# Estuarine Habitats

## *Climate Change Vulnerability Assessment Synthesis for Oʻahu*

***An Important Note About this Document:*** *This document represents an initial evaluation of vulnerability for estuarine habitats on Oʻahu based on expert input and existing information. Specifically, the information presented below comprises vulnerability factors selected and scored by habitat experts,[1] 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.*

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## Habitat Description

The following Oʻahu sub-habitats are considered to be estuarine: lowland/coastal saline wetlands, stream mouths, and anchialine pools (if present; Vuln Assessment Workshop, pers. comm., 2016). Lowland/coastal saline wetlands (i.e. tidal marshes, salt marshes, swamps) and fishponds typically feature herbaceous and emergent salt-tolerant vegetation fringing seasonal or permanent standing water (Stone 1988; Pacific Coast Joint Venture Hawaiʻi 2006), and have intermittent ocean connectivity (Mitsch & Gosselink 2000). Stream-mouth estuaries feature more extensive deep-water habitat and have direct ocean connectivity because they occur at the river-ocean interface (Pacific Coast Joint Venture Hawaiʻi 2006). 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 (Brock & Kam 1997; Pacific Coast Joint Venture Hawaiʻi 2006; The Nature Conservancy 2012). Example estuarine habitats on Oʻahu include Kahana, Pearl Harbor National Wildlife Refuge, Heʻeia Natural Estuarine Research Reserve, Nuʻupia, Kāneʻohe, Pouhala Marsh, and Haleʻiwa (Vuln. Assessment Workshop, pers. comm., 2016).

Estuarine habitats occur at the fresh and saltwater interface, and are characterized by brackish water conditions (Hawaiʻi Department of Land and Natural Resources 2015). Salinity, water temperature, water levels, and dissolved oxygen levels vary temporally and spatially according to freshwater input (including rainfall, streamflow, and groundwater) and the extent of tidal influence (Mitsch & Gosselink 2000; Pacific Coast Joint Venture Hawaiʻi 2006; The Nature Conservancy 2012). In general, estuarine habitats are dynamic systems, with complex food webs supported by inputs of terrestrial and marine organic matter that feeds primary (e.g., plankton) and secondary (e.g., invertebrates, fish) producers (Atwood et al. 2012). Estuaries and tidal wetlands support a variety of wildlife, including estuarine and anchialine pool specialist species, marine species, endemic waterbirds, and migratory waterfowl and shorebirds (Hawaiʻi Department of Land and Natural Resources 2015).

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[1] This information was gathered during a vulnerability assessment and scenario planning workshop in December 2016 (http://ecoadapt.org/workshops/oahuvulnerabilityworkshop). 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.

## Habitat Vulnerability

Estuarine habitats on Oʻahu were evaluated as having moderate-high vulnerability to climate change due to high sensitivity to climate and non-climate stressors, moderate-high exposure to projected future climate changes, and low-moderate adaptive capacity.

| Estuarine Habitats | Rank | Confidence |
|---|---|---|
| Sensitivity | High | High |
| Future Exposure | Moderate-High | Moderate |
| Adaptive Capacity | Low-Moderate | High |
| **Vulnerability** | **Moderate-High** | **High** |

Climatic factors such as sea level rise, saltwater intrusion, and streamflow affect estuarine salinity, hydrology, water quality, and water temperature. Hydrological, salinity, and water quality changes affect overall habitat distribution, availability, and species composition. Higher estuarine water temperatures as a result of increasing stream and sea surface temperatures may alter native species assemblages. Non-climate stressors such as invasive marine and terrestrial species and pollution and poisons will also contribute to loss of native species and increased exotic dominance. Stressors such as agriculture, development, and roads eliminate or alter estuarine habitat, and may compound climate-driven changes by affecting hydrology, sedimentation, and available space for habitat migration. Projected population growth on Oʻahu will likely exacerbate existing non-climate stressors.

Estuarine habitats on Oʻahu are abundant but vary in ecological integrity. Development, roads, agriculture, and alien species degrade these habitats, and also inhibit habitat migration in response to climatic changes. Estuarine habitats exhibit a moderate-high ability to resist and recover from changes, particularly when supported by restoration. Native estuarine species also exhibit a high tolerance for extreme conditions, which enhances habitat resilience. However, estuarine habitats are less resilient to invasive species and human-driven modifications. Estuarine management and conservation is supported by regulatory protection, constituency support, and recognition of the critical ecosystem services estuaries provide.

## Sensitivity and Exposure

### Climatic Factors and Disturbance Regimes

Estuarine habitats on Oʻahu are sensitive to climatic factors that alter salinity, hydrology, and water quality and temperature, including sea level rise, saltwater intrusion, streamflow regimes, and stream and sea surface temperatures (Table 1). Salinity levels affect estuarine vegetative and faunal composition and distribution, as well as vulnerability to invasive species. Species composition changes will be further affected by hydrological shifts driven by sea level rise and altered streamflow. Hydrological changes may also alter estuarine habitat availability and distribution, potentially increasing habitat size, creating new habitat, and/or eliminating habitat depending on area available for landward migration. Estuarine water quality and temperature are influenced by stream temperature, sea surface temperature, and streamflow regimes; high temperatures are generally detrimental to native aquatic species.

**Table 1.** Current and projected future trends in climatic factors and disturbance regimes, as well as their potential impacts on estuarine habitats. These habitats are 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 these habitats; additional factors that may influence these habitats to a lesser degree include extreme precipitation events and ocean acidification.

| **Climatic factors and disturbance regimes** | Moderate-high impact (high confidence) | |
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| *Sea level rise, coastal flooding & saltwater intrusion* | ***Historical and current trends***<br>• At Honolulu station, sea levels rose an average of 1.44 mm/year (0.06 in) from 1905–2016 (equivalent to a change of 0.14 m [0.47 ft] in 100 years; NOAA/National Ocean Service 2017)<br>• At Mokuoloe station, sea levels rose an average of 1.26 mm/year (0.05 in) from 1957–2016 (equivalent to a change of 0.12 m [0.41 ft] in 100 years; NOAA/National Ocean Service 2017)<br>• Sea level rise (SLR) has contributed to both marine inundation (i.e. flooding in areas with a direct hydrological connection to the ocean) and groundwater inundation (i.e. flooding in areas with an indirect hydrological connection due to elevated water table; Rotzoll & Fletcher 2013)<br><br>***Projected future trends***<br>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:<br>• 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 | ***Potential impacts on habitat***<br>• Sea level rise contributes to aquifer saltwater intrusion and more frequent tidal flooding, which can increase salinity in stream mouth estuaries, tidal wetlands (Gehrke et al. 2011; Polhemus 2015; Kane et al. 2015), and anchialine pools (Marrack 2014, 2016); salinity increases will be exacerbated by groundwater declines (Ferguson & Gleeson 2012)<br>  ○ Higher salinities may contribute to shifts toward more salt-tolerant vegetation (Oʻahu National Wildlife Refuge Complex & U.S. Fish and Wildlife Service 2010, 2011; Kane et al. 2014)<br>  ○ Higher salinities may reduce vegetative species richness and cover by decreasing seed germination and exceeding salinity tolerances of some plant species (Bantilan-Smith et al. 2009)<br>  ○ Increased salinity may favor exotic aquatic species in regional wetlands (MacKenzie & Bruland 2012)<br>  ○ Changes in estuarine salinity may alter species distributions (e.g., less tolerant species may shift upstream; Gehrke et al. 2011) and/or abundance (e.g., ʻeleʻele seaweed [*Enteromorpha* spp.] is typically associated with areas that have freshwater inputs, and does not occur in high-salinity areas; Vuln. Assessment Workshop, pers. comm., 2016)<br>  ○ The consequences of increased salinity on anchialine pool species are unknown (Marrack 2014, 2016), but salinity is known to influence anchialine pool shrimp distribution (Sakihara 2012) and larval survivorship (Havird et al. 2015)<br>• Sea level rise may increase flooding depth and duration by increasing groundwater inundation and marine flooding (Polhemus 2015; Kane et |

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| | Islands compared to global levels, ranging from 0.4 to 3.3 m (1.3 to 10.8 ft; Sweet et al. 2017)<br>• Sea levels in Honolulu may increase 0.26 to 1.41 m (0.85 to 4.6 ft) by 2100 (Kopp et al. 2014)<br><br>Coastal flooding projections are relatively uncertain because there are no downscaled sea level rise projections for this region. Possible future scenarios include:<br>• Within a 1 km (0.6 mile) shoreline buffer in Honolulu, 10% of the area would be flooded under 1 m (3.28 ft) of SLR (58% of the flooding due to groundwater inundation; Rotzoll & Fletcher 2013)<br>• At James Campbell National Wildlife Refuge in north Oʻahu, 2.5% of the total area would be flooded under 0.74 m (2.42 ft) of SLR (estimated to occur by 2100; Kane et al. 2015)<br>• There are no projections available for saltwater intrusion, but it is likely to increase due to SLR, drought, and groundwater withdrawals (Rotzoll et al. 2010; Ferguson & Gleeson 2012) | al. 2015)<br>o Prolonged flooding may promote more hydrophilic species and/or reduce vegetative cover (Bantilan-Smith et al. 2009), affecting habitat character; for example, existing marshes in the Honouliuli Unit and Waiawa Unit of the Pearl Harbor National Wildlife Refuge may lose marsh character and transition to ponds as groundwater inundation increases (Polhemus 2015)<br>o Increased tidal connectivity may help alleviate extreme conditions (e.g., elevated water temperatures and salinities, low dissolved oxygen levels; MacKenzie & Bruland 2012)<br>o Increased tidal and surface water connectivity may alter the relative abundance of different native species (e.g., increase predominance of marine species in anchialine pools; Brock & Kam 1997)<br>o Increased tidal and surface water connectivity may contribute to new exotic species introductions (MacKenzie & Bruland 2012; Marrack 2014, 2016), which could alter invertebrate communities and impact broader estuarine food webs (Oʻahu National Wildlife Refuge Complex & U.S. Fish and Wildlife Service 2010)<br>• Increasing inundation may shift estuarine habitat abundance and distribution:<br>o Increasing inundation will initially increase anchialine pool size and cause inland expansion of fishponds and tidal marshes (Oʻahu National Wildlife Refuge Complex & U.S. Fish and Wildlife Service 2010; Marrack & O'Grady 2014)<br>o An overall loss in estuarine habitat area may be experienced if landward/upstream habitat migration is not possible due to topography, development, or other human land uses (Gehrke et al. 2011; Marrack & O'Grady 2014; Polhemus 2015)<br>▪ Due to limited migration opportunities, Puohala Marsh will likely be lost to inundation by 2100 (i.e. convert to an embayment or flooded mangrove estuary; Polhemus 2015)<br>o Alternatively, increasing inundation could create new habitat in previously dry areas (Marrack & O'Grady 2014; Kane et al. 2014); |

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| | | for example, James Campbell National Wildlife Refuge has large areas of hydric, poor-draining soils that may promote brackish wetland formation as sea levels rise (Kane et al. 2015)<br><br>***Geographic variation***<br>• Estuarine habitat sensitivity to sea level rise and saltwater intrusion is generally consistent across the study region, although some systems are more adaptable (Vuln. Assessment Workshop, pers. comm., 2016)<br><br>***Potential refugia***<br>• The Nuʻupia Ponds are unlikely to be inundated by sea level or groundwater rise by 2100 because they are diked and actively managed (Polhemus 2015) |
| *Streamflow* | ***Historical and current trends***<br>• Streamflow is typically highest from Jan.–March (wet season) and lowest during July–Sept. (dry season; Bassiouni & Oki 2013)<br>• From 1943–2008, streamflow declined by 22% and baseflow declined by 23% compared to 1913–1943, with larger declines during the dry season and increased high-flow variability (Bassiouni & Oki 2013)<br>• Jan.–March streamflow is typically low following El Niño events, and high following La Niña events; this pattern is enhanced during positive Pacific Decadal Oscillation (PDO) phases (Bassiouni & Oki 2013)<br><br>***Projected future trends***<br>• By 2100, streamflow is likely to decrease by 6.7–17.2% in the Makaha watershed on the leeward coast (9.6–21.2% decrease in the wet season, 1.7% increase to 5.3% decrease | ***Potential impacts on habitat***<br>• Shifts in streamflow affect estuarine habitat extent, salinity, and species composition (Fitzsimons et al. 2005; Oʻahu National Wildlife Refuge Complex & U.S. Fish and Wildlife Service 2010)<br>○ High flow conditions are associated with a downstream contraction of estuaries and reduced abundance of species adapted to high salinities (Fitzsimons et al. 2005), and seasonal ponding via freshwater input to tidal marshes (Pacific Coast Joint Venture Hawaiʻi 2006)<br>○ Low flow conditions are associated with upstream expansion of stream mouth estuaries and salt-tolerant species (Fitzsimons et al. 2005) and higher salinities/extreme conditions in tidal marshes (Pacific Coast Joint Venture Hawaiʻi 2006)<br>○ If salinity increases due to reduced stream inputs, foundational native estuarine species will be lost (e.g., ʻeleʻele seaweed, ʻamaʻama [striped mullet; *Mugil cephalus*]; Vuln. Assessment Workshop, pers. comm., 2016)<br>• Oʻahu estuaries generally experience lower streamflow flushing than other islands (Englund et al. 2000b), which increases vulnerability to invasion (Englund et al. 2000b) and promotes hypoxic conditions (Fitzsimons et al. 2005) |

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| | in the dry season; Safeeq & Fares 2012)<br>• If mean annual rainfall decreases within a given watershed, it is likely that there will be:<br>  ○ Continuing decline of low flows and baseflow (Strauch et al. 2015)<br>  ○ Flashier and/or more variable streamflow (Strauch et al. 2015) | • If extreme precipitation events decline, estuaries will become more sensitive to rain events because a lack of regular flushing will allow build up of debris and sediment (Vuln. Assessment Workshop, pers. comm., 2016)<br>• High flow conditions deliver significant sediment, nutrients, and contaminants to estuarine systems, degrading water quality and affecting community composition (Anthony et al. 2004; Hoover et al. 2006; Mead & Wiegner 2010; Stimson 2015)<br>• High flow events temporarily increase oxygen (Fitzsimons et al. 2005) and reduce estuarine water temperature and salinity (Pacific Coast Joint Venture Hawaiʻi 2006; Mead & Wiegner 2010)<br>• Altered streamflows will likely impact estuarine food webs by altering inputs of particulate organic matter from terrestrial and marine sources, driving shifts in the abundance and distribution of bacteria and plankton (Atwood et al. 2012)<br>• Changes in the timing and magnitude of seasonal streamflow may impact the movement of amphidromous gobies, preventing larval survival and/or adult reproduction where low flow prevents migration and adequate habitat continuity (Gehrke et al. 2011)<br><br>***Geographic variation***<br>• Natural systems are more sensitive to altered streamflow regimes (Vuln. Assessment Workshop, pers. comm., 2016)<br>• Leeward estuaries appear to be less able to deal with extreme streamflow/flushing events (Vuln. Assessment Workshop, pers. comm., 2016)<br><br>***Potential refugia***<br>• Heʻeia and Kahana wetlands (Vuln. Assessment Workshop, pers. comm., 2016) |
| *Sea surface temperature & stream temperature* | ***Historical and current trends***<br>• Sea surface temperatures in the Pacific Ocean increased by 0.07°C to 0.23°C (0.13°F to | ***Potential impacts on habitat***<br>• Warmer water temperatures may alter native aquatic species' feeding, growth, reproduction, disease immunity, and survival, ultimately |

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| | 0.41°F) per decade from 1970–2010 (Australian Bureau of Meteorology & CSIRO 2011; IPCC 2013)<br>• In the Northeast Pacific, temperatures increased by 0.12°C (0.22°F) per decade from 1960–1990 (Casey & Cornillon 2001)<br>• No regional stream temperature trends are available, however, the following patterns typically occur:<br>  o Stream temperatures are lower in forested areas compared to urban areas (Brasher 2003)<br>  o Stream temperatures are lower in the wet season than during the dry season (MacKenzie et al. 2013)<br><br>***Projected future trends***<br>There is high certainty that sea surface temperature will increase, but the magnitude of change is less certain and depends on large-scale patterns of ocean mixing and atmospheric processes (e.g., El Niño-Southern Oscillation [ENSO] and Pacific Decadal Oscillation [PDO]). Possible future scenarios include:<br>• By 2100, increase between 1.3°C and 2.7°C (2.3°F and 4.9°F) compared to 1970-2010 (Australian Bureau of Meteorology & CSIRO 2011)<br><br>No regional stream temperature projections are available, but stream temperatures are likely to increase over the coming century (Gehrke et al. 2011) | affecting community composition (Keala et al. 2007; NOAA 2017)<br>• In general, native Hawaiian aquatic fauna prefer cooler, higher oxygenated waters; higher water temperatures lower dissolved oxygen levels (NOAA 2017), which may favor exotic species (Brasher 2003), particularly in habitats permanently or temporarily lacking ocean connectivity (MacKenzie & Bruland 2012)<br>• Surveys from other islands indicate that two species of anchialine pool shrimp (*Halocaridina rubra* and *Metabetaeus lohena*) 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; Hawaiʻi Department of Land and Natural Resources 2015) and have been recorded in areas with water temperatures up to 35°C (95°F; Chan & Fujii 1986)<br>• Other species of anchialine pool shrimp appear to be less tolerant of high water temperatures (Vuln. Assessment Reviewers, pers. comm., 2017)<br>• Chromatophores influence ʻōpaeʻula (*H. rubra*) color, and have been found to exhibit changes in response to high temperatures (32°C [89.6°F]; Vaught et al. 2014)<br><br>***Geographic variation***<br>• Estuarine sensitivity to water temperature is higher in summer (Vuln. Assessment Workshop, pers. comm., 2016)<br>• Estuarine habitats may be more sensitive to sea surface temperature increases than stream temperature increases (Vuln. Assessment Workshop, pers. comm., 2016)<br><br>***Potential refugia***<br>• Areas with groundwater contribution (if groundwater does not decline; Vuln Assessment Workshop, pers. comm., 2016) |

## 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). Development, agriculture, and roads have altered and destroyed native estuarine systems, and may further compound climate-driven habitat changes by altering runoff and sedimentation and/or preventing landward habitat migration. Invasive species alter community composition, often displacing or eliminating native species. Pollution and poisons contribute to direct estuarine species mortality and degrade water quality. These stressors can also affect adjacent ecosystems (e.g., nearshore systems, streams), which can ultimately affect estuaries due to the interconnectedness of these systems (Vuln. Assessment Workshop, pers. comm., 2016). Increasing human populations on Oʻahu are likely to exacerbate many of these stressors (Vuln. Assessment Workshop, pers. comm., 2016).

**Table 2.** Key non-climate stressors that affect the overall sensitivity of estuarine habitats to climate change. Factors presented are those ranked as having a moderate or higher impact on these habitats; additional factors that may influence these habitats to a lesser degree include recreation, water diversions, and invasive/problematic fish, parasites, and mammalian predators (e.g., cats, mongoose).

| **Non-climate stressors** | High impact (high confidence) |
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| *Invasive/ problematic terrestrial & marine species* | ***Potential impacts on habitat***<br>• Introduced aquatic fauna often displace or prey upon native species, and can also introduce novel diseases and parasites (Englund et al. 2000b, 2000a; Fitzsimons et al. 2005; McGuire 2006; Marrack et al. 2015)<br>• Invasive estuarine species have become dominant in many Oʻahu systems, including Pearl Harbor (Englund et al. 2000b); invasive dominance may increase with watershed urbanization and stream degradation (Brasher et al. 2003)<br>• Exotic jellyfish (e.g., upside-down jellyfish; *Cassiopea* spp.) are starting to spread to low-flow areas on Oʻahu (e.g., fishponds; Hofmann & Hadfield 2002)<br>• Invasive vegetation typically reduces habitat quality:<br>  ○ Mangroves (e.g., *Rhizophora mangle*) are the most significant terrestrial invasive in estuarine habitats (Vuln. Assessment Workshop, pers. comm., 2016) and have variable impacts; they enhance water quality and provide nursery habitat (Englund et al. 2000b), but can alter shoreline sediment dynamics, overgrow marsh and fishpond areas, and reduce foraging opportunities for waterbirds and shorebirds (Englund et al. 2000b; Oʻahu National Wildlife Refuge Complex & U.S. Fish and Wildlife Service 2010; MacKenzie & Kryss 2013)<br>  ○ California grass (*Urochloa mutica*), pickleweed (*Batis maritima*) and other invasive plants outcompete native vegetation (Stone 1988), affecting estuarine habitat availability and suitability for wildlife (e.g., by altering food availability and/or dissolved oxygen levels; Hawaiʻi Department of Land and Natural Resources 2015; Sakihara et al. 2017) or by increasing rates of anchialine pool infill (Marrack et al. 2015)<br>• Exotic seaweeds and algae (e.g., gorilla ogo; *Gracilaria salicornia*) overgrow, smother, and displace native algae and benthic organisms (Martinez et al. 2012)<br>• Exotic seaweeds can also alter sediment dynamics, acidity, and dissolved oxygen |

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| | levels, ultimately affecting community composition (Martinez et al. 2012)<br>• *Pattern of exposure:* Consistent across habitat for terrestrial invasive species (mangroves), more localized for marine invasive species |
| *Residential & commercial development* | ***Potential impacts on habitat***<br>• Development has driven coastal wetland habitat loss on Oʻahu (including brackish wetlands; Stone 1988; Pacific Coast Joint Venture Hawaiʻi 2006; Van Rees & Reed 2014; Hawaiʻi Department of Land and Natural Resources 2015), as well as filling and destruction of anchialine pools (Brock & Kam 1997)<br>• Development will continue to directly threaten brackish wetlands and anchialine pools due to high development demand in coastal plain areas (Pacific Coast Joint Venture Hawaiʻi 2006; U.S. Fish and Wildlife Service 2011), although there are laws and regulations that limit development in wetland areas (e.g., "no net loss of wetlands"; Vuln. Assessment Workshop, pers. comm., 2016)<br>• Impermeable surfaces associated with development increase surface runoff and decrease groundwater infiltration, which can alter hydroperiods and salinity and degrade water quality by increasing contaminant, nutrient, and sediment delivery; all of these changes affect habitat suitability for native species (Anthony et al. 2004; Oʻahu National Wildlife Refuge Complex & U.S. Fish and Wildlife Service 2010; Dalton et al. 2013; Marrack et al. 2015)<br>• Stream alterations (e.g., channelization, vegetation removal, bank reinforcement) associated with development can further alter stream mouth estuary hydrology (Brasher 2003); some estuaries are more intensely affected (Vuln. Assessment Workshop, pers. comm., 2016)<br>• Estuarine habitats disturbed or degraded by urban development may be more vulnerable to invasion (Bantilan-Smith et al. 2009)<br>• Development can also prevent landward migration of coastal habitats, including tidal wetlands and anchialine pools, in response to sea level rise (Kane et al. 2014, 2015; Marrack 2016)<br>• *Pattern of exposure:* Consistent exposure, but variable intensity across habitat; most development occurs outside of wetland/estuarine areas |
| *Pollutions & poisons* | ***Potential impacts on habitat***<br>• Pesticides and fertilizers containing phosphates and nitrates are delivered to estuarine habitats through runoff (Anthony et al. 2004; Oʻahu National Wildlife Refuge Complex & U.S. Fish and Wildlife Service 2010, 2011) and groundwater contamination (Anthony et al. 2004)<br>• Sewage inputs may contribute to coastal wetland nutrient loading (Bruland & MacKenzie 2010), high chloride concentrations (Pacific Coast Joint Venture Hawaiʻi 2006), and fecal coliform exposure (Vuln. Assessment Workshop, pers. comm., 2016); coastal wetlands in urbanized watersheds are particularly vulnerable (Bruland & MacKenzie 2010)<br>• Nutrient loading and toxic pollutants (e.g., organic chemicals, heavy metals) degrade water quality and reduce habitat suitability for valued aquatic and terrestrial wildlife including amphidromous fish, crustaceans, and birds (Anthony et al. 2004; Oʻahu National Wildlife Refuge Complex & U.S. Fish and Wildlife Service 2010, 2011; Hawaiʻi Department of Land and Natural Resources 2015)<br>  ○ Nutrient loading (e.g., elevated nitrogen and phosphorus levels) contribute to |

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| | phytoplankton blooms and nuisance algae (Anthony et al. 2004; Mead & Wiegner 2010), which can rapidly deplete dissolved oxygen in estuaries and wetlands (Anthony et al. 2004; Martinez et al. 2012) and affect anchialine pool community structure and function (Marrack et al. 2015 and citations therein)<br>○ Exposure to pollutants may reduce the temperature tolerance of fish, exacerbating the impact of increased water temperatures (Gehrke et al. 2011)<br>○ Flood-delivered contaminants (e.g., trace elements such as lead, zinc, and arsenic) can directly impact native fish and invertebrates (Anthony et al. 2004; Mead & Wiegner 2010)<br>○ Oil spills can disrupt waterbird nesting (Stone 1988)<br>○ Native anchialine pool shrimp are sensitive to pollution from human use (e.g., soaps, shampoos, litter) and human and pet refuse (Mitchell et al. 2005; Conservation Council for Hawaiʻi 2011)<br>• *Pattern of exposure:* Consistent exposure across habitat, but pollution and poison types vary from place to place |
| *Agriculture & aquaculture* | ***Potential impacts on habitat***<br>• Large-scale commercial agriculture and aquaculture are typically harmful to estuaries (Vuln. Assessment Workshop, pers. comm., 2016):<br>○ Agricultural conversion has eliminated some estuarine systems (Pacific Coast Joint Venture Hawaiʻi 2006)<br>○ Agriculture has elevated sediment and pollutant delivery in remnant estuaries (Anthony et al. 2004; Pacific Coast Joint Venture Hawaiʻi 2006; Bruland 2008; Bantilan-Smith et al. 2009; Bruland & MacKenzie 2010)<br>○ Agricultural fertilizers delivered by stream runoff and groundwater elevate estuarine nutrient levels (Anthony et al. 2004)<br>○ Water diversions for agriculture can exacerbate climate-driven water declines (Oki et al. 2006; Yeung & Fontaine 2007)<br>• Small-scale/organic/traditional agriculture and aquaculture may benefit or have a positive impact on estuaries, but there is low and localized estuarine exposure to beneficial impacts from these practices (e.g., Kahana Estuary; Vuln. Assessment Workshop, pers. comm., 2016)<br>• *Pattern of exposure:* Localized |
| *Roads, highways & trails* | ***Potential impacts on habitat***<br>• Roads prevent landward migration of coastal habitats threatened by sea level rise (Kane et al. 2015)<br>• Roads and highways can alter estuarine water quality and hydrology by increasing surface runoff and pollutant and sediment delivery (Conry & Cannarella 2010), potentially affecting estuarine habitat suitability for native species and vulnerability to invasion (Bantilan-Smith et al. 2009)<br>• *Pattern of exposure:* Consistent across habitat |
| *Invasive/ problematic ungulates* | ***Potential impacts on habitat***<br>• Ungulate grazing increases erosion and sediment delivery to estuaries and coastal wetlands (Pacific Coast Joint Venture Hawaiʻi 2006)<br>• Ungulate grazing also promotes invasive plant spread and dominance (Warshauer et al. 2009; Oʻahu National Wildlife Refuge Complex & U.S. Fish and Wildlife Service 2011; Hawaiʻi Department of Land and Natural Resources 2015) |

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| | • *Pattern of exposure:* Localized; pigs (*Sus scrofa*) are the primary ungulate of concern for Oʻahu estuarine habitats |
| *Population growth* | ***Potential impacts on habitat***<br>• Oʻahu is the most populous and developed island in the Hawaiian Islands, and the population is projected to continue to grow in the coming years (Trust for Public Land & Office of Hawaiian Affairs 2015)<br>• Increasing human populations may affect estuarine habitat availability and quality by competing for space (Pacific Coast Joint Venture Hawaiʻi 2006; U.S. Fish and Wildlife Service 2011), water (Conservation Council for Hawaiʻi 2011; Van Rees & Reed 2014), and increasing levels of disturbance (Brasher et al. 2003; Anthony et al. 2004) |

## Adaptive Capacity

Although Oʻahu still supports a variety of estuarine habitats, habitat integrity varies greatly (Table 3). Many estuarine habitats have been degraded or altered by invasive species and hydrological changes as a result of development, agriculture, and roads; these stressors also act as barriers to habitat migration in the face of climate change. Estuarine habitats exhibit some ability to resist and recover from climate impacts, particularly if aided by restoration, but are less resilient to invasive species and human-driven alterations. Native estuarine species are fairly tolerant of extreme conditions, which may reduce overall vulnerability to climate impacts. Estuarine habitats have regulatory protection and some constituency support, and some areas have protected status (e.g., National Wildlife Refuge), which may increase overall habitat resilience to climate change. Additionally, estuarine habitats provide several ecosystem services, which supports habitat management and conservation.

**Table 3.** Adaptive capacity factors that influence the ability of estuary 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 (-).

| **Adaptive capacity factors** | Low-moderate adaptive capacity (high confidence) |
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| *Extent & integrity*<br><br>Moderate (high confidence) | +/- Oʻahu has a large number of estuaries (Hawaiʻi Department of Land and Natural Resources 2015), but significant estuarine habitat has been lost since human settlement, particularly in the Honolulu, Pearl Harbor, and Kapolei regions (Van Rees & Reed 2014)<br>+/- Some estuarine habitats are in decent shape, while others are highly degraded (Pacific Coast Joint Venture Hawaiʻi 2006)<br>- Eight Oʻahu estuaries have been designated as water-quality impaired, primarily for exceeding turbidity and nutrient standards (Hawaiʻi State Department of Health 2017)<br>- Many estuarine habitats on Oʻahu are dominated by invasive species (e.g., Pearl Harbor) or have been degraded by urban and agricultural development (Englund et al. 2000b; Pacific Coast Joint Venture Hawaiʻi 2006)<br>- Anchialine pools are not abundant on Oʻahu (Stone 1988; The Nature Conservancy 2012) and are typically small in size (Conservation Council for |

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| | Hawaiʻi 2011; Yamamoto et al. 2015) |
| *Habitat isolation*<br><br>High<br>(high confidence) | - Primary barriers to estuarine habitat migration include roads, residential and commercial development, and alien vegetation, although many other barriers could be present in different locations and circumstances (Vuln. Assessment Workshop, pers. comm., 2016) |
| *Resistance & recovery*<br><br>Moderate-high<br>(high confidence) | + Estuarine species are typically tolerant of variable conditions due to the dynamic nature of these systems (Gehrke et al. 2011)<br>+ To date, Hawaiian estuaries have been better able to rebound and recover than some other native Hawaiian habitat types when given a "break" (e.g., when invasive species are removed, native ʻakiʻaki and other native plants have returned); this is likely due in part to the adaptability of estuarine species (Vuln. Assessment Workshop, pers. comm., 2016)<br>+/- Mangrove removal typically promotes recovery of native estuarine species; however, there are concerns about enhanced coastal erosion with mangrove removal (Vuln. Assessment Workshop, pers. comm., 2016)<br>- Coastal systems (e.g., estuaries, tidal marshes) have a limited capacity to accrete sediment and keep pace with sea level rise due to small tidal ranges (<2 m [<6.5 ft]; Kane et al. 2015)<br>- Some human-driven ecological changes in anchialine pools may be irreversible (Hawaiʻi Department of Land and Natural Resources 2015) |
| *Habitat diversity*<br><br>Low-moderate<br>(moderate confidence) | + Native aquatic fauna is typically highly endemic, rare, and unique (Brasher 2003; Pacific Coast Joint Venture Hawaiʻi 2006)<br>+ Native foundational estuarine species include mullet (two native species [*Mugil* spp. and *Neomyxus* spp.], one introduced [*Chelon engeli*]), ʻeleʻele seaweed, and native stream gobies (Vuln. Assessment Workshop, pers. comm., 2016)<br>+ Since estuarine species are often adaptable to ranges in environmental variables (e.g., temperature, salinity), it is possible that those species have relatively low vulnerability to climate change (Vuln. Assessment Workshop, pers. comm., 2016)<br>+ Habitat diversity typically improves with restoration (Vuln. Assessment Workshop, pers. comm., 2016)<br>- Disturbance and habitat alteration reduces native estuarine species diversity (Englund et al. 2000a)<br>- It is difficult to identify keystone vegetation species because estuaries have been significantly changed by development and invasion (e.g., see Englund et al. 2000b; Vuln. Assessment Workshop, pers. comm., 2016)<br>- Invasive dominance is quite high in several estuarine and coastal wetland functional groups, including mollusks, aquatic insects (Englund et al. 2000b), and other nekton; exotic dominance is particularly acute in hydrologically isolated wetlands and wetlands lacking ocean connectivity (MacKenzie & Bruland 2012) |
| *Management potential*<br><br>Low-moderate | + Moderate societal support for habitat conservation and management: Support is getting better via the newly designated Heʻeia National Estuarine Research Reserve, as well as efforts by the National Oceanic and Atmospheric Administration and fishpond initiatives (Vuln. Assessment Workshop, pers. |

| | |
|---|---|
| (moderate confidence) | comm., 2016)<br>+ Several constituency groups support estuary conservation and management, including birders, fishpond advocates, Hui Mālama Loko Iʻa, E Alu Pū Network, and Limu Hui (Vuln. Assessment Workshop, pers. comm., 2016)<br>+ Several estuarine habitats are managed and have some type of protected status (e.g., Pearl Harbor National Wildlife Refuge), which may help buffer some non-climate and climate change impacts (Stone 1988; Pacific Coast Joint Venture Hawaiʻi 2006)<br>+ Moderate manager capacity and ability to cope with impacts: Managers can work on climate preparedness and improving estuarine resilience (Vuln. Assessment Workshop, pers. comm., 2016)<br>+ Massive flooding events may increase support for estuarine management by demonstrating the link between functioning estuaries, flood protection, and human safety (Vuln. Assessment Workshop, pers. comm., 2016); extreme events elsewhere (e.g., Hurricane Katrina) have increased support for coastal habitat management by highlighting how natural systems bolster flood control (Tibbetts 2006)<br>+ Tidal wetlands and salt marshes provide a variety of ecosystem services, including flood and erosion control, food production, biodiversity, and water quality and supply regulation (Bruland 2008)<br>+/- Estuaries often conflict with development agendas, but are largely protected from development by several laws and regulations (e.g., "no net loss of wetlands"; Vuln. Assessment Workshop, pers. comm., 2016)<br>- Low-moderate public value: Education is needed because there is a general lack of understanding about what estuaries are and how they support other systems valued for food production (e.g., estuaries provide fish nursery habitat; Vuln. Assessment Workshop, pers. comm., 2016)<br>- Low likelihood of managing or alleviating climate change impacts: Managers have little to no control over climate impacts (Vuln. Assessment Workshop, pers. comm., 2016)<br>- Restored and constructed wetlands have different soil properties than natural wetlands, potentially affecting wetland function and habitat suitability (Bantilan-Smith et al. 2009) |

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# 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[2] (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:

**Vulnerability = [(Climate Exposure*0.5) x Sensitivity] - Adaptive Capacity**

[2] 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 (i.e. temperature and precipitation) as well as climate-driven changes (i.e. 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)

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