Fresh Water

Ecosystem Service Climate Change Vulnerability Assessment Synthesis for O'ahu

An Important Note About this Document: *This document represents an initial evaluation of vulnerability for fresh water on O'ahu 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 ecosystem service vulnerability to changing climate conditions, and to provide a foundation for developing appropriate adaptation responses.*

Ecosystem Service Description

Ecosystem services are defined as "the benefits provided to people, both directly and indirectly, by ecosystems and biodiversity" (Aylward et al. 2005). Fresh water is classified as a provisioning ecosystem service because it supplies both consumptive (e.g., drinking water, agricultural and industrial use) and non-consumptive (e.g., power generation) human uses (Aylward et al. 2005). Fresh water also supports other natural systems and processes that provide additional ecosystem services. For example, it supports aquatic habitats, which in turn provide ecosystem services such as food production, flood control, aesthetic values, and tourism and recreation (Aylward et al. 2005).

Native forests, wetlands, and other habitats help maintain fresh water supply by intercepting, slowing, and storing water. For example, O'ahu's forested Ko'olau Mountains provide an estimated 133 billion gallons of water per year (Sumiye 2002). Native habitats also enhance water quality by anchoring and filtering sediment and filtering pollutants (Sumiye 2002).

O'ahu's fresh water resources include both groundwater and surface water. Wai'anae and Ko'olau are O'ahu's primary aquifers (Sumiye 2002), with central O'ahu providing a majority of the island's groundwater resources (Hunt 2004). O'ahu has both confined and unconfined aquifers; extensive confined caprock aquifers prevent water discharge to the ocean, meaning O'ahu has more abundant groundwater resources than other Hawaiian Islands (Izuka et al. 2016). O'ahu also has extensive surface water resources in the form of perennial and intermittent streams and freshwater wetlands (Hawai'i Department of Land and Natural Resources 2015). Groundwater primarily provides drinking water and supports aquatic habitat via discharge to streams, seeps, and springs, while surface water supplies aquatic habitats and irrigation needs (Anthony et al. 2004).

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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.

Ecosystem Service Vulnerability

The fresh water ecosystem service on O‘ahu was evaluated as having 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.

Fresh Water	Rank	Confidence
Sensitivity	High	High
Future Exposure	High	Moderate[2]
Adaptive Capacity	Low-Moderate	High
Vulnerability	**High**	**High**

Climatic factors such as drought, air temperature, and altered storm and extreme precipitation events have the potential to reduce fresh water supply, and along with sea level rise, may impair water quality. Flooding can temporarily impair water quality, while wind, wildfire, insects, and disease have the potential to alter groundwater infiltration and surface runoff quality by affecting the health and composition of regional forests. Non-climate stressors, including residential and commercial development, agriculture and aquaculture, energy development, water diversions, and groundwater development, alter water use and delivery, potentially compounding future climate-driven reductions in water availability. Human land uses (e.g., roads, urban areas, agriculture) and activities (e.g., recreation) can also impair water quality by introducing contaminants, and affect water capture by increasing runoff and introducing invasive species. Invasive species undermine watershed health and integrity, reducing water storage and degrading water quality.

Fresh water is highly valued by the public and there are several statewide and island-based efforts focused on promoting water conservation and watershed health and function, helping enhance the adaptive capacity of this service in the face of climate change. However, increasing population growth and variable enforcement of laws and policies will challenge management of this ecosystem service. Additionally, fresh water provisioning and quality will largely depend on climate impacts to native forests.

Sensitivity and Exposure

Climatic Factors and Disturbance Regimes

Groundwater and surface water supply are sensitive to climatic changes and disturbance regimes that affect water availability (Table 1), although groundwater may be less sensitive than surface water due to greater storage capacity. Climatic changes that influence water

[2] Workshop participants identified relevant future climate exposure factors and evaluated their confidence in the projected degree of exposure to these factors. After reviewing the scientific literature, EcoAdapt scientists evaluated and modified confidence rankings as needed to reflect uncertainties related to future climate projections. For example, future projections for precipitation are highly variable, with some models showing no change and others showing significant decreases or increases in precipitation. For more information on climate trends and future projections, please see the *Hawaiian Islands Climate Vulnerability and Adaptation Synthesis*.

availability include tropical storms, extreme precipitation events, drought, warmer air temperatures, altered wind patterns, and wildfire, among others. These climatic changes and disturbance regimes affect water delivery, movement, and storage by altering vegetative cover, composition, and water utilization, runoff, and infiltration in O‘ahu’s native ecosystems.

Fresh water quality is sensitive to climatic changes and disturbance regimes including storms, extreme precipitation, wildfire, and flooding that can elevate surface runoff and contaminant and sediment delivery to regional water sources, as well as reduce vegetative cover and its associated filtering mechanisms. Groundwater quality is also sensitive to saltwater intrusion near the shoreline and in older, deeper wells as a result of sea level rise. Overall, surface water quality and quantity is more sensitive to climatic factors and disturbance regimes than groundwater quality and quantity, and water quality in general is less sensitive to climate change than water supply (Vuln. Assessment Workshop, pers. comm., 2016).

Table 1. Current and projected future trends in climatic factors and disturbance regimes, as well as their potential impacts on fresh water. This ecosystem service is sensitive to the climatic factors and disturbance regimes listed below, and will likely be exposed to projected future changes in them.

Climatic factors and disturbance regimes High impact (high confidence)		

Extreme precipitation events & tropical storms/ hurricanes	***Historical and current trends***
	• Since 1950, overall trend towards decreased intensity and frequency of extreme precipitation events (Chu et al. 2010)
	• From 1960–2000, the annual maximum one-day precipitation volume has decreased (Chen & Chu 2014)
	• Tropical storm frequency was particularly high from 1982–1995, but then decreased slightly from 1995–2000 (Chu 2002)
	• Overall, tropical storm frequency increased slightly since 1966–1981 (Chu 2002)
	
	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). Extreme precipitation projections are also highly uncertain because of the variability associated with precipitation projections. 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)
	• Reduced frequency of extreme precipitation events by 2100, particularly in dry areas (Timm et al. 2011, 2013)
	• Little to no change in the frequency of extreme precipitation events by 2100 (Takahashi et al. 2011)
		Potential impacts on ecosystem service
		• Significant precipitation associated with storms and heavy rainfall events stimulates surface runoff and groundwater recharge (Oki et al. 2006)
		  ○ Overall water storage is limited by the rapid transfer of water towards the coast due to small catchment basins, steep slopes, and limited channel storage (Brasher 2003)
		  ○ Healthy native forests help slow and store stormwater, but storms can damage the canopy, undermining water interception and storage (Sumiye 2002)
		• Fewer and smaller wet-season storms may decrease dry-season baseflow, reducing surface water availability (Bassiouni & Oki 2013)
		• Storm and extreme precipitation runoff can deliver contaminants (e.g., fecal indicator bacteria, pesticides, solvents) and sediment to streams, impairing surface water quality (Anthony et al. 2004; Izuka 2012)

	• Significant increase in extreme precipitation events by 2100 (Zhang et al. 2016)	
Sea level rise & saltwater intrusion	***Historical and current trends*** • 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) • 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) ***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) • Sea levels in Honolulu may increase 0.26 to 1.41 m (0.85 to 4.6 ft) by 2100 (Kopp et al. 2014) • There are no projections available for saltwater intrusion, but it is likely to increase due to sea level rise, drought, and groundwater withdrawals (Rotzoll et al. 2010; Ferguson & Gleeson 2012)	***Potential impacts on ecosystem service*** • Sea level rise and saltwater intrusion is likely to increase groundwater salinity, potentially decreasing fresh water supply and quality (Keener et al. 2012; Rotzoll & Fletcher 2013)
Drought	***Historical and current trends*** • Drought length increased in 1980–2011 compared to 1950–1979 (Chu et al. 2010) • Drought conditions are usually less prevalent during La Niña years, and more prevalent during El Niño years (Dolling et al. 2009; Chu et al. 2010)	***Potential impacts on ecosystem service*** • Drought can degrade native forests and may promote non-native vegetation dominance (Michaud et al. 2015), affecting water capture, storage, and infiltration (Sumiye 2002) • Drought decreases or eliminates streamflows, reducing surface water supply for instream and off-stream uses

	Projected future trends Drought projections are highly uncertain because they are primarily dependent on precipitation projections, which are variable and have high uncertainty. Possible future scenarios include: • Drought risk is likely to increase by 2100 for low-elevation leeward areas, decrease at high elevations, and remain static elsewhere (Keener et al. 2012)	(Bassiouni & Oki 2013) • Drought reduces surface water and groundwater supply and may impair water quality by shrinking the freshwater lens (Keener et al. 2012) • Drought conditions enhance fire risk, which can impact water quality (Conry & Cannarella 2010) ***Geographic variation*** • Increased precipitation in windward areas (where most groundwater is drawn from) could benefit water supply (Vuln. Assessment Workshop, pers. comm., 2016) • Leeward areas are particularly sensitive to decreases in precipitation (Vuln. Assessment Workshop, pers. comm., 2016)
Air temperature	***Historical and current trends*** • From 1975–2006, the rate of air temperature increases has accelerated to 0.2°C (0.36°F) per decade, compared to overall increases of 0.04°C (0.07°F) per decade for all records from 1919–1975; the strongest warming is found at high elevations and in winter minimum temperatures (Giambelluca et al. 2008) ***Projected future trends*** Projections that air temperature will increase are highly certain, although the magnitude of change is less certain. Possible future scenarios include: • Air temperature increases by 2°C (3.6°F) to 3.5°C (6.3°F) across the Hawaiian Islands by 2100, with more significant increases at higher elevations (Zhang et al. 2016) • More frequent and more intense extreme heat days (Keener et al. 2012)	***Potential impacts on ecosystem service*** • Higher air temperatures increase evaporation and evapotranspiration, which can reduce surface and groundwater availability (Keener et al. 2012), particularly when paired with decreases in precipitation (Safeeq & Fares 2012) • Increased temperature could increase habitat loss and cause forest alteration (Vuln. Assessment Workshop, pers. comm., 2016)

Wind & circulation	***Historical and current trends*** • Since the 1990s, the Pacific trade winds (both the Walker and Hadley cells) have increased, corresponding with a negative Pacific Decadal Oscillation (PDO) phase (England et al. 2014) • Trade wind direction has shifted from predominantly northeast to east from 1973–2009 (Garza et al. 2012), which represents a cyclical shift that is known to complete its cycle approximately every 45 years (Wentworth 1949) • The frequency of trade wind inversion (TWI) occurrence increased an average of 16% starting in 1990 (Longman et al. 2015) ***Projected future trends*** Projections for the TWI are moderately uncertain due to the influence of large-scale atmospheric patterns (e.g., El Niño-Southern Oscillation [ENSO] and Pacific Decadal Oscillation [PDO]). Possible future scenarios include: • 8% increase in TWI frequency of occurrence, corresponding to an almost 50% decrease in days without a well-defined TWI (decrease from 17% of days currently to 9% of days by 2100; Zhang et al. 2016) • Possible decrease in TWI base height, ranging from small (Zhang et al. 2016) to more significant (Lauer et al. 2013) Surface wind speed and direction may change, but studies have reached varying conclusions: • Nov.–Dec. surface wind speeds across the Hawaiian Islands may decrease strongly by 2100, with small changes in surface wind speed possible in other seasons (Storlazzi et al. 2015) • Surface winds in the Hawaiian Islands may increase	***Potential impacts on ecosystem service*** • Water supply and quality are likely to be affected by changing wind patterns because wind influences rainfall volume and frequency (Longman 2015) • Increased TWI frequency has reduced high-elevation rainfall over the past 25 years (Longman 2015) • More frequent TWIs in the future could reduce water supply by reducing orographic rainfall (Grubert 2010) • Shifts toward increasing TWI frequency are greater during severe El Niño events, which can result in droughts that significantly impact water supplies (Longman 2015)

	modestly, with a very modest increase in frequency of strong wind days (Zhang et al. 2016)	
Riverine flooding	***Historical and current trends*** • No consistent trends were found in stream peak discharge statewide (Oki et al. 2010) ***Projected future trends*** • No regional stream/river flooding projections are available, but flows may become more variable/flashy if mean annual precipitation declines (Strauch et al. 2015)	***Potential impacts on ecosystem service*** • Flash floods can temporarily impair water quality, particularly in highly altered urban watershed segments (Conry & Cannarella 2010)
Wildfire	***Historical and current trends*** • From 1904–2011, the overall trend has been towards increases in area burned across all of the Hawaiian Islands, but with high interannual variability (Trauernicht et al. 2015) ***Projected future trends*** • No regional wildfire projections are available, but increased wildfire is likely if drier conditions and more drought occur (Trauernicht et al. 2015)	***Potential impacts on ecosystem service*** • Wildfires can reduce future water supply by removing native vegetation and facilitating replacement by non-native species, which impair water capture and groundwater recharge (Conry & Cannarella 2010) • High heat associated with fires can also reduce soil permeability, reducing groundwater recharge (Sumiye 2002) • Wildfires impair surface water quality by removing vegetation, which increases runoff and erosion (Sumiye 2002; Trauernicht et al. 2015)
Insects	***Historical and current trends*** • No information is available about trends in insect outbreaks ***Projected future trends*** • 0.4 million forested acres across the Hawaiian Islands are at risk of experiencing a 25% decrease in standing live basal area by 2027 due to the combined threat of insects and disease (not taking climatic changes into account; Krist et al. 2014) ○ 61,000 acres across the Hawaiian Islands are at risk	***Potential impacts on ecosystem service*** • Insects, particularly invasive insects, may impact large areas of forest and cause extensive tree damage, affecting the ability of forests to regulate water supply and quality (Conry & Cannarella 2010)

	due to myoporum thrips (*Klambothrips myopori*; Krist et al. 2014) • 12,000 acres across the Hawaiian Islands are at risk due to Erythrina gall wasp (*Quadrastichus erythrinae*; Krist et al. 2014)	

Disease	***Historical and current trends***
	• No information is available for plant disease
	
	Projected future trends
	• 0.4 million forested acres across the Hawaiian Islands are at risk of experiencing a 25% decrease in standing live basal area by 2027 due to the combined threat of insects and disease (not taking climatic changes into account; Krist et al. 2014)
	  ○ On Oʻahu, the greatest threat from ʻōʻhia rust (*Austropuccinia psidii*) is on windward slopes (Krist et al. 2014)
	  ○ 53,000 acres across the Hawaiian Islands are at risk due to koa wilt (*Fusarium oxysporum* f. sp. *koae*; Krist et al. 2014)
	• Little change is expected in the suitable climatic space for ʻōʻhia rust (Hanna et al. 2012)
		Potential impacts on ecosystem service
		• Pathogens or diseases can cause native tree mortality, potentially affecting surface water supplies and groundwater recharge by altering forest water capture, storage, and infiltration (USDA Forest Service 2015)
		• The impact of native tree mortality on fresh water availability can be compounded in areas where dieback allows the increasing dominance of invasive species (Mortenson et al. 2016)

Non-Climate Stressors

Sensitivity of the ecosystem service to climate change impacts may be highly influenced by the existence and extent of, and current exposure to, non-climate stressors (Table 2). Non-climate stressors often alter watershed hydrology (e.g., by increasing urbanization, altering water delivery, use, and storage, and removing or replacing native vegetation), which impacts fresh water availability and quality. Non-climate stressors can also directly degrade water quality by elevating sediment delivery or introducing contaminants and pollutants.

Groundwater and surface water quality and supply are affected differently by non-climate stressors (Vuln. Assessment Workshop, pers. comm., 2016). The most critical stressors affecting water supply are invasive species, groundwater development, contamination, and water diversions. The most critical stressors affecting surface water quality are agriculture, development, pollution and poisons, mammalian predators, ungulates, roads, and recreation. The most critical stressors affecting groundwater quality are agriculture, development, pollution and poisons, injection wells, and roads (Vuln. Assessment Workshop, pers. comm., 2016).

Table 2. Key non-climate stressors that affect the overall sensitivity of fresh water to climate change. Additional factors that could affect this ecosystem service to a lesser degree include invasive/problematic fish.

Non-climate stressors High impact (high confidence)	
Residential & commercial development	***Potential impacts on ecosystem service*** • Development can destroy or degrade native habitats critical for regulating water supply and quality (e.g., wetlands; Stone 1988; Pacific Coast Joint Venture Hawai‘i 2006; Van Rees & Reed 2014; Hawai‘i Department of Land and Natural Resources 2015) • Development increases impermeable surface cover and runoff, reducing water capture and storage (Grubert 2010) • Runoff from developed areas delivers contaminants (e.g., solvents) to groundwater and surface water systems, impairing water quality (Anthony et al. 2004) • Urban runoff can also elevate suspended sediments in surface water systems, degrading surface water quality (Anthony et al. 2004)
Agriculture & aquaculture	***Potential impacts on ecosystem service*** • Reduced forest cover as a result of agricultural conversion (Bassiouni & Oki 2013) historically reduced surface water availability by causing shifts from perennial to intermittent streams (Wilcox 1997) • Agricultural irrigation reduces surface water availability for instream uses (Brasher 2003; Anthony et al. 2004; Oki et al. 2006) • Pesticides and herbicides used for agriculture can contaminate surface and groundwater (Anthony et al. 2004; Hunt 2004) • Agricultural fertilizers elevate groundwater and surface water nutrient levels, reducing water quality (Anthony et al. 2004)

	• Despite the decline of agriculture on O‘ahu, there are still legacy agricultural impacts on groundwater quality because unconfined aquifers allow contaminants to seep into deep aquifer zones; groundwater contamination is highest in Central O‘ahu due to extensive historical agricultural chemical use (Anthony et al. 2004; Hunt 2004) • Surface runoff in agricultural areas can increase suspended sediment in surface water, degrading water quality (Anthony et al. 2004; Izuka 2012) • Fresh water aquaculture effluent can degrade fresh water quality by elevating nutrients and suspended sediment (Ziemann et al. 1992)
Pollutions & poisons	***Potential impacts on ecosystem service*** • Pollutants (e.g., fertilizers, pesticides, nutrients, sewage inputs) degrade water quality, negatively affecting both natural and human communities (Hunt & De Carlo 2000; Conry & Cannarella 2010; O‘ahu National Wildlife Refuge Complex & U.S. Fish and Wildlife Service 2010; Bruland & MacKenzie 2010; O‘ahu National Wildlife Refuge Complex & U.S. Fish and Wildlife Service 2011) • Human land use activities (e.g., agriculture, urbanization) are the primary source of pollutants and impaired water quality on O‘ahu (Anthony et al. 2004; Conry & Cannarella 2010)
Energy production	***Potential impacts on ecosystem service*** • Biofuel production (e.g., sugarcane crops) can be water intensive, affecting future water use and supply (Grubert 2010)
Roads, highways & trails	***Potential impacts on ecosystem service*** • Roads, highways, and trails increase runoff, reducing water storage (Sutherland et al. 2001; Conry & Cannarella 2010) • Roads and highways can degrade surface and groundwater quality by introducing pollutants (e.g., oil, chemicals; Conry & Cannarella 2010)
Groundwater development	***Potential impacts on ecosystem service*** • Groundwater withdrawals can reduce or eliminate surface water availability in streams by reducing baseflow (Brasher et al. 2003; Brasher 2003; Oki et al. 2006; Yeung & Fontaine 2007; Mair & Fares 2010; Safeeq & Fares 2012) • Groundwater withdrawals that exceed recharge rates can compromise fresh water quality by increasing saltwater intrusion (Rotzoll et al. 2010; Ferguson & Gleeson 2012)
Water diversions	***Potential impacts on ecosystem service*** • Water diversions can eliminate or reduce stream surface water availability (Brasher et al. 2003; Brasher 2003; Oki et al. 2006; Yeung & Fontaine 2007) • Upstream water diversions may affect groundwater recharge, influencing future water availability (Hawai‘i Department of Agriculture 2003)
Recreation	***Potential impacts on ecosystem service*** • Recreation activities can promote invasive species spread, potentially affecting watershed health (Conry & Cannarella 2010)

Invasive/ problematic parasites & pathogens	***Potential impacts on ecosystem service*** • Surface water supply and groundwater recharge may be affected by shifts in forest structure and composition as a result of non-native pathogen introduction and spread (e.g., ʻōʻhia rust; Loope & Giambelluca 1998; Loope & Uchida 2012; USDA Forest Service 2015; Mortenson et al. 2016)
Invasive/ problematic flammable grasses	***Potential impacts on ecosystem service*** • Flammable invasive grasses contribute to increased wildfire severity and area burned, increasing erosion potential (Ellsworth et al. 2013, 2014; Trauernicht et al. 2015)
Invasive/ problematic mammalian predators	***Potential impacts on ecosystem service*** • Exotic mammalian predators (e.g., rats, mongoose, cats) may contribute to degraded water quality by elevating fecal indicator bacteria (Dunkell et al. 2011b) and shedding parasites (e.g., *Leptospira*, *Toxoplasma*; Dubey & Jones 2008; Buchholz et al. 2016)
Invasive/ problematic ungulates	***Potential impacts on ecosystem service*** • Feral ungulates increase runoff by trampling, consuming, and removing native vegetation and increasing soil compaction, which undermines water capture and storage (Bruland et al. 2010; Dunkell et al. 2011a) • Ungulate grazing can degrade surface water quality by increasing erosion and sedimentation (Pacific Coast Joint Venture Hawaiʻi 2006; Bruland et al. 2010; Dunkell et al. 2011b) ○ Enhanced sedimentation can impair functioning of native ecosystems critical for water supply and quality regulation (e.g., wetlands; Pacific Coast Joint Venture Hawaiʻi 2006) • Ungulate grazing can also degrade water quality by increasing surface water fecal indicator bacteria (Dunkell et al. 2011b; Strauch et al. 2016) and shedding parasites (Buchholz et al. 2016) • Feral ungulates also promote the spread and establishment of non-native plants, affecting watershed hydrology (Conry & Cannarella 2010)
Invasive/ problematic trees & shrubs	***Potential impacts on ecosystem service*** • Non-native forest vegetation (e.g., strawberry guava [*Psidium cattleianum*], miconia [*Miconia calvescens*]) may reduce surface water and groundwater availability by affecting annual streamflow, baseflow, and groundwater recharge, compounding climate-driven reductions in water availability (Kaiser 2006; Bassiouni & Oki 2013; Strauch et al. 2017) • In a study plot on the windward side of Hawaiʻi, results indicate that full restoration of wet forests invaded by strawberry guava would increase mean annual water yield by 2.8% (MacKenzie et al. 2014) • Invasive trees and shrubs can alter or degrade lowland wetland habitats (e.g., California grass [*Urochloa mutica*], pickleweed [*Batis maritima*], seashore paspalum [*Paspalum vaginatum*], and *Pulchea* species), affecting water storage and filtration (Stone 1988; Bantilan-Smith et al. 2009; Oʻahu National Wildlife Refuge Complex & U.S. Fish and Wildlife Service 2010, 2011; Hawaiʻi Department of Land and Natural Resources 2015)

Invasive/ problematic social insects	***Potential impacts on ecosystem service*** • Surface water supply and groundwater recharge may be affected by shifts in forest structure, composition, and health as a result of non-native social insects (e.g., ants; Conry & Cannarella 2010; USDA Forest Service 2015)
Population growth	***Potential impacts on ecosystem service*** • O‘ahu 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) • Population growth is likely to affect water demand and usage (CH2M Hill 2013), the distribution and integrity of native ecosystems critical for regulating water supply and quality (O‘ahu National Wildlife Refuge Complex & U.S. Fish and Wildlife Service 2011), and the degree of exposure to other non-climate stressors and their associated impacts (e.g., development, recreation; Anthony et al. 2004)

Adaptive Capacity

Management and maintenance of fresh water in the face of climate change is supported by high public value of this ecosystem service, mutual benefits with other ecosystem services (e.g., flood and erosion control), and statewide and regional planning and protection efforts (Table 3). However, variable enforcement of laws and policies and degraded resilience of native forests to climatic changes is likely to challenge management of this ecosystem service.

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

Adaptive capacity factors	Low-moderate adaptive capacity (high confidence)
Intrinsic value & management potential	**+** High public value: Clean and abundant fresh water is a necessity for life and many other aspects of societal living (e.g., agriculture; Vuln. Assessment Workshop, pers. comm., 2016) **+** Maintenance of the fresh water ecosystem service has mutual benefits for flood and erosion control and traditional cultural practices (Vuln. Assessment Workshop, pers. comm., 2016) **+** Land-use planning can help reduce groundwater contamination; for example, groundwater quality has been protected near Honolulu by ensuring that unconfined aquifer zones are not subjected to land uses associated with high contaminant levels (Anthony et al. 2004) **+** There are some statewide (e.g., Hawai‘i Water Conservation Plan) and island-based efforts (e.g., Ko‘olau and Wai‘anae Mountains Watershed Partnerships) to promote water conservation and maintain water quality (Sumiye 2002; CH2M Hill 2013) **+/-** Moderate societal support for ecosystem service conservation and management: There are laws and regulations in place, but these are often not enforced or backed by action and funding (Vuln. Assessment Workshop, pers.

	comm., 2016) +/- There are no alternate ways to access fresh water (CH2M Hill 2013) ○ Limited availability may increase human willingness to change behavior to continue to access this service (Vuln. Assessment Workshop, pers. comm., 2016) ○ However, excessive water usage can threaten availability of this resource in the future, particularly given an increasing human population and the threats of climate change (CH2M Hill 2013) +/- Low-moderate likelihood of managing or alleviating climate change impacts: Management will likely increase when fresh water becomes a serious issue, but management capacity to buffer climate impacts is less certain (Vuln. Assessment Workshop, pers. comm., 2016) - Increasing populations on O‘ahu will also challenge future fresh water management (Vuln. Assessment Workshop, pers. comm., 2016) - Conflicts with other services such as recreation, tourism, hunting, and cultural practices (Vuln. Assessment Workshop, pers. comm., 2016)
Other adaptive capacity factors	- Low resilience of native forests to climate impacts will undermine the resiliency of this ecosystem service (Vuln. Assessment Workshop, pers. comm., 2016)

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Literature Cited

Anthony SS, Hunt CD Jr, Brasher AMD, Miller LD, Tomlinson MS. 2004. Water quality on the island of O‘ahu, Hawai‘i, 1999-2001. Circular 1239. U.S. Department of the Interior, U.S. Geological Survey, Reston, VA.

Aylward B et al. 2005. Chapter 7: Freshwater ecosystem services. Pages 213–255 in K. Chopra, R. Leemans, P. Kumar, and H. Simons, editors. Ecosystems and human well-being: Policy responses. Findings of the Responses Working Group of the Millennium Ecosystem Assessment. Island Press. Available from http://www.millenniumassessment.org/en/Responses.html.

Bantilan-Smith M, Bruland GL, MacKenzie RA, Henry AR, Ryder CR. 2009. A comparison of the vegetation and soils of natural, restored, and created coastal lowland wetlands in Hawai‘i. Wetlands **29**:1023–1035.

Bassiouni M, Oki DS. 2013. Trends and shifts in streamflow in Hawai‘i, 1913–2008. Hydrological Processes **27**:1484–1500.

Brasher AMD. 2003. Impacts of human disturbances on biotic communities in Hawaiian streams. BioScience **53**:1052–1060.

Brasher AMD, Wolff RH, Luton CD. 2003. Associations among land-use, habitat characteristics, and invertebrate community structure in nine streams on the island of O‘ahu, Hawai‘i. Water-

Resources Investigations Report. U.S. Geological Survey, Reston, VA. Available from https://pubs.er.usgs.gov/publication/wri034256 (accessed December 22, 2016).

Bruland GL, Browning CA, Evensen CI. 2010. Effects of feral pigs (*Sus scrofa*) on watershed health in Hawai'i: A literature review and preliminary results on runoff and erosion. Pages 251–278 in J. Roumasset, Ki. M. Burnett, and A. M. Balisacan, editors. Sustainability Science for Watershed Landscapes. Institute of Southeast Asian Studies.

Bruland GL, MacKenzie RA. 2010. Nitrogen source tracking with δ15N content of coastal wetland plants in Hawai'i. Journal of Environmental Quality **39**:409–419.

Buchholz AE, Katz AR, Galloway R, Stoddard RA, Goldstein SM. 2016. Feral swine Leptospira seroprevalence survey in Hawai'i, USA, 2007–2009. Zoonoses and Public Health **63**:584–587.

CH2M Hill. 2013. Hawai'i water conservation plan. Hawai'i Department of Land and Natural Resources and U.S. Army Corps of Engineers, Honolulu, HI. Available from http://files.hawaii.gov/dlnr/cwrm/planning/hwcp2013.pdf.

Chen YR, Chu P-S. 2014. Trends in precipitation extremes and return levels in the Hawaiian Islands under a changing climate. International Journal of Climatology **34**:3913–3925.

Chu P-S. 2002. Large-scale circulation features associated with decadal variations of tropical cyclone activity over the Central North Pacific. Journal of Climate **15**:2678–2689.

Chu P-S, Chen YR, Schroeder TA. 2010. Changes in precipitation extremes in the Hawaiian Islands in a warming climate. Journal of Climate **23**:4881–4900.

Conry PJ, Cannarella RJ. 2010. Hawai'i statewide assessment of forest conditions and resource strategy. Hawai'i Department of Land and Natural Resources - Division of Foresty and Wildlife, Honolulu, HI. Available from http://dlnr.hawaii.gov/forestry/files/2013/09/SWARS-Entire-Assessment-and-Strategy.pdf.

Dolling K, Chu P-S, Fujioka F. 2009. Natural variability of the Keetch–Byram Drought Index in the Hawaiian Islands. International Journal of Wildland Fire **18**:459–475.

Dubey JP, Jones JL. 2008. Toxoplasma gondii infection in humans and animals in the United States. International Journal for Parasitology **38**:1257–1278.

Dunkell DO, Bruland GL, Evensen CI, Litton CM. 2011a. Runoff, sediment transport, and effects of feral pig (Sus scrofa) exclusion in a forested Hawaiian watershed. Pacific Science **65**:175–194.

Dunkell DO, Bruland GL, Evensen CI, Walker MJ. 2011b. Effects of feral pig (*Sus scrofa*) exclusion on enterococci in runoff from the forested headwaters of a Hawaiian watershed. Water, Air, & Soil Pollution **221**:313–326.

Ellsworth LM, Litton CM, Dale AP, Miura T. 2014. Invasive grasses change landscape structure and fire behaviour in Hawai'i. Applied Vegetation Science **17**:680–689.

Ellsworth LM, Litton CM, Taylor AD, Kauffman JB. 2013. Spatial and temporal variability of guinea grass (*Megathyrsus maximus*) fuel loads and moisture on O'ahu, Hawai'i. International Journal of Wildland Fire **22**:1083–1092.

England MH, McGregor S, Spence P, Meehl GA, Timmermann A, Cai W, Gupta AS, McPhaden MJ, Purich A, Santoso A. 2014. Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. Nature Climate Change **4**:222–227.

Ferguson G, Gleeson T. 2012. Vulnerability of coastal aquifers to groundwater use and climate change. Nature Climate Change **2**:342–345.

Garza JA, Chu P-S, Norton CW, Schroeder TA. 2012. Changes of the prevailing trade winds over the islands of Hawai'i and the North Pacific. Journal of Geophysical Research: Atmospheres **117**:D11109.

Giambelluca TW, Diaz HF, Luke MSA. 2008. Secular temperature changes in Hawai'i. Geophysical Research Letters **35**:L12702.

Grubert E. 2010. Maui's freshwater: Status, allocation, and management for sustainability. Master of Arts. The University of Texas at Austin, Austin, TX. Available from https://repositories.lib.utexas.edu/bitstream/handle/2152/ETD-UT-2010-08-1835/GRUBERT-THESIS.pdf?sequence=1&isAllowed=y.

Hanna JW, Graca RN, Kim MS, Ross-Davis AL, Hauff RD, Uchida JW. 2012. A bioclimatic approach to predict global regions with suitable climate space for *Puccina psidii*. In S. Zeglen & P. Palacios (Eds.), Proc. 59th Annual Western International Forest Disease Work Conference (pp. 131–136). Leavenworth, WA, US: Department of Agriculture, Forest Service, Forest Health Protection. October 11-14, 2011.

Hawaiʻi Department of Agriculture. 2003. Agricultural water use and development plan. Available from http://hdoa.hawaii.gov/arm/files/2012/12/AWUDP-Dec2003.pdf.

Hawaiʻi Department of Land and Natural Resources. 2015. Hawaiʻi's State Wildlife Action Plan (SWAP). Prepared by H. T. Harvey and Associates, Honolulu, HI. Available from http://www.state.hi.us/dlnr/dofaw/swap/ (accessed November 2, 2016).

Hunt CD Jr. 2004. Ground-water quality and its relation to land use on Oʻahu, Hawaiʻi, 2000-01. Water Resources Investigations Report 03-4305. U.S. Geological Survey, Honolulu, HI. Available from https://pubs.usgs.gov/wri/wri034305/pdf/wri034305.pdf.

Hunt CD Jr, De Carlo EH. 2000. Hydrology and water and sediment quality at James Campbell National Wildlife Refuge near Kahuku, Island of Oʻahu, Hawaiʻi. Water Resources Investigations Report 99–4171. U.S. Geological Survey and U.S. Fish and Wildlife Service, Honolulu, HI. Available from https://pubs.usgs.gov/wri/wri99-4171/pdf/wri99-4171.pdf.

Izuka SK. 2012. Sources of suspended sediment in the Waikele Watershed, Oʻahu, Hawaiʻi. Scientific Investigations Report 2012–5085. U.S. Geological Survey, Reston, VA. Available from https://pubs.usgs.gov/sir/2012/5085/sir2012-5085.pdf.

Izuka SK, Engott JA, Bassiouni M, Johnson AG, Miller LD, Rotzoll K, Mair A. 2016. Volcanic aquifers of Hawaiʻi—Hydrogeology, water budgets, and conceptual models. Page 172. USGS Numbered Series 2015–5164, Scientific Investigations Report. U.S. Geological Survey, Reston, VA. Available from http://pubs.er.usgs.gov/publication/sir20155164.

Kaiser BA. 2006. Economic impacts of non-indigenous species: Miconia and the Hawaiian economy. Euphytica **148**:135–150.

Keener VW, Marra JJ, Finucane ML, Spooner D, Smith MH. 2012. Climate change and Pacific Islands: Indicators and impacts. Report for the 2012 Pacific Islands Regional Climate Assessment (PIRCA). Island Press, Washington, D.C.

Kopp RE, Horton RM, Little CM, Mitrovica JX, Oppenheimer M, Rasmussen DJ, Strauss BH, Tebaldi C. 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. Earth's Future **2**:2014EF000239.

Krist FJ, Ellenwood JR, Woods ME, McMahan AJ, Cowardin JP, Ryerson DE, Sapio FJ, Sweifler MO, Romero SA. 2014. 2013–2027 National Insect and Disease Forest Risk Assessment. FHTET 14-01. USDA Forest Service Forest Health Technology Enterprise Team, Fort Collins, CO.

Lauer A, Zhang C, Elison Timm O, Wang Y, Hamilton K. 2013. Downscaling of climate change in the Hawaiʻi region using CMIP5 results: On the choice of the forcing fields. Journal of Climate **26**:10006–10030.

Longman RJ. 2015. The effects of trade wind inversion variability on high elevation climates in Hawaiʻi. University of Hawaiʻi at Mānoa. Available from http://gradworks.umi.com/37/17/3717196.html.

Longman RJ, Diaz HF, Giambelluca TW. 2015. Sustained increases in lower-tropospheric subsidence over the central tropical North Pacific drive a decline in high-elevation rainfall in Hawaiʻi. Journal of Climate **28**:8743–8759.

Loope LL, Giambelluca TW. 1998. Vulnerability of island tropical montane cloud forests to climate change, with special reference to East Maui, Hawaiʻi. Climatic Change **39**:503–517.

Loope LL, Uchida JY. 2012. The challenge of retarding erosion of island biodiversity through phytosanitary measures: an update on the case of *Puccinia psidii* in Hawaiʻi. Pacific Science **66**:127–139.

MacKenzie R, Giardina CP, Povak N, Hessburg P, Reynolds KM, Heider C, Salminen E, Kimball H. 2014. Development of a decision support tool for watershed management in the tropics. Institute of Pacific Islands Forestry, USDA Forest Service.

Mair A, Fares A. 2010. Influence of groundwater pumping and rainfall spatio-temporal variation on streamflow. Journal of Hydrology **393**:287–308.

Michaud J, Cordell S, Cole TC, Ostertag R. 2015. Drought in an invaded Hawaiian lowland wet forest. Pacific Science **69**:367–383.

Mortenson LA, Flint Hughes R, Friday JB, Keith LM, Barbosa JM, Friday NJ, Liu Z, Sowards TG. 2016. Assessing spatial distribution, stand impacts and rate of Ceratocystis fimbriata induced ʻōhiʻa (*Metrosideros polymorpha*) mortality in a tropical wet forest, Hawaiʻi Island, USA. Forest Ecology and Management **377**:83–92.

Murakami H, Wang B, Li T, Kitoh A. 2013. Projected increase in tropical cyclones near Hawaiʻi. Nature Climate Change **3**:749–754.

NOAA/National Ocean Service. 2017. NOAA Tides and Currents: Sea Level Trends. Available from http://tidesandcurrents.noaa.gov/sltrends/sltrends.html (accessed July 13, 2017).

Oʻahu National Wildlife Refuge Complex, U.S. Fish and Wildlife Service. 2010. Pearl Harbor National Wildlife Refuge comprehensive conservation plan. U.S. Fish and Wildlife Service. Available from https://www.fws.gov/uploadedFiles/Region_1/NWRS/Zone_1/Oahu_Complex/Pearl_Harbor/Documents/Pearl%20Harbor%20NWR%20Final%20CCP.pdf.

Oʻahu National Wildlife Refuge Complex, U.S. Fish and Wildlife Service. 2011. James Campbell National Wildlife Refuge comprehensive conservation plan. U.S. Fish and Wildlife Service, Honolulu, HI. Available from https://www.fws.gov/uploadedFiles/Region_1/NWRS/Zone_1/Oahu_Complex/James_Campbell/Documents/James%20Campbell%20NWR%20CCP%20(final)%2012-01-11.pdf.

Oki DS, Rosa SN, Yeung CW. 2010. Flood-frequency estimates for streams on Kauaʻi, Oʻahu, Molokaʻi, Maui, and Hawaiʻi, State of Hawaiʻi. U.S. Geological Survey Scientific Investigations Report 2010–5035. U.S. Geological Survey, Reston, VA.

Oki DS, Wolff RH, Perreault JA. 2006. Effects of surface-water diversion and ground-water withdrawal on streamflow and habitat, Punaluʻu Stream, Oʻahu, Hawaiʻi. Scientific Investigations Report 2006–5153. U.S. Geological Survey, Reston, VA.

Pacific Coast Joint Venture Hawaiʻi. 2006. Strategic plan for wetland conservation in Hawaiʻi. Ducks Unlimited. Available from http://www.pacificbirds.org/wp-content/uploads/2014/12/HWJVStrategicPlan-3.pdf.

Rotzoll K, Fletcher CH. 2013. Assessment of groundwater inundation as a consequence of sea-level rise. Nature Climate Change **3**:477–481.

Rotzoll K, Oki DS, El-Kadi AI. 2010. Changes of freshwater-lens thickness in basaltic island aquifers overlain by thick coastal sediments. Hydrogeology Journal **18**:1425–1436.

Safeeq M, Fares A. 2012. Hydrologic response of a Hawaiian watershed to future climate change scenarios. Hydrological Processes **26**:2745–2764.

Stone CP. 1988. Hawai'i's wetlands, streams, fishponds, and pools. Pages 125–136 in C. P. Stone and D. B. Stone, editors. Conservation biology in Hawaiʻi. Cooperative National Park Resources Studies Unit, University of Hawaiʻi, Honolulu, HI. Available from http://manoa.hawaii.edu/hpicesu/book/1988_chap/29.pdf.

Storlazzi CD, Shope JB, Erikson LH, Hegermiller CA, Barnard PL. 2015. Future wave and wind projections for United States and United-States-affiliated Pacific Islands. Page 455. USGS Numbered Series Open-File Report 2015-1001, Open-File Report. U.S. Geological Survey, Reston, VA. Available from http://pubs.er.usgs.gov/publication/ofr20151001 (accessed May 24, 2016).

Strauch AM, Bruland GL, MacKenzie RA, Giardina CP. 2016. Soil and hydrological responses to wild pig (*Sus scofa*) exclusion from native and strawberry guava (*Psidium cattleianum*)-invaded tropical montane wet forests. Geoderma **279**:53–60.

Strauch AM, Giardina CP, MacKenzie RA, Heider C, Giambelluca TW, Salminen E, Bruland GL. 2017. Modeled effects of climate change and plant invasion on watershed function across a steep tropical rainfall gradient. Ecosystems **20**:583–600.

Strauch AM, MacKenzie RA, Giardina CP, Bruland GL. 2015. Climate driven changes to rainfall and streamflow patterns in a model tropical island hydrological system. Journal of Hydrology **523**:160–169.

Sumiye J. 2002. Koʻolau Mountains Watershed Partnership Management Plan. Koʻolau Mountains Watershed Partnership. Available from http://hawp.org/_library/documents/koolau-mountains-wp/kmwpmp.pdf.

Sutherland RA, Bussen JO, Plondke DL, Evans BM, Ziegler AD. 2001. Hydrophysical degradation associated with hiking-trail use: a case study of Hawaiʻiloa Ridge Trail, Oʻahu, Hawaiʻi. Land Degradation & Development **12**:71–86.

Sweet WV, Kopp RE, Weaver CP, Obeysekera J, Horton RM, Thieler ER, Zervas C. 2017. Global and regional sea level rise scenarios for the United States. NOAA Technical Report NOS CO-OPS 083. National Oceanic and Atmospheric Administration, Silver Spring, MD.

Takahashi M, Elison Timm O, Giambelluca TW, Diaz HF, Frazier AG. 2011. High and low rainfall events in Hawaiʻi in relation to large-scale climate anomalies in the Pacific: Diagnostics and future projections. American Geophysical Union, Fall Meeting 2011, Abstract #GC51D-1024 **51**. Available from http://adsabs.harvard.edu/abs/2011AGUFMGC51D1024T (accessed June 2, 2016).

Timm OE, Diaz HF, Giambelluca TW, Takahashi M. 2011. Projection of changes in the frequency of heavy rain events over Hawaiʻi based on leading Pacific climate modes. Journal of Geophysical Research: Atmospheres **116**:D04109.

Timm OE, Giambelluca TW, Diaz HF. 2013. Climate change impacts on critical ecosystems in Hawaiʻi and US Pacific Islands territories: Final report. Final Report to PICCC. Pacific Islands Landscape Conservation Cooperative, Honolulu, HI. Available from https://www.sciencebase.gov/catalog/item/54b83e7de4b03ff52703c997.

Trauernicht C, Pickett E, Giardina CP, Litton CM, Cordell S, Beavers A. 2015. The contemporary scale and context of wildfire in Hawaiʻi. Pacific Science **69**:427–444.

Trust for Public Land, Office of Hawaiian Affairs. 2015. Finding balance between development and conservation: The Oʻahu Greenprint. Trust for Public Land, Honolulu, HI.

USDA Forest Service. 2015. Forest health: 2014 highlights. Available from http://fhm.fs.fed.us/fhh/fhh_14/HI_FHH_2014.pdf.

Van Rees CB, Reed JM. 2014. Wetland loss in Hawaiʻi since human settlement. Wetlands **34**:335–350.

Wentworth CK. 1949. Directional shift of trade winds at Honolulu. Available from http://scholarspace.manoa.hawaii.edu/handle/10125/8917 (accessed March 24, 2017).

Wilcox C. 1997. Sugar water: Hawaiʻi's plantation ditches. University of Hawaiʻi Press.

Yeung CW, Fontaine RA. 2007. Natural and diverted low-flow duration discharges for streams affected by the Waiāhole Ditch System, Windward Oʻahu, Hawaiʻi. Scientific Investigations Report 2006–5285. U.S. Geological Survey, Reston, VA. Available from https://pubs.usgs.gov/sir/2006/5285/sir2006-5285.pdf.

Zhang C, Wang Y, Hamilton K, Lauer A. 2016. Dynamical downscaling of the climate for the Hawaiian Islands. Part II: Projection for the late twenty-first century. Journal of Climate **29**:8333–8354.

Ziemann DA, Walsh WA, Saphore EG, Fulton-Bennett K. 1992. A survey of water quality characteristics of effluent from Hawaiian aquaculture facilities. Journal of the World Aquaculture Society **23**:180–191.

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[3] (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

[3] 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.

EcoAdapt. 2014b. A climate change vulnerability assessment for resources of Nez Perce-Clearwater National Forests. Version 3.0. EcoAdapt, Bainbridge Island, WA.

Glick P, Stein BA, Edelson NA. 2011. Scanning the conservation horizon: A guide to climate change vulnerability assessment. National Wildlife Federation, Washington, D.C.

Hutto SV, Higgason KD, Kershner JM, Reynier WA, Gregg DS. 2015. Climate change vulnerability assessment for the north-central California coast and ocean. Page 473. ONMS-15-02, Marine Sanctuaries Conservation Series. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD.

Intergovernmental Panel on Climate Change (IPCC). 2014. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

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

Lawler J. 2010. Pacific Northwest Climate Change Vulnerability Assessment. Available from http://climatechangesensitivity.org/.

Manomet Center for Conservation Science, National Wildlife Federation. 2013. The vulnerabilities of fish and wildlife habitats in the Northeast to climate change. A report to the Northeastern Association of Fish and Wildlife Agencies and the North Atlantic Landscape Conservation Cooperative. Manomet Center for Conservation Sciences, Plymouth, MA.

Moss R, Schneider S. 2000. Towards consistent assessment and reporting of uncertainties in the IPCC TAR. In R. Pachauri and T. Taniguchi, editors. Cross-cutting issues in the IPCC Third Assessment Report. Global Industrial and Social Progress Research Institute (for IPCC), Tokyo.