on habitat**
- Agriculture likely contributes to elevated nutrient and contaminant loads and water diversion issues (Vuln. Assessment Reviewer, pers. comm., 2017)
- *Pattern of exposure:* Highly localized

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**Adaptive Capacity**

Anchialine pools are small systems, but connectivity between pools may be high as a result of subsurface flow. Although anchialine pools are known for their unique aquatic assemblages, few pools have been formally surveyed, which leaves many unknowns about their diversity and ability to recover from climate- and human-caused changes. However, pool restoration and creation efforts on other islands have been successful, and can potentially be used to inform similar efforts on Maui. Anchialine pools have lower public value and societal support for management than other aquatic systems, and face competing interests with development and other water uses (Table 3).

**Table 3.** Adaptive capacity factors that influence the ability of anchialine pool habitats to adapt to projected future climate changes. Factors that receive a ranking of “High” enhance adaptive capacity for this habitat (+), while factors that receive a ranking of “Low” undermine adaptive capacity (-).

<table>
<thead>
<tr>
<th>Adaptive capacity factors</th>
<th>Low-moderate adaptive capacity (moderate confidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Extent &amp; integrity</strong></td>
<td></td>
</tr>
<tr>
<td>Low-moderate</td>
<td>+ Maui supports roughly 50 anchialine pools; Cape Hanamaniao supports high integrity pool habitat (Pacific Coast Joint Venture Hawai‘i 2006)</td>
</tr>
<tr>
<td>(high confidence)</td>
<td>- Anchialine pools are typically small, ranging from 15 acres to the size of a bathtub (Conservation Council for Hawai‘i 2011; Yamamoto et al. 2015)</td>
</tr>
<tr>
<td><strong>Habitat isolation</strong></td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td>+ Genetic and distribution studies of anchialine pool ‘ōpae and mollusks indicate relatively high subsurface connectivity between pools (Russ et al. 2010; Marrack 2016)</td>
</tr>
<tr>
<td>(low confidence)</td>
<td>+/- Anchialine pools lack surface connectivity, but can exist as isolated pools and/or groups depending on subsurface flow (Pacific Coast Joint Venture Hawai‘i 2006)</td>
</tr>
<tr>
<td><strong>Resistance &amp; recovery</strong></td>
<td></td>
</tr>
<tr>
<td>Low-moderate</td>
<td>+/- Anchialine pool recovery is variable (Vuln. Assessment Workshop, pers. comm., 2016)</td>
</tr>
<tr>
<td>(moderate confidence)</td>
<td>- Some human-driven ecological changes that impact Maui anchialine pools may be irreversible (Hawai‘i Department of Land and Natural Resources 2015)</td>
</tr>
<tr>
<td><strong>Habitat diversity</strong></td>
<td></td>
</tr>
<tr>
<td>Low-moderate</td>
<td>+ Maui anchialine pools support several ‘ōpae (shrimp) species and endemic amphipods, as well as occasional marine species (Hawai‘i Department of Land and Natural Resources 2015)</td>
</tr>
</tbody>
</table>
| (high confidence)                   | + Studies from Hawai‘i Island indicate that ‘ōpae‘ula (*H. rubra*) appear to be somewhat resilient to temperature, salinity, and dissolved oxygen changes (Sakihara 2012; Havird et al. 2014; Vaught et al. 2014; Marrack et
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al. 2015), as well as to food web changes induced by invasive plant canopy cover (Dudley et al. 2017)

+/- Native aquatic fauna is highly endemic, rare, and unique (Brasher 2003; Pacific Coast Joint Venture Hawaiʻi 2006)
- Diversity is naturally low in Hawaiian aquatic systems due to isolation of the Hawaiian archipelago (Brasher 2003)
- Relatively little is known about aquatic systems; greater knowledge is needed on topics such as keystone species and individual species vulnerability to climate change (Vuln. Assessment Workshop, pers. comm., 2016)
- Despite their abundance, few anchialine pools have been surveyed (Hawaiʻi Department of Land and Natural Resources 2015)

<table>
<thead>
<tr>
<th>Management potential</th>
<th>Low-moderate (high confidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>Management of anchialine pools is supported by the Division of Aquatic Resources (Vuln. Assessment Workshop, pers. comm., 2016)</td>
</tr>
<tr>
<td>+</td>
<td>Some pools are protected by the ʻĀhihi-Kīnaʻu Natural Area Reserve (The Nature Conservancy 2012)</td>
</tr>
<tr>
<td>+</td>
<td>On other islands, pool excavation restoration efforts and artificial pool creation projects have been successful; restored/created pools support native species (Marrack 2014, 2016)</td>
</tr>
<tr>
<td>+</td>
<td>Moderate likelihood of alleviating climate change impacts: Some climate and human impacts can be alleviated by effecting positive change and funding conservation groups and research (Vuln. Assessment Workshop, pers. comm., 2016). For example, managing water consumption and removing water diversions can reduce vulnerability to saltwater intrusion (Gingerich 2008; Gingerich &amp; Engott 2012; Ferguson &amp; Gleeson 2012)</td>
</tr>
<tr>
<td>+</td>
<td>Extreme events (e.g., tsunami, pollutant influx) would likely increase support for aquatic system management (Vuln. Assessment Workshop, pers. comm., 2016)</td>
</tr>
<tr>
<td>+/-</td>
<td>Low-moderate public value: Anchialine pools are valued for their rarity/existence, educational purposes (Vuln. Assessment Workshop, pers. comm., 2016), and their support of other activities (e.g., supply ʻōpaeʻula used for fishing bait; Conservation Council for Hawaiʻi 2011)</td>
</tr>
<tr>
<td>-</td>
<td>Low societal support for anchialine pool management and conservation: There is currently a gap in the degree to which anchialine pools are valued and societal willingness to pay for habitat protection, likely due to a lack of knowledge about this habitat (Vuln. Assessment Workshop, pers. comm., 2016)</td>
</tr>
<tr>
<td>-</td>
<td>Aquatic systems face competing interests with development, traditional agriculture, and other off-stream water uses (e.g., community use; Vuln. Assessment Workshop, pers. comm., 2016); conflicts are highest during the dry season when water is increasingly limited, and will likely increase if climate change reduces water supply (Bassiouni &amp; Oki 2013)</td>
</tr>
</tbody>
</table>
Recommended Citation


Produced in cooperation with the Pacific Islands Climate Change Cooperative, with funding from the U.S. Fish and Wildlife Service.

Literature Cited


Hawaiian Islands Climate Synthesis Project:
Vulnerability Assessment Methods and Application

Defining Terms

**Exposure**: A measure of how much of a change in climate or climate-driven factors a resource is likely to experience (Glick et al. 2011).

**Sensitivity**: A measure of whether and how a resource is likely to be affected by a given change in climate or factors driven by climate (Glick et al. 2011).

**Adaptive Capacity**: The ability of a resource to accommodate or cope with climate change impacts with minimal disruption (Glick et al. 2011).

**Vulnerability**: A function of the sensitivity of a particular resource to climate changes, its exposure to those changes, and its capacity to adapt to those changes (IPCC 2007).

**Vulnerability Assessment Model**

The vulnerability assessment model applied in this process was developed by EcoAdapt (Hutto et al. 2015, EcoAdapt 2014a, EcoAdapt 2014b, Kershner 2014), and includes evaluations of relative vulnerability by local stakeholders who have detailed knowledge about and/or expertise in the ecology, management, and threats to focal habitats and ecosystem services. Stakeholders evaluated vulnerability of each resource by discussing and answering a series of questions for sensitivity and adaptive capacity. Habitat exposure was evaluated by EcoAdapt using future climate projections from the scientific literature; ecosystem service exposure was evaluated by workshop participants using the climate impacts table provided by EcoAdapt. Each vulnerability component (i.e. sensitivity, adaptive capacity, and exposure) was divided into specific elements. For example, habitats included three elements for assessing sensitivity and five elements for adaptive capacity. Elements for each vulnerability component are described in more detail below.

Stakeholders assigned one of five rankings (High, Moderate-high, Moderate, Low-moderate, or Low) for sensitivity and adaptive capacity. Stakeholder-assigned rankings for each component were then converted into scores (High=5, Moderate-high=4, Moderate=3, Low-moderate=2, or Low=1) and the scores averaged (mean) to generate an overall score. For example, scores for each element of habitat sensitivity were averaged to generate an overall habitat sensitivity score. Scores for exposure were weighted less than scores for sensitivity and adaptive capacity; this was due to greater uncertainty about the magnitude and rate of future change. Sensitivity, adaptive capacity, and exposure scores were combined into an overall vulnerability score calculated as:

\[
\text{Vulnerability} = ([\text{Climate Exposure} \times 0.5] \times \text{Sensitivity}) - \text{Adaptive Capacity}
\]

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1 Sensitivity and adaptive capacity elements were informed by Glick et al. 2011, Manomet Center for Conservation Sciences 2013, and Lawler 2010.
Elements for each component of vulnerability were also assigned one of three confidence rankings (High, Moderate, or Low). Confidence rankings were converted into scores (High-3, Moderate-2, or Low-1) and the scores averaged (mean) to generate an overall confidence score. These approximate confidence levels were based on the Manomet Center for Conservation Sciences (2013) 3-category scale, which collapsed the 5-category scale developed by Moss and Schneider (2000) for the IPCC Third Assessment Report. The vulnerability assessment model applied here assesses the confidence associated with individual element rankings, and uses these rankings to estimate the overall level of confidence for each component of vulnerability as well as overall vulnerability.

Rankings and scores presented should be considered measures of relative vulnerability and confidence (i.e. comparing the level of vulnerability between the focal resources evaluated in this project).

Vulnerability and confidence rankings and scores for a given element were supplemented with information from the scientific literature. The final vulnerability assessment summaries for a given resource include stakeholder-assigned rankings, confidence evaluations, and narratives summarizing expert opinions and information from the scientific literature.

**Habitat & Ecosystem Service Elements**

**Sensitivity & Exposure (Applies to Habitats and Ecosystem Services)**

1. **Climate and Climate-Driven Factors:** e.g., air temperature, precipitation, freshwater temperature, sea surface temperature, sea level rise, soil moisture, altered streamflows, etc.

2. **Disturbance Regimes:** e.g., wildfire, flooding, drought, insect and disease outbreaks, wind, etc.

3. **Future Climate Exposure:** e.g., consideration of projected future climate changes (e.g., temperature and precipitation) as well as climate-driven changes (e.g., altered fire regimes, altered flow regimes, shifts in vegetation types). Experts were provided with a summary of historical, current, and projected future climate changes for the main Hawaiian Islands.

4. **Non-Climate Stressors:** e.g., land-use conversion (e.g., residential or commercial development), agriculture and/or aquaculture, transportation corridors (e.g., roads, railroads, trails), water diversions, invasive and other problematic species, pollution and poisons, etc. For non-climate stressors, experts were asked to evaluate sensitivity, whether the habitat or ecosystem service is currently exposed to that stressor, and whether the pattern of exposure is widespread and/or consistent across the study area or is highly localized (e.g., exposure to aquaculture is highly localized but exposure to invasive grasses is often widespread).

**Adaptive Capacity (Habitats)**

1. **Extent and Integrity:** e.g., habitats that occur in multiple locations vs. single, small areas; high integrity vs. degraded habitats

2. **Habitat Isolation:** e.g., adjacent to other native habitat types vs. isolated habitats, barriers to dispersal (e.g., development, energy productions, roads, water diversions, etc.)
3. Resistance and Recovery: e.g., resistance refers to the stasis of a habitat in the face of change, recovery refers to the ability to “bounce back” more quickly from stressors once they do occur

4. Habitat Diversity: e.g., diversity of component native species and functional groups in the habitat

5. Management Potential: e.g., ability of resource managers to alter the adaptive capacity and resilience of a habitat to climatic and non-climate stressors (societal value of habitats, ability to alleviate impacts)

Adaptive Capacity (Ecosystem Services)

1. Intrinsic Value and Management Potential: e.g., ability of managers to alter the adaptive capacity and resilience of a service to climatic and non-climate stressors (societal value of ecosystem services, ability to alleviate impacts)

Literature Cited

EcoAdapt. 2014a. A climate change vulnerability assessment for aquatic resources in the Tongass National Forest. EcoAdapt, Bainbridge Island, WA.


Kershner JM, editor. 2014. A climate change vulnerability assessment for focal resources of the Sierra Nevada. Version 1.0. EcoAdapt, Bainbridge Island, WA.

