A Climate Change Vulnerability Assessment for Aquatic Resources in the Tongass National Forest

A report to the Tongass National Forest

EcoAdapt

November 2014

Cover photo: Shakes Glacier, Stikine River, near Wrangell, Alaska. Photo courtesy of Carey Carmichael Case.

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This assessment is dedicated to the memory of Gregory Mark Killinger who died on 25 May 2014 while hiking in the spectacular forests of Southeast Alaska.

Greg's commitment to responsible resource management, his humble approach to executing that management, his gentle way of encouraging the best from others, and his passion for life (both at work and play) were all apparent in his leadership of the effort resulting in this report. We honor Greg by beginning to uncover the fascinating story of links between snowflakes, glaciers, streams, riparian systems, the bounty of freshwater & anadromous fish and the climate of Southeast Alaska that are the focus of this work, and the focus of his passion. Thank you Greg for your smile of encouragement and your biological insight.

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1. Introduction

This vulnerability assessment is an initial science-based effort to identify how and why important resources (snow, ice, and water features; riparian vegetation; fish species) across the Tongass National Forest are likely to be affected by both non-climate stressors and future climate conditions. In this assessment, vulnerability is a function of the sensitivity of the resource to climate and non-climate stressors, its anticipated exposure to climatic changes, and its capacity to adapt to or cope with changes. Specifically, sensitivity is defined as a measure of whether and how a resource is likely to be affected by a given change in climate, or factors driven by climate; exposure is defined as the degree of change in climatic factors a resource is likely to experience; and adaptive capacity is defined as the ability of a resource to accommodate or cope with climate change impacts with minimal disruption (Glick et al. 2011).[1] The goal of this vulnerability assessment is to help resource managers plan their management of snow, ice, and water features, riparian vegetation, and fish species in light of a changing climate. Specifically, this information can help identify management actions and responses and facilitate priority setting of those responses. The analyses and conclusions contained within this assessment are based on available information and expert opinion.

Climate change vulnerability assessments provide two kinds of information: (1) they identify which resources may be most affected by changing climate conditions, and (2) they improve understanding as to why these resources may be vulnerable. Knowing which resources may be most vulnerable facilitates setting priorities for management action, while understanding why provides a basis for developing appropriate management responses (Glick et al. 2011). Throughout this document we use the term vulnerability to describe the potential response to climate change. Despite the negative connotation of this term, and associated terms (e.g. sensitivity, impact), we emphasize that some outcomes will result in changes that compliment management goals. Hence, we do not assume that vulnerability and 'impacts' related to a changing climate are necessarily negative.

The goal of this assessment is to provide vulnerability information and supporting tools and resources that could help forest managers plan their management of important resources in a changing climate. To meet this goal, the assessment has three main objectives:

1. To use the latest scientific information and expert knowledge to evaluate vulnerabilities of important resources to climate change including assessing sensitivity, exposure, and adaptive capacity.
2. To quantify sensitivities and adaptive capacities of important resources to climate change, and understand how climate exposure for these resources varies spatially across the Southeast Alaska region.
3. To work with resource managers and planners to increase their institutional knowledge and capabilities to respond to climate change by providing vulnerability assessment resources (e.g., Scanning the Conservation Horizon), support, and tools (e.g., vulnerability assessment worksheets).

To achieve these objectives, a vulnerability assessment process was developed and applied across the Tongass National Forest. This report describes how this vulnerability process was developed and summarizes the results that were obtained when applied to the region. We recommend that resource managers and planners refer to the resource narratives rather than only this introductory section. The

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[1] Glick, P., Stein, B., & Edelson, N. (2011). Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment. Washington, D.C. National Wildlife Federation.

resource narratives more clearly and thoroughly describe resource vulnerabilities, including any sub-regional differences, which can be used to better refine management options for limiting potential impacts.

General Overview

For this vulnerability assessment the Tongass National Forest identified five resources: snow, ice, and water features, riparian vegetation, and fish species. Resource vulnerability was assessed by considering exposure to climate change, sensitivity to climate and non-climate stressors, and adaptive capacity. Climate exposure information for the region was provided by Jeremy Littell (Alaska Climate Science Center), Michael Goldstein (U.S. Forest Service), and Gordon Reeves (U.S. Forest Service) during presentations of the Vulnerability Assessment Workshop,[2] and included information on snowpack, precipitation, water temperature, and fish.

A vulnerability assessment workshop was convened to evaluate the vulnerability of each resource and included participants from the Tongass National Forest and stakeholders from the surrounding region. Sensitivity and adaptive capacity were assessed on a 1-3 scale (1 = low, 3 = high), while exposure to climatic changes was ranked in order of importance; both exercises were based on participant expertise. Each ranking also included a confidence evaluation.

The Report Section-by-Section

Section 1 provides a brief introduction to the project and how the information from vulnerability assessments can be used. Section 2 provides a general overview of the Tongass National Forest region and Section 3 presents general climate projections for the same region. Section 4 explores the results of the vulnerability assessments for the final suite of resources. Conclusions and next steps are addressed in Section 5. Appendix A discusses how the vulnerability assessment information in this report could be applied in management decision-making. Appendix B describes in greater detail the development of the vulnerability assessment process and its application. Appendix C provides an overview of the vulnerability assessment component evaluations for each resource.

Vulnerability Assessment Summary

The vulnerabilities for five resources: snow, ice, and water features; riparian vegetation; and fish species are summarized in Table 1 below. Snow, ice, and water features in Southeast Alaska exhibit moderate-high to high sensitivity to climatic changes including increased year-round temperatures, precipitation changes such as increased annual precipitation and/or shifts from snow to rain, reduced snowpack, and earlier timing of spring ice and snowmelt and later autumn snowpack accumulation. The most vulnerable areas to climatic changes likely include snow and ice features at lower elevations, on the outer islands, and in southern portions of the region. While a number of non-climate stressors could increase sensitivity of snow, ice, and water features to climate change, current sensitivity and exposure to these stressors is thought to be low (see Table 1). Snow, ice, and water features also exhibit low adaptive capacity, however, management systems may provide some potential for adaptation in terms of human use of these resources. For example, hydropower management strategies could adapt to partially accommodate changes in runoff timing.

Riparian vegetation demonstrates moderate-high sensitivity to climatic changes including increased year-round temperatures, carbon dioxide levels and availability, and changes in regional hydrology due

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[2] http://ecoadapt.org/workshops/climate-vulnerability-tongass

to reduced snowpack, earlier snowmelt, and shifts from rain to snow. Non-climate stressors and disturbance regimes that may increase the sensitivity of riparian vegetation to climate change include timber harvest, transportation corridors, insects and stem decay, and windthrow and avalanches. Current exposure of riparian vegetation to these non-climate stressors is thought to be low in the region. Riparian vegetation within Southeast Alaska likely has high adaptive capacity due to widespread, highly connected and diverse populations that are adapted to disturbance.

Fish species have a combination of moderate sensitivity to climate and climate-driven changes (e.g., increased stream temperature, altered flow regimes, changes in the marine environment), and moderate-high sensitivity to non-climate stressors (e.g., timber harvest, land use conversions, hydropower, fishing). Shifts in stream temperature and flow regimes can have myriad impacts on fish species including earlier fry emergence and out-migration, potential loss of habitat suitability (i.e., if stream reaches become too warm or flows too low), or increased roe scour or direct mortality (due to winter high flow events). Changes in marine ecosystems can also affect fish species by affecting primary productivity and food availability. However, it is important to note that both marine and freshwater changes may either improve or degrade conditions for fish, and impacts will likely vary widely across the region, within individual watersheds, and across different species and stocks. While fish species were evaluated as having moderate-high sensitivity to non-climate stressors, current exposure to these stressors in the region is considered low due to existing Forest Plan Standards and Guidelines, as well as the development and implementation of best management practices.

Table 1. Sensitivity to climatic changes and non-climate stressors for snow, ice, and water features; riparian vegetation; and fish species

Snow, Ice, and Water Features	**Riparian Vegetation**	**Fish Species**
Sensitivity to climatic changes (moderate-high to high): • Increased temperature at all elevations • Precipitation changes (snow to rain) particularly at low elevations • Reduced snowpack particularly at low elevations and on islands • Earlier ice and snowmelt timing • Extended ice and snow melt into autumn	*Sensitivity to climatic changes (moderate-high):* • Increased temperature • Changes in hydrology (high and low flows) and soil moisture • CO_2 levels and nutrient availability • Disturbance regimes such as windthrow and avalanches	*Sensitivity to climatic changes (moderate):* • Increased year-round stream temperature • Altered flow regimes (high and low flows) • Changes in the marine environment (e.g., temperature, salinity, pH, upwelling, food availability)
Sensitivity to non-climate stressors (low): • Snow: ○ Timber harvest • Ice: ○ Black carbon & windblown particulates ○ Isostatic rebound ○ Tectonic events • Water: ○ Dams & water diversions	*Sensitivity to non-climate stressors (high):* • Timber harvest • Transportation corridors • Insects & stem decay	*Sensitivity to non-climate stressors (moderate-high):* • Timber harvest • Land use conversions • Hydropower • Hatcheries/aquaculture • Fishing • Mining • Invasive species

Snow, Ice, and Water Features	Riparian Vegetation	Fish Species
○ Mining ○ Aquaculture ○ Transportation ○ Timber harvest		

The adaptive capacity component of this vulnerability assessment also considered potential management approaches for a given resource to facilitate adaptation to changing climate conditions. Most management approaches focused on alleviating current non-climate stressors (e.g., retrofitting existing roads, restoration activities), but represent important management action considerations to enhance resource resilience to climate change. More in-depth explorations of adaptive capacity, including summaries of general management actions designed to facilitate resource adaptation, are considered in Table 2 and in Section 4.

Table 2. Potential management actions summarized for each Tongass resource: snow, ice, and water features; riparian vegetation; and fish species.

Snow, Ice, and Water Features	Riparian Vegetation	Fish Species
Snow: • Conduct project feasibility assessments (e.g., on dam heights, storage capacity, and number of facilities) to plan and proactively manage for future water changes • Retrofit existing and design new roads that are better prepared for higher flows/flood risk • Encourage ski area modifications Ice: • Mitigate black carbon at local scales (e.g., from cars) • Increase use of natural gas and renewable energy in local electricity generation and heating • Expand a lower emissions electric grid • Advocate for global carbon emission reductions Water: • Create stream flow requirements to enhance water feature resilience to future changes • Increase water storage capacity • Increase water quality protection measures • Create water allocation charts to improve	• Continue to use and/or increase U.S. Forest Service (USFS) stream buffer regulations for timber harvest on federal lands • Continue to limit harvest in riparian areas and/or nearby beaches & estuaries • Restore areas of past timber harvest • Minimize road development, and practice climate-informed road construction (e.g., re-vegetate road shoulders) • Restore riparian areas where past mining activity has occurred	• Encourage generation and implementation of hydropower stream flow and lake level requirements to mitigate the duration, severity, & impacts of low flows • Increase public access to information regarding the impacts of overfishing • Promote the development of sustainable harvest quotas that include consideration of climate change vulnerabilities • Improve stream restoration strategies by including climate considerations • Limit jet boat access during spawning times or in vulnerable areas • Collaboratively work to manage/influence hatchery operations to mitigate impacts of hatchery stocks on wild fish populations, particularly in areas likely to experience significant climate impacts (e.g., longer summer low flows, increased rainfall intensity)

Snow, Ice, and Water Features	Riparian Vegetation	Fish Species
management and conservation of water resources		• Minimize road construction within the most vulnerable watersheds (e.g., watersheds where increased magnitude or frequency of flood events (due from increased extreme precipitation or shifts from snow to rain) may result in more landslides or erosion) • Continue to use or revise best management practices to incorporate climate considerations and vulnerabilities • Continue to restore riparian buffers in past timber harvest areas and mining zones • Implement a broad, forest-level monitoring program, which includes utilizing ADF&G fish population monitoring to track changes in aquatic systems.

This vulnerability assessment can be used as a foundation to better integrate the effects of climate change in resource management and planning. However, it is also important to continue to gather information to better understand local climate, its interactions with non-climate stressors, and the impacts to resources. This assessment is intended to be updatable so that as new information becomes available on sensitivity, adaptive capacity, or exposure for a given resource it can be integrated and used to re-evaluate vulnerability.

2. Overview of Region[3]

Southeast Alaska, including the Tongass National Forest, consists of a large group of islands known as the Alexander Archipelago and the narrow mainland strip between Dixon Entrance and Icy Bay. This area lies between latitudes 54½ degrees and 60½ degrees North and extends east to the 130th meridian. It is about 120 miles in width and 525 miles in length in a northwesterly to southeasterly direction. This report reflects the extensive overview of the Tongass National Forest presented in U.S. Forest Service (1974) and Nowacki et al. (2001), which will not be referenced further. Alternative sources are noted.

The many thousands of islands within the Alexander Archipelago are of various sizes, ranging from less than 4 to over 1,000 square miles in area. The largest of these are Prince of Wales, Chichagof, Admiralty, Baranof, Revillagigedo and Kupreanof, respectively. The islands are separated by a stream of seaways including sounds, straits, canals, narrows and channels. There are nearly 18,000 miles of shoreline along the islands and mainland, comprising about 20% of the coastline of the entire United States (Orians and Schoen 2013).

Along this rain-soaked region, most ecosystem patterns and processes are ultimately traced to the land’s ability to shed and process water. Glacial carving and erosion have left a rugged, highly dissected landscape with thousands (> 10,000) of small, steep streams running rapidly to the nearby marine ecosystem (Orians and Schoen 2013). Over 1,500 miles of Tongass National Forest streams are considered glacial in origin; most of these provide important fish spawning and rearing habitat. The Forest Service has classified and mapped 15,764 miles of salmon habitat streams in the Tongass National Forest, including another 1,926 miles through lakes. There are also 4,100 anadromous lakes on the Forest, providing 207,000 acres habitat.

Glaciers and icefields cover over 8 million acres of Southeast Alaska, including Glacier Bay National Park and the Tongass National Forest. Twenty glaciers in Southeast Alaska (including Glacier Bay National Park) have direct contact with marine waters from Hubbard Glacier near Yakutat in the north to LeConte Glacier near Petersburg in the south. Icebergs calving off tidewater glaciers provide important seal pupping sites and provide attractive scenery to locals and visitors alike. The frequent icebergs floating by were very attractive to Norwegian fishermen who founded Petersburg (in 1897) and used the ice to pack salmon for a cannery.

Glacial stream flow is directly linked to ice melt, as opposed to other streams in Southeast Alaska which are more influenced by periods of high precipitation and spring snowmelt. In glacial streams, summer flows are high and heavily laden with silt. Winter flows are low and may run clear and freeze over. Rapid melting events can result in outburst floods and channel avulsions. Side channels and sloughs are abundant and provide important fish rearing habitat and refugia during winter and floods. Many glacial streams are migratory routes to spawning habitat in clear water tributaries that are not glacially influenced.

Given the importance of the hydrologic process in Southeast Alaska, there is a complex interplay of tectonic, geomorphic and hydrologic processes, which in turn, govern the distribution of habitat types and natural disturbances in the landscape. These factors explain much of the coarse-scale variation in vegetation composition, structure and productivity; in soil genesis, morphology, organic carbon and nutrient cycling; stream channel types, groundwater levels, sedimentation rates, nutrient levels, lake

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[3] Section contributed by Patti Krosse (USFS), Julianne Thompson (USFS), and Greg Hayward (USFS).

and wetland distribution; fish and wildlife habitat and productivity; glacial history and erosional processes and their resultant landform features; and natural disturbance regimes: their type, frequency, and intensity. These ecosystem characteristics and functions will be briefly discussed to provide context to the significant role climate has on this landscape.

The present day archipelago, with its renowned fjords, developed as seawater flooded the deeply incised valleys and trenches left after the last major glacial retreat. Since deglaciation – about 14,000 years ago – coastlines have shifted dramatically due to tectonic events (folding and faulting), worldwide sea level changes, and land rebound associated with glacial unweighting as continental ice sheets retreated. During the past 14,000 years climate has varied with periods of glacial advance and retreat, exposing the species and system to a range of conditions and constantly shifting climate regimes. The geologic processes, along with pre- and post-glacial volcanic activity, are responsible for creating the huge diversity of igneous, sedimentary and metamorphic rocks in Southeast Alaska. The rock types have profound effects on terrestrial and aquatic patterns. Appreciative differences in water chemistry are associated with the type of bedrock from which they originate or are in contact with. Substrate bedrock influence soil productivity with basalt and limestone having the most pronounced effects on soil chemistry and overall forest productivity.

The topography of Southeast Alaska features the eastern boundary of the Coast Range Batholith and the intervening lower mountains of the Pacific Mountain System. These mountain ranges are an extension of the Cascades in Washington and the Coast Mountains of British Columbia. Elevations along the boundary range peaks are 6,000 to 10,000 feet. Over millions of years recurrent ice sheets formed and spilled from these mountains pushing seaward. Together, with smaller alpine glaciers, these rivers of ice reworked the topography of the land by rounding mountains, scouring bedrock, depositing glacial sediment, and carving U-shaped valleys and submarine trenches. Broad physiographic types include icefields, recently deglaciated areas, large mainland river systems, angular mountains, rounded mountains, hills, lowlands, and more recent volcanic areas.

The close proximity of the St. Elias and Coast Mountains to the North Pacific Ocean strongly interacts to influence atmospheric circulation patterns, climate, and hydrology in Southeast Alaska. The Gulf of Alaska is one of the most meteorologically active places on earth, where a semi-permanent low-pressure system, called the Aleutian Low, issues a near continuous procession of storms which peak during the fall and winter months. Additionally, a tremendous amount of heat is ushered into the region by ocean currents of tropical origin. These warm marine waters yield cool summers and moderate winters with considerable precipitation that is well distributed throughout the year. Heavy snowfall occurs at higher elevations and a high incidence of cloudiness prevails.

Southeast Alaska receives its year-round precipitation through the orographic lift of most marine air, resulting in accumulations between 60 (near Skagway) and 200 inches (at Little Port Walter) a year. Glacially bound water is released in mass quantities in the summer, causing mountain streams to swell. Productive forests thrive on low elevation, wind exposed sites, where water readily percolates through soils churned by recurrent disturbance caused by windthrow. On flat and gently rolling terrains and on the base of steep slopes, water often accumulates to form vast networks of forested wetlands, bogs and fens (peatlands). Peatland development is also fostered by the cool year-round temperature in the region which greatly suppresses decomposition rates, resulting in annual accumulation of sphagnum moss and other organic duff layers. According to the National Wetland Inventory,[4] 22% of Southeast Alaska is classified as wetland (Orians and Schoen 2013).

Precipitation in Southeast Alaska exceeds evapotranspiration in most of the region. Mainly because of the Late Pleistocene glaciation, the landscape has many depressions and extensive impermeable soil layers. As a result, there are extensive areas of wetlands comprised of organic soils (commonly referred to as "muskegs") on nearly level to slightly sloping areas. Muskegs and other wetlands are sources of bioavailable dissolved organic carbon, organic nitrogen and phosphorus to adjacent streams (Orians and Schoen 2013). These organic soils are saturated or nearly saturated with water most of the year. Organic soils in Southeast Alaska also include some alpine and forested areas, which have more well-drained organic soils derived from forest litter over bedrock or gravel. Only a fraction of the wet organic soils support forest vegetation; sphagnum mosses, sedges, low shrubs and forbs dominate most areas.

The forest of southeast Alaska is a segment of the continuous coastal temperate rainforest extending along the Pacific Rim from northern California to Cook Inlet in Alaska. Most of the forest consists of old-growth stands undisturbed by humans or fire. In the southern part of the forest, the trees are primarily western hemlock and Sitka spruce, with lesser amounts of western red cedar and Alaska yellow cedar. In the northern part, the percentage of hemlock increases and cedars are less dominant. Western red cedar extends only to the northern shore of Frederick Sound, and Alaska yellow cedar is often found as a minor forest component. In the northern portion of the area, mountain hemlock becomes more prominent. Other commonly found species are red alder (along streams, on landslides and other highly disturbed areas), black cottonwood (in major mainland river valleys), and lodgepole pine (adjacent to and within forested wetlands). Less common species include subalpine fir, Pacific silver fir, and Pacific yew.

The best stands of timber generally are found near tidewater and along riparian areas with the highest stand volume per acre diminishing progressively upslope. Interspersed with forest stands are openings, such as muskegs or bog plant communities growing on deep peat. Tree growth is sparse within muskegs and consists mostly of hemlock and lodgepole pine in scrub form. Between muskegs and the dense forest are more open forest stands growing primarily on organic soils. Tree growth is slow and tree form often poor in these stands. Alaska yellow cedar, mountain hemlock, western hemlock, lodgepole pine, and Sitka spruce are important species in these "mixed conifer" communities. The open canopy allows sufficient light to reach the forest floor to support dense understory vegetation of blueberry, huckleberry, rusty menzesia, and other tall shrubs and numerous small vascular plants. These stands are very important for wildlife habitat and contain some of the highest species diversity of all the plant communities.

Heathlands, grasses, and other low-growing plants dominate above timberline (generally 2,500 feet or higher) in the alpine zone. Plants such as deer cabbage cover wide areas and form excellent summer range for deer. Occasional trees occur, often with stunted or shrub like "krummholz" form, due to adverse growing conditions.

The existence of temperate rainforests at these high latitudes is unique and of global significance (Nowacki et al. 2001; DellaSalla 2011). Biological productivity is normally limited by the lack of water in other regions, yet the opposite is true in Southeast Alaska. Wet year-round weather curtails drought and fire, which are predominant disturbance factors in most other ecosystems. Instead, wind disturbance

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[4] http://www.fws.gov/wetlands/

associated with North Pacific storms largely drives forest dynamics along the West Coast. Wind represents the dominant disturbance agent; windthrow influences landscape patterns of forest structure, stand ages, and abundance of snags and downed trees. The constant input of precipitation in the form of snow and rain and the land's ability to shed and process this water combined with the geologic diversity of the landscape in terms of its basic chemistry and erosional processes, all interact to create an ecosystem of enormous beauty and importance to not only the fish and wildlife of the area, but to people as well.

The above overview highlights the extreme variation in environments experienced in Southeast Alaska. The geographic/topographic/elevation variation will translate into variable responses by resources to climate change. While the assessment seeks to emphasize the expectation for variable responses, we took some restraint in highlighting variability in the interest of brevity. Therefore, when considering responses to climate change, keep in mind general patterns highlighted in the next section that demonstrate south to north, island/mainland, west to east, and low to high elevation patterns of decreasing temperature and increasing snowpack. These geographic gradients play out in many features of the region and the resulting patterns of variance will influence resource response.

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3. Climate Projections for the Tongass National Forest

Response to regional climate trends will likely vary widely within the Tongass National Forest due to the high diversity of the region. The Tongass National Forest hosts a diverse landscape, spanning 6 degrees latitude as well as transitioning from coastal islands to coastal mainland mountains rising to an elevation of 10,000 feet. This diverse landscape will likely translate to highly variable filtering of regional climate trends. Local conditions will be influenced by elevation, latitude, and proximity to the coast, among other factors, and will feature different magnitudes and rates of change.

The Scenarios Network for Alaska & Artic Planning (SNAP)[5] has developed 2 km resolution downscaled climate projections that can be used to begin to understand general climate trends for Southeast Alaska. SNAP data is presented here to provide a general overview of climate trends for Southeast Alaska, but please note that local variability and conditions will influence how, when, and to what magnitude different areas of the Tongass National Forest may be affected by or respond to climate change. Furthermore, models used to produce the scenarios do not incorporate patterns in the Pacific Decadal Oscillation (PDO) or other climate cycles (e.g., El Niño).

Temperature

Mean annual temperature in Southeast Alaska increased 0.8°C from 1943-2005 (National Oceanic and Atmospheric Administration (NOAA) 2013), and is projected to increase 0.5-3.5°C by 2050 and 2-6°C by 2100 under high greenhouse gas emissions scenarios[6] (Wolken et al. 2011; SNAP 2013) (Figure 1).

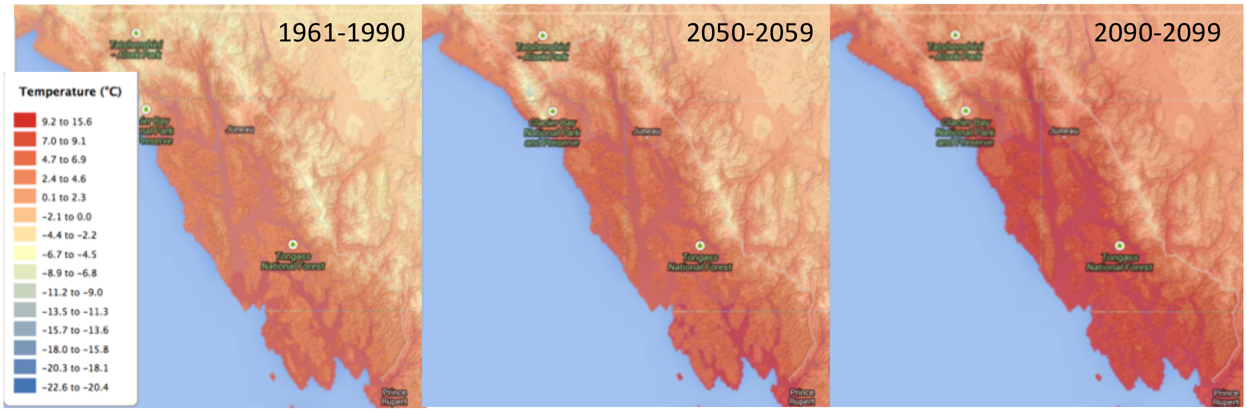

Figure 1. Average historical (1961-1990) and projected (2050-2059 and 2090-2099) annual temperatures for Southeast Alaska at a 2 km resolution. Historical temperatures are Prism 30-year averages. Future temperature projections are 10-year averages from 5 Global Climate Models (GCM) and assume a high-range emissions scenario (A2)[6]. All data from SNAP Map Tool, http://www.snap.uaf.edu/.

The highest rate of temperature increase will be seen in winter months, with mean winter temperatures projected to increase 1-3.5°C by 2050 and 2.5-6°C by 2100 under high greenhouse gas emissions scenarios[3] (SNAP 2013). Elevation, among other factors, will moderate local trends (Figure 1) and impacts of regional warming. For example, lower elevations in much of the region have already exceeded freezing level, while higher elevations still may not exceed freezing level during much of the winter by the end of the century (Figure 1). In areas where future temperature increases exceed

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[5] https://www.snap.uaf.edu/

[6] Note that the "high greenhouse gas emission scenarios" are slightly lower than actual emissions trajectories today.

freezing level more frequently, precipitation will shift from snow to rain and snow accumulation will diminish (see Precipitation and Day of Freeze/Thaw sections below). Snow accumulation affects snowpack, glacier mass balance, and the hydrology of regional water bodies, with potential impacts on numerous species (e.g., salmonids, riparian vegetation) that have ecological and economic importance for natural and human communities. These relationships will be discussed further in respective sections of this report (see Section 4). Specific elevation-based temperature projections can be inferred from regional climate maps (Figure 1) and from more in-depth analyses of other climatically and geographically similar Alaskan forests (i.e., see Kenai/Chugach Climate Vulnerability Assessment, Hayward et al., *in preparation).*

General trends project increased mean annual temperatures for Southeast Alaska, but local conditions will influence the extent to which these increases will impact terrestrial and aquatic systems. For example, comparing temperature projections for three Southeast Alaskan cities – Juneau, Sitka, and Ketchikan – demonstrates how latitude and proximity to the coast can influence temperatures (Figure

Juneau
Northern coastal mainland
Latitude: 58.3000 °N

Sitka
Mid-latitude outer coastal island
Latitude: 57.0516 °N

Ketchikan
Southern island
Latitude: 55.3500 °N

Figure 2. Latitude, general location descriptions, and average historical and projected monthly temperatures for three cities in Southeast Alaska. Projected monthly temperatures were generated using high-range emission scenarios (A2)[6]. Temperature data from SNAP Community Chart Tool, http://www.snap.uaf.edu/charts.php.

2). Juneau, the northern-most city located on the mainland, is not projected to pass the winter freezing point threshold until later in the century, whereas Ketchikan and Sitka, southern and mid-latitude outer coastal cities, have already exceeded or are projected to exceed winter freezing point thresholds during the current decade (2010-2019).

Precipitation

Mean annual precipitation[7] has been increasing in Southeast Alaska, with a 10% (6.6 cm) increase from 1943-2005 (NOAA 2013). Although precipitation patterns are hard to project, annual precipitation could increase 5-15% by 2050 and 15-35% by 2100 (SNAP 2013) (Figure 3).

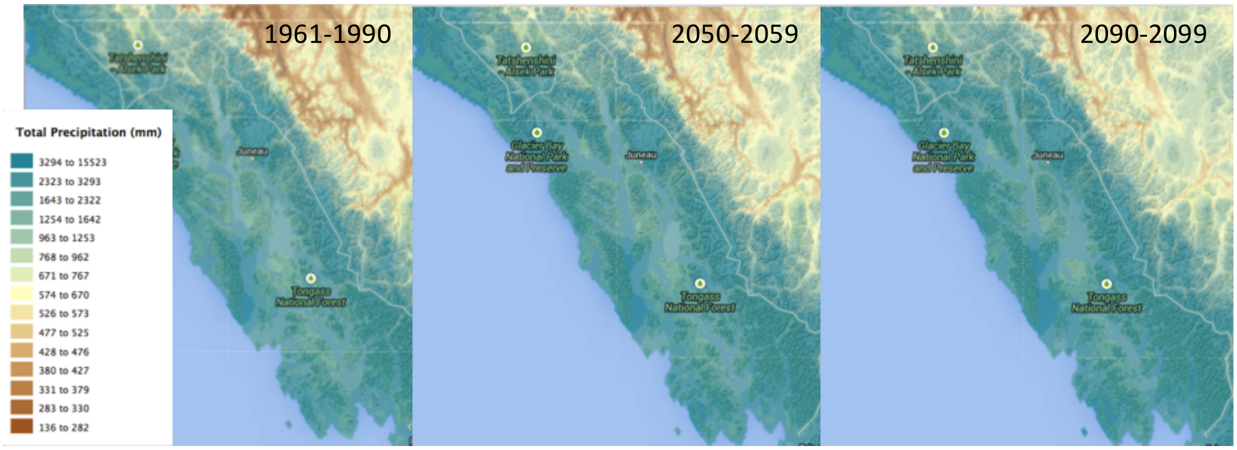

Figure 3. Average historical (1961-1990) and projected (2050-2059 and 2090-2099) annual precipitation for Southeast Alaska at a 2 km resolution. Historical precipitation data are Prism 30-year averages. Future precipitation projections are 10-year averages from 5 Global Climate Models (GCM) and assume a high-range emissions scenario (A2)[6]. All data from SNAP Map Tool, http://www.snap.uaf.edu/.

Precipitation increases are expected in all seasons, with the greatest increases likely in winter and fall months (Figure 4). Winter precipitation could increase by 5-15% by 2050 and 25-35% by 2100 (SNAP 2013). Whether precipitation falls as snow or rain will be dictated by temperature and other local conditions such as elevation, topography, and proximity to the ocean. McAfee et al. (2013) project declining snow-day fractions (the number of days in a given month where precipitation falls as snow) for Southeast Alaska by the end of the century, particularly in the late winter and early spring[8] (e.g., February and March). However, these projections rely on data from relatively lower elevation monitoring stations, and projections varied widely between different climate models used in the study (McAfee et al. 2013). Overall, local conditions will moderate actual precipitation form (McAfee et al. 2013), and a high degree of regional and local variability in snow-day fractions is likely. For example, higher elevations where temperatures are projected to stay below freezing may experience increased snowpack due to projected increases in regional precipitation. In contrast, lower elevations and areas near or exceeding freezing point boundaries may experience shifts from snow to rain as well as declining snowpack as regional temperatures warm. High regional and local variability in precipitation form (rain versus snow) will likely translate to high variability in hydrograph responses and subsequent impacts on fish and riparian species.

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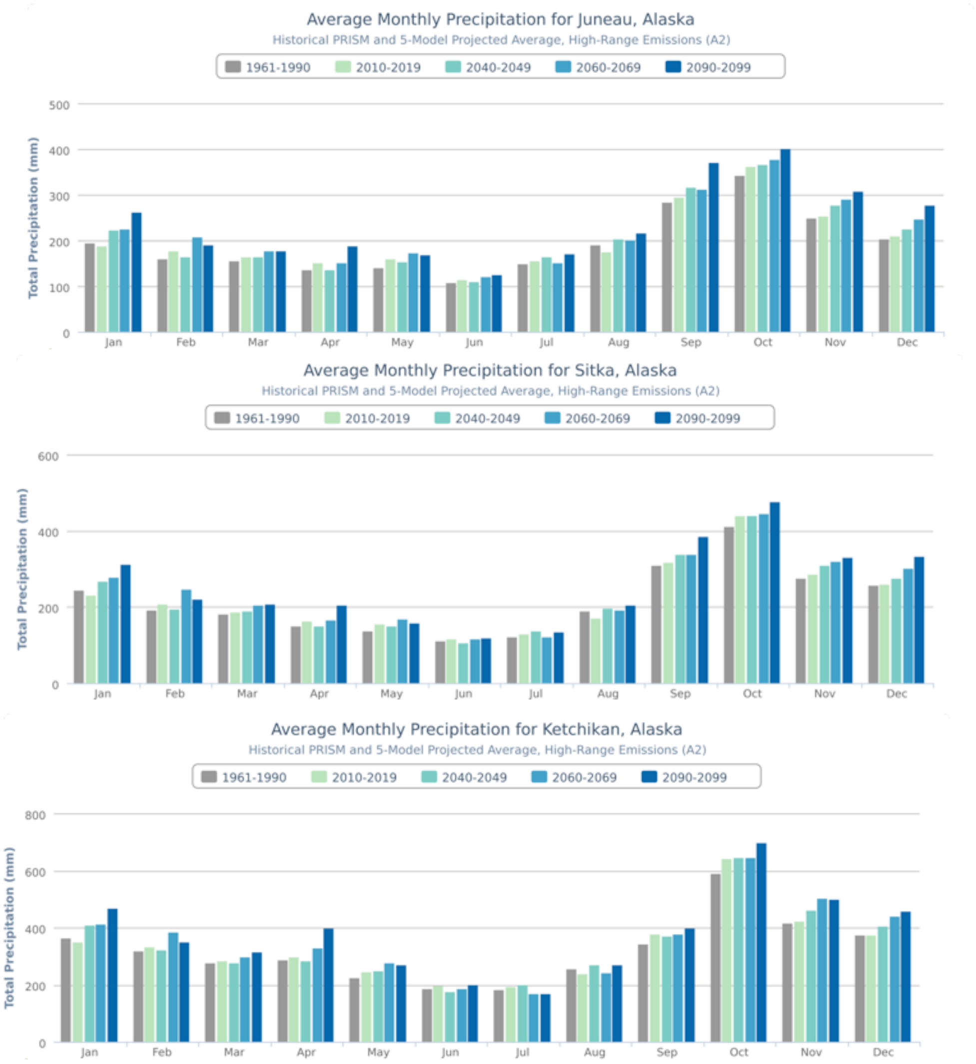
[7] Most weather records for Southeast Alaska are from below 500 m in elevation.

[8] Snow-day fractions are also projected to decline in fall, but to a lesser extent than in late winter and spring (McAfee et al. 2013).



Juneau
Northern coastal
mainland
Latitude: 58.3000 °N

Sitka
Mid-latitude outer
coastal island
Latitude: 57.0516 °N

Ketchikan
Southern island
Latitude: 55.3500 °N

Figure 4. Latitude, general location descriptions, and average historical and projected monthly precipitation for three cities in Southeast Alaska. Projected monthly precipitation was generated using high-range emission scenarios (A2)[6] Precipitation data from SNAP Community Chart Tool, http://www.snap.uaf.edu/charts.php.

Day of Freeze and Day of Thaw

The day of freeze is projected to occur later in Southeast Alaska by the end of the century (Figure 5), and changes could be seen within the current decade (2010-2019). The day of freeze is defined as the estimated day where consecutive monthly midpoint temperatures transition from positive to negative (above 0°C/32°F to below 0°C/32°F) (SNAP 2013), a scenario that provides the potential for snow accumulation. The day of freeze in inland areas could occur 5-10 days later by 2050 and 10-20 days later by 2100, while coastal areas may freeze even later and less frequently (SNAP 2013). Later freeze dates are projected within the current decade (2010-2019), especially at lower elevations (e.g., near Juneau) (Figure 5). Later freeze dates can affect annual snow accumulation, glacier accumulation, and precipitation runoff to regional water features.

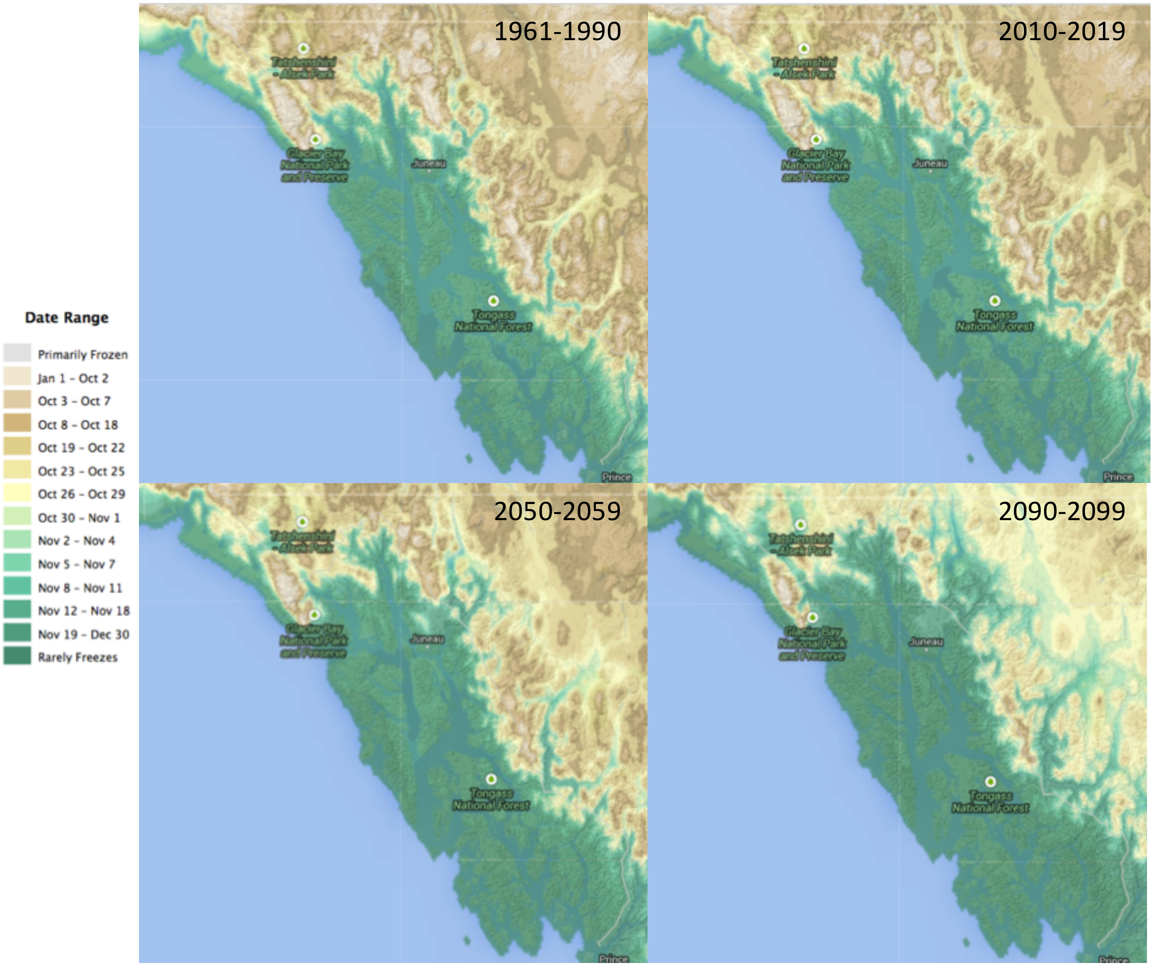


Figure 5. Average historical (1961-1990) and projected (2010-2019, 2050-2059 and 2090-2099) day of freeze for Southeast Alaska at a 2 km resolution. Historical day of freeze data are Prism 30-year averages. Future day of freeze projections are 10-year averages from 5 Global Climate Models (GCM) and assume a high-range emissions scenario (A2)[6]. All data from SNAP Map Tool, http://www.snap.uaf.edu/.

The day of thaw is projected to occur earlier in Southeast Alaska by the end of the century (Figure 6). The day of thaw is defined as the estimated day where consecutive monthly midpoint temperatures transition from negative to positive (below 0°C/32°F to above 0°C/32°F) (SNAP 2013), a scenario that reduces the potential for snow accumulation and increases the potential for snow and glacial melt. Earlier days of thaw are projected within the current decade (2010-2019), especially at lower elevations (e.g., near Juneau), and will occur progressively earlier across the region by the end of the century (Figure 6). Earlier days of thaw affect the duration of snow cover and glacial ablation rates, which influence regional hydrographs.

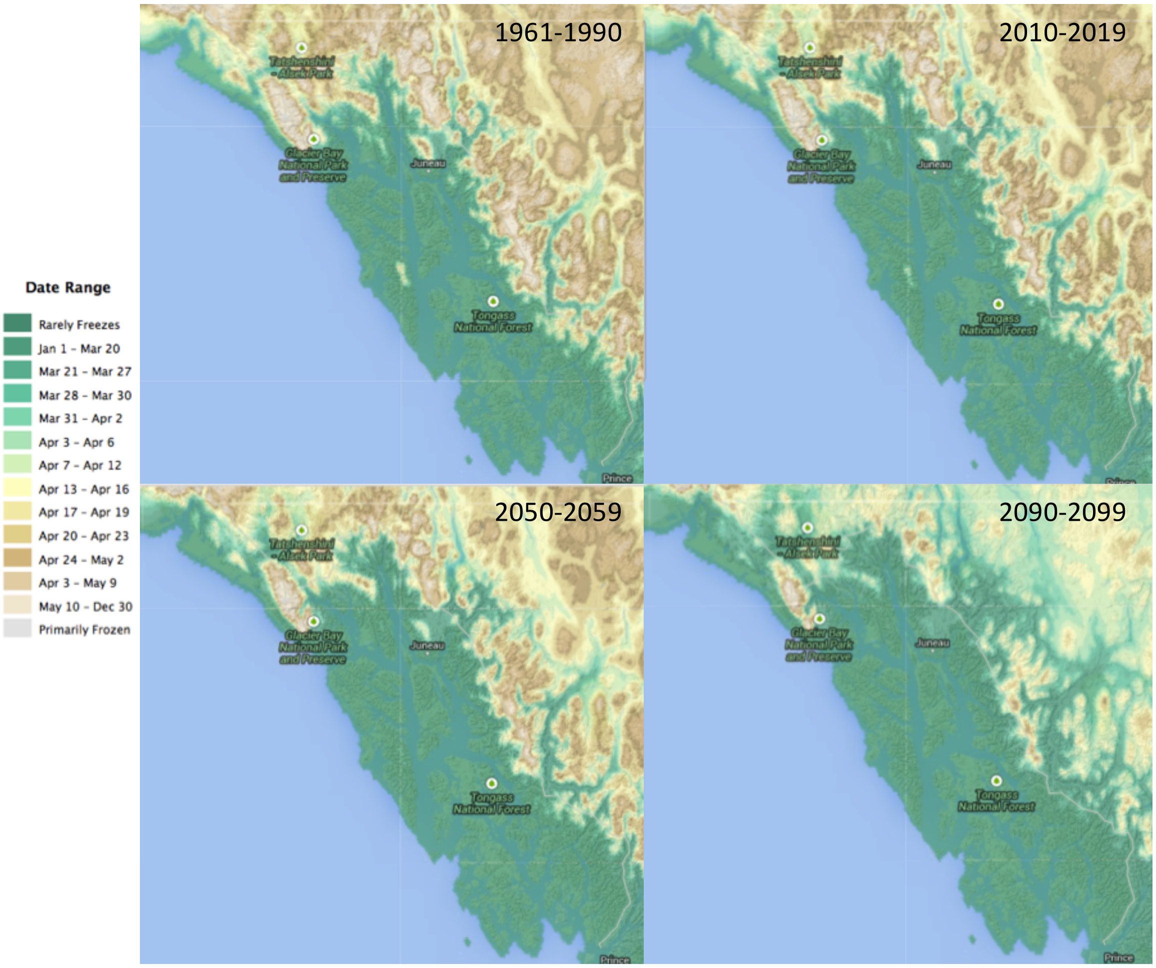


Figure 6. Average historical (1961-1990) and projected (2010-2019, 2050-2059 and 2090-2099) day of thaw for Southeast Alaska at a 2 km resolution. Historical day of thaw data are Prism 30-year averages. Future day of thaw projections are 10-year averages from 5 Global Climate Models (GCM) and assume a high-range emissions scenario (A2)[6]. All data from SNAP Map Tool, http://www.snap.uaf.edu/.

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4. Vulnerability Assessment Results

Integration of climate change into management and planning decisions represents a significant challenge for resource managers. Vulnerability assessments provide a foundation for understanding how and to what degree resources are altered by (positively or negatively) climate change, and can help resource managers set priorities as well as enable more efficient allocation of resources. Vulnerability assessments are also the first step in developing adaptation strategies and improving management practices to better prepare for and respond to potential changes. Specifically, vulnerability assessments can be used to inform the development and implementation of adaptation strategies designed to reduce the vulnerability or capitalize on the positive outcomes of resources to actual or expected climate change effects.

The following section presents individual climate change vulnerability assessment results for five Tongass National Forest resources: snow, water, and ice features; riparian vegetation; and fish species. Please note that the vulnerability assessment summaries refer to the larger geographic region of Southeast Alaska, which includes the Tongass National Forest.

Snow, Ice, and Water Features

Executive Summary

In this assessment, the relative vulnerability[9] of snow, ice, and water features in Southeast Alaska is considered moderate to high[10] due to moderate-high to high sensitivity to climate and climate-driven changes, low sensitivity and exposure to non-climate stressors, and low adaptive capacity. In general, snow, ice, and water features are sensitive to climate and climate-driven changes such as:

- increased year-round temperatures,
- precipitation changes (increased annual precipitation and/or shifts from snow to rain),
- reduced snowpack, and
- earlier timing of spring ice and snowmelt and later autumn snowpack accumulation.

There will likely be high variability in the response of snow, ice, and water features to climatic changes, and the most vulnerable areas are likely snow and ice features at lower elevations, on the outer islands, and in southern portions of the region. Water bodies dependent on meltwater from these vulnerable snow and ice features are likely more sensitive to climatic changes as well. In these more vulnerable areas, warmer temperatures may shift snow to rain in lower elevation sites that currently receive snowfall, cause reduced snowpack and earlier snowmelt, prolong glacial ablation periods, and drive increases in stream and lake temperatures. Increased annual precipitation and earlier melting could increase runoff and alter streamflow regimes and water chemistry (which may benefit fish productivity; see Fish Species summary). Alternatively, higher elevation snow and ice features and water bodies connected to them may experience other changes such as increased snowpack, increased glacial accumulation, or extended snowmelt periods, especially if temperatures remain below freezing for much of the year. Water bodies that receive significant groundwater inputs are likely more resilient in many ways to climatic changes.

Snow, ice, and water features in Southeast Alaska have low sensitivity and exposure to non-climate stressors, lessening their overall vulnerability. Continuing to minimize exposure to these non-climate stressors will help maintain the resilience of these features in the future.

Non-climate stressors impacting **snow** features:

- Timber harvest

Non-climate stressors impacting **ice** features:

- Black carbon & windblown particulates
- Isostatic rebound
- Tectonic events (e.g., major earthquakes)

Non-climate stressors impacting **water** features:

- Dams & water diversions
- Mining
- Aquaculture
- Transportation
- Timber harvest
- Tourism (cruise ships)

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[9] In this context, "relative vulnerability" refers to a combination of sensitivity and adaptive capacity scores. Participants were not asked to score exposure as part of this assessment.

[10] This rating was generated based on score averages from workshop participants and in comparison to scores for other focal resources. See associated scoring summaries in Appendix C.

The adaptive capacity of snow, ice, and water features is considered low, but management systems provide some potential for adaptation in terms of human use of these resources. For instance, hydropower management strategies can change to partially accommodate changes in runoff timing and continue providing electricity generation. For recreation planning, trailheads can be moved to higher elevations to facilitate winter recreation despite changes in snowline.

Snow, ice, and water features are highly valued, found throughout Southeast Alaska, mostly continuous with relatively high structural and functional integrity, and provide a broad range of ecosystem services that would be difficult to replace. These features face several significant use conflicts with varied potential for climate-informed management. Potential climate-informed management approaches that could increase resilience of human uses of these resources include:

- Assess and improve the ability of dams and hydroelectric facilities to manage changing stream flow regimes (e.g., more extreme flow events, higher winter flows, lower summer flows, increased silt loads). For example, ensure current facilities have sufficient storage capacity to both minimize more extreme flood risks and store water to augment summer low flows. Additionally, creating and implementing adaptive water allocation charts and in-stream flow requirements could mitigate climate-driven changes in stream flow.
- Retrofit current and future roads (e.g., install larger culverts to accommodate higher flows, re-vegetate shoulders, reinforce armor at bridges, assess the elevation of facilities) to reduce risk of flood damage and erosion.
- Reduce regional non-climate stressors and anthropogenic contributions to climate change. For example, mitigate black carbon emissions (e.g., from ships and automobiles) to reduce black carbon deposition on ice and snowfields, which could help reduce rates of summer melt. Additionally, switching to cleaner energy sources (e.g., natural gas, more hydroelectric facilities) could help reduce fossil fuel emissions that drive regional warming trends.

Sensitivity and Exposure

Sensitivity to climate and climate-driven changes

General Information:

Workshop participants and reviewers evaluated the overall sensitivity of snow, ice, and water features to climate and climate-driven changes as moderate-high to high.[11] Workshop participants identified each feature to be sensitive to the following climate and climate driven changes:

- Snow features: temperature and precipitation changes, earlier snowmelt timing;
- Ice features: temperature and precipitation changes, earlier onset of spring ice melt;
- Water features: temperature and precipitation changes, decreased snowpack, earlier snowmelt timing.

It is important to note that these are broad generalizations of sensitivity, which is a function of exposure and likely varies widely by elevation, proximity to the coast, and location within a watershed, among other factors. For instance, snow features will likely be most sensitive in geographic settings where temperature is near the freezing threshold (frequently during precipitation) or where changing climatic conditions shift the conditions for snowmelt onset and/or duration.

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[11] Workshop participant ranking: Moderate-High (Confidence: High). Reviewer ranking: High.

Workshop participants also identified wildfire, soil moisture, and low in-stream flows as additional climatic factors that may be important to consider when assessing the sensitivity and exposure of snow, ice, and water features to climate change. In general, however, the impacts of these factors were considered to be low or less significant in Southeast Alaska. Drought conditions, defined as periods with less than average precipitation, were also identified by workshop participants as a potential concern for snow, ice, and water features, as they can reduce annual snow accumulation, potentially impact glacier growth, or exacerbate shifting flow regimes in regional water features. Drought conditions have occurred in Southeast Alaska within the past year (U.S. Drought Monitor),[12] however these periods tend to be transient in nature (i.e., the region can phase out of drought conditions over the course of few, wet weeks; A. Jacobs, pers. comm., 2014).

SNOW FEATURES

In general, snow features in areas where temperatures are already near freezing point boundaries and where snow accumulation is currently low (e.g., lower elevations, southern zones, outer coastal areas) are likely more sensitive to temperature and precipitation changes and earlier snowmelt. Snow features in areas where air temperature is often well below freezing (e.g., higher elevations, northern zones, inland areas), especially during winter, will likely be less sensitive to such changes in the short-term (Motyka et al. 2003; United Nations Environment Programme (UNEP) 2007; U.S. Forest Service (USFS) 2013).

Southeast Alaska features a diversity of snow features, including perennial snowfields, transient (seasonal) snowpack, and accumulated snow layers that will eventually become incorporated into regional glaciers via complete recrystallization. A variety of factors – season, elevation, latitude, aspect, exposure, local topography, wind, humidity, vegetation cover, proximity to the ocean, and others – influence the extent, type, and behavior of snow features found within different areas of Southeast Alaska. For example, inland mountainous areas (e.g., the Coast Range), western slopes, and northern parts of the region tend to accumulate more snow and feature perennial snowfields due to generally cooler temperatures, while southern, coastal, and lower elevation areas, coastal islands, and eastern slopes tend to receive less snowfall and feature transient snowpacks due to more mild temperatures (Stowell 2006; Shulski and Wendler 2007). Workshop participants evaluated snow features as sensitive to temperature and precipitation changes and earlier snowmelt timing (Table 3), though impacts from these changes are likely moderated by local conditions.

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[12] http://droughtmonitor.unl.edu/MapsAndData/MapArchive.aspx

Table 3. Potential responses of snow features to climate and climate-driven changes.

Climate or Climate-Driven Change	**Anticipated Snow Response**	**Most Vulnerable Areas**
Temperature increases	• Earlier and/or faster snowmelt • Reduced snow accumulation, snow feature extent, and snowpack depth • Snowline movement upslope • Altered internal snow conditions, potentially increasing avalanche risk	• Areas currently near freezing point limits • Lower elevations • Southern zones • Outer coasts & islands
Precipitation changes	• Lower elevations (shifts from snow to rain): o Reduced snowfall, snowpack depth, and snow feature extent • Higher elevations (increased snowfall): o Increased snowpack depth and snow feature extent	
Earlier snowmelt	• Less persistent snow cover • Reduced snow feature extent	

Snow features are highly sensitive to temperature changes, which affect snow accumulation, duration of snow cover, snow type, and snowmelt rates. Temperature changes at freezing point boundaries (e.g., lower elevations) that cause shifts from snow- to rain-dominant or transient watersheds can reduce snow accumulation, snowpack depth, and the geographic extent of existing snow features (Motyka et al. 2003; Larsen et al. 2007; G. Killinger, pers. comm., 2014). Additionally, warmer temperatures can move the snowline higher in elevation (Larsen et al. 2007), although temperatures at the highest elevations are not projected to rise above freezing by the end of the century (SNAP 2013; see Figure 1, Climate Projections section). Temperature also influences melting rates and the internal conditions of snow features. Warmer temperatures can increase the number of ice layers within snowpack due to more thaw-freeze events (UNEP 2007) or alter snowpack stability by facilitating snow facet formation, increasing avalanche danger (Scheler et al. 2003). Warming temperatures can also cause earlier thaw events (Beier 2007) and/or initiate or increase the rates of snowmelt (UNEP 2007), potentially reducing overall snow extent, snowpack depth, and/or the duration of seasonal snow cover (USFS 2013). Temperature-induced changes to snow extent can also cause positive feedback cycles and exacerbate other climate trends. For example, 95% of recent summer warming trends in Alaska are attributed to shorter snow cover duration (UNEP 2007).

Snow features are highly sensitive to precipitation changes that directly impact gross snow surface accumulation. While increases and decreases in total precipitation can affect snow features, particularly at higher elevations, shifts in precipitation form (e.g., shifts from snow to rain) likely exert the most influence on snow features by affecting snow accumulation, snowpack depth, and snow feature extent, particularly in areas that currently have transient snowpacks or low annual snowfall (e.g., lower elevations, outer coastal areas, southern zones) (Motyka et al. 2003; UNEP 2007; SNAP 2013).

Snow features are also highly sensitive to earlier snowmelt timing. Earlier snowmelt and thaw events decrease overall snow feature extent, reduce seasonal duration of snow cover, may negatively affect regional vegetation (Beier 2007), and can exacerbate positive feedback cycles of regional warming and snow loss (UNEP 2007). Similar to other trends in snow features, earlier snowmelt and thaw events are more likely at lower elevations (Beier 2007), in areas with less persistent snow features (e.g., outer coastal areas and southern zones; USFS 2013), and in areas that may surpass freezing point boundaries (see Figures 1 and 6, Climate Projections section).

ICE FEATURES

In general, ice features and ice accumulation in zones where temperatures are already near freezing point boundaries (e.g., lower elevations, southern areas, coastal and island zones) are likely more sensitive to temperature and precipitation changes and earlier ice melt. Ice features and ice accumulation in zones where air temperature is often well below freezing, especially during winter, and snowfall is abundant (e.g., higher elevations) may be less sensitive to such changes in the short-term (Motyka et al. 2003; Larsen et al. 2007; UNEP 2007). Sensitivity of ice features also varies according to the type of ice feature, temporal climate cycles (e.g., Pacific Decadal Oscillation), and physical processes in bedrock and component ice, resulting in differential responses to the same regional climate signals (Boyce et al. 2007; Larsen et al. 2007). Tidewater glaciers generally respond less to climate signals than lacustrine and land-terminating glaciers (Boyce et al. 2007; Larsen et al. 2007).

Ice features in Southeast Alaska generally increase in frequency and size with elevation and latitude, and include alpine glaciers in the Coast Mountains (including tidewater, lake calving, and land-terminating glaciers), small glaciers on islands of the Alexander Archipelago, icefields,[13] and floating icebergs calved from parent glaciers (Stowell 2006; Larsen et al. 2007; Molnia 2008). Glaciers in the Coast Mountains are much larger and better studied than glaciers in the Alexander Archipelago. Glacial area in the Coast Mountains at times measures 10,500 km^2, and many of the named glaciers and icefields (e.g., Stikine and Juneau Icefields, Taku Glacier) have historical data records describing their extent (Molnia 2008). Comparatively, glacial area in the Alexander Archipelago was less than 150 km^2 as of the mid-twentieth century, and most remnant glaciers are unnamed and have no historical record of study (Molnia 2008).

Glaciers in Southeast Alaska are classified as temperate alpine and maritime, and have high accumulation and ablation rates due to moderate air temperatures and abundant precipitation (Larsen et al. 2007). Workshop participants evaluated ice features as sensitive to temperature and precipitation changes and earlier ice melt (Table 4). However, it is important to note that the sensitivity of various ice features in Southeast Alaska will depend on their altitude, location, topography below the glacier, and other microsite conditions. For example, higher elevation ice features will likely be less sensitive to the factors described in the table below (e.g., temperature increases, precipitation changes, earlier melt), while ice features at lower elevations, lower latitudes, and in the archipelago will likely be more sensitive. Further, climate cycles and physical processes in both underlying bedrock and the ice itself can moderate responses of regional ice features to the same climate signal (Boyce et al. 2007; Larsen et al. 2007). Some glacier mass volume changes occur over several years or decades, resulting in apparent disconnects from current climate conditions.

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[13] The term "icefield" is used and defined as "an extensive mass of land ice covering a mountain region consisting of many interconnected alpine and other types of glaciers, covering all but the highest peaks and ridges" (Jackson 1997).

Table 4. Potential responses of ice features to climate and climate-driven changes.

Climate or Climate-Driven Change	Anticipated Ice Response	Most Vulnerable Areas
Temperature increases	• Earlier, faster, and prolonged glacial melt periods • Negative surface mass balances may become more common in lower elevation glaciers, leading to glacial thinning and retreat • Higher elevation glaciers may see little change unless temperatures rise above freezing points	• Glaciers with accumulation zones near freezing point boundaries • Lower elevation glaciers • Southern glaciers • Glaciers in outer coasts & on islands • Non-calving glaciers (land and some lake-terminating)
Precipitation changes	• Lower elevation glaciers (shifts from snow to rain): ○ Reduced accumulation ○ Negative surface mass balances ○ Glacial thinning and retreat • Higher elevation glaciers (increased snowfall): ○ Increased accumulation ○ Potential thickening, positive surface mass balances could become more common	
Earlier melt	• Glacial thinning and recession • Negative mass balances may become more common • Possible destabilization of tidewater and lake-calving termini leading to mass wastage events	

The surface mass balance of glaciers is influenced by tradeoffs between summer air temperatures (controlling surface melting rates) and annual snowfall (controlling surface accumulation) (Larsen et al. 2007). Temperature and precipitation changes can have a variety of impacts on ice features, but these impacts are largely moderated by elevation and whether temperatures surpass freezing point thresholds. For example, warmer winter temperatures at lower elevations can induce shifts from snow to rain, reducing surface accumulation and negatively affecting the mass balance of lower elevation glaciers (Motyka et al. 2003; Larsen et al. 2007). Alternatively, at higher elevations temperature increases may not exceed freezing point thresholds, suggesting glacier accumulation zones in these areas will likely be unaffected. Warmer temperatures can also affect the timing and rate of ice melt. For example, surface melting correlated with warmer regional temperatures was identified as a major cause of glacier thinning and retreat in Southeast Alaska from 1948-2002 (Motyka et al. 2003), particularly for glaciers located at lower elevations, southern zones, and on oceanic islands (Molnia 2008). Further, rapid temperature-related thinning and melt water input can trigger the destabilization and calving of tidewater and some lacustrine glaciers, leading to additional ice loss (Boyce et al. 2007; Larsen et al. 2007; UNEP 2007).

Ice features are highly sensitive to earlier ice melt. Depending on annual accumulation rates, earlier ice melt can contribute to glacial thinning or recession, or exacerbate positive feedback cycles of regional warming and ice loss. However, the significance of ice melt timing and melt rates varies according to the type of ice feature in question. For example, tidewater glaciers lose the majority of their ice from calving events; ablation rates have a relatively minor influence on tidewater glacier mass balance unless melt events trigger a positive feedback cycle of calving events at the glacier terminus (Van der Veen 1996 cited in Boyce et al. 2007; Larsen et al. 2007). Comparatively, the mass balance of lake-terminating or land-terminating glaciers are more sensitive to melt timing and rate, as ablation plays a larger role in annual cycles of mass balance for these ice features. For example, thinning of the lake-terminating Mendenhall Glacier may be accelerating the glacier's rate of recession (Boyce et al. 2007).

Patterns in glacier mass balance and movement (advance vs. retreat) vary at temporal scales, with major climate cycles, and according to physical processes of ice and surrounding bedrock. Analyzing glacial conditions at different time scales yields different patterns of glacier activity; most glaciers in Alaska have been retreating since the Little Ice Age in response to rising temperatures (Arendt et al. 2002), but embedded within those long-term time frames are periods of stabilization (Boyce et al. 2007). Glacier activity can also display time lags over multiple years or decades as glaciers fluctuate in response to major climate cycles such as the Pacific Decadal Oscillation (PDO) (Neal et al. 2002; Larsen et al. 2007). Additionally, glacial mass balance patterns also respond to physical processes in ice and bedrock. For example, the advance-retreat cycle of tidewater glaciers may be more controlled by physical ice processes rather than climate warming (Post and Motyka 1995 cited in Boyce et al. 2007; Larsen et al. 2007). Tidewater calving can increase ice loss by increasing terminus surface slopes and glacier-wide flow velocities, drawing down the parent icefield and increasing calving flux (Pfeffer et al. 2000; O'Neel et al. 2001). Alternatively, larger calving events can also eliminate the entire ablation zone for tidewater glaciers, leading to a temporary "advance" phase as gravity continues to pull ice downward and the glacier terminus rebuilds itself (Larsen et al. 2007). The response of tidewater glaciers to climate, particularly flow dynamics to atmospheric and ocean temperature change, is extremely complex (Post et al. 2011), and these glaciers can exhibit rapid retreats several orders of magnitude greater than terrestrial glaciers. Bedrock topography can also play a major role in glacial stabilization; for example, bedrock topography has stabilized the Mendenhall Glacier in between retreat periods, effectively compressing ice and preventing calving events (Boyce et al. 2007).

WATER FEATURES

Individual stream sensitivity to climatic changes will vary greatly across Southeast Alaska due to the high diversity of factors that shape and moderate stream conditions. Non-glacial streams may exhibit increased winter stream flow, decreased summer stream flow, and increased temperatures in response to warmer air temperatures, decreased snowpack depth, and earlier snowmelt. Glacial streams may display increased flow volumes during all seasons and little temperature change in response to the same conditions (Neal et al. 2002; Hodgkins 2009; Hood and Berner 2009). Groundwater-dominated streams will likely show the least variation in response to these climate trends. Though there will be high variability in stream response to changes in temperature, precipitation, and snowpack, in general, island, coastal, and lower elevation streams and streams that are not connected to stable higher elevation snowpack, groundwater, or glacial inputs are likely most sensitive to climate and climate-driven changes (Neal et al. 2002; USFS 2013).

Water features in Southeast Alaska can be classified as either glacial or non-glacial[14] (USFS 2010), though both often include groundwater inputs. Glacial and non-glacial streams behave differently[15] (Figure 7), especially during summer (Hood and Berner 2009), and thus will have varying sensitivities and responses to regional shifts in climate.

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[14] Glacial watersheds are defined as watersheds with at least 15% of the watershed being covered by a glacier or permanent snowfield (USFS 2010).

[15] Stream behavior can change rapidly as glacial coverage declines toward 0% (Hodgkins 2009; Hood and Berner 2009).

No glacial coverage: rain-dominated regimes	High glacial coverage: snowfields and glaciers
• Precipitation-driven hydrograph (lower summer flows, rainfall peaks) • Lower annual streamflows • Warmer summer stream temperatures • Lower turbidity	• Temperature- and melt-water driven hydrograph (higher summer flows with diurnal variations, rainfall peaks) • Higher annual streamflows • Colder summer stream temperatures • Higher turbidity

Figure 7. General differences in stream characteristics according to glacial coverage within the watershed (Neal et al. 2002; Hodgkins 2009; Hood and Berner 2009).

Workshop participants evaluated water features as generally sensitive to temperature and precipitation changes, earlier snowmelt, decreased snowpack, and derivative changes in water temperature and hydrograph volume and timing (Table 5). However, sensitivity can vary widely based on location within the region or a particular basin, proximity to headwaters, glacial and proglacial lake input, groundwater input, non-glacial lake inputs, and local physical variations (e.g., geomorphology, topography, and geography as it relates to groundwater movement and storage), leading to differential filtering of the same regional climate signal (USFS 2008; Hood and Berner 2009; Armstrong and Schindler 2013).

Table 5. Potential responses of water features to climate and climate-driven changes.

Climate or Climate-Driven Change	**Anticipated Water Response**		**Most Vulnerable Areas**
	Glacial Streams	**Non-Glacial Streams**	
Air temperature increases	• Larger and/or earlier glacial melt inputs • Increased stream flow in all seasons; higher diurnal peaks • Increased water temperatures unlikely unless glacial source disappears	• Higher winter flows (increased rain runoff) and reduced summer flows (less and earlier snowmelt contributions) • Increasing water temperatures,[16] especially in summer • Less dissolved oxygen	• Non-glacial streams that are not connected to stable higher-elevation snowpack or groundwater • Glacial streams that pass the threshold between

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[16] Water temperatures are influenced by a variety of factors, including: topographic shade, upland and riparian vegetation, humidity, longitude and latitude, discharge, glacial, groundwater, and lake inputs, local geomorphology (e.g., sinuosity and stream gradient), solar angle, and radiation.

Climate or Climate-Driven Change	Anticipated Water Response		Most Vulnerable Areas
	Glacial Streams	Non-Glacial Streams	
Precipitation changes	• Shifts from snow to rain: o Increased winter runoff and turbidity • Increased precipitation: o Increased flows and turbidity o Higher magnitude rainfall peak flows • More extreme precipitation events: o Increased runoff, flood magnitudes, and turbidity	• Shifts from snow to rain: o Increased winter runoff and turbidity, reduced summer runoff • Increased precipitation: o Increased flows and turbidity o Higher magnitude rainfall peak flows o Potential to augment low summer flows • More extreme precipitation events: o Increased runoff, flood magnitudes, and turbidity	glaciated and non-glaciated • Streams with young growth riparian stands • Lower elevation streams • Southern streams • Streams in outer coastal areas & on islands • Lower elevation, shallow and tanic stained lakes
Reduced snowpack and earlier melt	• Increased summer stream flows	• Prolonged, lower summer stream flows • Decreased annual peak flows	

The hydrological regimes of Southeast Alaskan water features are somewhat sensitive to changes in air temperature, as changes in air temperatures influence precipitation and snow/ice melt rates, affecting monthly hydrological discharge patterns and stream temperatures. For example, warmer winters often feature elevated rainfall and decreased snowfall, translating to higher winter rainfall runoff but lower summer snowmelt runoff for non-glacial streams (Neal et al. 2002). Alternatively, cooler winters feature more snowfall and water storage, translating to lower winter stream flows and higher summer stream flows as snow and ice melt (Neal et al. 2002). Warmer temperatures also affect stream flow by altering melt volume and/or timing (Stewart et al. 2005). For example, glacially fed rivers in Southeast Alaska had increased stream flow in all seasons during warmer years (Neal et al. 2002), likely due to a combination of higher winter rain and increased summer melt inputs. Warmer temperatures can also affect flow volumes by increasing evapotranspiration (Neal et al. 2002).

Warmer air temperatures can drive increases in stream temperature, though factors such as topographic shade, upland and riparian vegetation, humidity, longitude and latitude, discharge, glacial, groundwater, and lake inputs, local geomorphology (e.g., sinuosity, stream gradient), and solar angle and radiation also influence thermal regimes (Poole and Berman 2001; Ebersole et al. 2003; USFS 2008; Hood and Berner 2009). For example, without the benefit of glacial meltwater or groundwater inputs, non-glacial streams are more sensitive to rising summer air and water temperatures than glacial streams (Hood and Berner 2009). Further, increasing temperatures in concert with other factors (e.g., reduced flows, increased primary production) can decrease dissolved oxygen concentrations (Bryant 2009). However, an increase in rain-on-snow events and associated reduction in the depth and duration of snow cover may increase winter-spring oxygen levels in ice-covered, off-channel fish habitats through increased photosynthesis and more frequent infusions of oxygenated water (Greenbank 1945). Stream temperatures define habitable zones for almost all aquatic biota, including economically important salmonids, and changing thermal regimes can cause shifts in species distribution, phenology, and life histories, with subsequent impacts on local economies (Rieman and Isaak 2010; see Fish Species summary).

Water features are highly sensitive to changes in precipitation form (e.g., snow to rain) that alter seasonal stream flow patterns (Neal et al. 2002) by shifting runoff timing and reducing water storage in snowpack. For example, shifts from snow to rain have been documented to increase winter flows and decrease summer flows for non-glacial streams in Southeast Alaska (Neal et al. 2002). Precipitation shifts and rain-on-snow events, particularly in snowmelt-dominated basins, can also cause flashier runoff events, larger flood magnitudes, and increased erosion rates and landslides, temporarily impairing water quality (Hamlet and Lettenmaier 2007). For example, a rain-on-snow event in January 2014 led to record level flood flows measured at the Staney Creek stream gauge on Prince of Wales Island (G. Killinger, pers. comm., 2014). This short-term but extreme event resulted in several landslide events in Southeast Alaska, including at least six that reached and/or closed roads on the island. Additionally, rain-on-snow events during the winter prevent water storage as snow or ice (Stewart 2009), and have been correlated with decreased flows the following summer in Southeast Alaska (Neal et al. 2002).

Water features are also sensitive to increases in annual precipitation. Both glacial and non-glacial stream hydrograph peaks are associated with rainfall events, particularly in the fall when large frontal storms hit the Southeast Alaskan coast (Hood and Berner 2009). These peaks are also correlated with turbidity increases, impacting water quality (USFS 2008). Increases in summer precipitation could augment summer low flows in non-glacial streams.

Although air temperature and precipitation patterns vary intra- and inter-annually in Southeast Alaska, they are also influenced by the PDO, and shifts between the warm and cool phases of the PDO can have significant impacts on the hydrologic regimes of water features. For example, both glacial and non-glacial streams had increased winter stream flow during warm phases of the PDO, with glacial streams having the largest magnitude increases in winter flow volume (Hodgkins 2009). The warm PDO phase also increased summer stream flow for glaciated basins while simultaneously decreasing summer stream flow for non-glaciated basins (Hodgkins 2009), indicating that both regional climate and glacial coverage (as well as other factors) play important roles in controlling hydrographs.

Water features in Southeast Alaska, particularly non-glacial streams that are not connected to stable higher elevation snowpack or groundwater inputs, are also highly sensitive to reduced snowpack and earlier ice and snow melt. Snowmelt plays an important role in non-glacial stream flow regulation during summer, when regional precipitation is generally lowest. Snowpack reductions and/or earlier snowmelt can exacerbate and prolong low flow conditions in non-glacial streams, especially those that are not connected to stable higher elevation snowpack or groundwater inputs, and those located in southern, coastal, or lower elevation areas (USFS 2013). Additionally, reduced snowpack or shifts in snowmelt timing may reduce annual peak flows for non-glaciated basins (Hodgkins 2009). Alternatively, streams with higher glacial coverage may experience increased summer flows and diurnal hydrograph peaks if glacial ablation begins earlier and lasts longer into the fall (Hodgkins 2009). Hydrograph shifts induced by regional changes in temperature, precipitation, snowpack, and melt timing influence a plethora of stream-related features such as morphology, water temperature, and biota, potentially affecting a variety of ecosystem services (see Adaptive Capacity section below).

Future climate exposure

General Trends:

Workshop participants and reviewers considered the most important future climate and climate-driven changes for snow, ice, and water features to include: temperature and precipitation changes, reduced snowpack, and earlier snowmelt timing.

Temperature

Mean annual temperature in Southeast Alaska increased 0.8°C from 1943-2005 (NOAA 2013) and is projected to increase 0.5-3.5°C by 2050 and 2-6°C by 2100 under high greenhouse gas emissions scenarios[17] (Wolken et al. 2011; SNAP 2013). The highest rate of increase will be seen in winter months, with mean winter temperatures projected to increase 1-3.5°C by 2050 and 2.5-6°C by 2100 under high greenhouse gas emissions scenarios (SNAP 2013). Warmer winter temperatures may cause shifts from snow to rain and reduce annual snowfall, particularly at lower elevations and in more southern and outer coastal areas. Southeast Alaskan temperatures, particularly winter temperatures, have historically been higher during warm PDO phases (Neal et al. 2002), and the PDO will likely continue to influence temperature trends in the region. In addition to overall warmer temperatures, Southeast Alaska is also projected to experience more warm events (e.g., 3-6 times more warm events and 3-5 times fewer cold events by 2050) and fewer months with freezing temperatures, especially at lower elevations and along the coastline (Timlin and Walsh 2007; National Park Service (NPS) 2013). Southern islands will likely see lower rates of change than the northern mainland.[18]

It is important to note that temperature trends and impacts on snow, ice, and water features could be ameliorated or compounded by other local factors, such as solar input (cloud cover), humidity, wind, particulate pollution influencing the surface absorbance of snow, and topography, among others. Relative humidity is hard to project, with increases or decreases (0-20%) equally possible over the next century (SNAP 2013). Windspeed is projected to increase 2-4% by 2050 and 4-8% by 2100 (Abatzoglou and Brown 2011).

Precipitation

Mean annual precipitation[19] has been increasing in Southeast Alaska, with a 10% (6.6 cm) increase from 1943-2005 (NOAA 2013). Although precipitation patterns are hard to project, precipitation could increase 5-15% by 2050 and 15-35% by 2100 (SNAP 2013). These increases are expected in all seasons, with the greatest increases likely in winter and fall months. Winter precipitation could increase by 5-15% by 2050 and 25-35% by 2100 (SNAP 2013), but precipitation form (e.g., snow or rain) could vary across the region. For example, shifts from snow to rain may become more common, as snow-day fractions (the number of days in a given month where precipitation falls as snow) are projected to decrease in

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[17] Note that the “high greenhouse gas emission scenarios” are slightly lower than actual emissions trajectories today.

[18] For more information on climate projections for Southeast Alaska, please view the Climate Impact Tables and Maps provided on the EcoAdapt Tongass National Forest Vulnerability Assessment Workshop support page: http://ecoadapt.org/workshops/climate-vulnerability-tongass.

[19] Most weather records for Southeast Alaska are from below 500 m in elevation.

Southeast Alaska by the end of the century,[20] particularly in the late winter and early spring (e.g., February and March)[21] (McAfee et al. 2013). Shifts from snow to rain will likely be most common at lower elevations, in coastal/island areas, in southern ranges of the region, and in areas projected to surpass freezing point thresholds (Neal et al. 2002; SNAP 2013; USFS 2013; see Figure 1, Climate Projection section). Projected changes in extreme precipitation events vary within the region (NPS 2013), although warmer regional temperatures increase the likelihood that when extreme precipitation events do occur they are likely to be rain-on-snow incidents (Rennert et al. 2009). Workshop participants indicated that potential refugia from shifts in precipitation form include higher elevation areas.

Reduced snowpack and earlier snowmelt timing

A combination of later freeze dates and warmer temperatures could lead to reduced snowpack in some parts of Southeast Alaska, including lower elevations, coastal areas, southern zones, and areas that are projected to surpass freezing point thresholds (see Figure 1, Climate Projections section). The day of freeze in inland areas could occur 5-10 days later by 2050 and 10-20 days later by 2100, while coastal areas may freeze even later and less frequently (SNAP 2013). Later freeze dates are projected within the current decade (2010-2019), especially at lower elevations (see Figure 5, Climate Projections section). Additionally, warmer temperatures may drive shifts from snow to rain and reduce annual snowfall in vulnerable areas (i.e., lower elevations, southern areas, coastal/island areas, and areas projected to surpass freezing point thresholds). Lower elevations and outer coastal areas, especially in southern locations, will experience the largest decrease in snowfall, receiving little or no snowfall by 2100 (SNAP 2013). These trends may be amplified during warm PDO cycles; past analyses have shown that snowfall in Juneau was 35% lower during warm versus cold PDO cycles (Neal et al. 2002). Alternatively, higher elevation areas where winter temperatures remain below freezing may maintain or experience higher than historical snow levels due to increasing winter precipitation (SNAP 2013).

In addition to snowpack changes, some areas of Southeast Alaska may also experience earlier thaw and melt timing. For example, the number of snow thaw events occurring in late winter (e.g., February) has increased in the latter half of the 20th century (Beier 2007), the onset of glacier melt occurred earlier between 1988-98 compared to historical records, and glacial ablation periods have been lasting longer (Ramage and Isacks 2003), trends that will likely be exacerbated by warming regional temperatures. Additionally, the day of thaw is projected to occur earlier by the end of the century, and shifts to earlier thaw will likely be seen within the current decade (2010-2019) (SNAP 2013; see Figure 6, Climate Projections section). Workshop participants indicated that potential refugia from decreased snowpack and earlier melting will likely be influenced by aspect, elevation, and local topography, with higher elevations and north- and east-facing aspects acting as the most likely refugia.

SNOW FEATURES

Projected climate changes including temperature and precipitation changes, reduced snowpack, and earlier melt are likely to affect snowpack depth, duration of snow cover, snow structure and stability,

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[20] These projections rely on data from relatively lower elevation monitoring stations, and projections varied widely between different climate models and forcings used in the study. Overall, local conditions will likely moderate actual precipitation form and a high degree of regional and local variability in snow-day fractions is likely (McAfee et al. 2013).

[21] Snow-day fractions are also projected to decline in fall, but to a lesser extent than in late winter and spring (McAfee et al. 2013).

and snowmelt rates, although individual snow feature response will vary by subregion, elevation, proximity to the ocean, historical snowpack, and other factors. Snow features in areas projected to surpass freezing point thresholds (e.g., lower elevations, coastal areas, southern portions of the region; see Figure 1, Climate Projections section) will be most vulnerable to these climatic changes, and may experience upslope movement of the snowline, a reduction in snowpack depth and snow cover, altered snowpack structure and stability (Scheler et al. 2003; UNEP 2007), and a reduction in net surface accumulation due to shifts from snow to rain, decreasing snow-day fractions, and earlier melt onset (Beier 2007; Larsen et al. 2007; UNEP 2007; SNAP 2013). Average temperatures in lower elevation, coastal temperate areas are projected to be above freezing for 12 months of the year by 2100 (SNAP 2013), which could lead to complete loss of snow features in these areas. Further, the southern islands, which have lower snowpack to begin with, may rarely have snowpack at sea level in the future, and the southwestern side of some southern outer coastal islands (e.g., the City of Craig on Prince of Wales Island) rarely have snowpack at sea level even now, a trend that could be perpetuated due to warming regional air temperatures (G. Killinger, pers. comm., 2014).

Alternatively, some regions of Southeast Alaska (e.g., higher elevation areas in the Coast Mountains) may not experience temperatures above freezing point thresholds in the near future (SNAP 2013; see Figures 1 and 5, Climate Projection section). These higher elevation snow features may be enhanced by increased precipitation falling as snow, and experience greater snowpack depth (Larsen et al. 2007).

ICE FEATURES

Similar to snow features, relative impacts and responses of ice features to projected climatic changes will vary by geographic location, elevation, and according to other factors (i.e., glacier type). Glaciers located at lower elevations, in coastal/island areas, and in southern parts of Southeast Alaska (i.e., areas projected to surpass freezing point thresholds) are likely most vulnerable to climatic changes. A combination of warmer winter temperatures driving shifts from snow- to rain-dominant or transient watersheds, reducing snowfall accumulation (particularly at lower elevations), and warmer spring and summer temperatures causing earlier and/or faster rates of ice melt and/or prolonged glacial ablation periods could contribute to glacial recession or thinning (Arendt et al. 2002; Motyka et al. 2003; Ramage and Isaks 2003; Boyce et al. 2007; Molnia 2007; Molnia 2008), particularly among lake-terminating and land-terminating glaciers (Boyce et al. 2007). Earlier and faster melt rates may also exacerbate positive feedback cycles of regional warming and ice loss, such as perpetuating mass wastage events in calving glaciers (Boyce et al. 2007; Larsen et al. 2007). However, fine scale weather patterns can confound regional patterns in accumulation and ablation.

Alternatively, ice features with accumulation zones at higher elevations (i.e., areas not projected to surpass freezing point thresholds; SNAP 2013) may experience increases in mass balance or thickening, or advance if they experience increased precipitation falling as snow (Larsen et al. 2007). Given projected increases in precipitation, the increase in snow accumulation and associated glacial thickening at higher elevations could be substantial (G. Hayward, pers. comm., 2014). Further, tidewater glaciers are generally less sensitive to melting trends than lake- and land-terminating glaciers, unless melting triggers a large calving event (Boyce et al. 2007; Larsen et al. 2007).

WATER FEATURES

Increasing regional temperatures will likely drive hydrological changes in regional stream networks, though stream responses will exhibit high variability at both the watershed and local scale. For example, non-glacial streams, especially those disconnected from stable higher elevation snowpack or groundwater inputs, will likely experience higher winter flows and lower summer flows due to temperature-driven shifts from snow to rain, particularly during warm PDO phases when less precipitation is stored in snowpack (Neal et al. 2002). Glacial streams, particularly those at lower elevations, will see an increase in stream flow in all seasons under similar conditions due to a combination of higher rainfall runoff in the winter and more melt during the summer. Warmer air temperatures could also drive increases in stream temperatures in non-glacial streams (particularly if they lack significant groundwater inputs or connection to high elevation snowpack) (Hood and Berner 2009), potentially affecting local cold-water species such as salmonids. However, stream thermal regimes are moderated by many factors (e.g., sinuosity, stream gradients, riparian and topographical shade, glacial, lake and groundwater inputs, etc.), suggesting that magnitudes and rates of stream and lake temperature increases will vary widely across Southeast Alaska.

Overall precipitation increases will likely increase inputs to water features, affecting hydrograph volume and timing and impacting stream geomorphology. For example, larger rainfall hydrograph peaks could become more common (Hood and Berner 2009). Increased precipitation during summer will likely benefit non-glacial streams by augmenting low flows. Increases in annual precipitation and increases in extreme precipitation events, such as rain-on-snow incidents, could increase runoff and flood magnitudes. For example, mean annual flood magnitudes in the Tongass National Forest could increase 17.3% by 2040 and 28.2% by 2080 relative to current conditions (1977-2000; M. Sloat, pers. comm., 2014), though there will be high variability due to local topographic and other hydrological controls. Higher flood magnitudes and/or frequencies could affect water quality, stream geomorphology, aquatic biota, and human infrastructure in various ways. For example, increased precipitation and/or more frequent extreme precipitation events could cause higher flows and turbidity (USFS 2008) or adjustments in river channel depth and width (M. Sloat, pers. comm., 2014), or increase fish access to new habitat areas and food sources in floodplains and side channels (Lang et al. 2006).

Precipitation shifts from snow to rain, which are most likely in areas that surpass freezing point thresholds (see Figure 1, Climate Projections section), could affect the seasonality of stream flow timing and overall water availability by affecting snow-water equivalents (SWE) and water stored in ice and snow catchments. SWE are projected to decrease an average of 26% by mid-century (2030-2059) relative to historical (1971-2000) conditions, indicating reduced water storage capacities during fall (October, November) and at lower elevations.[22] High winter flows and low summer flows will likely become more common in non-glacial Southeast Alaskan streams, particularly during warm PDO phases, as less precipitation will be stored in snowpack (Neal et al. 2002; Hodgkins 2009). Additionally, glacial streams will likely experience increased flow volume in all seasons if shifts from snow to rain increase winter runoff and are paired with warmer summer temperatures and higher melt inputs (Neal et al. 2002; Hodgkins 2009).

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[22] This data was presented by regional scientists at the Tongass National Forest Vulnerability Assessment Workshop, and reflects trends documented in the Chugach National Forest, which may or may not be similar to trends in the Tongass National Forest. The powerpoint can be found at http://ecoadapt.org/data/documents/Littell_ChugachSnow_13Jan14.red.pdf. For additional information on this on-going study, please visit the SNAP Chugach Climate Change Scenarios Planning page at http://www.snap.uaf.edu/project_page.php?projectid=25.

Reduced snowpack and earlier melt timing could alter regional hydrographs; for example, non-glacial streams may experience earlier hydrograph peaks and lower summer flows and glacial streams may experience higher summer stream flows, while groundwater-dominated streams may experience very little change. Non-glacial streams that are not connected to stable higher elevation snowpack (e.g., isolated watersheds at lower elevations, in coastal areas, and in southern zones) or groundwater-controlled are most vulnerable to snowpack reductions and earlier melt timing, and may experience lower and prolonged summer low flows (Hodgkins 2009; Stewart 2009) or reduced annual peak flows. For example, non-glacial streams had significantly lower summer stream flows during warm PDO phases (which feature less snow, more rain) than during cool PDO phases (Hodgkins 2009). Additionally, water quality in non-glacial streams may be degraded if reduced snowmelt inputs contribute to rising water temperatures (USFS 2008). Groundwater, lake water, and/or increased summer precipitation could augment low flows and mitigate temperature increases.

Glacial streams are also vulnerable to earlier melt timing. Summer stream flows and diurnal variations in glacial streams could increase if glacial ablation begins earlier and lasts longer. However, basins with small glacial coverage could experience large shifts in hydrograph timing and behavior if earlier and prolonged melt periods substantially reduce glacial coverage within the basin (Hodgkins 2009; Hood and Berner 2009).

Groundwater-controlled or groundwater-influenced streams can occur in a variety of settings (USFS 2010), and typically feature more stable flows and temperatures.

Sensitivity and exposure to non-climate stressors

General Information:

Workshop participants identified several non-climate stressors that affect the sensitivity of snow, ice, and water features. Snow features were judged to be sensitive to timber harvest.[23] Ice features were judged to be sensitive to non-climate stressors such as black carbon, windblown particulates, isostatic rebound, and major tectonic events.[24] Water features were judged to be sensitive to dams and water diversions, mining, timber harvest, transportation, and aquaculture.[25] However, snow, ice, and water features generally have low sensitivity and exposure to non-climate stressors; most snow and ice features tend to occur in remote locations not frequently accessed by non-climate stressors, and water features are generally protected through best management practices. Continuing to minimize these non-climate stressors will likely play a role in maintaining the resilience of these features.

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[23] The collective degree these stressors increase sensitivity of snow features was considered Low, and the confidence associated with this evaluation was Moderate. Current exposure to these non-climate stressors in Southeast Alaska was judged to be Low (Confidence: High).

[24] The collective degree these stressors increase sensitivity of ice features was considered Low-Moderate, and the confidence associated with this evaluation was Low-Moderate. Current exposure to these non-climate stressors in Southeast Alaska was not judged.

[25] The collective degree these stressors increase sensitivity of water features was considered Low, and the confidence associated with this evaluation was High. Current exposure to these non-climate stressors in Southeast Alaska was judged to be Low (Confidence: Not stated).

SNOW FEATURES

Workshop participants and reviewers identified timber harvest as the key non-climate stressor impacting snow features. Timber harvest, particularly clear-cuts, can influence local snow drift and distribution, snowpack depth (i.e., by reducing canopy interception), and snowmelt rates (i.e., by increasing wind-induced sublimation) (Storck et al. 2002; Grant et al. 2008). These changes can impact avalanche risk (Germain et al. 2005) and foraging opportunities and habitat for local wildlife (Sigman 1985), alter stream hydrology, and increase flood risk during rain-on-snow events, particularly in transient watersheds (Storck 2000; Grant et al. 2008). Overall, however, the current degree of exposure of snow features to timber harvest activities is considered low in Southeast Alaska, particularly on federally managed lands.

ICE FEATURES

Workshop participants and reviewers identified black carbon and windblown particulates, isostatic rebound, and major tectonic events (e.g., major earthquakes) as the key non-climate stressors impacting ice features. Black carbon aerosols stem from a variety of sources and can be easily transported by wind and deposited on glaciers and ice fields in Southeast Alaska. For example, black carbon from both anthropogenic pollution sources (e.g., ships, automobiles, and local fuel combustion for electricity and heat generation) and natural biomass sources (e.g., boreal wildfires; Hegg et al. 2009) have been found on Alaskan ice fields (Kim et al. 2005). Accumulated black carbon and wind-blown particulates can increase summer ice melt by reducing ice albedo (Kim et al. 2005; Hegg et al. 2009), compounding climate-driven ice melt resulting from warmer temperatures.

Glacial isostatic adjustment is defined as the readjustment of earth’s crust and underlying layers in response to the changing weight of glaciers on its surface (Motyka et al. 2007). Isostatic rebound occurs when land surfaces rise in response to the decreasing weight of melting and receding glaciers (Motyka et al. 2007). Isotactic rebound displays a time lag in response to ice loss and occurs across centuries and millennia; based on past ice losses in Southeast Alaska (Larsen et al. 2007), isostatic rebound is projected to continue for several hundred more years, and will likely be amplified as a result of current glacier recession and thinning across the region (Motyka et al. 2007). Rising land surfaces are projected to cause relative decreases in regional sea levels (Kelly et al. 2007), and calving rates of tidewater glaciers may decrease when they are in shallower water (Pelto and Warren 1991; Post 1975 cited in Larsen et al. 2007). Tidewater glaciers may actually experience less calving-related ice loss due to isostatic rebound and associated decreases in sea levels, which could temper or negate trends in regional ice loss; regional ice losses due to glacial melting would likely be unaffected.

Tectonic events can have variable impacts on regional ice features. Earthquakes can affect structural components of ice features, and likely have a greater effect on weak and fractured portions of glaciers (e.g., crevasses, ice falls, termini) (Nielsen 1965). Direct impacts include collapse of ice bridges, widening of crevasses, collapse of ice dams, and increased calving at glacier termini (Nielsen 1965; Ragle et al. 1965). Earthquakes can also increase or decrease ice flow velocities by altering topography. For example, avalanches and landslides caused by a 7.9 earthquake increased ice flow velocities for several years post-earthquake in central Alaska (Balcerak 2012). Further, ice loss may increase tectonic activity in both the short- and long-term. For example, the 1979 St. Elias earthquake may have been caused by fault destabilization associated with regional glacial thinning and recession over an 80-year period (Sauber and Molnia 2004; Freymueller et al. 2008). Additionally, more earthquakes were recorded in summer and fall during warmer years (2002-2006) than during cooler years (1988-2001) (Freymueller et al. 2008).

WATER FEATURES

Workshop participants and reviewers identified timber harvest, transportation corridors, dams and water diversions, aquaculture, and mining as the key non-climate stressors impacting water features, although the current degree of exposure to these non-climate stressors is considered low in most of Southeast Alaska. Human land uses can impact water quality, stream diversity, and the resilience of water features. For example, road networks and timber harvest can increase sediment delivery, alter large woody debris recruitment, simplify stream function (Trombulak and Frissell 2000), alter hydrographs (Grant et al. 2008), fragment stream networks, and impede the migration of aquatic species (Fausch et al. 2002; Rieman and Isaak 2010). Timber harvest can accelerate the frequency and volume of debris slides and hillslope sediment loss (Naiman et al. 2005), impacting water quality and sediment loading, and can increase hydrograph peaks by reducing canopy interception and evapotranspiration (Grant et al. 2008). Road construction and timber harvest can also exacerbate climate-driven warming in stream temperatures by removing riparian vegetation and reducing shaded stream portions (Isaak et al. 2011). Dams, hydropower development, and other water diversions can limit habitat and impede connectivity for fish and riparian vegetation, and contribute to lower stream flows in summer. In Southeast Alaska, most stream alterations occur on stream systems without anadromous fish, although there are exceptions. For the most part, anadromous habitat impacts associated with dams, hydropower, and other water diversions are not widespread. While the impacts of dams are considered low in the region, increased tourism may increase demand for hydropower, as cruise ships and other larger water craft may need to use electricity rather than diesel in ports, leading to the potential necessity of constructing more dams (G. Hayward, pers. comm., 2014). Aquaculture operations can degrade water quality by releasing untreated nutrients, chemicals, fecal waste, and pharmaceuticals into regional water sources (Naylor et al. 2003; Bisson 2006), although exposure to these non-climate stressors is likely low.

Mining operations can also degrade water quality by altering stream temperature and pH (US Environmental Protection Agency (US EPA) 2012), and increasing heavy metal concentrations and sedimentation (Miranda et al. 2010). Southeast Alaska has two operating mines, as well as new projects being discussed and developed on Prince of Wales Island. However, intensive federal regulation and monitoring ensures that current and future mines have negligible impacts on downstream water quality (G. Killinger, pers. comm., 2014). There are both current and proposed Canadian mines on large trans-boundary rivers that flow into Southeast Alaska, and with different monitoring and regulatory processes, it is unknown how or to what extent these mines will impact downstream water quality within the region (G. Killinger, pers. comm., 2014).

Adaptive Capacity

Feature extent, integrity, continuity, and replaceability

General Information:

Workshop participants evaluated the overall adaptive capacity of snow, ice, and water features as moderate-high.[26] However, regional reviewers argue that human uses of these features may have moderate-high adaptive capacity, but the adaptive capacity of the features themselves is minimal due to their direct response to shifts in climate (G. Hayward, pers. comm., 2014).

SNOW FEATURES

Workshop participants evaluated the adaptive capacity of snow features as moderate-high,[27] but regional reviewers emphasize that snow features likely have minimal to low adaptive capacity due to their direct response to changes in precipitation and temperature. However, human uses and/or ecosystem services of snow features may have somewhat higher adaptive capacity.

Snow features occur across Southeast Alaska, but are non-continuous features. Snow features can be perennial at higher elevations, but are seasonal and disconnected at lower elevations, along coastlines, on islands, and in the southern portions of the region. They exhibit somewhat degraded structural and functional integrity.

If and when snow features transition to ice or water features, many ecosystem services will be impacted in Southeast Alaska (Table 6). Snow features provide several ecosystem services – including water storage and supply, tourism and recreation, and climate regulation – that would be difficult to replicate or replace. Similar to sensitivity, however, the replaceability of snow would vary greatly at local scales and within watersheds. For example, the loss or transition of perennial to transient snowfields would likely have more impact than reductions in transient snowpack depth.

Table 6. Trends and impacts resulting from changes in ecosystem services provided by snow features.

Ecosystem Service provided by Snow	Trend in Service	Potential Impacts
Water storage and supply	• Decreasing due to shifts from snow to rain, decreased snowpack, and earlier snowmelt	• Hydropower: Hydrograph shifts could alter peak power generation times; reduced snowpack and melt inputs could reduce stream flow volume and hydropower generation in summer in non-glacial streams • Non-hydroelectric dams and water diversions: Higher exposure to high volume flows, especially during winter; hydrograph shifts could alter storage volumes • Salmon harvest: Hydrograph and temperature shifts as a result of reduced snowpack and melt inputs could affect salmon survival and stock

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[26] Confidence associated with this evaluation was High.
[27] Confidence associated with this evaluation was High.

Ecosystem Service provided by Snow	Trend in Service	Potential Impacts
		numbers (Bryant 2009; for further discussion see Fish Species summary) • Hatchery operations: Altered water availability (timing and volume derived from snowpack) could affect operations • Flood risk: Increased risk in winter due to elevated precipitation and shifts from snow to rain (reduced storage as snow) • Stream restoration: Altered water availability (volume and timing of melt inputs) affecting sediment movement and wood delivery and reduced thermal insulation for riparian vegetation • Infrastructure: Increased flood risk but reduced snow-loading risk • Water supply/groundwater recharge: Decreased water supply (especially in summer); reduced duration of groundwater recharge
Tourism and recreation	• Decreasing due to shifts from snow to rain, decreased snowpack, and earlier snowmelt	• Skiing (downhill, cross country) and snowmobile recreation: Reduced opportunities and season length; potential loss of tourism/recreation in some areas if large snowpack reductions occur
Climate regulation	• Decreasing due to shifts from snow to rain, decreased snowpack, and earlier snowmelt	• Decreased surface albedo & accelerated warming and snow loss trends • Vegetation: Increased freeze-related tree mortality in the absence of snow insulation

ICE FEATURES

Workshop participants evaluated the adaptive capacity of ice features as moderate-high,[28] but regional reviewers again emphasize that the adaptive capacity of ice features is likely much lower due to their sensitivity to changes in precipitation and temperature. However, ice features may have slightly higher adaptive capacity than snow or water features due to the broad range of factors that influence their activity. For example, glacier activity (i.e., mass balance changes, advance, retreat) is influenced by both short-term and long-term climate forcings, including annual changes in air temperatures and precipitation patterns, and shifts between warm and cold PDO phases (Boyce et al. 2007; Larsen et al. 2007). Physical processes in ice and bedrock also influence ice feature activity (Boyce et al. 2007; Larsen et al. 2007). The diversity of factors influencing glacier activity may increase the adaptive capacity of ice features by moderating or opposing climate trends (e.g., tidewater glacier activity may respond over the short- and mid-term more to internal ice processes than regional warming (Post and Motyka 1995 cited in Boyce et al. 2007; Larsen et al. 2007). Additionally, human uses and/or ecosystem services of ice features may have somewhat higher adaptive capacity than the features themselves.

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[28] Ratings were generated “relative to short management timeframes”. Confidence associated with this evaluation was High.

Ice features occur across much of Southeast Alaska, excluding some specific areas such as non-glaciated islands. Most ice features in Southeast Alaska are found in the Coast Mountains, although there are also smaller glaciers on some islands in the Alexander Archipelago (Stowell 2006; Larsen et al. 2007; Molnia 2008). Where they occur, ice features have a relatively continuous presence and, despite thinning and recession of most glaciers since the end of the Little Ice Age (Molnia 2008), Southeast Alaskan ice features have largely maintained their structural and functional integrity.

The loss of ice features via transition to water features could impact many human uses and natural processes (Table 7). Ice features provide similar ecosystem services as snow features, including water storage and supply, as well as tourism and recreation, but also play a key role in flood control.

Table 7. Trends and impacts resulting from changes in ecosystem services provided by ice features.

Ecosystem Service provided by Ice	Trend in Service	Potential Impacts
Water storage and supply	• Decreasing water storage but increasing water area due to ice melt and reduced winter ice accumulation • Altered hydrologic regimes due to shifts in runoff timing and volume, shifts from snow to rain, and earlier melt	• Salmon harvest and fish passes: Increased headwater and cold water refugia for salmon colonization as ice melts; altered hydrological regimes could impact fish life history (for further discussion, see Fish Species summary) • Fish hatcheries: Altered hydrological regimes could impact operations; flood risk could increase • Hydropower: More melt water for power generation in summer but potential for greater silt load • Dams and water diversions: More melt water for use in summer • Infrastructure (including roads): Altered hydrologic regimes could cause higher flood protection and storage demand • Stream restoration: Altered hydrological regimes could facilitate or make restoration more difficult
Tourism and recreation	• Decreasing as glaciers thin or recede (land- and lake-terminating) • Increasing as glaciers thicken and advance (tidewater)	• Helicopter glacier viewing: Fewer opportunities for land-terminating and lake-calving glaciers; potential increase in flight distances; impact on local economy • Marine-based glacial viewing: Maintain or increase opportunities in short-term
Flood protection	• Decreasing as glacial mass declines and glaciers recede	• Ice dams: May break and inundate communities, infrastructure, and ecosystems lower in the watershed

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WATER FEATURES

Workshop participants evaluated the adaptive capacity of water features as high[29] due to their regional presence, high continuity and relatively high structural and functional integrity. Regional reviewers agree that water features likely have fairly high adaptive capacity; they show direct responses to changes in climate, but they are fed by a variety of sources (e.g., groundwater, glacial melt, snowmelt, precipitation), and are not likely to be lost in the immediate future. Shifting hydrological regimes could affect key ecosystem services provided by water features (i.e., water supply, tourism and recreation, hydropower; Table 8), but human uses of water features also have a relatively high adaptive capacity.

Table 8. Trends and impacts resulting from changes in ecosystem services provided by water features.

Ecosystem Service provided by Water	Trend in Service	Potential Impacts
Water supply	• Altered hydrologic regimes due to shifts in runoff timing and volume, shifts from snow to rain, and earlier melt ○ Glacial streams: Increased flow in all seasons ○ Non-glacial streams: Increased winter flow, decreased summer flow	• Drinking water: Degraded water quality due to increased turbidity • Flood risk: Increased during winter • Infrastructure: Increased flood risk during winter; may not be able to handle larger flow volumes • Fish harvest: Could alter timing and success of fish migration, spawning, and juvenile rearing and/or alter availability of suitable fish habitat • Hatchery operations: Altered water availability for operations, especially in summer • Stream restoration: Altered hydrologic regimes could make restoration more or less difficult (i.e. variable success)
Tourism and recreation	• Glacial streams: Increased flow and associated opportunities in all seasons • Non-glacial streams: Decreased summer flow and associated opportunities	• Rafting: Altered season timing; some non-glacial rivers may be unraftable during late summer • Fishing: Some non-glacial streams may see changes in fish population sizes and run timing
Hydropower	• Glacial streams: Increasing (short-term) in all seasons due to sustained glacier presence but larger melt and rainwater inputs • Non-glacial streams: Variable, depending on precipitation	• Glacial stream facilities: Increased power generation opportunities in the short term if facilities can handle larger volumes of water and silt • Non-glacial stream facilities:

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[29] Confidence associated with this evaluation was High.

Ecosystem Service provided by Water	Trend in Service	Potential Impacts
	regimes; increasing in fall and winter, decreasing in summer	Increased opportunities in winter; reduced opportunities in summer

Management potential

General Information:

Workshop participants noted that climate-informed management of human activities related to snow, ice, and water features could improve the resilience of these features as well as their related ecosystem services. Workshop participants highlighted that the resilience of ecosystem services provided by snow features may be enhanced through dam, hydropower and water facility assessments, road design, and project planning and feasibility assessments. Workshop participants highlighted that the resilience of ice features could be enhanced through black carbon mitigation, increasing use of natural gas and renewable energy, expansion of lower emission electric grids, and advocacy and development of carbon reduction strategies. Workshop participants highlighted that the resilience of water features could be enhanced through implementation of stream flow requirements, water storage, water quality protection, and water allocation efforts.

SNOW FEATURES

Workshop participants judged snow features to be highly valued by the public[30] due to the variety of ecosystem services they provide and their impacts on local economy and culture. Workshop participants identified dam, hydropower and water facility assessments, road design, project planning and feasibility assessments, and ski area modifications as potential management approaches to facilitate ecosystem services adaptation to changing climate conditions. These management strategies are further outlined below; please note they represent only general, preliminary ideas of how to enhance resilience of ecosystem services provided by snow features in Southeast Alaska.

Workshop-Generated Management Strategies:[31]

- Conduct assessments on dam heights, storage capacity, and number of hydroelectric and water facilities.
    - Likelihood of implementation or effectiveness: High
    - Potential benefits: Evaluate current capabilities, plan and proactively manage (e.g., retrofit, create new facilities) for larger storage and flood control needs, which could reduce physical and economic vulnerability.
    - Potential challenges: Financial barriers.
- Retrofit existing roads (e.g., install larger culverts, reinforce armor at bridges, assess the elevation of facilities) and design roads to better deal with higher flows and/or flood risk (e.g., increase culvert size, build outside of floodplain).
    - Likelihood of implementation or effectiveness: High

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[30] Confidence associated with this evaluation was High.

[31] Workshop-generated management strategies were developed by participants at the Tongass National Forest Vulnerability Assessment Workshop held in January 2014.

  - Potential benefits: Reduce flood risk and vulnerability of infrastructure to higher flows resulting from reduced water storage in snowpack.
  - Potential challenges: Financial barriers, conflicts with other road needs (e.g., direct routes, aesthetics).
- Conduct project feasibility assessments.
  - Likelihood of implementation or effectiveness: High
  - Potential benefits: Reduce project vulnerability to changes in snowpack, earlier snowmelt, and impacts on regional hydrology.
  - Potential challenges: May require enforcement, results of assessment may not align with stakeholder goals.
- Encourage ski area modifications (e.g., Eaglecrest Ski Area in Juneau built a mid-mountain chairlift to access snow at higher elevations, allowing them to open even when snow was absent from lower parts of the mountain).
  - Likelihood of implementation or effectiveness: Moderate
  - Potential benefits: Maintain revenue and recreational value of snow features.
  - Potential challenges: Financial or administrative barriers.

ICE FEATURES

Workshop participants judged ice features to be highly valued by the public[32] due to the variety of ecosystem services they provide and their derivative impacts on local economy and culture. Workshop participants identified black carbon mitigation, increasing use of natural gas and renewable energy, expansion of lower emission electric grids, and advocacy and development of carbon reduction strategies as potential management approaches to facilitate adaptation to changing climate conditions. These management strategies are further outlined below; please note they represent only general, preliminary ideas of how to enhance resilience of ice features in Southeast Alaska.

Workshop-Generated Management Strategies:[33]

- Mitigate black carbon at local scales (e.g., from ships, automobiles, and local fuel combustion for heat and energy needs).
  - Likelihood of implementation or effectiveness: High
  - Potential benefits: Reduce deposition on snow and ice fields, reduce rates of summer melting associated with reduced albedo and make ice more resilient to climate-induced warming.
  - Potential challenges: Natural sources of black carbon (e.g., boreal fires) could be hard to control, may require enhanced regulatory oversight, institutional capacity and be expensive to monitor.
- Increase use of natural gas and renewable energy in local electricity generation and heating.
  - Likelihood of implementation or effectiveness: High
  - Potential benefits: Reduce local emissions from more intensive fossil fuel use, reduce black carbon deposition, reduce local warming rates.
  - Potential challenges: Retrofits, required natural gas infrastructure, and renewables could be expensive.
- Expand a lower emissions electric grid.

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[32] Confidence associated with this evaluation was High.

[33] Workshop-generated management strategies were developed by participants at the Tongass National Forest Vulnerability Assessment Workshop held in January 2014.

    - Likelihood of implementation or effectiveness: High
    - Potential benefits: Reduce local emissions, reduce local rates of warming.
    - Potential challenges: Retrofits or expansions could be expensive, may not be practical in some areas.
- Advocate for global carbon emission reductions and create reduction strategies.
    - Likelihood of implementation or effectiveness: High
    - Potential benefits: Reducing greenhouse gas (GHG) emissions could slow rate of change in Southeast Alaska, generating strategies could spur action.
    - Potential challenges: Impacts of past emissions will likely still cause changes in Southeast Alaska.

WATER FEATURES

Workshop participants judged water features to be highly valued by the public[34] due to the variety of ecosystem services they provide and their derivative impacts on local economy and culture. Workshop participants identified implementing instream flow requirements, water storage, water quality protection, and water allocation measures as potential management approaches to facilitate adaptation to changing climate conditions. These management strategies are further outlined below; please note they represent only general, preliminary ideas of how to enhance resilience of water features in Southeast Alaska.

Workshop-Generated Management Strategies:[35]

- Create instream flow requirements.
    - Likelihood of implementation or effectiveness: High
    - Potential benefits: Make water features more resilient to climate-induced seasonal changes in stream flow.
    - Potential challenges: Conflicts with urban and community water demand, as demand will likely be highest during times of lowest instream flow (e.g., summer).
- Increase water storage capacity (e.g., lakes, reservoirs).
    - Likelihood of implementation or effectiveness: High
    - Potential benefits: Compensate for lost storage in glaciers and snowpack, offset climate-induced low flow periods.
    - Potential challenges: If current storage mechanisms do not exist, could be expensive to expand or create new storage options.
- Increase water quality protection measures (e.g., federal best management practices, stream buffers)
    - Likelihood of implementation or effectiveness: High
    - Potential benefits: Reduce likelihood of non-climate stressors compounding climate-driven changes in water quality (e.g., temperature, turbidity, and sediment loading).
    - Potential challenges: Likely requires time, money, and enforcement, some applicable management changes may not be socially acceptable or palatable.
- Create water allocation charts.
    - Likelihood of implementation or effectiveness: High

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[34] Confidence associated with this evaluation was High.

[35] Workshop-generated management strategies were developed by participants at the Tongass National Forest Vulnerability Assessment Workshop held in January 2014.

    - Potential benefits: Improve water management and conserve water resources, making them more resilient to climate change impacts
    - Potential challenges: Requires public buy-in and may be difficult to implement.

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Riparian Vegetation

Executive Summary

In this assessment, the relative vulnerability[36] of riparian vegetation is considered low-moderate,[37] due to moderate-high sensitivity to climate and climate-driven changes, high sensitivity but low exposure to non-climate stressors, and high adaptive capacity. Riparian vegetation is sensitive to climate and climate-driven changes such as:

- increased year-round temperatures,
- changes in regional hydrology due to reduced snowpack, earlier snowmelt, and shifts from snow to rain,
- CO_2 levels and nutrient availability, and
- disturbance regimes such as windthrow and avalanches.

Warming temperatures could increase growth for riparian plant species by lengthening the growing season. Alternatively, warmer temperatures could trigger early emergence from dormancy in the spring, potentially increasing the risk of frost damage and freeze-related mortality. Changes in regional hydrology resulting from reduced snowpack, earlier snowmelt, and shifts from snow to rain can affect riparian succession. For example, high flows and runoff events, including landslides, scour riparian areas, reset successional stages, and alter age class distributions of riparian vegetation. Riparian nutrient deficiencies (e.g., along non-salmon bearing streams) can increase the sensitivity of riparian vegetation to CO_2 levels, potentially altering growth rates. Windthrow is the dominant disturbance agent in Southeast Alaska, and more frequent or intense wind events may increase windthrow mortality in riparian stands or increase woody debris input to stream networks.

Riparian vegetation is also sensitive to a variety of non-climate stressors including:

- timber harvest,
- transportation corridors,
- insects and stem decay, and
- beavers (fluctuating pond levels).

These stressors can exacerbate the sensitivity of riparian vegetation to climatic changes. For example, transportation corridors and timber harvest can increase erosion and sedimentation, impacting establishment success and/or nutrient availability for riparian plant species. However, overall exposure to these non-climate stressors is considered low in Southeast Alaska due to existing laws (e.g., the Tongass Timber Reform Act), Forest Plan Standards and Guidelines, and the development and implementation of best management practices (BMPs) on federal lands. Continuing to mitigate non-climate stressors will likely play a large role in maintaining the resilience of riparian vegetation in the future.

The adaptive capacity of riparian vegetation was evaluated as high; riparian vegetation in the region is likely highly valued and typically has high connectivity and diversity. Potential climate-informed management approaches that may maintain or enhance the resilience of riparian vegetation include:

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[36] In this context, "relative vulnerability" refers to a combination of sensitivity and adaptive capacity scores. Participants were not asked to score exposure as part of this assessment.

[37] This rating was generated based on score averages from workshop participants and in comparison to scores for other focal resources. See associated scoring summaries in Appendix C.

- During all activities in riparian areas, follow Tongass Forest Plan Riparian Standards and Guidelines, including no-harvest stream buffers, to maintain resilience of riparian vegetation.
- Consider riparian objectives during restoration and other treatments in riparian young growth stands.
- Apply treatments that increase resilience and reduce vulnerability of riparian vegetation.
- In previously disturbed riparian areas (e.g. historical mining areas, developed recreation sites) restore riparian areas to reduce erosion and increase resilience to climate change effects.
- Minimize road development and practice climate-informed road construction (e.g., re-vegetate road shoulders).
- Minimize the effects of stream diversions (e.g. hydropower) that could increase vulnerability of riparian vegetation to climate impacts.

Sensitivity and Exposure

Sensitivity to climate and climate-driven changes

Riparian ecosystems encompass the zone of interaction between aquatic and terrestrial environments, displaying vegetation, soil and hydrologic conditions that are distinct from adjacent uplands. Riparian vegetation analyzed in this assessment include sites dominated by Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), and red alder (*Alnus rubra*), with or without black cottonwood (*Populus trichocarpa*) and willow (*Salix* spp.). Riparian areas in Southeast Alaska extend considerable distances upslope from stream channels (Everest and Reeves 2007). Riparian systems are highly dynamic, and are both shaped by and adapted to disturbance from seasonal high flows, periodic flood events (e.g., glacial outburst floods, rain-on-snow events), and landslides. These processes scour riparian areas, cause channel erosion, raise lake levels, reset succession patterns (Harris and Farr 1974; Helfield and Naiman 2001), and transport large woody debris, which can alter channel hydraulics, provide long-term refugium for riparian vegetation colonization and growth (Naiman et al. 2000), contribute to riparian networks with high habitat heterogeneity and age class diversity (Everest and Reeves 2007; Luce et al. 2012), and provide additional high value aquatic habitat.

Workshop participants and reviewers evaluated the overall sensitivity of riparian vegetation to climate and climate-driven changes as moderate-high.[38] Workshop participants identified riparian vegetation in Southeast Alaska as sensitive to a variety of climate and climate-driven changes including year-round temperature changes and changes in regional hydrology due to shifts from snow to rain, decreased snowpack, and earlier snowmelt (Table 9). Additional sensitivities noted by workshop participants include CO_2 levels and nutrient availability, as well as disturbance regimes such as avalanches and windthrow.

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[38] Confidence associated with this evaluation was Moderate-High.

Table 9. Anticipated riparian vegetation response to climate and climate-driven changes.

Climate and climate-driven changes	**Anticipated riparian vegetation response**
Warmer year-round temperatures	• Prolonged growing season, reduced dormancy length • Increased growth rates • Increased transpiration • Summer: Increased diurnal flows in glacial streams, affecting water availability and disturbance • Higher risk of scour from glacial outburst floods
Shifts from snow to rain, increased annual precipitation, reduced snowpack, and earlier snowmelt leading to altered hydrology	• Winter: Shifts in avalanche activity, higher and more frequent hydrograph peaks, higher likelihood of landslides and floods leading to altered riparian age classes • Summer: Decreased water availability and prolonged low flow periods in non-glacial streams • Altered soil stability • Reduced snow insulation and increased root frost damage (especially at low elevations)
Elevated CO_2 levels	• Nutrient-poor environments (non-salmon streams): Prolonged dormancy, smaller growth rates • Nutrient-rich environments (salmon streams): No response
Higher wind speeds and/or more high wind events (due to increased storm intensity and/or frequency)	• Larger and/or more frequent windthrow mortality events and wood recruitment in specific stream reaches • Reduced future wood recruitment sources • More frequent mass wasting, landslides, and debris flows from hillside stream channels and increased sediment/wood deposition downstream

Riparian vegetation is highly sensitive to temperature changes, but increasing year-round temperatures will likely have differential impacts on component species. For example, warmer temperatures can prolong the growing season and increase annual growth rates (Beier et al. 2008), especially for young forests (Berman et al. 1999), by reducing dormancy length. Warmer temperatures can also have indirect impacts on riparian vegetation by influencing precipitation, reducing snowpack depth, and causing earlier snowmelt timing, which can lengthen the snow-free growing season and/or alter seasonal water availability. For example, warmer winters with reduced snowpack resulted in lower non-glacial stream flow during the growing season in Southeast Alaska (Neal et al. 2002). Reduced snowpack and earlier snowmelt, leading to decreased snow insulation, can increase frost damage in cold-sensitive, shallow roots of some riparian species (e.g., yellow cedar) (Beier et al. 2008).

Riparian species in Southeast Alaska are highly sensitive to precipitation shifts, reduced snowpack, and earlier snowmelt that lead to changes in regional hydrology (e.g., timing, magnitude, and duration of high and low flows) and soil moisture. Increased annual precipitation and precipitation shifts from snow to rain can increase seasonal water availability and flood risk (e.g., during winter) in all stream systems, but can also reduce water availability in non-glacial streams during the growing season by reducing snowpack and snowmelt inputs (Neal et al. 2002). Shifts from snow to rain have been most pronounced at lower elevations (Motyka et al. 2003), in coastal areas, and in southern portions of Southeast Alaska (USFS 2013; see Snow, Ice, and Water Features summary). In addition to precipitation shifts, earlier snowmelt can lengthen the duration of summer low flows (Yarnell 2010) in non-glacial streams. Reduced stream flow and/or soil moisture can impact tree growth and establishment success if not counteracted by increased seasonal precipitation. Regional hydrology is also sensitive to climatic events such as the Pacific Decadal Oscillation (PDO). For example, cool phases of the PDO are associated with higher precipitation and storm intensity in Southeast Alaska (Everest and Reeves 2007), affecting disturbance rates and runoff volumes in riparian areas. Riparian species are sensitive to both increases and decreases in soil moisture, as moisture levels impact plant fixation rates, species distributions, and soil stability (Nowacki and Kramer 1998). Additionally, drought periods would likely exacerbate soil moisture deficits and low flows, and could have negative impacts on the growth and establishment of riparian vegetation. Drought conditions, defined as periods with less than average precipitation, have occurred in Southeast Alaska within the past year (U.S. Drought Monitor),[39] but tend to be transient in nature (i.e., the region can phase out of drought conditions over the course of few, wet weeks; A. Jacobs, pers. comm., 2014).

Riparian vegetation is also sensitive to nutrient availability and carbon dioxide (CO_2) levels. Nutrient levels can vary widely between salmon bearing and non-salmon bearing streams, primarily due to the presence of marine-derived nutrients delivered by anadromous Pacific salmon as they return to spawn. Nitrogen is a common limiting agent in northern temperate forests (Chabot and Mooney 1985, Kimmins 1997 cited in Helfield and Naiman 2001), and marine-derived nitrogen improves the fitness of riparian vegetation. For example, Sitka spruce growing within 25 m of spawning streams have almost triple the annual basal area growth of trees further away from the stream (Helfield and Naiman 2001). Riparian vegetation adjacent to spawning streams derive 22-24% of their foliar nitrogen from salmon sources (Helfield and Naiman 2001), and salmon-derived nitrogen has been found more than 500 m away from salmon bearing streams, particularly in areas where bears feed on and distribute salmon carcasses (USFS 2012). Nutrient availability may moderate the sensitivity of riparian vegetation to CO_2 levels. For example, a laboratory study in England demonstrated that Sitka spruce trees growing in nutrient-poor environments emerged later in the spring and entered fall dormancy earlier when exposed to higher than ambient CO_2 levels, resulting in a significantly reduced growing season (Murray et al. 1994). Alternatively, Sitka spruce trees grown in fertile soils showed no phenological response to elevated CO_2 levels (Murray et al. 1994), suggesting that nutrient deficiencies (e.g., in non-salmon bearing streams) can increase the sensitivity of riparian vegetation to CO_2 levels.

Riparian vegetation is also sensitive to disturbance regimes such as avalanches and windthrow. Stand-replacing avalanches can occur in riparian areas, especially after rain-on-snow events (Rennert et al. 2009), and occur most commonly at higher elevations with snowpack and in riparian areas with steep slopes (e.g., >25 degrees) that can sustain avalanche activity. Windfall is the major disturbance factor for most riparian forests in Southeast Alaska (Kramer et al. 2001; Everest and Reeves 2007) with variable impacts on forest and aquatic systems. Windfall is a common cause of tree mortality and drives heterogeneous patterns of forest recruitment, succession, productivity, and diversity throughout the region, including within forested riparian stands. For example, forests in windthrow-susceptible areas may never achieve late seral stages (Kramer et al. 2001). Windfall-prone areas also likely have higher forest productivity (e.g., through increased mineral weathering and organic material decomposition), while protected landscapes may have more diverse species composition due to heterogeneous light availability and stand structure (Kramer et al. 2001). Windfall can also affect aquatic habitats by increasing woody debris delivery to adjacent stream channels. Wood loading in hillslope stream channels can cause landslides and debris torrents that deliver sediment and woody debris to

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[39] http://droughtmonitor.unl.edu/MapsAndData/MapArchive.aspx

downstream valley bottom floodplain channels, helping maintain the long-term productivity and habitat diversity of fish-bearing streams within the region (Everest and Reeves 2007). Sitka spruce and western hemlock are particularly vulnerable to windthrow due to their shallow rooting system (Harris and Farr 1974), tall tree heights, and top-heavy canopies (Foster 1988 cited in Nowacki and Kramer 1998). Soil stability decreases with saturation, so riparian susceptibility to windthrow may be highest during wet, stormy periods with large gusts, which typically occur in fall and winter (Foster 1988, Harris 1989 cited in Nowacki and Kramer 1998; USFS 2013).

Windthrow is influenced by landform (i.e., geomorphic and vegetation characteristics) and prevailing storm and wind directions (Kramer et al. 2001). Riparian areas on southern, eastern, and western slopes may be more vulnerable to wind damage due to direct exposure to prevailing southeast storms and wind acceleration around mountain flanks (Harris 1998, Kramer 1997 cited in Everest and Reeves 2007; USFS 2013). Alternatively, riparian vegetation in large, relatively sheltered valleys may have lower exposure to windthrow events due to the protection from prominent ridges (Everest and Reeves 2007), while riparian vegetation in more moderate, flat topography (e.g., near ridges <300 m high) may be more vulnerable to leeward windthrow events as smaller ridges are unable to protect leeward slopes and valleys from prevailing winds (Kramer et al. 2001). Wind patterns in Southeast Alaska are highly variable and unpredictable, and even seemingly sheltered wide valleys (e.g., Game Creek near Hoonah) feature large, distinct areas of windthrow mortality and resultant swaths of young forest stands (Kramer et al. 2001; G. Killinger, pers. comm., 2014). Large scale, catastrophic wind events from oceanic storms have been documented in coastal Southeast Alaska and have roughly 100-year return intervals (Wolken et al. 2011). Windthrow events typically decrease in inland areas, though strong, local wind events may occur near snow and ice fields and in major river valleys (Kramer et al. 2001; USFS 2013).

Soil disturbance and canopy openings in conifer-dominated riparian stands can favor the establishment of red alder, resulting in higher soil and stream nitrogen levels as well as detritus and litter fall beneficial to fish (Johnson and Edwards 2002; Wipfli and Musslewhite 2004). The distribution of alder and cottonwood could also favor beaver colonization and resulting inundation of riparian areas associated with actively maintained beaver ponds, which can be important rearing habitat for salmonids.

Riparian forests are also sensitive to wildfire, but the cool, moist microclimate of Southeast Alaska minimizes regional fire risk (i.e., fire return intervals are more than 1000 years) (Lertzman et al. 2002).

Future climate exposure

Workshop participants and reviewers identified soil moisture changes, low flows, and high flows as the most important future climate and climate-driven changes to consider for riparian vegetation.

Soil moisture

Soil moisture has historically not been a limiting factor for riparian vegetation in Southeast Alaska due to high annual average precipitation and abundant glacial and snowmelt during the summer (USFS 1974). Future soil moisture characteristics are difficult to project as they are controlled by a variety of factors (e.g., precipitation, air temperature, soil temperature, root absorption, topography and evapotranspiration) and will likely vary widely at local scales. Mean annual air temperature in Southeast Alaska increased 0.8°C from 1943-2005 (NOAA 2013) and is projected to increase 0.5-3.5°C by 2050 and

2-6°C by 2100 under high greenhouse gas emission scenarios[40] (Wolken et al. 2011; SNAP 2013). Higher air temperatures can increase evapotranspiration rates, reducing available soil moisture; however, elevated evapotranspiration rates may be counteracted by increased precipitation. Mean annual precipitation has been increasing in Southeast Alaska, with a 10% (6.6 cm) increase from 1943-2005 (NOAA 2013). Although precipitation patterns are difficult to project, precipitation could increase 5-15% by 2050 and 15-35% by 2100 (SNAP 2013). Increases in soil moisture could increase landslides and windthrow upslope and within riparian areas, though these interactions are likely to be highly variable and dependent on other localized landscape factors, such as the type of substrate, angle of bedrock and slope gradient, as well as climatic factors. Overall, projected changes in temperature and precipitation suggest that soil moisture in Southeast Alaska may not measurably change from current conditions at a broad scale.

Low Flows

Decreased summer stream flows and prolonged low flow periods in non-glacial streams could become more common in Southeast Alaska due to earlier and reduced snowmelt contributions (see Snow, Ice, and Water Features summary). These impacts may be especially pronounced in southwest-facing watersheds, watersheds with lower overall elevation and topography, and in southern and outer areas of Southeast Alaska (Motyka et al. 2003; UNEP 2007; SNAP 2013; USFS 2013). Snow-day fractions (the number of days in a given month where precipitation falls as snow) are projected to decrease in Southeast Alaska by the end of the century,[41] particularly in the late winter and early spring[42] (e.g., February and March) (McAfee et al. 2013). Additionally, snowmelt is projected to occur 10-20 days earlier by the end of the century (Stewart et al. 2005). Riparian vegetation along glacial streams will likely have less exposure to low summer flow issues unless regional warming and precipitation shifts lead to complete loss of glacial coverage within the watershed (Hodgkins 2009; see Snow, Ice, and Water Features summary). Workshop participants identified creek or stream confluences and lake systems as potential refugia from low flows. However, lake temperatures may increase as a result of low flows and general regional warming.

High Flows

Higher flows may increase in both frequency and magnitude in Southeast Alaska due to warming temperatures, increased annual precipitation and/or extreme precipitation events, and potential shifts from snow to rain. Warming temperatures could increase glacial stream flow in summer (Neal et al. 2002; Hodgkins 2009). Higher annual precipitation and shifts from snow to rain may increase the likelihood, frequency, and magnitude of high flows and runoff in both glacial and non-glacial streams, particularly in winter (Neal et al. 2002; Hodgkins 2009) or fall when large frontal storms hit the Southeast Alaskan coast (Hood and Berner 2009; see Snow, Ice, and Water Features summary). Mean annual flood magnitudes in the Tongass National Forest could increase 17.3% by 2040 and 28.2% by 2080 relative to current conditions (1977-2000), though there will likely be high variability due to local topographic and other hydrological controls (M. Sloat, pers. comm., 2014). Larger and more frequent

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[40] Note that the "high greenhouse gas emission scenarios" are slightly lower than actual emissions trajectories today.

[41] These projections rely on data from relatively low elevation monitoring stations, and projections varied widely between different climate models and forcings used in the study. Overall, local conditions will likely moderate actual precipitation form and a high degree of regional and local variability in snow-day fractions is likely (McAfee et al. 2013).

[42] Snow-day fractions are also projected to decline in fall, but to a lesser extent than in late winter and spring (McAfee et al. 2013).

flood events can increase erosion, channel scour, channel adjustment (i.e., width and depth), wood transport, and downstream sediment deposition, as well as alter establishment and age class characteristics of regional riparian networks (Everest and Reeves 2007). Future projections regarding the frequency of extreme precipitation events in Southeast Alaska are uncertain (NPS 2013), but warmer regional temperatures increase the likelihood that when extreme precipitation events do occur they are likely to be rain-on-snow incidents (Rennert et al. 2009). More frequent rain-on-snow events, high volume flows, and/or landslides could alter riparian vegetation extent, create new areas for riparian vegetation colonization, and change the age class distribution of current riparian forest stands (Neal et al. 2002; Everest and Reeves 2007; Bryant 2009). High flow and scour events could also be caused by glacial outburst floods (Molnia 2008; Moore et al. 2009), which may become more common with increasing temperatures and glacial recession (Moore et al. 2009).

Wind speed increases and warmer year-round temperatures

Although not identified by participants, wind speed increases and warmer year-round temperatures are also likely important future factors to consider for riparian vegetation. Wind speed is predicted to increase by 2-4% by 2050 and 4-8% by 2100 in Southeast Alaska (Abatzoglou and Brown 2011), potentially affecting the scale or frequency of windthrow events. High wind events, in combination with saturated soils and more frequent and/or extreme storms, have the potential to increase the areal extent of windthrow in riparian stands (Nowacki and Kramer 1998) and increase wood recruitment to streams in the short-term. However, these events could negatively impact specific stream reaches if wood availability exceeds stream capacity, or if substantial numbers of streamside trees in riparian areas are blown down, decreasing local large wood recruitment sources for many years.

Warmer year-round temperatures can also impact riparian vegetation growth, survival, and distribution. For example, Sitka spruce may experience earlier bud burst and prolonged growth with warmer temperatures (Murray et al. 1994). Alternatively, warmer temperatures and earlier emergence from dormancy could expose riparian species to frost and/or thaw-freeze damage. For example, warmer temperatures may trigger early dehardening of yellow cedar, which in the absence of insulating snow cover could lead to root freezing injury and crown death and cause further declines of this species at lower elevations (Beier et al. 2008). Additionally, yellow cedar dieback may expand upslope into currently robust and unaffected populations as snowlines rise with warming temperatures (Beier et al. 2008). Similarly, if bud emergence is followed by frost periods, Sitka spruce individuals could experience frost damage (Murray et al. 1994). Warmer temperatures could also allow for northern expansion of species currently limited by cold temperatures (Berman et al. 1999), potentially shifting riparian vegetation composition. For example, increased glacial and snowmelt resulting from warmer temperatures could open up new areas for riparian vegetation to colonize (Berman et al. 1999), especially at lower elevations (Motyka et al. 2003).

Sea level rise is an additional climate stressor for riparian habitat in coastal floodplains. However, continuing isostatic rebound and land uplift in Southeast Alaska is likely ameliorating the magnitude of this effect in the near-term (Bryant 2009; see Snow, Ice, and Water Features summary).

Sensitivity and exposure to non-climate stressors

Workshop participants identified several non-climate stressors with the potential to impact riparian vegetation including timber harvest, transportation corridors, and insects and stem decay.[43] However, overall exposure to these stressors is considered low in Southeast Alaska due the development and implementation of best management practices (BMPs) on federal lands (e.g., the Tongass Timber Reform Act and Forest Plan Standards and Guidelines). Continuing to mitigate non-climate stressors will likely play a large role in maintaining the resilience of riparian plant species in the future.

Timber harvest in riparian areas was historically practiced in Southeast Alaska, but current exposure is considered low due the development of BMPs and harvest buffers for riparian zones. Although historical timber harvest practices did target large trees in highly productive valley-bottom floodplain areas (Sisk 2007), only about 6% of riparian areas along fish bearing streams experienced actual harvest (USFS 2012), and serious degradation of riparian forest stands only occurred during the initial phases of industrial logging in the 1950-70s (Bryant and Everest 1998). Riparian plant species such as Sitka spruce are still important timber species (Bryant and Everest 1998), but current laws and management guidelines on the Tongass National Forest greatly limit riparian harvest and help reduce both direct and indirect timber harvest impacts on riparian vegetation (Bryant and Everest 1998; Everest and Reeves 2007).

In general, federal timber management activities are only permitted in riparian areas if they will have a neutral or beneficial impact on water quality, fish habitat, and riparian resources (USFS 2001; USFS 2006). For example, the 1990 Tongass Timber Reform Act, the 2008 Tongass Forest Plan, and federal BMPs prohibit commercial timber harvest within 100 feet of Class I (anadromous fish) or Class II (resident fish) streams that flow directly into a Class I stream (USFS 2001; USFS 2006; USFS 2008). However, Piccolo and Wipfli (2002) suggest that riparian harvest may be more common along Class III and Class IV headwater streams, with potential impacts on riparian communities, downstream food webs, and the productivity of salmonid-rearing habitat. Riparian buffers are also widened to protect the most vulnerable water bodies and riparian areas (e.g., in areas with windthrow hazard), and "special attention" is given to adjacent terrestrial harvest areas to minimize indirect impacts (e.g., increased sedimentation, windthrow exposure) on neighboring riparian sites (USFS 2001; USFS 2006). Windthrow has been documented in riparian buffer areas adjacent to timber harvest (USFS 2013), suggesting that revised management practices for harvest areas and windfirm riparian buffers may be warranted.

Riparian vegetation in Southeast Alaska is also sensitive to transportation and utility corridors. Similar to timber harvest, the development and implementation of BMPs for construction, operation, and maintenance of transportation and utility corridors have helped reduce the exposure of riparian vegetation to direct and indirect impacts of transportation and utility corridor activity. For example, the 2008 Tongass Forest Plan recommends using a variety of methods (e.g., road closure, maintenance) to keep road-top and roadside erosion to low or background levels, preventing altered sedimentation regimes in riparian areas and stream networks (USFS 2008). Additionally, bridge abutments are designed to minimize disturbance to stream banks and within associated riparian stands (USFS 2001; USFS 2006; USFS 2008). In recent years, the Forest Service has been storing/closing roads within the region (G. Killinger, pers. comm., 2014), further reducing transportation corridor impacts on riparian vegetation.

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[43] The collective degree these stressors increase sensitivity of riparian vegetation was considered High within the region, and the confidence associated with this evaluation was High. Current exposure to these non-climate stressors in Southeast Alaska was judged to be low but variable (Confidence: High).

Riparian vegetation is also sensitive to insects and fungi-induced stem decay, which act as small-scale mortality and disturbance agents within stands. There have been several past spruce beetle (*Dendroctonus rufipennis*) outbreaks in Southeast Alaska. These outbreaks are typically short-lived as cooler temperatures and high precipitation limit spruce beetle development and growth (Werner et al. 2006), however warming temperatures could increase spruce beetle invasion rates in the region. Warmer temperatures and longer growing seasons also have the potential to increase growth rates of stem fungi, which could increase mortality rates in Southeast Alaskan riparian vegetation (Wolken et al. 2011). Paired with wind breakage and other climate stressors, increased insect or fungi presence may increase the proportion of early successional tree species across regional riparian landscapes (Wolken et al. 2011).

Workshop participants also noted that riparian vegetation may be sensitive to dams and water diversions, energy production and mining, invasive species, and land use conversions, but current exposure to these activities is considered relatively low within Southeast Alaska.

Adaptive Capacity

Species extent, continuity, and diversity

Workshop participants evaluated the overall adaptive capacity of riparian vegetation in Southeast Alaska as high,[44] due to widespread, highly connected populations that are adapted to disturbance as well as the demonstrated phenological diversity of most component species. Riparian vegetation typically has robust and widespread populations with high population connectivity along stream networks. While riparian vegetation can disperse up and down river corridors via water or air, dispersal is generally limited to their current watershed. Riparian systems in Southeast Alaska are highly dynamic and spatially diverse. High natural disturbance rates (e.g., from flooding, mass wastage events, avalanches, and windthrow) and inter- and intra-annual variations in stream flow contribute to riparian networks with high habitat heterogeneity and age class diversity (Everest and Reeves 2007; Luce et al. 2012).

Some riparian plant species show phenological diversity in response to changing environmental conditions. For example, Sitka spruce displays clinal variation in adaptive growth and phenological traits; individuals in Southeast Alaska feature different height increments, growth rates, and bud set timing compared to individuals in the continental U.S., reflecting local adaptation and plastic responses to current climatic conditions (Mimura and Aitken 2010). Other riparian plant species likely have lower adaptive capacity. For example, although not a dominant riparian species, yellow cedar populations found along small order streams, muskegs, and in poorly drained areas at lower elevations (<300 m) have been experiencing elevated root freeze-related mortality as a result of warmer temperatures and the loss of insulating snowpack (Beier et al. 2008), suggesting that this species may decline as the snowline moves up in elevation.

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[44] Confidence associated with this evaluation was High.

Management potential

Workshop participants judged riparian vegetation to be very highly valued by the public.[45] Workshop participants identified timber harvest, transportation and utility corridors, and mining as potential use conflicts, and noted that there are already regulations in place and activities underway to improve management of these use conflicts in relation to riparian vegetation (e.g., see USFS 2001; USFS 2006; USFS 2008). Workshop participants recommended reforestation, thinning, bank stabilization, and stream and floodplain restoration measures as treatment factors that could affect the adaptive capacity of riparian vegetation; some of these topics have been discussed in regional literature (e.g., see Dorava 1999; Ott and Juday 2002; McClellan 2004; Orlikowska et al. 2004; Deal 2007; Deal et al. 2010; Hanley et al. 2013; USFS 2014). For example, regional literature suggests thinning older forest stands, incorporating red alder into forest restoration efforts, and implementing bank stabilization techniques to further bolster riparian resilience and associated benefits to terrestrial and aquatic communities (Dorava 1999; Piccolo and Wipfli 2002; Orlikowska et al. 2004; Deal 2007). Regional literature also suggests better tailoring management practices, such as timber harvest, to incorporate and address windthrow and other natural disturbance regimes in long-term planning and forest management (Kramer et al. 2001). For example, annual Monitoring and Evaluation Reports for the Tongass National Forest include evaluations of windthrow incidence in riparian buffers (USFS 2013); this data could be used to inform future management strategies (e.g., avoiding significant harvest in late-seral stage forest protected from storm damage). Workshop participants also identified recreational use (e.g., OHV) and fishing as potential use conflicts, but the impacts on riparian vegetation appear to be minimal and/or highly localized (e.g., Situk River) relative to other factors in Southeast Alaska. Potential management strategies are further outlined below; please note they represent only general, preliminary ideas of how to enhance resilience of riparian vegetation in Southeast Alaska.

Workshop-Generated Management Strategies:[46]

- Continue to use and/or increase federal Forest Service stream buffer regulations (USFS 2001; USFS 2006; USFS 2008) for timber harvest on federal lands.
    - Likelihood of implementation or effectiveness: High
    - Potential benefits: Protect riparian species, reduce disturbance.
    - Potential challenges: Conflicts with timber harvest interests.
- Continue to prevent harvest in riparian areas and/or near beaches and estuaries except when done to improve conditions for fish, wildlife, or riparian forest condition.
    - Likelihood of implementation or effectiveness: High
    - Potential benefits: Protect riparian species, reduce disturbance.
    - Potential challenges: Conflicts with timber harvest interests, such as recent discussions regarding commercial thinning of young growth beach fringe stands.
- Restore areas of past timber harvest.
    - Likelihood of implementation or effectiveness: High
    - Potential benefits: Increase resilience of riparian species.
    - Potential challenges: Financial barriers.
- Minimize road development, and practice climate-informed road and utility corridor construction (e.g., re-vegetate road shoulders).
    - Likelihood of implementation or effectiveness: High

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[45] Confidence associated with this evaluation was High.

[46] Workshop-generated management strategies were developed by participants at the Tongass National Forest Vulnerability Assessment Workshop held in January 2014.

    - Potential benefits: Reduce disturbance, erosion, runoff, and infrastructure vulnerability.
    - Potential challenges: Could increase costs of transportation and associated timber harvest activities and utility corridor placement.
- Restore riparian areas where past mining activity has occurred.
    - Likelihood of implementation or effectiveness: High
    - Potential benefits: Reduce erosion.
    - Potential challenges: Financial barriers.

Literature-Generated Management Strategies:[47]

- Use available data (USFS 2013) and tailor management activities to mirror and be more compatible with natural disturbance processes. For example, in wind-protected areas (i.e., late seral forests), use single-tree or small-group selection harvest practices to mimic small disturbance events/canopy gaps (Kramer et al. 2001; Ott and Juday 2002; Deal et al. 2010).
    - Potential benefits: Maintain ecosystem processes (e.g., coarse woody debris inputs), function, and habitat condition.
    - Potential challenges: May require more frequent entry points over larger areas to maintain current harvest levels.
- Implement moderate to light intensity thinning in older forest stands (McClellan 2004; Deal 2007; Deal et al. 2010).
    - Potential benefits: Maintain original diversity of overstory stand structure and understory plant communities, reduce windthrow vulnerability of adjacent stands.
    - Potential challenges: Older forest stands may be hard to access, could be within riparian buffer zones.
- Incorporate red alder into conifer forest restoration efforts (Piccolo and Wipfli 2002; Orlikowska et al. 2004; Deal 2007), as red alder has been shown to increase forest biomass and structural diversity and increase export of aquatic invertebrate biomass and detritus to stream networks (Wipfli and Musslewhite 2004).
    - Potential benefits: Increase understory biomass and diversity more quickly than in pure conifer stands, maintain diversity of forest structure, increase aquatic invertebrate biomass and detritus export (which may benefit salmon in downstream reaches).
    - Potential challenges: Headwater streams could be hard to access, financial barriers.
- Implement streambank stabilization and floodplain restoration techniques (Dorava 1999).
    - Potential benefits: Reduce bank erosion from higher flows, maintain fish habitat, and provide stable sites for riparian conifer establishment.
    - Potential challenges: Financial and/or institutional barriers, requires understanding of local conditions.

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Fish Species

Executive Summary

In this assessment, the relative vulnerability[48] of fish species in Southeast Alaska is considered moderate[49] due to moderate sensitivity to climate and climate-driven changes, moderate-high sensitivity but low exposure to non-climate stressors, and high adaptive capacity. Vulnerability of fish species is complex to assess broadly, as species are influenced strongly by biological (e.g., physiology, life history, phenology) and physical (e.g., hydrology, marine environment) variation. Substantial variation in the consequences of regional climate change occurs across gradients of decreasing temperature and increasing snowfall; particularly important are those gradients that occur west to east, south to north, and island to mainland. As emphasized throughout this summary, fish 'vulnerability' should not be assumed to result in negative outcomes; consequences for fish will be both positive and negative. In general, fish species are sensitive to climate and climate-driven changes such as:

- increased stream temperatures,
- altered flow regimes resulting from increased annual precipitation, precipitation changes, extreme precipitation events, and earlier snowmelt, and
- changes in the marine environment (e.g., temperature, salinity, pH, upwelling).

Changes in freshwater and marine environments may improve or degrade conditions for different fish species and stocks; impacts will vary widely across the region and at local scales. Temperatures can affect fish development, emergence, and survival. Increased annual precipitation, precipitation shifts from snow to rain, and more rain-on-snow events can affect fish survival by increasing the frequency and magnitude of high flow events; by development of new habitat after floods; and by the associated consequences of changes to habitat quality, which will influence fish species and individual stocks in different ways. Earlier snowmelt timing my contribute to lower flows earlier in the season, which in turn can affect smolt outmigration and survival, spawning opportunities, and alter rearing habitat. Changes in the marine environment can also affect fish species by affecting primary productivity and food availability.

Fish species are also sensitive to a variety of non-climate stressors including:

- timber harvest,
- land use conversions (e.g., road construction, including stream crossings),
- hydropower and dams and water diversions,
- hatcheries/aquaculture,
- fishing,
- mining, and
- invasive species.

Current exposure to these non-climate stressors is considered low in Southeast Alaska due to the development and implementation of Forest Plan Standards and Guidelines and stringent best management practices (BMPs). Continuing to implement effective mitigation strategies will likely play a large role in maintaining the resilience of fish species in the future.

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[48] In this context, "relative vulnerability" refers to a combination of sensitivity and adaptive capacity scores. Participants were not asked to score exposure as part of this assessment.

[49] This rating was generated based on score averages from workshop participants and in comparison to scores for other focal resources. See associated scoring summaries in Appendix C.

The adaptive capacity of fish species is considered high; they are highly valued species with high population connectivity and high (but variable) genetic, phenotypic, and life history diversity, but face several use conflicts. Potential climate-informed management approaches include:

- Generate and implement hydropower stream flow requirements to mitigate the negative impacts of climate-driven low flows on fish species. Additionally, prioritize funding for regulatory and licensing portions of federal and state hydropower management to ensure that future hydropower construction and operation will not compound negative climate-driven changes and impacts on fish species.
- Minimize road building within the most vulnerable watersheds (e.g., those transitioning from snow- to rain-dominated systems) to minimize impacts on aquatic habitat and increase resilience of fish species. Ensure new road-stream crossings are constructed in a manner that accounts for altered flow regimes.
- Collaborate with the Alaska Department of Fish and Game to mitigate impacts of hatchery stocks on wild fish population productivity and genetic diversity, particularly in watersheds where wild fish populations are facing heightened climate stressors.

Sensitivity and Exposure

Sensitivity to climate and climate-driven changes

Southeast Alaska supports a diversity of fish species that display genetic, phenotypic, and life history adaptations specific to their local watershed (Bryant 2009). Fish species assessed in this document include pink, chum, coho, sockeye, and Chinook salmon, steelhead and rainbow trout (*Oncorhynchus mykiss* life history variants), cutthroat trout, and Dolly Varden char. The diversity inherent to Southeast Alaskan fish stocks also generates diversity in potential responses to climate and climate-driven changes, with sensitivity, exposure, and adaptive capacity likely varying widely across species, stocks, and watersheds. For example, due to longer freshwater residence times, coho (lake rearing juveniles), sockeye, and Chinook salmon as well as steelhead, cutthroat trout and Dolly Varden, may be more vulnerable to negative freshwater climate change impacts, especially those distressing rearing juveniles. Freshwater juvenile steelhead and cutthroat trout, and Dolly Varden can experience even longer freshwater residency, increasing their vulnerability; however the most vulnerable species may be the resident stocks of those species. Pink and chum salmon are the shortest freshwater residents, spending only a few weeks to a month in freshwater; though also likely sensitive to climate and climate-driven changes they may exhibit sensitivity in different ways (Bryant 2009). Additionally, fish that reside or spawn in non-glacial streams may experience larger environmental changes than fish that occupy glacial streams, as these two stream classes are likely to exhibit different responses to the same regional climate signal (see the Snow, Ice, and Water Features summary).

We emphasize again that outcomes for fish in relation to a changing climate will be a mix of positive and negative responses. The particulars of this variation in response will be highlighted below.

Workshop participants and reviewers evaluated the overall sensitivity of fish species in Southeast Alaska to climate and climate-driven changes as moderate.[50] Workshop participants and reviewers identified stream flow and thermal regimes, which describe seasonal variation in water quantity and temperatures (Poff et al. 1997; Caissie 2006), as the two most important environmental characteristics to consider for

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[50] Confidence associated with this evaluation was Moderate-High.

fish species (Table 10). These attributes are not independent; for example, the magnitude of stream flow, among other factors (e.g., canopy cover, residence time of water), mediates the seasonal dynamics of water temperature (Caissie 2006; Dickson et al. 2012; Armstrong and Schindler 2013). However, flow and temperature have distinctly different effects on fish species, so it is useful to consider them separately when assessing the sensitivity of fish species to climatic changes. Workshop participants and reviewers also noted that salmonid species of Southeast Alaska are likely sensitive to changes in the marine environment (Table 10).

Workshop participants also identified soil moisture and sea level rise as potential stressors for cold-water fish species. However, these factors are unlikely to be important during the near-term in Southeast Alaska, where soil moisture is projected to remain high and a significant rise in sea level has a low probability of occurring.

Table 10. Anticipated fish response to climate and climate-driven changes.[51]

Climate and climate-driven changes	**Anticipated fish response**
Warmer stream temperatures (primarily in non-glacial streams)	• Warmer winter temperatures: Faster development, earlier fry emergence, earlier out migration • Increased metabolic demand with associated opportunities for higher or lower growth rates • Habitat alterations: Increased productivity of previously low productivity habitats, loss of habitat suitability (e.g., if stream reaches become too warm)
Altered flow regimes	• Winter high flow events: Increased habitat availability due to runoff • If floodplain is altered: Increased roe scour, increased sedimentation, direct mortality, creation of new habitat • Summer low flow events (primarily in non-glacial streams): Decreased habitat availability, prolonged low flow periods, warmer stream temperatures, potential increased vulnerability to predators, decreased growth and survival
Changes in marine temperature, salinity, upwelling, and pH	• Altered prey availability and competition dynamics ○ Changes in pH may lead to significant changes in food webs. These changes are likely to negatively influence salmon growth and survival. • Potential positive feedback loop of altered salmon growth and reproductive potential

Thermal regimes

Increasing air temperatures contribute to shifting freshwater thermal regimes, and warmer water temperatures can have differential impacts on fish species. For example, warmer temperatures affect different stages of fish life cycles (Bryant 2009) such as development rates, fry survival, migration timing, habitat quality and productivity, and predation risk (Kelly et al. 2007; Taylor 2008; Martinson 2011). Species that migrate upstream during low flow/high stream temperature periods (e.g., mid-summer),

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[51] Please note that these changes may not happen in all watersheds, and these changes can have both negative and positive impacts on fish. Further, even within one watershed, some fish species may benefit from these changes while others may not.

such as pink, sockeye, and chum salmon, are likely to be most affected by seasonal water temperatures increases. Higher water temperatures in waters that are relatively warm induce thermal stress, heighten the metabolic cost of upstream migration, and can contribute to pre-spawning mortality via oxygen depletion if fish are trapped in remnant pools (Bryant 2009). In general, damaging warmer water temperatures are more likely during low flow periods (i.e., summer). For example, there are documented fish kill cases on Prince of Wales Island when large returns of spawning adult pink salmon travel through stream reaches experiencing summer low flows and elevated stream temperatures (Halupka et. al. 2000; USFS 2013b). Sensitivity of stream reaches and resident fish to thermal shifts likely varies by location. For example, Staney Creek is a lower elevation, southwest-facing outer coastal watershed in the southern-most region of Southeast Alaska (Stillwater Sciences 2012; USFS 2013b); this watershed features many topographic variables associated with the highest likelihood of shifting temperature, precipitation, and stream flow patterns (see the Snow, Ice, and Water Features summary). Alternatively, other watersheds may experience few changes in thermal regime. For example, Glacial River, draining into the South Arm of Kelp Bay on northeast Baranof Island is an example of a higher elevation, northeast-facing watershed with substantial year-round snowpack that is less likely to be affected by shifting temperatures and other climate change-related factors (G. Killinger, pers. comm., 2014). In other cases, increasing water temperature may lead to increased stream productivity and improved growth rates for fish.

Flow regimes

Flow regimes in Southeast Alaska vary greatly depending on broad geographic location (which influences broad climate patterns), basin geomorphology, snow cover, and glacial coverage, and are sensitive to temperature, precipitation, and melt timing. Warmer temperatures, shifts from snow to rain, earlier snowmelt, and longer glacial ablation periods can contribute to shifting flow regimes in both glacial and non-glacial streams, though the magnitude and nature of flow regime changes differ between these two stream classifications (USFS 2010; see Snow, Ice, and Water Features summary). Flow regime changes, including changes in flow magnitudes and timing, can have several direct and indirect effects on fish species.

High flow events scour and deposit sediments, disturbing the benthos and reorganizing stream channels (Stanford et. al. 2005). The effects of high flow events on fish species are scale and location-dependent. For example, at the small spatial and temporal extent (i.e., within specific watersheds and stream reaches), floods can temporarily increase fish access to new habitat areas and food sources (Lang et al. 2006) and/or reduce suitable spawning habitat by increasing scour (M. Sloat, pers. comm., 2014). Conversely, low flows during outmigration may result in pond and off-channel rearing salmonids being trapped for extended periods at smolt size. These fish would then have a higher rate of returning as jacks the same year they out-migrate because of larger smolt size (S. Jacobsen, pers. comm., 2014).

Flood events and their associated effects on fish species will be highly variable across different regional watersheds, and impacts will be moderated by both the dynamic capacity of the watershed and by the life histories and adaptations of local fish stocks (M. Sloat, pers. comm., 2014). At broader scales, high flow events may be critical for maintaining the habitat features that fish species depend upon (Reeves et al. 1995). Fish species have evolved their life cycles to both capitalize on and take refuge from high flow events (Lytle and Poff 2004). Changes in the timing of high flow events may have deleterious effects by exposing flood-vulnerable life stages to flooding or by not exposing flood-reliant life stages to flooding. The impacts of changes in high flow events will vary with species, with resident stocks likely being the most vulnerable. Salmon will likely adapt much more readily than other species to meet spawning needs. For example, the Wilson River stocks of pink salmon, located in the channels of Misty Fiords National Monument (southern southeast) are known for their larger size and pronounced pelvic fins. This may be a stock morphological adaptation necessary to hold and spawn in this large and powerful river system, which supports annual escapements of 100,000 to 200,000 individuals. If a larger body size is required to survive a given stream system scour zone and stream reaches, it appears this species is capable of adapting to high flows in a matter of generations (R. Medel, pers. comm., 2014).

Low flow events – most common in non-glacial watersheds that are not connected to stable high elevation snowpack or groundwater-controlled – can stress fish species in several ways. As flow decreases so does habitat area, which results in fish competing for less space and potentially increases vulnerability to terrestrial and avian predators. Decreased flows are accompanied by decreased stream velocities, which result in less food being delivered in the stream drift (Wilzbach and Hall 1985, Hetrick et al. 1998, Hughes 1998 cited in Bryant 2009). Lastly, low flows during summer facilitate warmer stream temperatures, and the combination of reduced food abundance and increased water temperatures can result in decreased growth potentials for some fish species. For example, juvenile coho and sockeye salmon, steelhead, cutthroat trout, and Dolly Varden that rear in freshwater over the summer may be more sensitive to low flow conditions and subsequent impacts on fish growth. Additionally, spawning adults also depend on adequate water flow for access to spawning habitat and for water quality regulation. Low flow events coupled with warm stream temperatures can exacerbate shifting thermal regimes and dissolved oxygen deficiencies (Bryant 2009), especially in areas where juveniles and adults are trapped together (S. Jacobson, pers. comm., 2014).

Marine environment

Anadromous salmon spend a significant portion of their life in the marine environment, and thus are sensitive to changes in ocean conditions, including changes in temperature, salinity, upwelling, O_2 concentration, and pH. Ocean temperatures vary across different temporal scales responding to different climatic trends such as the Pacific Decadal Oscillation (PDO), El Niño Southern Oscillation (ENSO), and the Aleutian Low (Hare et al. 1999; Kaeriyama et al. 2004; Bryant 2009). Substantial reductions in ocean habitat suitable for salmon are predicted by the end of the century because of bioenergetically unfavorable water temperatures (Abdul-Aziz et al. 2011). Increased water temperatures have the potential to affect fish metabolic rates and in turn, fish may alter migration patterns to meet physiological needs and adjust to potentially reduced energy sources (food). Ocean temperatures can affect salmon survival and growth by affecting primary production and prey availability. For example, Alaskan salmon stocks typically have higher survival during warm PDO phases (cooler offshore temperatures, warmer nearshore temperatures) (Mantua et al. 1997; Bryant 2009; Martinson 2011) due to elevated prey availability (Hare et al. 1999), though fish size can also decrease during these high survival years due to increased inter- and intra-specific competition (Pyper and Peterman 1999; Orsi et al. 2000). Increased temperatures and decreased salinity levels can affect nutrient supply, impacting primary productivity with subsequent potential effects on salmon foraging and growth (Roessig et al. 2005). However, glacier runoff into the Gulf of Alaska contributes important sources of dissolved organic matter to nearshore coastal environments, suggesting that increased glacial melting due to warming temperatures may increase nutrient and carbon inputs, at least in the short- and mid-term (Fellman et al. 2010). Additionally, shifting salinities could affect habitable zones for juvenile salmon (Orsi et al. 2000) and alter interspecific competition between salmon species in the marine environment. Upwelling also has the potential to affect ocean temperatures and productivity, but it is uncertain how upwelling will be affected by climate change.

Altered marine pH can affect trophic chains and food availability for anadromous fish species, in turn affecting fish size, survival, and reproductive success in freshwater breeding habitats. Examples of key salmon prey organisms in the Northeast Pacific that are vulnerable to acidification include pteropods, which are important prey of pink salmon (Armstrong et al. 2008; Bednarsek et al. 2014), and squid (Kaeriyama et al 2004; Atcheson et al 2012; Kaplan et al. 2013), which are important for growth of maturing individuals of all species – except chum salmon – and, in particular, coho and Chinook salmon and steelhead. Furthermore, elevated pH can also increase the exposure or effect of contaminants on fish species (Pörtner et al. 2004; Guinotte and Fabry 2008).

Although research efforts have increased, large knowledge gaps remain regarding the oceanic stages of salmon life cycles and how salmonids might respond to changing ocean conditions (Haufler et al. 2010; Martinson 2011). Additionally, high variability in both regional coastal marine environments (Mueter et al. 2002) and survival trends of different salmon species further complicates understanding of and projecting fish responses to climatic changes in the marine environment. Options for mitigating climate change effects may be limited in the marine environment.

Future climate exposure

Workshop participants identified increasing temperatures, precipitation changes that lead to low stream flows and/or high flood/scour events, and earlier snowmelt as key future factors to consider for fish species in Southeast Alaska.

Temperature

Mean annual air temperatures in the Southeast Alaska region increased 0.8°C from 1943-2005 (NOAA 2013) and are projected to increase 0.5-3.5°C by 2050 and 2-6°C by 2100 under high greenhouse gas emission scenarios[52] (Wolken et al. 2011; SNAP 2013). The highest rate of increase will be seen in winter months, with mean winter temperatures increasing 1-3.5°C by 2050 and 2.5-6°C by 2100 under high greenhouse gas emission scenarios (SNAP 2013). Temperature changes can have indirect impacts on fish species by causing shifts in precipitation form (e.g., snow to rain) and increasing glacial and snow melt rates, which can affect flow regimes. Additionally, increasing air temperatures drive warming stream and ocean temperatures, affecting fish habitat quality.

Stream Temperature

In general, increasing air temperatures may contribute to warmer stream temperatures (Rieman et al. 2007; Wenger et al. 2011). However, recent research by Arismendi et al. (2012) in the continental U.S. indicates a less direct association between air and stream temperature trends, highlighting the importance of local, non-climatic factors in understanding future stream temperature trends. Research from Cook Inlet, Alaska, suggests that stream temperatures in non-glacial streams and some lakes are projected to increase, potentially warming 1-3°C by 2050 and 2-4°C by 2100 (Kyle and Brabets 2001). A recent study of watersheds with variable glacier coverage in Southeast Alaska found that streams with less than 30% glacial coverage experienced summertime warming in response to warmer air temperatures, while streams with more than 30% glacial coverage exhibited decreasing stream temperatures under the same conditions (Fellman et al. 2014). The influence of air temperature on stream temperature in glacial systems will be strongly

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[52] Note that the “high greenhouse gas emission scenarios” are slightly lower than actual emissions trajectories today.

influenced by groundwater inputs, the length and gradient of the stream system below the glaciers, presence of lakes and ponds in the system, and stream shading. Additionally, the increased probability of intense summer and fall rainfall may lessen the negative impacts of increased air and stream temperatures.

Fish in surface water-fed streams and rivers, as well as in low gradient forested watersheds (especially large, shallow- and dark-water lakes and wetlands), may be the most exposed to increasing water temperatures, as they lack glacial inputs to mitigate rising stream temperatures (although groundwater and lake inputs, shade, and other local factors can also mitigate stream temperature increases). Increased winter water temperatures in surface water-fed streams could have both positive and negative impacts on fish species, potentially increasing development rates, causing earlier emergence of fry for a variety of fish species, and affecting growth rates, timing of ocean migration, and overall survival (Kelly et al. 2007; Bryant 2009). The impacts of increasing summer water temperatures on adult mortality and juvenile fish growth and survival will likely vary widely by location and fish stock. For example, summer runs of pink, chum, and sockeye salmon in some watersheds could incur higher metabolic costs and elevated mortality as they travel upstream to spawn (Bryant 2009).

Alternatively, smolt residing in streams that are currently limited by cold temperatures could benefit from water temperature increases. For example, daily utilization and migration between cold water feeding habitats and warmer resting habitats increased the growth rates of juvenile coho salmon compared to individuals who did not engage in this behavioral thermoregulation (Armstrong et al. 2013). Impacts of increasing water temperatures on fish species could also be amplified during warm PDO cycles, which are typically associated with warmer air temperatures (Neal et al. 2002). However, the PDO may confound regional and global temperature changes in some situations.

Ocean Temperature

Ocean temperatures moderate primary production and salmon prey availability, and are influenced by climatic events (e.g., PDO, ENSO, Aleutian Low), currents, upwelling, and air temperatures. For example, a regime shift from the negative (cold) to positive (warm) phase of the PDO in 1976-77 was followed by increases in Alaskan salmon stocks over the next three decades due to warmer ocean temperatures, particularly nearshore temperatures, and higher prey availability (Hare et al. 1999; Boldt et al. 2005). However, global climate models project increasing ocean temperatures in the Gulf of Alaska through the rest of the century (Beltrán et al. 2012), which could alter the timing of spring phytoplankton blooms, nutrient availability in near and offshore marine salmon habitat, and salmon growth and survival (Martinson 2011). For example, sea surface temperatures above 12°C have been linked with lower adult harvest of chum and pink salmon (Martinson 2011), and global climate models project that summer water temperatures in the Gulf of Alaska could well exceed 12°C by 2020 and beyond (Beltrán et al. 2012). Both winter and summer thermal ocean habitats of Pacific salmon are projected to decrease significantly (e.g., anywhere from 30-86% using the IPCC A1B scenario and depending on species) by the end of the century as compared to historical time frames (Abdul-Aziz et al. 2011). Additionally, climatic events could compound or buffer trends in ocean temperatures and salmon fitness. For example, PDO cycles tend to shift every 20-30 years (Hare et al. 1999), and future shifts between cold and warm phases of the PDO could affect salmon stocks. Shorter-term events, such as El Niño or La Niña cycles, could also affect prey availability and salmon productivity, as these cycles also influence ocean temperature, water column stability, and primary production (Freeland 1998; Freeland 2001; Kaeriyama et al. 2004).

Precipitation

Mean annual precipitation has been increasing in Southeast Alaska, with a 10% (6.6 cm) increase from 1943-2005 (NOAA 2013). Although precipitation patterns are hard to project and vary greatly across Southeast Alaska due to site-specific features, precipitation could increase 5-15% by 2050 and 15-35% by 2100 (SNAP 2013). These increases are expected in all seasons, with the greatest increases likely in winter and fall months. For example, winter precipitation could increase by 5-15% by 2050 and 25-35% by 2100 (SNAP 2013).

Increasing regional precipitation may have variable impacts on fish species. For example, early winter rain events may facilitate emigration of juveniles from off-channel ponds that later reach critically low oxygen levels while under ice. Results of a study in the Chilkat River Valley in the early 1980s suggest that late-fall and winter flow can be critical for coho salmon to avoid entrapment in waters that reach a lethally low oxygen concentration by early spring (R. Josephson, pers. comm., 2014). Additionally, an increase in summer precipitation and stream flow may benefit rearing populations of coho salmon (Mathews and Olson 1980) by increasing access to new food and habitat in floodplains and side channels (Lang et al. 2006). Alternatively, projected increases in flood magnitude as a result of increased regional precipitation and warmer temperatures may reduce the number of stream networks providing suitable salmon spawning habitat, though there is high variability in stream response to increasing flood magnitudes (M. Sloat, pers. comm., 2014).

Relationships between hydrology, fish species, and climate are very complex, and both local and regional trends can influence local watershed- and species-specific outcomes. For example, in the Berners River, a mainland system with extensive wetlands and high water storage capacity, coho salmon smolt production was strongly correlated with July–November precipitation in the year prior to smolting from 1989-2005 (L. Shaul, pers. comm., 2014). However, smolt production trended lower and ceased tracking summer-fall precipitation after the mid-2000s, coincident with a cooling trend in the PDO and lower spring air temperatures recorded at the Juneau Airport. A concurrent decreasing pattern in coho salmon production is also evident in the Chilkat River since 2000, supporting the hypothesis that runs in both systems were reduced by a geographically broad influence, such as the recent cooling trend in North Pacific climate that may have reduced over-winter survival in peripheral habitats.

Fish species are also sensitive to precipitation shifts (e.g., from snow to rain) that affect hydrologic and thermal regimes within watersheds (e.g., magnitude, duration, and volume of seasonal stream flow), as these changes affect salmon survival, spawning, and outmigration. Shifts from snow to rain and subsequent impacts on hydrology and fish species will be more likely to occur at lower elevations, in coastal/island areas, and in southern portions of the region, as well as in streams that are not connected to stable high elevation snowpack, glacial inputs, or groundwater. Snow-day fractions (the number of days in a given month where precipitation falls as snow) are projected to decrease in Southeast Alaska by the end of the century,[53] particularly in late winter and early spring[54] (e.g., February and March) (McAfee et al. 2013). In glacial and non-glacial streams, shifts from snow to rain can increase winter

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[53] These projections rely on data from relatively low elevation monitoring stations, and projections varied widely between different climate models and forcings used in the study. Overall, local conditions will likely moderate actual precipitation form and a high degree of regional and local variability in snow-day fractions is likely (McAfee et al. 2013).

[54] Snow-day fractions are also projected to decline in fall, but to a lesser extent than in late winter and spring (McAfee et al. 2013).

flows, which may affect winter egg development by modifying stream temperatures or by increasing roe scour in altered floodplains. Alternatively, an increase in winter rain-on-snow events and an associated reduction in the depth and duration of snow cover may increase winter-spring oxygen levels in ice-covered off-channel fish habitats, thereby reducing potential winter-kill (Greenbank 1945). In non-glacial streams, shifts from snow to rain also contribute to decreased summer flows (Neal et al. 2002), which can contract summer habitat and affect summer run adult migrations (Bryant 2009).

Increased precipitation and shifts from snow to rain could also increase pollutant mobilization by increasing erosion and/or decreasing ice cover (Macdonald et al. 2005; Schiedek et al. 2007). These impacts will likely be more pronounced during warm PDO cycles, which typically feature higher winter flows and lower summer flows (Neal et al. 2002). Finally, drought events can have a myriad of impacts on fish species (e.g., by affecting spawning or rearing habitat). Drought conditions, defined as periods with less than average precipitation, have occurred in Southeast Alaska within the past year (U.S. Drought Monitor),[55] but tend to be transient and typically short-lived in nature (i.e., the region can phase out of drought conditions as rapidly as over the course of a single good rain event or a few, wet weeks) (A. Jacobs, pers. comm., 2014).

Future projections regarding the frequency of extreme precipitation events in Southeast Alaska are uncertain (NPS 2013), but warmer regional temperatures increase the likelihood that when extreme precipitation events do occur they are likely to be rain-on-snow incidents (Rennert et al. 2009). Rain-on-snow events increase runoff and can lead to high volume flows and/or landslides (Neal et al. 2002; Bryant 2009), negatively impacting fish stocks in the short-term by scouring redds and increasing sediment deposition downstream (Bryant 2009). The impacts of scour events could be exacerbated if returning adults are smaller, as smaller fish have shallower redds; the likelihood and potential impacts of scour events will vary between species and depend upon watershed location. For example, Dolly Varden and coho salmon spawn in higher gradient streams, which may increase their exposure to scour events (S. Jacobson, pers. comm., 2014). Smaller species (e.g., pink salmon) could also have higher exposure to scour events since they lay shallower redds than larger species (e.g., coho salmon) (Chapman 1988). Rain-on-snow events will also be more likely to occur during warm PDO phases when temperatures are typically higher (Neal et al. 2002). Alternatively, more winter rain-on-snow events that coincide with reduced snow cover duration and snowpack depth may increase winter-spring oxygen levels in ice covered off-channel fish habitats (Greenbank 1945). Workshop participants identified floodplain areas where flows distribute and lose velocity as potential refugia from high flows and scour events, and groundwater-fed streams, glacier-fed streams, ponds, estuaries, and spring-fed tributaries as potential refugia from low flows.

Earlier snowmelt

Southeast Alaska experienced earlier snowmelt timing from 1988-98 (Ramage and Isacks 2003), and the day of thaw, defined as the day on which consecutive monthly midpoint temperatures transition from negative to positive, is projected to occur progressively earlier by the end of the century (SNAP 2013; see Figure 6, Climate Projections section). Earlier snowmelt and warmer stream temperatures in non-glacial streams and earlier ablation periods in glacial streams can trigger earlier fry outmigration, potentially reducing survival of smaller smolts and/or all smolts if marine food abundance is too low at that time (Bryant 2009). Earlier snowmelt can also prolong low flow periods during summer in non-glacial streams (Stewart 2009), while longer glacial ablation periods may increase summer flows and available fish habitat in glacial streams (Bryant 2009). Earlier ice melt in sockeye salmon habitat can

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[55] http://droughtmonitor.unl.edu/MapsAndData/MapArchive.aspx

increase adult growth opportunities by lengthening the growing season in freshwater lakes and increasing the size of smolts (G. Killinger, pers. comm., 2014). In the Wood River system in Southwest Alaska, Schindler et al. (2005) found that a progression toward earlier spring break-up dates over a period of four decades was associated with warmer water temperatures and increased zooplankton densities that translated into increased growth of sockeye salmon during their first year of life. The species likely most dependent on spring and early summer snowmelt are Chinook salmon (R. Medel, pers. comm., 2014).

Marine environment

Aside from temperature shifts, other future changes in the marine environment (e.g., salinity, pH, upwelling) could also influence the fitness of Southeast Alaskan salmon species. However, there is currently great uncertainty in projected oceanic changes and how various species and stocks will respond to shifts in the marine environment. For example, steelhead and Chinook and chum salmon stocks may show less fluctuation in response to changes in ocean temperature and productivity due to their diversity of life history strategies and high variation among juvenile and adult behavior; in comparison, pink, coho, and certain types of sockeye salmon may show large shifts in stock numbers as ocean productivity changes due to less variable life history strategies (Hare et al. 1999). However, variation in numbers and size of salmon may also depend upon their trophic position. For example, maturing Chinook and coho salmon and steelhead depend heavily upon micro-nekton, particularly squid, for growth in offshore waters of the Northeast Pacific, while pink, sockeye, and chum salmon have more flexible diets (Kaeriyama et al. 2004) that may allow them to more readily adapt to changes in the food web.

Sensitivity and exposure to non-climate stressors

Workshop participants identified several non-climate stressors that affect the sensitivity of fish species, although overall exposure to these stressors is considered low in Southeast Alaska and on Tongass National Forest lands due to the development and implementation of best management practices (BMPs) on federal lands. Avoiding future exposure to non-climate stressors is likely a critical component of maintaining the resilience of Southeast Alaskan fish species in the future. Workshop participants identified timber harvest, land use conversions (e.g., road development), hydropower and dams and water diversions, aquaculture and hatcheries, fishing, mining, and invasive species as key non-climate stressors with the potential to impact fish species.[56]

Timber harvest and land use conversions (e.g., road development) can alter habitat conditions and/or disrupt water quality. For example, transportation corridors and timber harvest along fish-bearing streams affect stream habitat by increasing sediment and soil erosion, disrupting migration corridors and affecting connectivity, altering recruitment of large woody debris, and contributing to warming water temperatures (Rieman and Isaak 2010). However, within the Tongass National Forest, only approximately 6% of streamside habitat along salmon streams has been impacted by timber harvest or road construction, and many restoration projects are underway to restore salmon habitat in the most productive systems (USFS 2012; USFS 2013b). Additionally, the development and implementation of

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[56] The collective degree these stressors increase sensitivity of fish species was considered Moderate-High, but variable within the region, and the confidence associated with this evaluation was Moderate-High. Current exposure to these non-climate stressors in Southeast Alaska was judged to be Low, especially on federal lands, although there could be higher exposure in localized areas (Confidence: Moderate-High).

Forest Plan Standards and Guidelines and BMPs (e.g., the Tongass Timber Reform Act) minimizes current and future exposure to timber harvest and other non-climate stressors within the Tongass National Forest. For example, federal BMPs aim to preserve water quality, watershed function, and aquatic habitat quality by requiring minimum 100 foot riparian buffers around fish-bearing (Class I and II) streams (USFS 2006; USFS 2008). Slope break buffers are also required on Class III streams, and Class IV streams have their own associated BMPs. Piccolo and Wipfli (2002) suggest that upstream harvest activities can also influence downstream fish habitat and food availability; for example, they suggest that harvest along Class IV headwater streams could impact aquatic invertebrate and detritus delivery.

In addition to implementing BMPs, the Tongass National Forest has also been assessing, replacing, and monitoring culverts in fish bearing streams to facilitate juvenile fish passage and ensure access to fish habitat (USFS 2006; USFS 2008; USFS 2013a). While some culvert barriers remain, they typically occur in small and/or steep streams with relatively limited amounts of upstream habitat (G. Killinger, pers. comm., 2014). However, extreme precipitation events could enhance the likelihood of culvert overload or cause culverts to become plugged with debris. Continued monitoring – called for by regional land management guides and BMPs (e.g., USFS 2006; USFS 2008) – may help minimize future impacts from these events by triggering management actions (e.g., install culverts designed to withstand a 100-year flood) before impacts occur.

Dams, hydropower development, and other water diversions can limit habitat and impede connectivity for fish species, and can contribute to lower stream flows in summer. However, exposure to such impacts is considered low in Southeast Alaska due to careful facility placement and fish-conscious management of such facilities. For example, hydropower facilities on Tongass National Forest lands operate under Special Use Permits (USFS 2006), which can be designed to align with management objectives for watershed and fish habitat health (USFS 2008). Additionally, hydropower facilities in Alaska are located in areas with extreme topography, so facility operations generally have minimal impacts on fish habitat (Cherry et al. 2010). However, associated powerline construction and maintenance may result in many stream crossings and impacts to riparian areas.

Fish species are also sensitive to aquaculture and hatchery operations. Alaskan hatcheries release more than 1.6 billion salmon annually into the Pacific[57] (Naish et al. 2007), and Prince William Sound and Southeast Alaska are the main regions in which salmon hatcheries operate (Environmental and Natural Resources Institute (ENRI) 2001). Hatchery stocks can decrease the genetic variation of wild stocks through hybridization, genetic drift, altered selection regimes, and/or affect wild stock productivity through elevated competition and/or predation (Waples 1991; Naish et al. 2007). These impacts are particularly evident in the marine environment; elevated competition can decrease fish body size, and in some cases, survival of wild populations (Naish et al. 2007). For example, pink salmon hatcheries in Prince William Sound (PWS) led to the decline of PWS wild pink salmon stocks while other Alaskan wild pink salmon stocks increased during the same time period (Hilborn and Eggers 2000; Hilborn and Eggers 2001). The competition dynamics between wild and hatchery salmon could become more significant under changing climate and ocean conditions, particularly if the carrying capacity of regional marine zones decreases. In addition to genetic and competition concerns, hatchery operations can increase disease risk in wild populations through several pathways (Naish et al. 2007), although disease monitoring and control protocols (e.g., Alaska Fish and Shellfish Health and Disease Control Policy;

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[57] Southeast Alaska annually releases 450 million chum and 100 million pink salmon, while the Pacific Northwest releases 800 million pink and 200 million chum for an overall total of 1.6 billion salmon annually (R. Medel, pers. comm., 2014)

Sockeye Salmon Culture Manual) may reduce disease risk in Southeast Alaska (ENRI 2001). Detrimental impacts from hatchery operations have been documented among threatened salmonid populations elsewhere in the world (e.g., the Pacific Northwest; see Levin et al. 2001), and could become more important for Alaskan fish species in the face of climate change. The Alaska Department of Fish and Game (ADFG) is engaged in long-term research projects to better understand how regional hatcheries affect wild fish stocks (ADFG Hatcheries Research 2014) and has numerous policies designed to minimize impacts of hatchery fish on wild stocks.

Fishing – including subsistence, recreational, and commercial fisheries – is a common and critical component of Alaska's economy and culture (Bryant 2009). On average, 48 million wild salmon are caught annually from the Tongass National Forest, and the combined economic impact of fisheries was estimated to be $986 million in 2007 (USFS 2012). Despite its historical practice and cultural and economic importance, fishing, particularly overharvest, can alter stock structure and decrease resilience of Southeast Alaskan fish stocks. For example, some small sockeye runs are heavily used for subsistence purposes, but have dropped below historical population levels due to incidental take as they migrate through pink salmon fishing grounds, prompting federal monitoring via weirs (G. Killinger, pers. comm., 2014). Fishing can also remove potential nutrient sources for upper stream reaches, as Pacific salmon are a key source of marine-derived nutrients, such as nitrogen (Helfield and Naiman 2001; see Riparian Vegetation Species summary). Although current exposure to detrimental fishing practices is considered low in Southeast Alaska, the impacts from fishing could become more significant if climate change causes declines in salmonid populations.

Mining operations can also impact fish species, but current exposure to mining operations is considered low in Southeast Alaska. The region has two operating mines and several proposed mining projects for Prince of Wales Island, but intensive federal regulation and monitoring ensures that they have negligible impacts on downstream fish stocks (G. Killinger, pers. comm., 2014). However, there are both current and proposed Canadian mines on large trans-boundary rivers that flow into Southeast Alaska, and with different monitoring and regulatory processes, it is unknown how or to what extent these mines will impact downstream water quality and fish stocks within Southeast Alaska (G. Killinger, pers. comm., 2014). Historical mining activity in Southeast Alaska is considered to be the main source of mining impacts on regional fish, such as altered stream pH, mercury bioaccumulation, high metal concentrations in water and fish, acid rock, and radiation (US EPA 2012). However, extensive cleanup and restoration of abandoned mines has been a priority on federal lands in Southeast Alaska for many years.

Fish species are also sensitive to invasive species and, although current exposure is considered low in Southeast Alaska, there is concern that warming temperatures may increase proliferation potential for species that were previously excluded due to cold temperatures. Invasive species can impact native species in a variety of ways, including altering habitat characteristics or food webs that may already be shifting due to climatic changes. Ships (via ballast water discharge and hull fouling) could be important sources of future exotic species introductions as conditions change in the region. Southeast Alaska typically has more ship arrivals than other Alaskan regions (McGee et al. 2006), potentially increasing its vulnerability to exotic species invasion.

Adaptive Capacity

Species extent, continuity, and diversity

Workshop participants and reviewers evaluated the overall adaptive capacity of fish species as high[58] due to high historical genetic, behavioral, and life history diversity, high phenotypic plasticity, and generally robust, widespread, and connected populations, though some natural and anthropogenic barriers to fish dispersal might exist. In general, Alaskan fish stocks are robust, widespread, and have high population connectivity, although population connectivity varies according to species biology and system. For example, population connectivity of fish species in freshwater systems may be slightly less than in marine systems due to anthropogenic (e.g., nets, culverts) and natural barriers (e.g., waterfalls, low flows). Fish also encounter genetic barriers because most return to and spawn only in their rearing stream.

Fish species in Southeast Alaska, particularly Pacific salmonids, have historically featured a high diversity of life history strategies and high genetic, behavioral, and phenotypic plasticity. For example, rainbow trout and Dolly Varden located upstream of barrier falls can retain anadromous traits. Southern runs of Alaskan coho salmon return earlier in the year than northern runs in Southeast Alaska, and coho juveniles typically spend an extra year rearing in freshwater habitats compared to coho salmon in British Columbia and the Pacific Northwest (Halupka et al. 2000). Southeast Alaskan fish species also typically have high genetic diversity. For example, coho salmon populations in Southeast Alaska are more genetically diverse than Northern Alaska populations, potentially due to increased gene flow with populations in British Columbia and the Pacific Northwest (Olsen et al. 2003). Additionally, Southeast Alaskan fish have high behavioral and phenotypic plasticity (e.g., ability to utilize a broad diversity of habitats) and phenotypic adaptions to localized features (Bryant 2009). For example, in recent history the short outlet stream of Benzeman Lake (at the head of Necker Bay, south of Sitka) was covered by a landslide and filled with large boulders. Sockeye salmon from the lake must now navigate upstream through this boulder field, which features large outflows through small access channels, and have phenotypically adapted to the local conditions through smaller body size (i.e., they are less than half the size of normal returning adult sockeye in other Southeast Alaskan systems; G. Killinger, pers. comm., 2014).

Management potential

Workshop participants judged fish species to be very highly valued by the public[59] due to their economic, cultural, recreational, and social importance. Workshop participants identified hatcheries, timber harvest, road construction, hydropower, mining, overharvest, and jet boat recreation as potential use conflicts, and noted that current BMPs are successful at mitigating timber harvest and road construction impacts on fish species. Although workshop participants suggested several strategies for mitigation or improved management of other use conflicts, they also noted that management choices may need to be addressed at state, municipal, or local – rather than federal – levels for maximum effect. Regional reviewers suggested additional management strategies to enhance monitoring and develop indicators for habitat conditions and salmon populations. Potential management strategies are further outlined below; please note they represent only general, preliminary ideas of how to enhance the resilience of fish species in Southeast Alaska.

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[58] Confidence associated with this evaluation was High.
[59] Confidence associated with this evaluation was High.

Workshop-Generated Management Strategies:[60]

- Generate and implement hydropower stream flow requirements to mitigate the duration, severity, and impacts of low flows.
    - Likelihood of implementation or effectiveness: High
    - Potential benefits: Improve resilience of fish stocks to climate and climate-driven changes (e.g., low flows and high temperatures), reduce migration stranding.
    - Potential challenges: Conflicts with hydropower interests, could limit hydropower generation or alter generation timing.
- Maintain and fund regulatory/licensing procedures to prevent construction of future hydroelectric dams that could negatively impact fish species and/or reduce species resilience to climate change impacts.
    - Likelihood of implementation or effectiveness: High
    - Potential benefits: Improve resilience of fish stocks to climate and climate-driven changes (e.g., high temperatures), prevent improper siting and future conflict between user groups.
    - Potential challenges: Funding limitations and budget cuts could undermine regulatory and licensing budgets.
- Increase public access to information regarding the impacts of overfishing, and promote the development of sustainable harvest quotas that include consideration of climate change vulnerabilities.
    - Likelihood of implementation or effectiveness: Moderate
    - Potential benefits: Reduce overharvest, sustain fish stocks for future harvest, increase or maintain delivery of marine-derived nutrients to upstream reaches.
    - Potential challenges: May be expensive, and Forest Service only has management/cooperative management authority over subsistence stocks, so outreach efforts may not generate change in commercial or recreational fisheries.
- Improve stream restoration strategies such that they include climate change considerations.
    - Likelihood of implementation or effectiveness: Moderate
    - Potential benefits: Improve long-term stability and maintenance of fish habitat.
    - Potential challenges: Financial barriers, fishing and/or other activities could hinder restoration efforts.
- Limit jet boat access to areas that are not impacted by their use, and/or restrict jet boat access during spawning times.
    - Likelihood of implementation or effectiveness: Moderate
    - Potential benefits: Reduce non-climate stressor on fish reproduction.
    - Potential challenges: Conflicts with fishing interests.
- Work with the Alaska Department of Fish and Game to manage hatchery operations to mitigate impacts of hatchery stocks on wild fish population productivity and genetic diversity, particularly in watersheds where wild fish populations are facing heightened climate stressors (e.g., low flows).
    - Likelihood of implementation or effectiveness: Low-Moderate
    - Potential benefits: Improve resilience of wild stocks (e.g., maintain genetic diversity, reduce competition and disease incidence, etc.).
    - Potential challenges: Major commercial fishing industry not likely amenable to reducing hatchery production, hatchery reductions would likely increase fishing

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[60] Workshop-generated management strategies were developed by participants at the Tongass National Forest Vulnerability Assessment Workshop held in January 2014.

pressure on wild salmon populations (including those supporting subsistence fish harvests), Forest Service has little to no control over hatchery management.

- Minimize road construction and concentrate road storage and decommissioning efforts within the most vulnerable watersheds (e.g., non-glacial, low elevation rivers) and continue to use/revise BMPs (e.g., riparian buffers) to incorporate climate-informed design and construction methods (e.g., ensure that culverts allow for adequate fish passage during current and potential future flow regimes).
    - Likelihood of implementation or effectiveness: High
    - Potential benefits: Protect fish habitat and bolster fish resilience to climate and climate-driven changes, reduce non-climate stressors (e.g., sedimentation, stream alteration).
    - Potential challenges: Conflicts with development interests.
- Continue to use and/or increase federal Forest Service stream buffer regulations (e.g., USFS 2006, USFS 2008) for timber harvest and young growth treatments on federal lands.
    - Likelihood of implementation or effectiveness: High
    - Potential benefits: Protect fish habitat and enhance resilience of fish species, reduce disturbance.
    - Potential challenges: Conflicts with timber harvest interests.
- Continue to restore riparian buffers in past mining zones.
    - Likelihood of implementation or effectiveness: Low-Moderate
    - Potential benefits: Reduce erosion, acid drainage, and leaching to fish habitat, improve fish health (e.g., reduce bioaccumulation of mercury and other heavy metals).
    - Potential challenges: Financial barriers may not be top priority as many mine sites have already been cleaned up, trans-boundary mines could still impact fish stocks and are largely managed by Canadian entities, so Forest Service may have minimal influence on management strategies.

Reviewer-generated Management Strategies:[61]

- Implement a regional monitoring program to track key aquatic climate-related factors and fish populations. Develop a strategic and cost-efficient design that provides information for managers and researchers in the short- and long-term.
    - Key monitoring program components:
        - Track stream temperature and flows in areas of concern (e.g., transitioning or degraded fish-bearing watersheds)
        - Continue to index stream fish counts across Southeast Alaska (i.e., primarily through Alaska Department of Fish and Game)
        - Monitor fish populations in areas where they currently occur (i.e., through Forest Service Subsistence Program – Fisheries Resource Monitoring Program)
    - Potential benefits: Monitoring may help identify problem areas earlier, which can increase potential for successful management and will provide baseline data to inform management actions and future research needs.
    - Potential challenges: Financial and institutional barriers, monitoring at large scales may be difficult due to hard-to-access areas. Divert financial resources from more direct actions to manage fish.
- Increase understanding of potential impacts of timber harvest and other management activities on water yield, snow retention and other stream flow and aquatic habitat-related factors when

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[61] These strategies were developed by regional reviewers during an initial revision process of this report.

contemplating management activities in more vulnerable watersheds (e.g., watersheds transitioning from snow to rain).

  - Other potential indicators for vulnerable watersheds:
    - Lower average elevation and topography (less snowpack),
    - Outer coastal and southern locations (less snowpack),
    - Less groundwater input,
    - Existing history of periodic low flows and/or high temperatures at/near lethal levels to fish
  - Potential benefits: Minimize anthropogenic impacts and reduce risk of exacerbating climate impacts, increase or maintain resilience of fish species in vulnerable watersheds.
  - Potential challenges: Conflicts with other management objectives (e.g., timber harvest).

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5. Conclusions and Next Steps

This vulnerability assessment is an initial examination of a focused subset of potential climate change impacts on Tongass National Forest aquatic resources. The results of this assessment are meant to help guide and support managers or planners in 1) identifying which aquatic resources are likely to be most affected by changing climate conditions; 2) improving understanding as to why those resources are likely to be vulnerable; and 3) provide insights into potential management actions. It is intended to help inform an amendment to the 2008 Tongass Forest Plan, which will explicitly consider climate change implications for the Forest. While this report only addresses a small suite of Tongass resources, it lays the groundwork for potential future methodologies, structure, and content for assessing the vulnerability of other important forest resources. The results of this assessment are a new toolset among many that can be used in managing natural resources under changing climate conditions.

Future research needs identified during this assessment include:

- Installing precipitation stations on icefields to improve understanding related to drought,
- Installing precipitation stations at higher elevations to improve precipitation projections across elevational ranges,
- Improving climate change predictions for riparian and aquatic areas in order to identify “most vulnerable” watersheds,
- Long term stream and lake temperature monitoring, and
- Further defining what elevations may be most vulnerable to changing climate conditions.

Appendix A. Potential Management Applications

The vulnerability assessment information presented in this report can help inform Forest- and project-level planning, and can be used to address multiple U.S. Forest Service (USFS) Climate Change Performance Scorecard elements. Specifically, vulnerability assessment information helps:

- Meet Climate Change Performance Scorecard Element 6 – Assessing Vulnerability
- Meet Climate Change Performance Scorecard Element 8 – Monitoring, by informing the identification of broad-scale and plan-level monitoring strategies to track climate change impacts and management action effectiveness
- Inform the development, revision, and/or amendment of Forest Plan components, including Desired Conditions, Objectives, Standards and Guidelines

Below we explore how vulnerability assessment information could be used to inform the development of monitoring strategies and revisions and/or amendments to Forest Plan components.

Monitoring strategies

Two of the primary purposes for monitoring are assessing progress towards goals and evaluating the effectiveness of management actions. Information collected to assess ecosystem and species conditions and trends, as well as management effectiveness, can also be useful for evaluating and adapting to climate change. However, this requires explicit consideration of climate change in the monitoring framework.

Table 11 illustrates how monitoring for climate change impacts could be incorporated into existing monitoring efforts by using an adaptive framework. **Please note that this table is just an example to demonstrate how climate impacts may be incorporated into monitoring efforts. The table contents do not represent specific recommendations; rather the table is intended as a framework or template for what could be developed by the forest.** The categories within Table 11 – fish habitat restoration and fish production – were selected using two existing monitoring strategies from the 2008 Tongass National Forest Land and Resource Management Plan:

1. Conduct monitoring of fish habitat restoration and improvement projects to ensure their continued function at the design level of operation.
2. Monitor fish production on a representative sample of restoration and improvement projects to evaluate effectiveness of the overall improvement program.

The table begins with clear, measurable restoration or fish production targets then identifies a suite of climate changes and habitat or species changes to monitor. Climate changes were selected based on information from the fish species vulnerability assessment, which identified stream temperatures and altered flow regimes (i.e., both high and low flows) as key sensitivities to consider. Each management target has an associated management trigger for action if the habitat or species are not performing well. For each management trigger, there is a list of potential actions that resource managers might take if a management trigger is reached. This type of adaptive management table helps to identify the relevant climate changes to monitor in order to evaluate management action effectiveness in achieving a given target.

Table 11. Adaptive management table that describes examples of management targets, monitoring parameters, management triggers, and potential management actions for fish habitat restoration and fish production in the Tongass National Forest. **Please note that this table is just an example to demonstrate how climate impacts may be incorporated into monitoring efforts. The table contents do not represent specific recommendations; rather the table is intended as a framework or template for what could be developed by the forest.**

Category	Management Target	Monitoring Parameters	Spatial Scale for Monitoring Results	Management Triggers	Potential Management Action
Fish habitat restoration	No long-term net loss of aquatic or riparian habitat in a given location	Climate changes: • Stream temperature > Increasing temp in low gradient watersheds > Decreasing temp in glacial melt dominated watersheds • Summer (JAS) flow or 7Q10 • Peak winter flow or channel-forming flow Habitat changes: • Riparian habitat amount • Riparian and aquatic habitat quality rated as high, medium, or low based on fish species	Project- or site-level	• Observed net loss of aquatic or riparian habitat greater than the range of natural variability • Field data collection and/or observation indicates that flood risk is greater than that predicted by climate models • Field data collection and/or observation indicates that stream temperatures are increasing (e.g., in low gradient watersheds) beyond species thermal tolerances	• Convene scientists to assess if observed changes are due to climate changes • If habitat restoration is not meeting goals in light of climate change, assess biological significance of long-term loss of aquatic/riparian habitat • Adjust pace, scope, or design of restoration activities in light of climate change impacts

Fish production	Maintain or enhance numbers of fish species in the Drainage of interest (at specified baseline/target number)	Climate changes: • Stream temperature > Increasing temp in low gradient watersheds > Decreasing temp in glacial melt dominated watersheds • Summer (JAS) flow or 7Q10 • Peak winter flow or channel-forming flow Species info: • Use previously collected data on species abundance (e.g., smolt production coefficients), as well as modeled abundance, to set targets for abundances of fish species • Monitor species abundances • Monitor changes in species composition	Watershed	• Decline in the abundance of fish species (i.e., below targets for X number of consecutive years)	• Convene scientists and managers to assess if observed declines are due to climate changes, management actions, or other external factors • Adjust pace, scope, or design of restoration activities to provide better suited habitat for fish species

Forest Plan revision or amendment

In order to implement robust, durable management actions today that will sustain Tongass National Forest resources into the coming decades and centuries, it is imperative that climate change be considered explicitly in management planning. The following examples for fish species and riparian vegetation demonstrate how vulnerability information could be incorporated into Forest Plan components.

Box 1. Revising Standards & Guidelines for Fish Species

Fish species of the Tongass National Forest may experience climate-driven changes such as warming stream temperatures and altered flow regimes including increases in winter or spring high flow events or longer summer low flow events. Warmer stream temperatures and altered flow regimes can affect fish species growth rates, spawning and juvenile rearing success, migration, and survival. Consequences may be positive or negative and may differ by taxa and across watersheds. Below are two examples of how climate change information could be integrated into existing management objectives, standards, or guidelines.

Example 1. Objectives/Guidelines for Management Affecting Fish Habitat
Current Standards & Guidelines: Maintain, restore, or improve, where feasible, stream conditions that support the migration or other movement of aquatic organisms inhabiting a water body. If a stream crossing cannot be avoided, the best solution for aquatic organism passage is generally to maintain the natural stream form and processes from the inlet, through the crossing, and into the downstream channel. Bridges, open-bottom culverts, and stream-simulated culverts designed and installed to applicable best management practices and design standards to best meet this objective.

Potential Vulnerabilities: Climate-driven changes in flow regimes, including increased winter or spring high flow events due to shifts from snow- to rain-dominant watersheds or increased extreme precipitation events, may exceed current design standards (i.e., result in structural failure) of culverts or bridges.

Recommended Revision/Addition to Current Standards & Guidelines: Using best available climate change science, design culverts or bridges to accommodate flood capacity and projected future peak flows (e.g., Q100 or Q500). Structural design should provide for maintaining channel stability and allowing for increased debris movement as a result of increased flows. Ensure adequate grade controls are in place that will withstand increased flows.

Example 2. Standards & Guidelines for Fish Habitat and Channel Processes
Current Standard: Recognize watershed function and channel processes when planning for the protection, restoration or enhancement of fish habitat.

Current Guideline: Consider topics such as erosion processes, watershed hydrology, vegetation, stream channel morphology, water quality, wilderness designation, recommendations for inclusion into the Wild and Scenic River System, species and habitats, and human uses, during analyses.

Potential Vulnerabilities: Climate-driven changes in flow regime may affect watershed function and alter channel processes. Additionally climate-driven changes including altered flow, precipitation, temperature, and pH are expected to affect or interact with erosion processes, watershed hydrology, vegetation, and water quality.

Recommended Addition to the Guideline: Consider topics such as erosion processes, watershed hydrology, vegetation, stream channel morphology, water quality, ***climate change (including its interactions with aforementioned topics)***, wilderness designation, recommendations for inclusion into the Wild and Scenic River System, species and habitats, and human uses, during analyses.

Box 2. Revising Management Objectives for Riparian Areas

Riparian areas are characterized by high natural disturbance rates and high soil moisture, and exhibit sensitivity to changes in precipitation type, timing, and amount. Decreased snowpack, earlier snowmelt, or shifts from snow- to rain-dominant watersheds can affect riparian habitat quality, community composition, and connectivity. Below is an example of how climate change information could be integrated into existing management objectives for riparian areas.

Current Objectives:

- Maintain or restore the natural range and frequency of aquatic habitat conditions on the Tongass National Forest to sustain the diversity and production of fish and other freshwater organisms.
- Consider the management of both terrestrial and aquatic resources when managing riparian areas. Consider the effects of terrestrial and aquatic processes on aquatic and riparian resources.
- Evaluate the effect of management (including windthrow) of adjacent areas on riparian habitats.

Potential Vulnerabilities: Changes in precipitation type, timing, and amount (e.g., decreased snowpack, earlier snowmelt and runoff) can affect stream flow patterns and volume, altering sediment loading and debris and riparian vegetation composition. More frequent or intense wind events may increase windthrow mortality in riparian stands or increase woody debris recruitment to stream networks.

Recommended Revisions to Objectives:

- Maintain or restore the natural range and frequency of aquatic habitat conditions, ***considering the potential impacts of climate change***, on the Tongass National Forest to sustain the diversity and production of fish and other freshwater organisms.
- Consider the management of both terrestrial and aquatic resources when managing riparian areas. Consider the effects of terrestrial and aquatic processes, ***including under changing climatic conditions***, on aquatic and riparian resources.
- Evaluate the effect of management (including windthrow) of adjacent areas on riparian habitats; ***include the potential for synergistic effects between management activities and climate change***.

Considerations to incorporate climate change into program- or project-level planning

Decision-support flow charts provide helpful frameworks for considering climate change in program- or project-level planning. The series of questions in these flow charts (Figures 8 and 9) are designed to help a manager assess whether climate change has been adequately considered before moving forward. Below we provide a general example for considering climate change in program-level planning (Figure 8). This particular flow-chart represents one approach to consider.

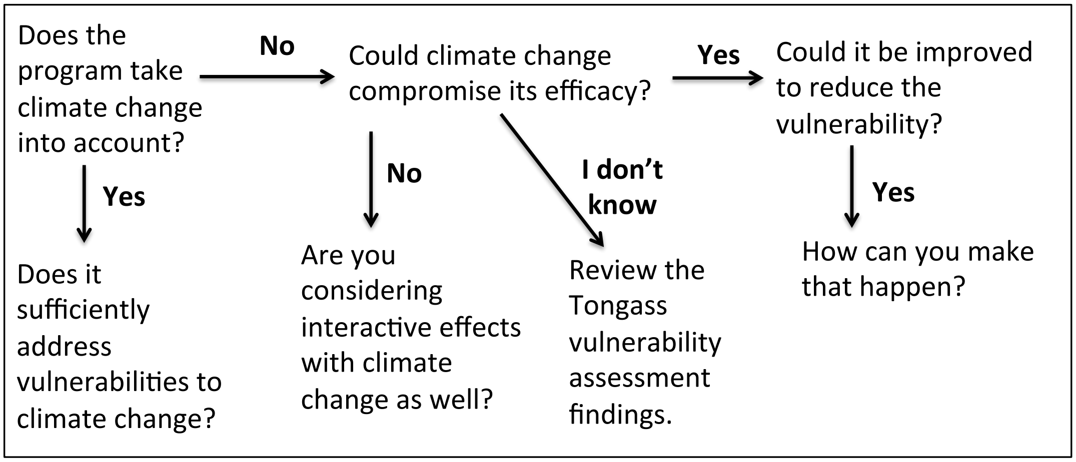

Figure 8. Decision-support flow chart for considering climate change in program-level planning.

This kind of decision-support tool is also useful when considering climate change in project-level planning. Below is an example using the 2008 Tongass Forest Plan, which describes project-level considerations for watershed resources planning (Figure 9). Although this is a specific example, the same concept can be applied to other project-level decision-making.

From the Soil and Water Forest-wide Standards and Guidelines Watershed Resources Planning section of the 2008 Tongass Forest Plan: "Seek to avoid adverse impacts to soil and water resources (such as accelerated surface erosion or siltation of fish habitat) when conducting land use activities on wetlands, floodplains, and riparian areas."

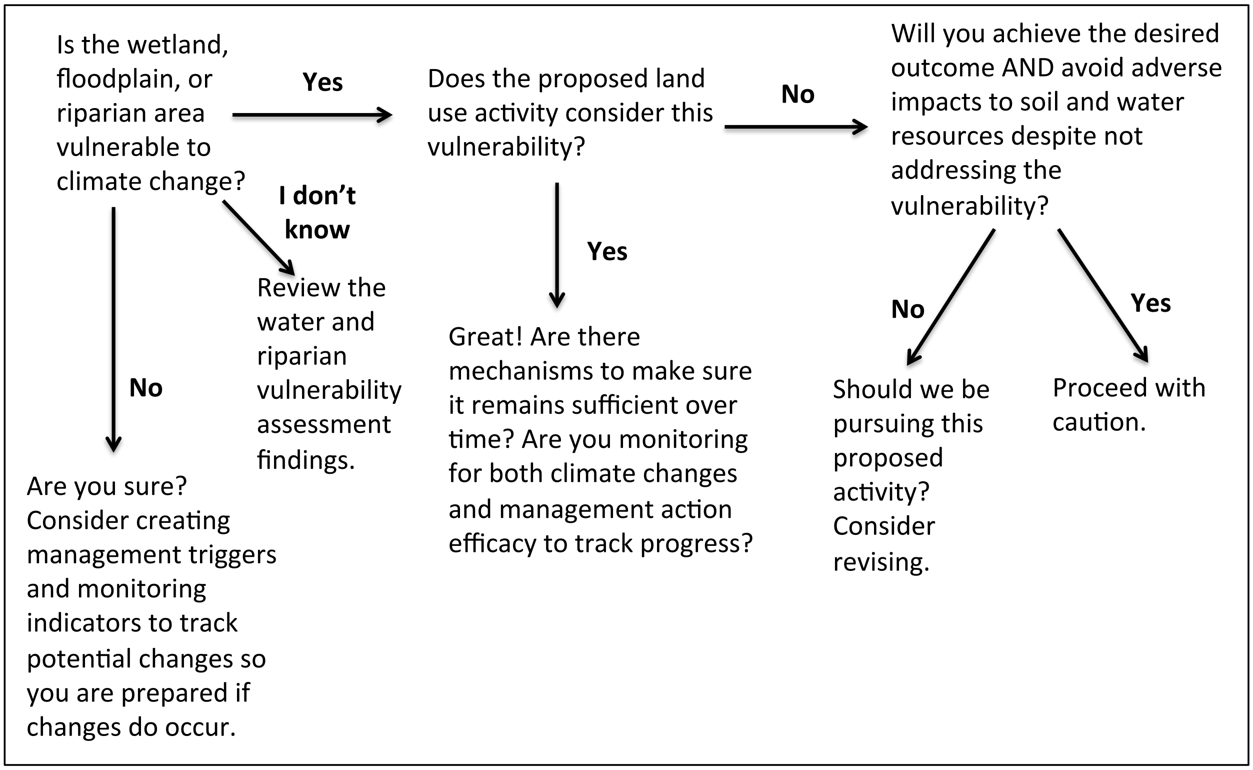

Figure 9. Decision-support flow chart for considering climate change in water resource project-level planning.

Appendix B: Methods

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 (Intergovernmental Panel on Climate Change (IPCC) 2007).

Development of Collaborative Process

This project used a collaborative, expert elicitation-based approach that involved representatives from the Tongass National Forest as well as regional stakeholders. Expert elicitation has a long history in conservation and regulation. These approaches are effective where there is greater uncertainty about current system function or future projections but where there is a reservoir of detailed knowledge and expertise. Expert elicitation also has the benefits of being relatively rapid, encouraging ownership and buy-in, and lower cost. Further, participants in this process had extensive knowledge about the ecology, management, and threats to Tongass resources, and also comprise many of the professionals who will use the results of the project.

Roles of the Vulnerability Assessment Workshop Participants

Using the vulnerability assessment model described below as a guide, workshop participants were asked to apply their knowledge and expertise about a selected resource to evaluate its vulnerability to climate and non-climate stressors.

Vulnerability Assessment Model[62]

The vulnerability assessment model used in this process comprises three vulnerability components (sensitivity, adaptive capacity, and exposure), confidence evaluations for all components, and relative vulnerability and confidence for a resource (Figure 10). In this report, each component of vulnerability includes expert assigned rankings as well as narratives summarizing expert comments and information from the scientific literature. The aim of the narratives that accompany rankings is to make transparent the rationales and assumptions underlying the rankings and confidences assigned to each variable.

Sensitivity, adaptive capacity, and exposure components were broken down into specific elements better suited to assessing the vulnerability of particular resources for this assessment. For example, sensitivity comprises two main elements for features and species including: sensitivity to climate (i.e., temperature and precipitation) and climate-driven changes (e.g., snowpack, soil moisture, low flows), and non-climate stressors. Adaptive capacity comprises three main elements for features and four main elements for species. Sensitivity and adaptive capacity elements for ecosystems and species were

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[62] This process was modeled after the Northeast Association of Fish & Wildlife Agencies (NEAFWA) Habitat Vulnerability Model (Manomet Center for Conservation Sciences 2012).

informed by Glick et al. (2011), Manomet Center for Conservation Sciences (2012), and Lawler (2010). Exposure elements were created by EcoAdapt. Elements for each vulnerability component are described in more detail below.

Experts assigned one of three rankings (High-3, Moderate-2, or Low-1) for each component of vulnerability. Expert assigned rankings for each component were then averaged (mean) to generate an overall score. For example, rankings for each element of sensitivity were averaged to generate an overall sensitivity score for a given resource. No scores were assigned for exposure; instead, experts were asked to rank, in order of importance, the exposure elements most important to consider for the ecosystem or species. Elements for each component of vulnerability were also assigned one of three confidence rankings (High-3, Moderate-2, or Low-1). This ensured the degree of confidence assessors had in ranking each variable was explicit. Confidence rankings for each vulnerability component were averaged (mean) to generate an overall confidence score.

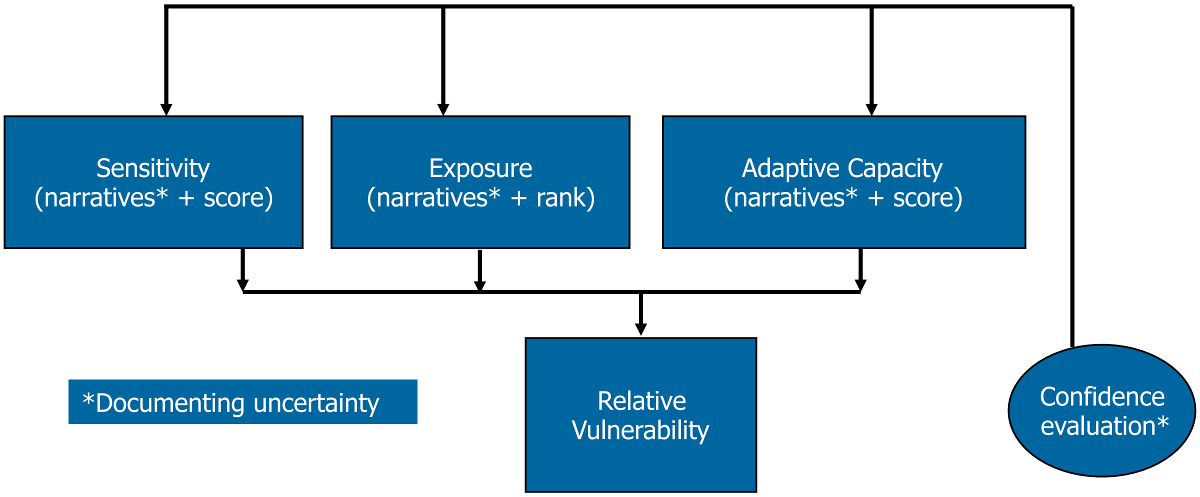

Figure 10. Structure of the vulnerability assessment model.

Model Elements – Features

This section lists the elements that were considered in the expert elicitation-based vulnerability assessment model for features (snow, ice, water; riparian vegetation). This list of elements for sensitivity and adaptive capacity were informed by Glick et al. (2011), Manomet Center for Conservation Sciences (2012), and Lawler (2010). Exposure elements were generated by EcoAdapt. The expert elicitation vulnerability assessment worksheets for ecosystems can be found on the EcoAdapt workshop support page.[63]

Feature Sensitivity & Exposure

1. Climate and Climate-Driven Changes. The two ways feature sensitivity to changes in temperature and precipitation were considered in this project were: (1) does the feature inhabit a relatively narrow climatic zone, and (2) does the feature experience large changes in composition or structure with small climatic changes in temperature or precipitation? Features that inhabit a narrow climatic zone and/or experience large changes in composition or structure in response to small changes in climate have

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[63] http://ecoadapt.org/workshops/climate-vulnerability-tongass

higher sensitivity (Lawler 2010). Benefits to the feature as a result of climate and climate-driven changes were also considered.

2. Future Climate Exposure. A number of climate and climate-driven factors may be important to consider for a feature. These factors may include, but are not limited to: temperature, precipitation, climatic water deficit (i.e., reduced soil moisture), wildfire, snowpack, runoff, timing of flows, low flows, high flows, and stream temperature. Participants were asked to rank, in order of most important to least important, the climate and climate-driven factors most relevant to consider for the feature and why, and document any potential areas of refugia.

3. Non-Climate Stressors. Other non-climate stressors have the potential to exacerbate the effects of climate change on features, or vice versa. Features that have to endure multiple non-climate stressors are likely more sensitive to climate changes. Non-climate stressors can include land use conversion, agriculture and/or aquaculture, energy production and mining, transportation corridors, logging and wood harvesting, dams and water diversions, biological resource use (e.g., hunting, fishing), invasive and other problematic species, recreation, or pollution and poisons, among others (Glick et al. 2011; Manomet Center for Conservation Sciences 2012). Participants were asked to identify non-climate stressors most likely to increase sensitivity of the feature to climate change, assess the degree to which the stressor affects sensitivity and the degree of current exposure to the stressor, and evaluate confidence.

Feature Adaptive Capacity

1. Extent, Integrity and Continuity. Features that are currently widespread in their geographic extent, with high integrity and continuity may be better able to withstand and persist into the future despite climate and non-climate stressors. Features that are degraded, isolated, limited in extent, or currently declining due to climate and non-climate stressors will likely have lower adaptive capacity (Manomet Center for Conservation Sciences 2012).

2. Replaceability. Some features are interchangeable with other features. This element considered, for example, if a transition from ice or snow to water would be detrimental.

3. Management Potential. Humans have the potential to intervene and change features in ways that reduce the impacts of climate change. For example, humans already control the flow regimes of most stream ecosystems (through dams) (Poff et al. 1997), so flow regimes could be manipulated to minimize stressful effects of climate change, such as low flows during late summer (Xu et al. 2010). The costs and benefits of management actions will vary among systems.

Model Elements – Species

This section lists the elements that were considered in the expert elicitation-based vulnerability assessment model for fish species. This list of elements for sensitivity and adaptive capacity were informed by Glick et al. (2011), Manomet Center for Conservation Sciences (2012), and Lawler (2010); exposure elements were generated by EcoAdapt. The expert elicitation vulnerability assessment worksheets for species can be found on the EcoAdapt workshop support page[64].

Species Sensitivity & Exposure

1. Climate and Climate-Driven Changes. Physiological sensitivity is directly related to a species' physiological ability to tolerate changes in climate or climate-driven factors that are higher or lower than the range that they currently experience. Species life history may also be affected by changes in climate

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[64] http://ecoadapt.org/workshops/climate-vulnerability-tongass

or climate-driven factors. Species that are able to tolerate a wide range of variables are likely less sensitive to climate change (Glick et al. 2011). Species sensitivity also likely depends on the sensitivities of ecological relationships and/or interspecific interactions. For example, the effects of climate or climate-driven changes on predator/prey relationships, foraging, habitat, pollination, dispersal, or competition, among others, are likely to influence a species' overall sensitivity to climate change. Benefits to the species as a result of climate and climate-driven changes were also considered.

2. Future Climate Exposure. A number of climate and climate-driven factors may be important to consider for a species. These factors may include, but are not limited to: temperature, precipitation, climatic water deficit (i.e., reduced soil moisture), wildfire, snowpack, runoff, timing of flows, low flows, high flows, and stream temperature. Participants were asked to rank, in order of most important to least important, the climate and climate-driven factors most relevant to consider for the species and why, and document any potential areas of refugia.

3. Non-Climate Stressors. Other non-climate stressors have the potential to exacerbate the effects of climate change on species, or vice versa. Species that have to endure multiple non-climate stressors are likely more sensitive to climate changes. Non-climate stressors can include land use conversion, agriculture and/or aquaculture, energy production and mining, transportation corridors, logging and wood harvesting, dams and water diversions, biological resource use (e.g., hunting, fishing), invasive and other problematic species, recreation, livestock grazing, fire suppression practices, or pollution and poisons, among others (Glick et al. 2011; Manomet Center for Conservation Sciences 2012). Participants were asked to identify non-climate stressors most likely to increase sensitivity of the species to climate change, assess degree stressor affects sensitivity and degree of current exposure to stressor, and evaluate confidence.

Species Adaptive Capacity

1. Extent, Status and Dispersal Ability. Species that are currently widespread in their geographic extent, with a robust population status, connectivity, and a high ability to disperse may be better able to withstand and persist into the future despite climate and non-climate stressors. Species that are endemic, endangered, or with isolated or fragmented populations and/or limited ability to disperse will likely have lower adaptive capacity (Manomet Center for Conservation Sciences 2012).

2. Barriers to Dispersal. In general, species that are poorer dispersers (disperse slowly and over short distances) are more susceptible to climate change and likely have less adaptive capacity (Glick et al. 2011). Similarly, the adaptive capacity of species with high innate dispersal ability may decrease if there are significant barriers to dispersal. Barriers to dispersal can include roads, land use conversion, logging and clear cuts, energy production and mining, dams and culverts, geologic features (e.g., mountains, rivers), fire suppression, grazing, or agriculture, among others (Lawler 2010).

3. Intraspecific/Life History Diversity. Species that demonstrate a diversity of life history strategies (e.g., variations in age at maturity, reproductive or nursery habitat use, or resource use) are likely to have greater adaptive capacity. Similarly, species able to express different and varying traits (e.g., phenology, behavior, physiology) in response to environmental variation have greater adaptive capacity than those that cannot modify their physiology or vary behavior to better cope with climate changes and its associated effects. Many species exhibit phenotypic plasticity in response to inter-annual variation in temperature and precipitation. Some species and/or populations will be better able to adapt evolutionarily to climate change. For example, species may have greater adaptive capacity if they exhibit characteristics such as faster generation times, genetic diversity, heritability of traits, larger population size, or multiple populations with connectivity among them to allow for gene flow.

4. Management Potential. Humans have the potential to intervene in ways that reduce the impacts of climate change on a particular species. For example, if a species is listed as threatened or endangered, it can provide opportunities for implementing specific management measures likely to help populations persist. The costs and benefits of management actions will vary among species. Actions will be most feasible when resources are culturally and economically valued and the costs of implementing new management strategies are low. Further, use conflicts for the species (e.g., recreation or development pressure) may reduce its adaptive capacity if management potential is low.

Confidence Evaluation

Each of the sensitivity, adaptive capacity, and exposure elements described above for resources were assigned a confidence rank: High, Moderate, or Low. These approximate confidence levels were based on the scale developed by Moss and Schneider (2000) for the IPCC Third Assessment Report. This vulnerability assessment model assesses the confidence associated with the individual element rankings and uses these rankings to estimate the overall level of confidence for each component of vulnerability by calculating mean confidence rankings across elements.

Vulnerability Assessment Application

Model Application

EcoAdapt, in collaboration with the USFS, convened a 2-day workshop entitled *Assessing Vulnerability in Tongass National Forest*, held January 14-15, 2014 in Juneau, AK. The main focus of the workshop was assessing the vulnerabilities of resources to climate and non-climate stressors. Approximately 20 scientists, resource managers, and stakeholders participated in this workshop from the Tongass National Forest and surrounding region. Information from the workshop such as the agenda, presentations, handouts, readings, and other resources can be found on the workshop support page.[65]

This workshop was structured to provide participants with a foundation of information from which they could assess the vulnerabilities of the selected resources. Participants were introduced to general vulnerability assessment theory and approaches (following the process described in Glick et al. 2011), provided with past and projected climate trends in the Southeast Alaska region, and organized into several different small working group arrangements to discuss and evaluate the vulnerability of resources.

Workshop participants were directed to apply the vulnerability assessment model described above to the list of resources. As this was an expert elicitation process, participants were encouraged to make decisions based on their knowledge and expertise.

Participant assessments and comments were compiled and assembled into this vulnerability assessment report. As part of this report, resource vulnerability summaries were created which synthesize participant comments and peer-review references for each resource. These vulnerability summaries can be found in Section 4 of this report.

Model Application – peer review process

The draft vulnerability assessment report was sent to workshop participants and additional experts for review. Comments and revisions from these reviewers were incorporated into the final report.

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[65] http://ecoadapt.org/workshops/climate-vulnerability-tongass

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Appendix C: Overview of Vulnerability Component Evaluations

As part of the Vulnerability Assessment Workshop, workshop participants evaluated different vulnerability components for each focal resource. These evaluations are summarized on the following pages.

Snow Features – Overview of Vulnerability Component Evaluations

Sensitivity Factor	Sensitivity Evaluation	Confidence
Sensitivities to Climate & Climate-Driven Changes	**Overall: 2.5 Moderate-High**	**Overall: 3 High**
• Temperature	• 3 High	• 3 High
• Precipitation	• 3 High	• 3 High
• Drought	• 2.5 Moderate-High	• 3 High
• Wildfire	• 2 Moderate	• 2 Moderate
• Timing of snowmelt & runoff	• 3 High	• 3 High
• High lentic/lotic temperatures	• 2 Moderate	• 2 Moderate
• Other: Wind & relative humidity	• 2.5 Moderate-High	• 3 High
• Other: Sun	• 2.5 Moderate-High	• 3 High
Non-Climatic Stressors – Influence Overall Sensitivity to Climate	**Overall: 1 Low**	**Overall: 2 Moderate**
• Timber harvest	• 1 Low	• 2 Moderate
Non-Climatic Stressors – Current Exposure to Stressor	**Overall: 1 Low**	**Overall: 3 High**
• Timber harvest	• 1 Low	• 3 High
Other Sensitivities	**None identified by participants**	**Not applicable**

Overall Averaged Ranking (Sensitivity)[66]: 1.5 Low-Moderate

Overall Averaged Confidence (Sensitivity)[67]: 2.5 Moderate-High

Adaptive Capacity Factor	Adaptive Capacity Evaluation	Confidence
Geographic Extent	**3 High (Regional)**	**3 High**
Structural & Functional Integrity	**2 Moderate (Somewhat degraded)**	**2 Moderate**
Feature Continuity	**2 Moderate (Distributed)**	**3 High**

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[66] Overall averaged ranking is an average of the sensitivity or adaptive capacity evaluation columns above.

[67] Overall averaged confidence is an average of the confidence column for sensitivity or adaptive capacity.

Adaptive Capacity Factor	Adaptive Capacity Evaluation	Confidence
Feature Replaceability[68] • Inland salmon harvest • Stream restoration • Infrastructure, including road maintenance • Hatcheries • Fish passes • Hydroelectric development • Other dams & water diversions • Water quality for communities • Tourism & recreation • Flood control	**Overall: 1.5 Low-Moderate** • 1 Low • 2 Moderate (but variable) • 2 Moderate (but variable) • 1 Low • 2 Moderate (but variable) • 1 Low • 2 Moderate • 2 Moderate • 1 Low • 3 High	**Overall: 2.5 Moderate-High** • 3 High • 1.5 Low-Moderate • 2 Moderate • 2.5 Moderate-High • 2 Moderate • 3 High • 2 Moderate • 2 Moderate • 3 High • 2 Moderate
Feature Value	**3 High**	**3 High**
Management Approaches and Potential for Implementation and/or Effectiveness • Ski area modifications • Dam assessment projects • Road retrofits and design updates • Project feasibility assessments	**Overall: 3 High** • 2 Moderate • 3 High • 3 High • 3 High	**No answer provided by participants**
Other Adaptive Capacities	**No answer provided by participants**	**No answer provided by participants**

Overall Averaged Ranking (Adaptive Capacity)[66]: 2.5 Moderate-High

Overall Averaged Confidence (Adaptive Capacity)[67]: 3 High

Important Climate Exposure Factors[69]	Potential Areas of Refugia
Increased temperature	Higher elevations
Precipitation changes	Higher elevations

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[68] This category evaluates how easily factors (e.g., ecosystem services, biological processes) could replace the role of snow if snow features transitioned to rain-dominant and/or water features. A lower rating signifies that the factor is highly dependent on the continued availability of snow, and decreases in snow feature extent would likely have a negative impact on the listed factor.

[69] These factors were listed in order of importance to the feature.

Important Climate Exposure Factors[69]	Potential Areas of Refugia
Earlier snowmelt & runoff	No answer provided by participants
Decreased snowpack	North-facing aspects; shape of watershed/area
Extreme events: high temperature & humidity	No answer provided by participants
Increased relative humidity, wind & solar radiation	

Ice Features – Overview of Vulnerability Component Evaluations

Sensitivity Factor	Sensitivity Evaluation	Confidence
Sensitivities to Climate & Climate-Driven Changes • Temperature • Precipitation • Extreme events: high flows & runoff • Drought • Snowpack depth (in fall) • Snow-water equivalent • Timing of snowmelt • Snowmelt volume	**Overall: 2.5 Moderate-High** • 3 High • 3 High • 2.5 Moderate-High • 1.5 Low-Moderate • 1 Low • 3 High • 3 High • 3 High	**Overall: 3 High** • 3 High • 3 High • 2 Moderate • 3 High • No answer given • 3 High • No answer given • 3 High
Non-Climatic Stressors – Influence Overall Sensitivity to Climate • Black carbon & dark ice • Wind blown particulates	**Overall: 1.5 Low-Moderate**[70] Stressors were not evaluated individually	**Overall: 1.5 Low-Moderate**[59] Stressors were not evaluated individually
Non-Climatic Stressors – Current Exposure to Stressor • Black carbon & dark ice • Wind blown particulates	**No answer given by participants**	**No answer given by participants**
Other Sensitivities • Sea level rise • Isostatic rebound • Tidewater glaciers • Ocean interactions • Fine scale weather patterns	**No answer given by participants**	**Overall: 3 High** Factors were not evaluated individually

Overall Averaged Ranking (Sensitivity)[71]: 2 Moderate

Overall Averaged Confidence (Sensitivity)[72]: 2.5 Moderate-High

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[70] Participants only evaluated the overall degree to which non-climate stressors may increase feature sensitivity to climate change. Individual non-climate stressors were not evaluated individually.

[71] Overall averaged ranking is an average of the sensitivity or adaptive capacity evaluation columns above.

[72] Overall averaged confidence is an average of the confidence column for sensitivity or adaptive capacity.

Adaptive Capacity Factor	Adaptive Capacity Evaluation	Confidence
Geographic Extent	**2.5 Moderate-High (Across region, except for non-glaciated islands)**	**3 High**
Structural & Functional Integrity	**3 High (Pristine)**	**3 High**
Feature Continuity	**3 High (Continuous, except for non-glaciated islands)**	**3 High**
Feature Replaceability[73]	**Overall: 1 Low**	**Overall: 2.5 Moderate-High**
• Local salmon harvest	• 2.5 Moderate-High	• 2 Moderate
• Stream restoration	• 1.5 Low-Moderate	• 2 Moderate
• Infrastructure, including road maintenance	• 1 Low	• No answer given
• Fish passes	• 1 Low	• No answer given
• Hydroelectric development	• 1 Low	• No answer given
• Other dams & water developments	• 1 Low	• 3 High
• Tourism & recreation	• 1 Low	• 3 High
• Flood control	• 1 Low	• No answer given
Feature Value	**3 High**	**3 High**
Management Approaches and Potential for Implementation and/or Effectiveness • Mitigate black carbon at local/small scale and from ships • Increase use of natural gas • Expand low-emission electrical grid • Advocate for global carbon reductions and create reduction strategies	**No answer provided by participants**	**No answer provided by participants**
Other Adaptive Capacities	**No answer provided by participants**	**No answer provided by participants**

Overall Averaged Ranking (Adaptive Capacity)[71]: 2.5 Moderate-High

Overall Averaged Confidence (Adaptive Capacity)[72]: 3 High

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[73] This category evaluates how easily factors (e.g., ecosystem services, biological processes) could replace the role of ice if ice features transitioned to rain-dominant and/or water features. A lower rating signifies that the factor is highly dependent on the continued availability of ice, and decreases in ice feature extent would likely have a negative impact on the listed factor.

Important Climate Exposure Factors[74]	Potential Areas of Refugia
Increased temperature	No answer provided by participants
Precipitation changes	
Decreased snowfall	
Earlier snowmelt & runoff	

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[74] These factors were listed in order of importance to the feature.

Water Features – Overview of Vulnerability Component Evaluations

Sensitivity Factor	Sensitivity Evaluation	Confidence
Sensitivities to Climate & Climate-Driven Changes • Temperature • Precipitation • Extreme events: high flows & runoff • Drought • Wildfire • Soil moisture • Snowpack depth • Timing of snowmelt & runoff • Low instream flows • High lentic/lotic temperatures	**Overall: 3 High** • 1 Low • 2.5 Moderate-High • 3 High • 3 High • 3 High • 3 High • 3 High • 3 High • 3 High • 3 High	**Overall: 3 High** • 3 High • 3 High • 3 High • 3 High • 3 High • 3 High • 3 High • 3 High • 3 High • 3 High
Non-Climatic Stressors – Influence Overall Sensitivity to Climate • Dams & water diversions • Energy production & mining • Aquaculture: fish processing/hatcheries • Transportation • Timber harvest	**Overall: 1 Low** • 1 Low • 1 Low • 1 Low • 1 Low • 1 Low	**Overall: 3 High** • 3 High • 3 High • 3 High • 3 High • 3 High
Non-Climatic Stressors – Current Exposure to Stressor • Dams & water diversions • Energy production & mining • Aquaculture: fish processing/hatcheries • Transportation • Timber harvest	**Overall: 1 Low** • 1 Low • 1 Low • 1 Low • 1 Low • 1 Low	**No answer provided by participants**
Other Sensitivities	**None identified by participants**	**Not applicable**

Overall Averaged Ranking (Sensitivity)[75]: 1.5 Low-Moderate

Overall Averaged Confidence (Sensitivity)[76]: 3 High

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[75] Overall averaged ranking is an average of the sensitivity or adaptive capacity evaluation columns above.

Adaptive Capacity Factor	Adaptive Capacity Evaluation	Confidence
Geographic Extent	**3 High (Transcontinental)**	**3 High**
Structural & Functional Integrity	**3 High (Pristine)**	**2 Moderate**
Feature Continuity	**3 High (Continuous)**	**3 High**
Feature Value	**3 High**	**3 High**
Management Approaches and Potential for Implementation and/or Effectiveness • Instream flow requirements • Increase storage capacity • Water quality protection (BMPs, buffers) • Create allocation charts	**Overall: 2.5 Moderate-High**[77]	**No answer provided by participants**
Other Adaptive Capacities • Pacific Decadal Oscillation – can buffer or accelerate effects	**No answer provided by participants**	**No answer provided by participants**

Overall Averaged Ranking (Adaptive Capacity)[75]: 3 High

Overall Averaged Confidence (Adaptive Capacity)[76]: 3 High

Important Climate Exposure Factors[78]	Potential Areas of Refugia
Precipitation changes	Groundwater or wetland areas; elevation gradients
Extreme events: runoff	Off-channel areas
Increased drought	Groundwater areas
Decreased snowpack	Higher elevation areas
Decreased instream flow	Groundwater or lake storage
Temperature changes	Groundwater inputs; winter vs. summer

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[76] Overall averaged confidence is an average of the confidence column for sensitivity or adaptive capacity.
[77] Participants did not evaluate each management option individually, but did score the overall management potential for the feature.
[78] These factors were listed in order of importance to the feature.

Riparian Vegetation Species – Overview of Vulnerability Component Evaluations

Sensitivity Factor	Sensitivity Evaluation	Confidence
Sensitivities to Climate & Climate-Driven Changes	**Overall: 2.5 Moderate-High**	**Overall: 2.5 Moderate-High**
• Temperature	• 3 High	• 3 High
• Precipitation	• 3 High	• 3 High
• Extreme events: high flows & runoff	• 2 Moderate	• 2.5 Moderate-High
• Wildfire	• 3 High	• 3 High
• Drought	• 2 Moderate	• 3 High
• Soil moisture	• 3 High	• 3 High
• CO2	• 3 High	• 3 High
• Snowpack depth	• 3 High	• 3 High
• Timing of snowmelt & runoff	• 2 Moderate	• 2 Moderate
• Low instream flows	• 2 Moderate	• 3 High
• pH	• 1 Low	• 1 Low
• Other: windthrow	• 3 High	• 1.5 Low-Moderate
• Other: channel erosion	• 3 High	• 1.5 Low-Moderate
Non-Climatic Stressors – Influence Overall Sensitivity to Climate	**Overall: 3 High**	**Overall: 3 High**
• Transportation corridors (State & Forest)	• 3 High	• 3 High
• Timber harvest	• 3 High	• 3 High
• (Lumped) Dams & water diversions; energy production and mining	• 3 High	• 3 High
• Recreational & subsistence hunting, trapping, and fishing	• 1.5 Low-Moderate	• 3 High
• Invasive and other problematic species, insects, and disease	• 3 High	• 3 High
• Land use conversion & urban effects	• 3 High	• 3 High

Sensitivity Factor	Sensitivity Evaluation	Confidence
Non-Climatic Stressors – Current Exposure to Stressor • Transportation corridors (State & Forest) • Timber harvest • (Lumped) Dams & water diversions; energy production and mining • Recreational & subsistence hunting, trapping, and fishing • Invasive and other problematic species, insects, and disease • Land use conversion & urban effects	**Overall: 1 Low** • Variable • 2 Moderate • 1 Low • Variable • 1 Low • 1 Low	**Overall: 3 High** • 3 High • 3 High • 3 High • 3 High • 3 High • 3 High
Other Sensitivities • Glacier dam release • Surface mass wasting • Avalanches	**Overall: 2 Moderate** Factors were not evaluated individually	**Overall: 2 Moderate** Factors were not evaluated individually

Overall Averaged Ranking (Sensitivity)[79]: 2 Moderate

Overall Averaged Confidence (Sensitivity)[80]: 3 High

Adaptive Capacity Factor	Adaptive Capacity Evaluation	Confidence
Geographic Extent	**3 High (Transcontinental)**	**3 High**
Population Status	**3 High (Robust)**	**3 High**
Population Connectivity	**3 High (Continuous)**	**3 High**
Number and Types of Barriers to Dispersal	**2 Moderate (Some barriers)**[81]	**3 High**
Degree Barriers Affect Dispersal	**1 Low**[81]	**3 High**
Species Value	**3 High**	**3 High**

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[79] Overall averaged ranking is an average of the sensitivity or adaptive capacity evaluation columns above.
[80] Overall averaged confidence is an average of the confidence column for sensitivity or adaptive capacity.
[81] When calculating overall adaptive capacity (below), this score was inverted for consistency with other scoring structures.

Adaptive Capacity Factor	Adaptive Capacity Evaluation	Confidence
Potential Use Conflicts and Ability to Manage or Alleviate Impacts - Timber harvest - Transportation - Mining - Fishing - Recreation	**Overall: 3 High** - 3 High - 3 High - 3 High - 3 High - 3 High	**No answer provided by participants**
Other Adaptive Capacities - Treatments (adaptive actions) - Reforestation - Thinning - Bank stabilization	**No answer provided by participants**	**No answer provided by participants**

Overall Averaged Ranking (Adaptive Capacity)[79]: 3 High

Overall Averaged Confidence (Adaptive Capacity)[80]: 3 High

Important Climate Exposure Factors[82]	Potential Areas of Refugia
Soil moisture changes	No answer provided by participants
Extreme events: high flows & runoff	
Decreased instream flow	Areas of confluence
pH	No answer provided by participants
Wildfire	

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[82] These factors were listed in order of importance to the species.

Fish Species – Overview of Vulnerability Component Evaluations

Sensitivity Factor	Sensitivity Evaluation	Confidence
Sensitivities to Climate & Climate-Driven Changes	**Overall: 2 Moderate**	**Overall: 2.5 Moderate-High**
• Temperature	• 2.5 Moderate-High	• 2.5 Moderate-High
• Precipitation (mean)	• 1 Low	• 3 High
• Precipitation (extremes)	• 3 High	• 3 High
• Extreme events: high flows & runoff	• 2.5 Moderate-High	• 2.5 Moderate-High
• Wildfire	• 1 Low	• 3 High
• Drought	• 2.5 Moderate-High	• 2.5 Moderate-High
• Soil moisture	• 2 Moderate	• 2 Moderate
• Snowpack depth	• 3 High	• 3 High
• Timing of snowmelt & runoff	• 1-3 Low to High	• 2.5 Moderate-High
• Low instream flows	• 1-3 Low to High	• 3 High
• High lentic/lotic temperatures	• 1-3 Low to High	• 2 Moderate
• pH	• 2 Moderate (some species or stocks may have low sensitivity)	• 1 Low
• Dissolved O_2	• 3 High (some species or stocks may have low sensitivity)	• 3 High
Non-Climatic Stressors – Influence Overall Sensitivity to Climate	**Overall: 2.5 Moderate-High**	**Overall: 2.5 Moderate-High**
• Land use conversion	• 3 High	• 3 High
• Timber harvest (Tongass)	• 3 High	• 3 High
• Timber harvest (State and Native Corporation lands)	• 3 High	• 3 High
• Timber harvest (Southeast Alaska)	• 3 High	• 3 High
• Hydropower (Southeast Alaska)	• 3 High	• 3 High
• Dams & water diversions	• 3 High	• 3 High
• Aquaculture	• 2 Moderate (but variable)	• 1 Low
• Mining	• 2 Moderate	• 2 Moderate
• Transportation Corridors	• 2 Moderate	• 2 Moderate
• Hunting, trapping, and fishing	• 2.5 Moderate-High	• 2 Moderate
• Invasive species	• 2 Moderate	• 1 Low

Sensitivity Factor	Sensitivity Evaluation	Confidence
Non-Climatic Stressors – Current Exposure to Stressor	**Overall: 1 Low**	**Overall: 2.5 Moderate-High**
• Land use conversion	• 1 Low	• 2 Moderate
• Timber harvest (Tongass)	• 1 Low	• 3 High
• Timber harvest (State and Native Corporation lands)	• 1 Low	• 3 High
• Timber harvest (Southeast Alaska)	• 2 Moderate	• 3 High
• Hydropower (Southeast Alaska)	• 1 Low	• 3 High
• Dams & water diversions	• 1 Low	• 3 High
• Aquaculture	• 1.5 Low-Moderate	• 2 Moderate
• Mining	• 1 Low	• 3 High
• Transportation Corridors	• 1 Low	• 3 High
• Hunting, trapping, and fishing	• 1 Low	• 2 Moderate
• Invasive species	• 1 Low	• 1 Low
Other Sensitivities • Pacific Decadal Oscillation • Marine environment variability • Microclimates	**Overall: 3 High** Factors were not evaluated individually	**Overall: 3 High** Factors were not evaluated individually

Overall Averaged Ranking (Sensitivity)[83]: 2.5 Moderate-High

Overall Averaged Confidence (Sensitivity)[84]: 2.5 Moderate-High

Adaptive Capacity Factor	Adaptive Capacity Evaluation	Confidence
Geographic Extent	**3 High (Transcontinental)**	**3 High**
Population Status	**3 High (Robust)**	**3 High**
Population Connectivity	**3 High (Continuous)**	**3 High**

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[83] Overall averaged ranking is an average of the sensitivity or adaptive capacity evaluation columns above.

[84] Overall averaged confidence is an average of the confidence column for sensitivity or adaptive capacity.

Adaptive Capacity Factor	Adaptive Capacity Evaluation	Confidence
Number and Types of Barriers to Dispersal - Low water - High water - Genetic - Nets - Culverts	**1.5 Low-Moderate (Few to some barriers)[85]** Barriers were not evaluated individually	**2.5 Moderate-High** Barriers were not evaluated individually
Degree Barriers Affect Dispersal	**2 Moderate[85]**	**3 High**
Intraspecific/Life History Diversity - Diversity of life history strategies - Genetic diversity - Behavioral plasticity - Phenotypic plasticity	**Overall: 3 High** - 2.5 Moderate-High - 3 High - 3 High - 3 High	**Overall: 3 High** - 3 High - 3 High - 3 High - 3 High
Species Value	**3 High**	**3 High**
Potential Use Conflicts and Ability to Manage or Alleviate Impacts - Hatchery - Timber harvest - Road construction - Hydropower - Mining - Overharvest - Recreation (jet boats)	**Overall: 2 Moderate** - 1.5 Low-Moderate - No answer given - No answer given - 3 High - No answer given - 2 Moderate - 2 Moderate	**No answer provided by participants**
Other Adaptive Capacities - Ocean conditions (including oceanic changes in response to climate change)	**Overall: 1 Low[85]** Factors were not evaluated individually	**Overall: 2 Moderate** Factors were not evaluated individually

Overall Averaged Ranking (Adaptive Capacity)[83]: 2.5 Moderate-High

Overall Averaged Confidence (Adaptive Capacity)[84]: 3 High

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[85] When calculating overall adaptive capacity (below), this score was inverted for consistency with other scoring structures.

Important Climate Exposure Factors[86]	Potential Areas of Refugia
Drought	No answer provided by participants
Extreme events: temperature	
Earlier snowmelt & runoff	
Decreased snowpack	
Decreased instream flow	Estuaries, wetlands, ponds, spring-fed tributaries
Precipitation changes	No answer provided by participants
Increased temperature	Glacial back channels, wetlands, shaded areas

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[86] These factors were listed in order of importance to the species.

Recommended Citation

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