United States Department of Agriculture

# Draft Aquatic Ecosystems Resource Assessment

## Tongass National Forest Plan Revision

Forest Service | Alaska Region | Tongass National Forest | December 2024

**Cover Photo:** Kalinin Creek, Kruzof Island on the Tongass National Forest.

In accordance with Federal civil rights law and US Department of Agriculture (USDA) civil rights regulations and policies, the USDA, its Agencies, offices, and employees, and institutions participating in or administering USDA programs are prohibited from discriminating based on race, color, national origin, religion, sex, gender identity (including gender expression), sexual orientation, disability, age, marital status, family/parental status, income derived from a public assistance program, political beliefs, or reprisal or retaliation for prior civil rights activity, in any program or activity conducted or funded by USDA (not all bases apply to all programs). Remedies and complaint filing deadlines vary by program or incident.

Persons with disabilities who require alternative means of communication for program information (e.g., Braille, large print, audiotape, American Sign Language, etc.) should contact the responsible Agency or USDA's TARGET Center at (202) 720-2600 (voice and TTY) or contact USDA through the Federal Relay Service at (800) 877-8339. Additionally, program information may be made available in languages other than English.

To file a program discrimination complaint, complete the USDA Program Discrimination Complaint Form, AD-3027, found online at *www.ascr.usda.gov/complaint_filing_cust.html* and at any USDA office or write a letter addressed to USDA and provide in the letter all of the information requested in the form. To request a copy of the complaint form, call (866) 632-9992. Submit your completed form or letter to USDA by: (1) mail: US Department of Agriculture Office of the Assistant Secretary for Civil Rights, 1400 Independence Avenue SW, Washington, DC 20250-9410; (2) fax: (202) 690-7442; or (3) email: *program.intake@usda.gov*.

USDA is an equal opportunity provider, employer, and lender.

# Draft Aquatics Resource Assessment

## Tongass National Forest Plan Revision

### Forest Service, Alaska Region

**Prepared by:** Tara Chestnut
Ecologist
USDA Forest Service, Pacific Planning Service Group

*This page intentionally left blank.*

# Table of Contents

# Figures

*This page intentionally left blank.*

# Introduction

> *"Water is the most critical resource issue of our lifetime and our children's lifetime. The health of our waters is the principal measure of how we live on the land."* Luna Leopold

The Tongass National Forest is a thriving aquatic ecosystem with more than 900 largely intact watersheds (see Watershed Condition and Water Resources assessment section), nearly 46,000 miles of free-flowing freshwater streams (USDA 2016a), and wild salmon that have fed the indigenous people of Southeast Alaska for more than 9,000 years.

Simply defined, ecosystems are an interacting system of living and non-living things (biotic and abiotic) in a specific space. The previous Tongass National Forest Land Management Plan addressed aspects of ecosystems but did not evaluate the ecosystem integrity of the Tongass National Forest ecosystem as a whole. This assessment seeks to describe the components of the Tongass ecosystem and assesses the integrity of each component. Each of the ecosystem components are interconnected and as such, this assessment integrates the aquatic, wetland and terrestrial components to evaluate the ecosystem integrity of each component and the influence of one ecosystem component to another.

Aquatic ecosystems on the Tongass are interconnected by water in various forms including snow, ice, and both surface and groundwater. Most of the freshwater resources in Alaska are stored as glacial ice, covering about 5% of the state. The remaining waters are found in lakes, groundwater, rivers, streams, and springs. These waters act as a mechanism of transport by which nutrients, minerals, and chemicals move and contribute to the ecological condition. These conditions result in diverse and complex habitats across the landscape which are critical to lifecycles of fish and other aquatic species.

# Scope and Scale

This assessment seeks to describe the components of the Tongass aquatic ecosystem. Each of the ecosystem components are interconnected and as such, this assessment integrates the aquatic, wetland, and terrestrial components to evaluate the ecosystem integrity. For more information on terrestrial ecosystems, see the Terrestrial Ecosystems assessment section.

# Types of Aquatic Ecosystems

## Glaciers

### *Key Takeaways*

- The effects of changes in climate are evident to a greater degree in high-latitude regions where glacial extent is decreasing.
- A shift in precipitation from snow to rain is predicted to result in loss of diversity of species across aquatic ecosystems.
- Decreased glacial extent is resulting in newly available salmon habitats

## Ecosystem Description

Glaciers are maintained through precipitation (snow), stable winter temperatures and gravity. The amount of precipitation, whether in the form of snowfall, freezing rain, avalanches, or wind-drifted snow, is important to glacier survival. When annual snow accumulation equals or is greater than melt and ablation (e.g., loss of snow due to melting, evaporation, wind and avalanches), a glacier will remain in balance or even grow. In their upper parts, glaciers generally accumulate more snow than they lose from melting, evaporation, or calving. If the accumulated snow survives one melt season, it forms a denser, more compressed layer called firn. The snow and firn are further compressed by overlying snowfall, and the buried layers slowly grow together to form a thickened mass of ice. Under the pressure of its own weight, a glacier will begin to move, or flow, outwards and downwards.

Continental ice sheets shaped the landscape of Southeastern Alaska over millions of years. The slow-moving ice carved deep fjords, sharpened mountain summits, and transported tons of sediment and debris onto the landscape. Large-scale deglaciation ended approximately 14,000 years ago. A glacier is an accumulation of ice and snow that slowly flows over land. Alpine glaciers are frozen rivers of ice, slowly flowing under their own weight down mountainsides and into valleys. Glaciers that calve directly into the sea are known as tidewater glaciers.

Glaciers are dynamic, and several elements contribute to glacier formation and growth. Snow usually falls at the highest elevation of the glacier which adds to the glacier's mass. As the snow slowly accumulates and turns to ice, and the glacier increases in weight, the weight begins to deform the ice, forcing the glacier to flow downhill. Further down the glacier, usually at a lower altitude, is the ablation area, where most of the melting and evaporation occur. Between these two areas a balance is reached, where snowfall equals snowmelt, and the glacier is in equilibrium. Whenever this equilibrium is disturbed, either by increased snowfall or by excessive melting, the glacier either advances or retreats at more than its normal pace. Glacier change can be used as a barometer of warming effects, and all are vulnerable to accelerated regional and global changes in climate.

The glaciers we see today are not considered stagnant features. Many are still receding and losing mass balance at varying rates. Some retreating glaciers are exposing new land on an annual basis, providing opportunities for research on plant succession, hydrologic processes, or gaining new recreation opportunities and enhancing fish and wildlife habitat.

Multiple species of plants, birds, and other animals use glacial habitats as home or feeding areas. There are some species that are unique to glacial ecosystems, such as ice worms and snow algae. Ice worms belong to the genus Mesenchytraeus, the same genus as earthworms. Ice worms are the only annelid worms known to spend their entire lives on glacier ice. Ice worms can be up to an inch (2.5 cm) long and can be black or blue in color. The ice worms come to the surface of the glaciers in the evening and morning to feed on snow algae.

## Ecosystem Services

- Glacier fed rivers and streams have more stable base flows and temperatures, which keeps water cooler during the summer.
- Cooler summer temperatures allow for higher dissolved oxygen in the water, which supports the conditions needed for healthy salmon runs
- Melt water from glaciers and snowfields provide downstream environments with a fresh supply of sediments, minerals and nutrients

### *Status and Trends*

Glaciers are projected to recede and, in some cases, disappear entirely in watersheds across the Tongass (Zieman et al. 2016; Rounce et al. 2023). In the next 50 years, the Juneau Ice Field is projected to decrease in volume and area by approximately 60% (Zieman et al. 2016). Over the last 10 years, maximum glacier ice melt occurred 2.5 days earlier in watersheds draining the western margin of the Juneau Icefield (Young et al. 2021). This has resulted in a shift in freshwater flow downstream in the early summers (Young et al. 2021). The reduction of glaciers is resulting in increased salmon streams and increasing access to minerals for mining (Pitman et al. 2020). Currently, the western Juneau Icefield watersheds are still in an increasing glacier runoff period and have not reached peak water discharge. However, in watersheds with smaller glaciers where peak water discharge has already occurred, glacier meltwater contributions to lakes and rivers are declining. The timeline for glacier loss and impacts on stream hydrology in southeast Alaska is not well studied, though one study estimated that a period of peak water runoff to the Gulf of Alaska will occur between 2060-2070 (Huss and Hock 2018).

Several glaciers exist on the Tongass including the LeConte Glacier, the Mendenhall Glacier, the Baird Glacier, the Hubbard Glacier, the Patterson Glacier and the Shakes Glacier. The massive Yakutat, Juneau, Stikine and Chickamin Ice Fields stretch across the crest of the Coast Mountains and the St Elias Range from Yakutat Bay to Misty Fjords. Many of Tongass glaciers empty into a glacial lake or have a silty river flowing from under the ice which eventually reaches the sea. In many cases, these glacial lakes and rivers possess abundant populations of anadromous and resident fish. The large mainland rivers of the Tongass such as the Unuk, Alsek, Taku, Stikine and Chickamin, are fed by glaciers and adjacent icefields.

The LeConte Glacier is a southernmost tidewater glacier. LeConte Glacier and LeConte Bay reside in the Stikine-LeConte Wilderness. This glacier produces multiple calving events with numerous icebergs across the bay. These floating ice giants play host to harbor seals, especially during the pupping season in May and June.

The Mendenhall Glacier flows into Mendenhall Lake, which drains to the Mendenhall River. Glacier retreat has resulted in the formation of Mendenhall Lake in the 1930s. As it is located thirteen miles from downtown Juneau, it is the most accessible glacier to visit on the Tongass. The glacier has been thinning and retreating since the end of the Little Ice Age, in the late eighteenth century (Motyka et al. 2002; Molnia 2007). Subsequent calving activity accelerated the glacier's recession, resulting in ~3 km of retreat during the twentieth century (Motyka et al. 2002; Boyce et al. 2007). Over the last two decades the glacier receded more than a kilometer, thinned by up to 150 meters in its lower reaches (Berthier et al. 2018). Modeling studies predict continued retreat during the twenty-first century (Ziemen et al. 2016). In Southeast Alaska, ice-dammed lakes account only for 6% of the total lake abundance, however, given their high outburst activity, ice-dammed lakes are among the most hazardous of all meltwater lakes (Veh et al. 2023).

Baird Glacier is approximately 20 miles northeast from the town of Petersburg. Due to a large glacial lake outburst flood in 2015 (called a jökulhlaup) the terminus broke apart and retreated almost a half mile, presently ending at the edge of a shallow lake, and is no longer accessible by hiking from the moraine. However, this glacier has an outwash plain and the terminal moraine is still accessible by boat. The outwash plain serves as the summer nesting and feeding grounds to many seabirds, including the Arctic Tern.

The Hubbard Glacier is located near Yakutat and is the largest tidewater glacier in North America. In a region where many glaciers are retreating, the Hubbard Glacier is advancing. The glacier begins at approximately 11,000 feet in elevation and flows 76-miles to the sea. The 300+ foot tall terminus is six miles wide where it meets Disenchantment Bay and Russel Fjord.

Patterson Glacier, near Petersburg, Alaska has receded significantly in the last 20 years and the lake is now accessible via floatplane. The area near the glacier once supported an older forest that was lost during the Little Ice Age, roughly 200 years ago. Remnants of this ancient forest remain in the area.

Shakes Glacier is in the Stikine LeConte Wilderness near the town of Wrangell. The glacier once reached the Stikine River in the late 1600's and has been receding ever since, with a more rapid retreat since 1995. It is accessible by boat on the Stikine River to Shakes Lake.

### *Drivers and Stressors*

The main stressors for glaciers are changes in precipitation (rain), increasing temperatures, the albedo effect, and other changes in climate. A shift in winter precipitation from snow to rain is an important hydrological potential trend that is projected for the Tongass National Forest (Zieman et al. 2016; Littel et al. 2018; Lader et al. 2020,Figure 1). These changes are expected to result in a loss in the diversity of hydrological regimes and will potentially result in temperature changes across aquatic ecosystems. The implications of these changes could negatively alter productivity and resilience of aquatic food webs (e.g. aquatic invertebrates, fish, wildlife) at watershed and regional scales.

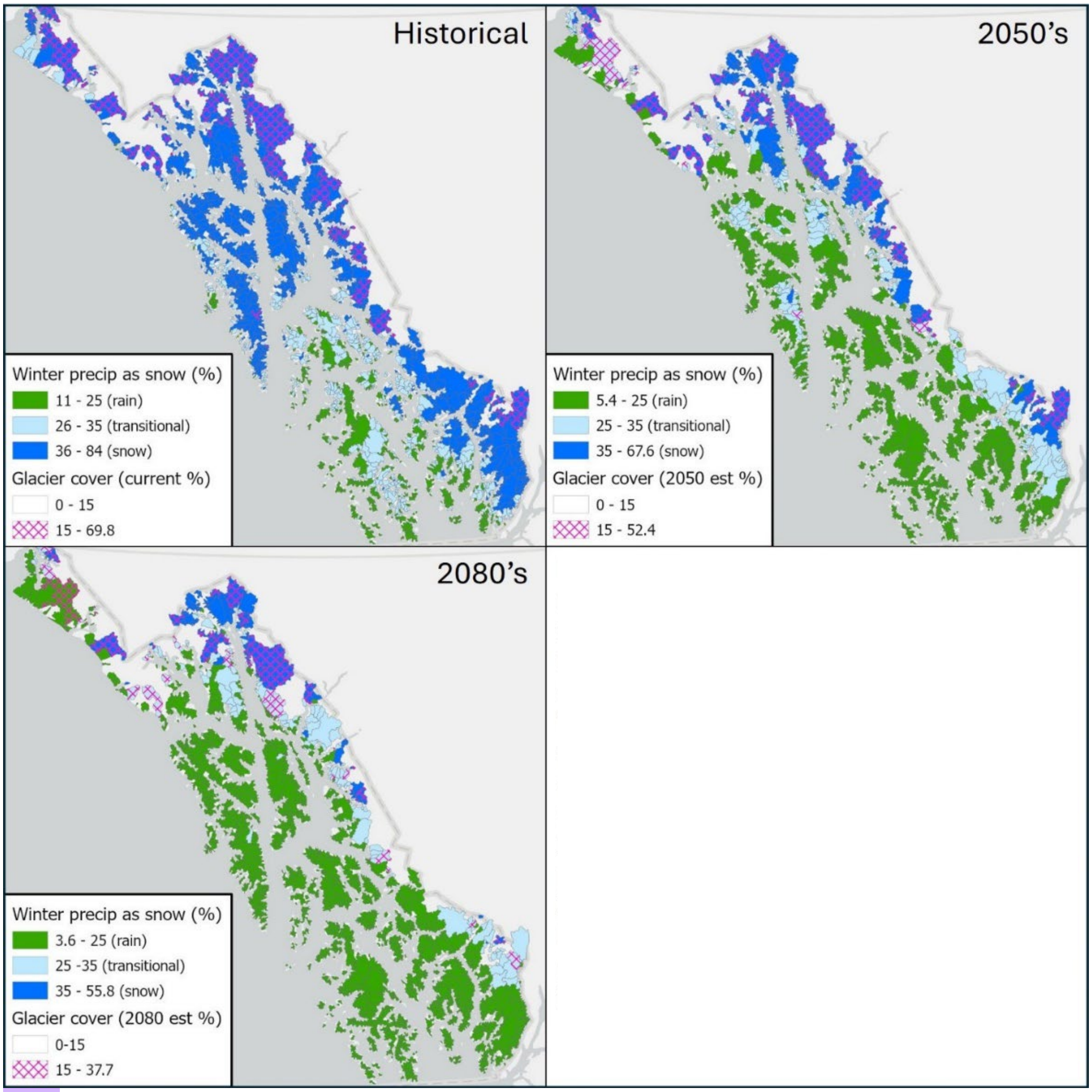

Figure 1. Adapted from Sergeant et al. 2020. Watershed hydrologic type based on projected fraction of winter precipitation as snow historically, for the 2050s, and 2080s under RCP8.5 (Littell et al. 2018) and current and estimated future glacial cover. Watersheds with 15% or more glacial cover are assumed to exhibit glacial runoff characteristics regardless of snow fraction. Glacier loss was assumed to be 25% for the 2050s and 46% for the 2080s based on projected changes for the Juneau Icefield from Zieman et al. 2016. Assigned watershed hydrologic type is based on snow fraction and permanent ice cover for classified watersheds in Sergeant et al., 2020 and is a heuristic (learning purposes) only.

## Rivers and Streams

### *Key Takeaways*

- Stream and river ecosystems on the Tongass are some of the world's most valuable freshwater ecosystems to salmon and other aquatic species.

- Large wood instream and on floodplains act to mitigate flood flows and provide critical components to aquatic ecosystems by diversifying sediments, forming pools and riffles, and capturing food and for aquatic species.
- Harvested riparian areas can result in fewer standing trees available for instream wood recruitment over time. As existing instream wood decays, there may be a gap in time before natural wood recruitment rates are attained.
- Shallow stream flows and warm stream temperatures can lead to low dissolved oxygen and fish die-offs. This can be exacerbated when the conditions exist in summer months when large numbers of adult fish return to spawn.
- The salmon lifecycle provides a pathway for marine derived nutrients to supplement freshwater aquatic and terrestrial ecosystems.
- Stream ecosystems provide recreation, food resources, and both cultural and social values to people and communities that have access to them.
- Invasive plant species can be transported along streams and pose a threat to aquatic and terrestrial ecosystems.

## *Ecosystem Description*

The Tongass National Forest includes over 900 sixth-level watersheds with nearly 46,000 miles of stream contributing to the aquatic ecosystem across the forest (USDA 2016, Watershed Condition and Water Resources Assessment). These ecosystems rely on an interconnected web of marine, terrestrial and freshwater interactions and contribute to the cultural, social, and economic values of Southeast Alaska communities.

The Tongass is considered a salmon forest due to the ecological interconnectedness between the salmon, the trees, and the people. All five species of Pacific salmon spend a portion of their lifecycle in coastal freshwater streams of Southeast Alaska. Nearly 90% of Southeast Alaska households use salmon for food. Between 1998 and 2008 an estimated 66,000 salmon were harvested through subsistence and personal use fisheries (USDA 2024). Approximately 25% of all commercially caught salmon in Alaska are supported by streams on the Chugach or Tongass National Forests (McDaniel, J. et. al. 2020). Salmon are a source of food and jobs supporting 1 in 10 jobs across Southeast Alaska (USDA 2024).

Tongass streams and rivers have been categorized by class, based on their fish production values. There are four category classes including Class I for anadromous fish or adfluvial fish, Class II for resident fish or fish habitat, Class III for perennial or intermittent stream without fish, and Class IV for smaller intermittent and ephemeral streams with insufficient follow or sediment transport capability to directly influence downstream water quality or fish habitat capability.

Tongass stream categorizations are also based on the Alaska Region Channel Type Classification System (Paustian et.al. 1992 revised October 2010). In this process, streams are categorized into channel types, which are grouped into nine process groups, or a combination of similar channel types based on major differences in landform, gradient, and channel shapes (USDA 2016, Appendix D).

A streams’ ability to carry water and nutrients from the mountaintops to the valley bottom and eventually out to the estuary and ocean can influence to the overall ecological integrity of the stream system. Each process group plays a role in the value of the overall aquatic ecosystem. The high gradient contained process group tends to source and transport sediments downstream while low elevation, low gradient floodplain streams tend to be more depositional in nature and act as salmon spawning and rearing habitats. Of the 46,000 miles of stream nearly 63% are high gradient contained process group (HC) and about 9% are high value salmon habitat floodplain (FP) streams (USDA 2016).

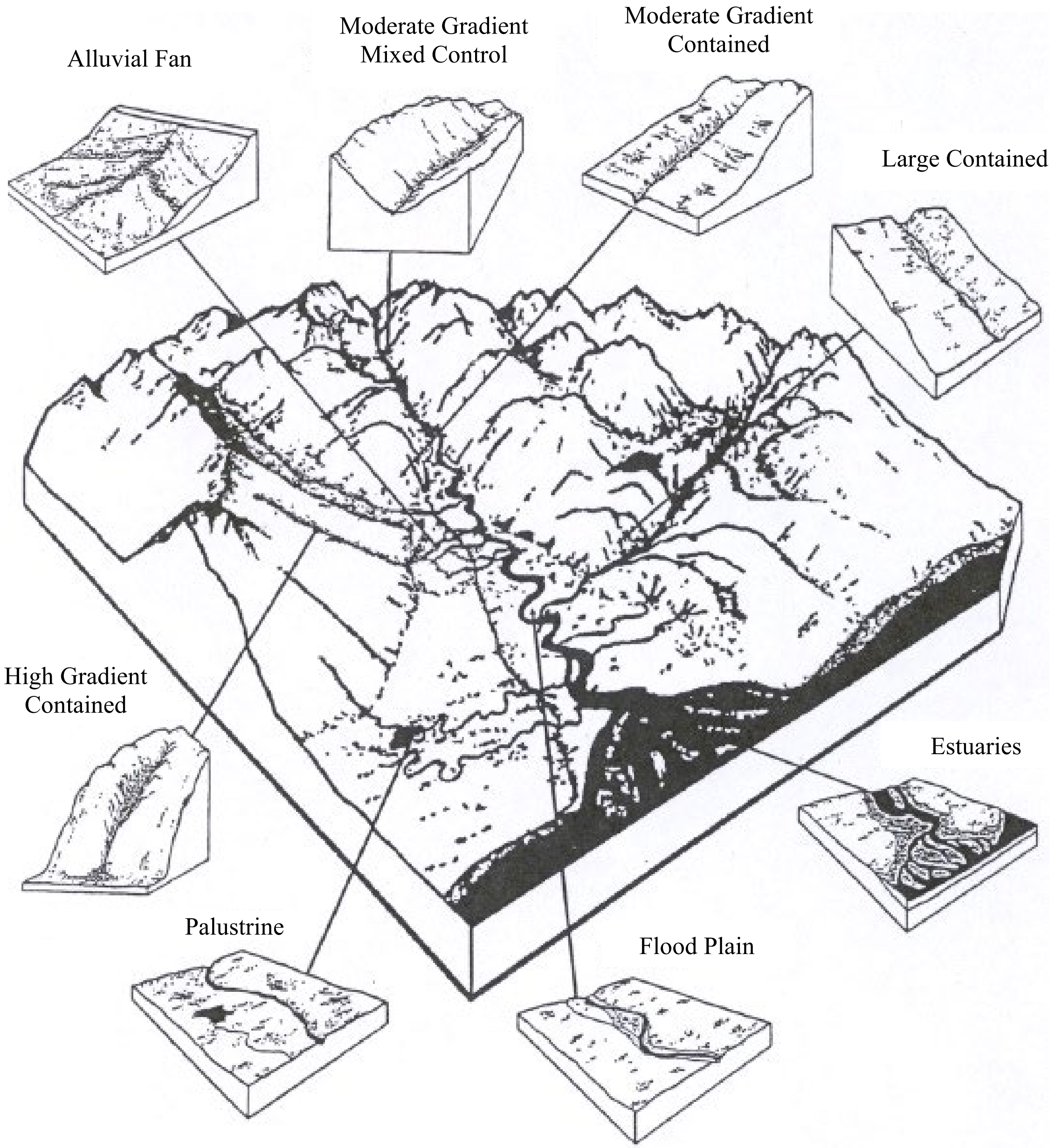

Figure 2. Typical distribution of process groups within watersheds of the Tongass National Forest. This image was copied from Appendix D of the current Forest Plan (USDA 2016).

## Stream Process Groups (Figure 2)

### *Flood Plain*

Flood plain streams are relatively efficient at trapping nutrients from riparian forest detritus and inorganic sediment delivered from headwater areas. These streams also buffer against flood disturbances by spreading runoff across densely vegetated flood plains and into numerous side channels and sloughs.

Shallow alluvial aquifers associated with these streams store runoff from flood flows and hillslope tributaries and slowly release groundwater to surface channels during periods of low rainfall. The ability of flood plain channels to dampen the effects of runoff extremes and to store nutrients are primary factors contributing to productive aquatic communities found in these streams. These streams offer high quality spawning and rearing habitat for a variety of salmonid species.

### *Glacial Outwash*

Glacial outwash streams share many of the attributes of the flood plain process group. However, glacial streams tend to have larger seasonal variations in stream flow and large sediment loads that result in more dynamic or unstable channels and flood plains. These factors, along with colder water temperatures, tend to limit overall aquatic productivity. Adequate fish habitat and fish populations can vary in this process group, but typically offers highly productive populations of resident and anadromous fishes within channel margins and side channels.

### *Alluvial Fan*

Alluvial fan habitats can be intermittent or seasonally productive. Scour and dam pools formed by large woody debris (LWD) can be very important for fish rearing habitat in alluvial fan streams. High sediment transportation within alluvial fans is very important for supplying downstream streambed material that results in complex habitat features. Heterogenous habitat features aid in spawning and rearing for resident and anadromous fishes. Gravel aquifers associated with alluvial fan drainages are commonly an important source of groundwater discharge to adjacent valley bottom streams.

### *Moderate Gradient Mixed Control*

Mixed moderate channels are a mixture of stream channel containment. These channel types are moderate gradient (2-6 percent) streams where sediment deposition processes are limited. Some segments are constrained by bedrock outcrop or the valley walls, while other areas develop narrow flood plains. Streambanks are dominated by coarse alluvium (boulders, cobbles) or bedrock. These stream segments generally have a balance between sediment transport and deposition. Riparian vegetation is important in regulating stream energy losses through large woody debris input. LWD forms such water energy dissipaters as log step pools and lateral scour pools. LWD can strongly influence channel form, sediment storage and pool and cover habitat in streams with minor bedrock control. This process group provides high quality rearing habitat, and spawning habitat in many cases, for resident and anadromous fish populations. Productivity can be variable in these segments, depending on flow regimes and seasonality variations. Riparian areas seldom extend beyond 100 feet from stream banks.

### *Large Contained*

Large contained channels are well contained by adjacent landforms. Bedrock outcrops that constrain or control channel migration and downcutting are common. This process group includes LC1 (low gradient) and LC2 (low to moderate gradient 1-3 percent) large contained channel types. The riparian influence zone often extends over 100 feet up channel side slopes on these entrenched streams. Channel side slope vegetation plays a major role in controlling the rate of downslope soil movement and large woody debris into stream channels. LWD accumulations also dissipate stream energy (slow its velocity) and store sediment within the stream channel. The larger valley and lowland streams often have narrow alluvial terraces within the river gorge. Riparian areas are discontinuous, and are generally less than 150 feet wide. Streambed and banks are dominantly composed of coarse alluvium (cobble to boulder size) and occasional bedrock outcrops. These streams generally have a balance between sediment transport and deposition. Waterfalls and cascades that form at bedrock knick points can be barriers to upstream anadromous fish migration. Fish populations are moderately productive within this process group. Resident fish typically occupy channel margins and deep pools with slower moving water. Anadromous fish often utilize these reaches for migration to more appropriate spawning habitat. Predominant bedrock channel beds offer low quality spawning habitat.

### *Moderate Gradient Contained*

Moderate gradient contained channels are completely contained by adjacent landforms and channel side slopes. Streambank and streambed erosion are frequently controlled by bedrock outcrops. These channels have balanced or transport oriented sediment regimes. Gravel bars are infrequent channel features (plain bed channels). Large woody debris within the wetted channel provide localized sediment storage sites and habitat diversity. Riparian areas are limited to the bank influence zone and are generally less than 100 feet. Resident and anadromous fish population are present in this process group. Spawning habitat is often limited due to variations of bedrock and alluvium streambed materials. These segments provide high quality rearing habitat and seasonal refugia for many fish species.

### *High Gradient Contained*

High gradient contained channels are shallowly to deeply incised, high gradient (over 6 percent), mountain slope streams. High gradient glacial meltwater streams are also included in this process group. These steep, headwater streams are important source areas for runoff, organic and inorganic sediment transported to downstream riparian and fish habitats. Stream channels are well contained within the narrow valley bottoms or ravines. Riparian areas generally extend to the upper stream side slope break. Riparian vegetation consists of narrow strips (often less than 50 feet wide) of alder, salmonberry, devil's club, or currant/shrub communities. Spruce and hemlock forests are also present on ravine side slopes. These channels are predominantly influenced by hillslope erosion processes. Soils in the adjacent upland area are shallow and subject to mass wasting. Although these are dominantly transport or erosive channels, significant amounts or forest litter and sediment can be trapped and stored temporarily behind woody debris jams. Most often, these segments are utilized by resident fish populations for various life stages. However, they also provide rearing habitat for anadromous fishes - typically in reaches less than 12% gradient.

### *Palustrine*

Palustrine channels are low gradient (less than 1 percent slope) and associated with low relief landforms dominated by wetlands. Water movement and sediment transport rates are low. These channel types typically act as storage areas for fine sediments. Streambanks are composed of dense organic root mats that are resistant to bank erosion. Streambeds consist of fine alluvial gravel and sand, and organics. Flood waters spread out across adjacent wetlands to buffer against downstream flooding. Another important function of these channels is to sustain streamflows during dry periods. Slow flowing palustrine streams can have elevated water temperatures that can be detrimental to some aquatic species during summer months. Riparian areas are usually wider than 100 feet and can be very wide in peatland landscapes. Streambed material is typically too fine to provide spawning habitat for fish. These segments provide high quality rearing habitat for juveniles, and in some cases, adult fish may overwinter within palustrine areas.

### *Estuarine*

Estuarine channel types occur at the mouths of watersheds with estuarine landforms (located along inlets and deltas at the head of bays). Water level fluctuations, channel morphology, sediment transport, water chemistry are influenced to some degree by saltwater inundation in these channel types. Riparian areas consist of saltwater marches, meadows, mudflats, and gravel deltas that are depositional environments. Estuarine channels are usually single to multiple thread channels, shallowly entrenched, and poorly constrained. Stream substrate is fine textured alluvium that is easily eroded by currents and wave action. Much of the sediment produced from any given watershed is ultimately deposited in or along the estuarine channel types, consequently, these channels are highly sensitive to upstream disturbances. Sedge and grass communities dominate the riparian vegetation. The amount of stream migration and channel braiding vary, depending on bank and bed materials and upstream erosion and sediment transport regimes. Riparian areas are normally more than 100 feet wide and are often several hundreds of feet wide on large river deltas. Estuarine areas provide habitat for highly productive spawning areas. Foraging activities are substantial for marine and freshwater fish within these areas. Wetted vegetation in estuaries provides refugia for rearing fish, including salmon species.

### *Drivers and Stressors*

The drivers and stressors to rivers and streams include both natural and human induced influences. Natural influences include changes in climate conditions, frequency in landslides, and migration of species. Human induced influences can influence the natural conditions and also have direct impact on ecosystem condition and function. Some human influences include lands management activities such as road building, timber harvest, and mining,

Changing climate conditions are driving changes in glacial melt, stream temperatures, and runoff regimes. Glacier fed rivers have relatively high total summer streamflow and low summer streamflow variability as compared to non-glacier-fed rivers. Overall, the effects of receding glaciers on their associated aquatic ecosystem will initially result in a decrease in temperature and increase in flows, turbidity and nutrient cycling (Milner et al. 2017; Young et al. 2022).

As glaciers recede, some streams will initially have harsher conditions (e.g. scouring summer flows, cold and high turbidity). However, as glaciers shrink past a certain size relative to watershed area, glacier-fed streams will become less harsh and likely become more biologically productive and have a greater capacity to support fish. Although this may be associated with an increase in average biological productivity as streams warm, it could also reduce the unique foraging and growth opportunities that these systems likely provide, especially for cold-water species like salmon (Halofsky et al. DRAFT). Warmer streams may reduce the diversity of available foraging and growth opportunities for juvenile salmon and other freshwater fishes. Shifts in food availability for juvenile salmonids could decrease the capacity of watersheds to provide favorable year-round habitat.

In addition to glacier loss, warming winters are projected to result in less precipitation falling as snow across southeast Alaska and declining contributions of snowmelt to summer streamflow (Littell et al. 2018; Chapter 1). Thus, snow-fed streams that typically display a large meltwater pulse in the spring and early summer will behave more like rainfed streams, becoming flashier, with a lower watershed residence time for water as a greater fraction of precipitation runs off the landscape directly to fluvial channels. Winter streamflow will also increase, seasonal accumulations of snow will be reduced except at the highest of elevations (Lader et al. 2022), and the snowmelt freshet will be smaller and occur earlier, while late summer and early autumn water levels will become more responsive to rainfall events. Projections for snowfall in coming decades can provide insights into where and when a critical loss of meltwater may occur, with shifts from transitional to rain-dominated and snow-dominated to transitional first occurring in lower-elevation, southern and coastal watersheds. However, by 2080, even many higher elevation watersheds are projected to become transitional (Littell et al. 2018; Bidlack et al. 2021).

Human induced threats to the integrity of aquatic ecosystems include roads, mining, timber harvest, landslides, dams, and invasive species. Best management practices are used to reduce effects to ecosystems; however, some influences continue to have short- and long-term impacts on the function and condition of ecosystems.

Timber harvest along streams can influence stream temperature, large wood contributions, and extent of refuge fish can find from summer low flows. In a study of fish populations and stream habitats on the Tongass, researchers found that fish may have greater opportunities for refuge from late summer, low flow conditions in watershed with greater than 42% old growth (Flitcroft et. al. 2022).

Timber harvest along streams has been buffered on the Tongass since the implementation of Tongass Timber Reform Act in 1992; however, effects of harvest practices prior to TTRA have altered forest ecosystems. Recent publications suggest key large wood is decreasing in all streams, regardless of management history (Filtcroft et. al. 2022).  Smaller sized (large) wood, such as alder and smaller conifer trees, which are recruited from previously harvested riparian area; play a less significant role moderating streamflow and capturing sediments.

The abundance of dams can alter streamflow and the movement of sediment and nutrients in a stream system. Large dams which are generally developed for water sources or sources of energy are discussed in the Energy and Minerals assessment section. Smaller ‘dams’ can be formed when road crossings block (or inhibit) water from flowing and fish from migrating. These dams are known as ‘red’ culverts on the Tongass.

The number of red crossings evolve over time due to natural conditions (landslides or plugging) or maintenance activity (removals or replacements). There are approximately 1,200 red culverts currently inventoried along the Tongass road system, according to the Tongass National Forest road crossing database. Since 1998, approximately 700 culverts (approximately 57%) have been removed, replaced, or retrofitted to restore access to fish habitats. Continued maintenance of road drainage, and improvements to road crossings will retain access to fish habitats and support properly functioning ecosystems.

Landslides are a natural disturbance on the landscape which can alter streamflow, impact road drainage, contribute sediment and trees to streams, and impact people and infrastructure. Increased frequency and intensity of extreme weather events have resulted in increased frequency of landslides (Thoman and Mcfarland 2024) and increased the impacts to people in Southeast Alaska.

The ecological health of the Tongass National Forest is tied to the seasonal pulses of marine derived nutrient delivered by salmon populations in Southeast Alaska (Rinella et. al. 2013). When adult salmon return to the freshwater ecosystem they contribute nutrients to wildlife, forests, and people. Bear, wolves, and people feed on salmon from freshwater streams. Dead and dying fish are food for aquatic invertebrates. Fish carcasses flooded onto the floodplain, or carried by wildlife intro the riparian areas, contribute nutrients to the soils, plants and trees. Changes in fish populations over time could have subsequent changes in nutrient cycling and associated food webs.

Southeast Alaska is relatively free of invasive freshwater species; however, warming conditions and increased access to freshwater ecosystems for recreation and tourism may pose a threat to the spread of invasives. The limitations of invasives are a function of frost-free days, subbasin land surface runoff, and snow cover (Geist et. al. 2023).  Invasive species that could become established in river and stream ecosystems include Atlantic salmon, New Zealand mudsnail, zebra/quaaga mussels and Norway rat. The Department of Natural Resources has restricted the sale, distribution, import and transport of five aquatic invasive species (Canadian waterweed, Western waterweed, Brazilian waterweed, Hydrilla, and Eurasian water milfoil) due to the degradation of fish habitat, displacement of native flora and fauna, reduction of recreation and transportation access, and reduction of waterfront property values. They provide guidance to reduce the risk of spread by boats and float planes, and aquarium enthusiasts and teachers.

The Tongass has several known infestations of non-native and potentially invasive aquatic animal species (USDA 2014). These species include the red legged frog (Rana aurora), pacific tree frog (Pseudacris regilla) and Atlantic salmon (Salmo salar). The Alaska Department of Fish and Game (ADF&G) is responsible for inventory and monitoring of Atlantic salmon. There are several other species receiving attention throughout the state didymo or ‘rock snot’ (Didymosphenia geminata), Norway rat (Rattus norvegicus) and introduced (non-naturally occurring) northern pike (Esox lucius). These species are generally being managed by other agencies including the ADF&G and U.S. Fish and Wildlife Service (USFWS). Canadian waterweed (Elodea canadensis) is a highly invasive aquatic plant that has been found in the interior of Alaska and is spreading, but it has not yet been found in southeast Alaska. In 2023 and 2024, the Tongass received funding through the Bipartisan Infrastructure Law for the identification and treatment of invasive plant species, and inventories to identify and prioritize treatment sites (Geist, M. et. al. 2023).

## Karst

### *Key Takeaways*

- Karst systems are integral to maintaining healthy streams:
- Karst systems are vital in maintaining a healthy stream pH and critical to the health of aquatic life. The carbonates have important buffering effects. Very acidic waters flow from the peatlands (pH 2.4 to 5.8) into karst systems, emerging at a slightly basic pH of 7.5 to 9.
- Karst systems moderate the effects of storms on streams, critical in an era of increased precipitation events and extreme weather patterns. Resident time for groundwater in karst systems results in cool, even temperature water. Flow rates through caves are relatively consistent. The storage capability of the karst systems results in lower peak flows and higher low flows. This helps to moderate the effects of storm events on resurgence streams.
- Karst systems support a large diversity of aquatic invertebrate populations, both within the caves and in the streams. There also seems to be greater moss and algae growth within the carbonate dominated systems, most likely reflective of nutrient availability.
- Karst and cave systems provide critical habitat, food, and shelter for fish populations. Smolts and resident trout use the cave systems for protection from predation, for shade, and for a feeding area, since many invertebrates utilize the photic zone of the cave system for breeding and shelter. Adult salmon have been seen spawning through some cave systems, and evidence of salmon spawning in the caves has been found.
- Cave systems are particularly vulnerable to surface pollution. The cave systems filter out some debris and sediments, although they do not filter out large debris, chemical impurities, or microorganisms.
- Karst systems are well drained and maintain old-growth Sitka spruce, western hemlock, and cedar trees. Old-growth temperate rainforests hold a higher density of biomass than any other ecosystem on Earth, which uniquely positions the Tongass karst forests as one of the most important tools for naturally sequestering carbon in the nation.

### *Ecosystem description*

Karst ecosystems, formed by the dissolution of soluble bedrock like limestone, are distinctive environments characterized by a unique interplay between surface and subsurface processes. Karst areas are characterized by distinctive landforms such as caves, sinkholes, and springs. The high degree of connectivity, driven by water readily moving between the surface and subsurface, creates distinct sediment, energy, and nutrient cycles not found in other ecosystems. Southeast Alaska hosts a globally rare convergence of temperate rainforest and karst terrain, with the Tongass National Forest containing almost 500,000 acres of such landscape. This region is characterized by high precipitation, acidic groundwater drainage from muskegs, and pure limestone, contributing to rapid limestone dissolution rates and a truly unique ecological environment.

Cave ecosystems are the most exotic subsection of the karst environment. Caves provide stable environments in total darkness with buffered pH, high humidity, and constant temperatures between 37 and 42° Fahrenheit. Due to the darkness and resulting lack of photosynthesis in caves, there are very few energy inputs in the ecosystem. Most energy enters the caves in the form of particulate organic matter or dissolved organic carbon (Simon and Benfield 2001). This dark, stable, low-energy ecosystem is hostile to most life, except for species that are well adapted to it. Of the species that can thrive in the cave environment, many can only survive underground. As such, caves are often home to endemic and rare species not found anywhere else.

Muskeg peat plays an important role in the formation of karst and cave features due to the acidic waters that flow from them, accelerating the rate of dissolution. The peat forms atop poorly drained rock such as compact glacial tills or marine silts that overlie or are adjacent to carbonates. Surface waters originating from these poorly drained areas seldom flow more than a few yards onto carbonate substrate before diving below the ground, down vertical shafts or into cave entrances. The highly acidic waters from the peatlands accelerate karst and cave development. The pH levels of waters flowing from these Sphagnum-dominated wetlands can be as low as 2.4 (Aley et al., 1993). Waters flowing from the cave systems that accept these waters commonly show a pH range of 7.5 to 9.0. The buffering capabilities of the pure carbonates is evident.

Karst watersheds do not follow the same characteristics as non-carbonate watersheds, which are defined by topographic divides and surface streams. Due to the three-dimensional subsurface nature of karst groundwater, these watersheds are delineated by methods like dye tracing, in order to map subsurface flow paths and direction. Recharge zones need to be considered in these watersheds, since the recharge area and type contributes to fluctuations in groundwater flow regimes. There are two types of groundwater recharge processes in these systems, autogenic and allogenic. Autogenic recharge occurs when precipitation makes direct contact with carbonates, whereas allogenic precipitation falls on adjacent non-carbonate bedrock that eventually flows from a surface stream and into caves and karst features. Understanding the zone of recharge for these watersheds is a crucial step in understanding the flow regimes of karst groundwater basins and how to manage these areas.

Epikarst is exceptionally well developed throughout karst areas on the Tongass. The alpine epikarst is characterized by deep shafts, crevasse-like dissolved fissures, eroded dissolution rills of all sizes, and spires and spikes of limestone. In the sub-alpine, the epikarst exhibits similar features to the bare alpine settings, except it is vegetated. Typical thickness of the epikarst zone ranges from more than 100 feet in the alpine zone to less than 5 feet along the coast and lower elevations. The epikarst thickness appears to be more a function of glacial history than altitude. The epikarst is extremely important in moving water, nutrients, organic matter, and soil from the land surface and rooting zone and into the subsurface where these materials can move laterally to seeps and springs or to vertical collector structures which channel them downward into cave networks (Aley et al. 1993).

Karst ecosystems in the region create a prime environment for mature, well-developed forest, particularly Sitka spruce and western hemlock, which thrive on the well-drained, nutrient-rich soil atop carbonate bedrock. These forests become windfirm, anchoring their roots into the cracks and fissures of the surficial epikarst. Additional characteristics include increased productivity for plant, animal, and aquatic communities (Baichtal and Swanston 1996).

Karst landscapes function differently than other ecosystems on the Forest. Subsurface drainage networks generally operate independently of, and with more complexity than, the surface drainage systems above (Aley and Aley, 1993; Huntoon 1992a). The watershed characteristics of the surface may have little or no relationship to the subsurface karst drainage system. On karst lands, the many solution-widened fissures at the surface become injection points into a more complex subsurface drainage system. These fissures rapidly move water and sediment from surface sources vertically downward and into the underground lateral systems. Thus, sediment and water transported from roads and disturbed lands may emerge unexpectedly at one or more distant springs including across surface watershed boundaries (Baichtal and Swanston 1996).

A large portion of a karst system's vulnerability to management disturbance is the system's openness. The degree to which the surface is connected to the karst system conduits at depth relates directly to the effect of any planned land use. A high density of solution and collapse features indicates the presence of well-developed underground systems. The presence of a single sinkhole demonstrates a direct surface/subsurface connection, even if the sinkhole intermittently retains water. Sediment transport mechanisms are different between karst and non-karst landforms. A particle of soil in non-karst lands is transported by gravity, landslides, and/or surface water flow, sometimes over great distances into a watercourse, to become sediment. Atop a karst landform, depending on the openness of the karst system, a soil particle only needs to be transported laterally a few inches or feet before it can be washed vertically through the surface or epikarst into the karst conduits at depth.

The catchment areas for karst systems, composed of carbonate or non-carbonate substrate, are an integral portion of those systems. These catchment areas must be effectively managed to protect the resource values of the karst systems into which they flow. The higher the resource values found within a particular karst block, the higher the degree of protection which is needed within a contributing catchment area. As a minimum, such things as potential for increased runoff and increased stream velocities, increased sediment transport capability, mass wasting potential of the soils within the watershed, and increased wind-throw potential should be considered when developing management strategies for these catchment areas. The vulnerability of the karst system's catchment areas should be considered equal to the highest down-gradient karst vulnerability values. As part of site-specific analysis, management strategies developed for the catchment areas should insure protection of the down-gradient karst resource values.

### *Ecosystem Services*

The karst landscape influences productivity of its aquatic habitats in several aspects. The geochemistry associated with karst development contributes to productivity in aquatic environments through its carbonate buffering capacity and carbon input from dissolved limestone bedrock. This has significant downstream effects on the aquatic food chain and biotic community. The karst ecosystem may be eight to ten times more productive than adjacent non-karst dominated aquatic habitats. It supports a higher abundance, distribution, density, and variety of invertebrate species than the non-carbonate-based systems, has higher growth rates for smolts and resident fish, reflects less variable water temperatures and flow regimes, and contains unique habitat affecting species distribution, abundance, and adaptations (Baichtal and Swanston 1996).

### *Status and Trends*

One way of demonstrating the productivity of the karst area is to compare timber volume differences between karst and non-karst areas. Exceptionally dense stands of very large diameter spruce and hemlock at lower elevations are characteristic of karst landscapes. On karst landscapes worldwide, timber harvest has led to serious, often long-term declines in soil depth and fertility, in some cases culminating in permanent deforestation (Harding and Ford 1993; Huntoon, 1992 a,b; Kiernan 1993). Trees growing on karst generally have roots extending down into the dissolved cracks and fissures in the bedrock. These roots act to pump water and nutrients back up into the forest canopy. Much of the site productivity is tied up in this nutrient cycle and in the forest canopy. When trees are harvested this nutrient cycle is broken.

Hydrologic models currently used for estimating the cumulative effects of proposed surface management activities are not designed to model the effects of timber harvest on the karst landscapes. Evidence suggests that timber harvest increases available surface waters, thereby increasing sediment and debris transport capabilities and flooding passages which have not flooded for centuries. Observations in some caves suggest that passages which now flood result in fragile ceiling formations becoming tannin-stained and showing signs of dissolution. Many cave entrances are infilled and/or blocked by logging slash, sediment, and debris. Runoff generated from road surfaces commonly is diverted into karst features.

The cumulative effects of past timber harvest on the epikarst landscape on the Tongass is not well studied (Baichtal 1993c). Field observations and aerial photo interpretations show strong evidence of greatly increased surface runoff on karst areas after harvest. This increases sediment, nutrient, and debris transport capability of these systems. Transport capability increases both vertically and laterally. Current harvesting techniques leave the slash within the unit, which helps to protect the shallow fragile soils from erosion and drying. A considerable percentage of the easily accessible low-level karst areas have been harvested. Timber harvest is now moving onto steeper, higher elevation karst areas which are characterized by shallower, better-drained soils. Observations suggest that with harvest atop these soils, much of the soil may be removed if adequate log suspension is not achieved. Often, only a thin organic mat covers the karst. The exceedingly shallow soils become excessively dry once the protective forest canopy is removed. The high rainfall of the area can rapidly move these fragile soils into the well developed epikarst. Observations suggest that these steeper, higher elevation karst areas show less than desirable regeneration or remain as bare rock slopes within harvested units.

## Lakes and Ponds

### *Key Takeaways*

- Lakes on the Tongass National Forest are in overall pristine condition.
- Lakes provide important physical and biological roles within the watershed by physically influencing streamflow and temperature, and by providing habitat to aquatic and terrestrial organisms.
- Lakes are important to the communities in Southeast Alaska as hydropower sites, hatchery and remote release locations, and for their subsistence and recreational values.
- As with many other resources, lake conditions are likely to change with projected changes in temperature and hydrologic regime.

### *Ecosystem description*

"Lakes in southeast Alaska have been similarly categorized as turbid, clear, and stained/brown water based on their physicochemistry, which diverges based, to some extent, on their runoff source, similar to fluvial systems (Koenings and Edmundson 1991). Darkly colored or "brownwater" lakes have high dissolved organic carbon concentrations, including colored tannins and humic acids resulting from runoff through organic-rich soils. In contrast, clear-water lakes, which are often found at higher altitudes and in drainages with shallower soils, have low turbidity, nutrients, and organic carbon concentrations (McCoy et. al. 1976). Lakes fed by glacial meltwater (proglacial lakes) are turbid and cold, and can have high total phosphorus depending on watershed lithology (Burpee et. al. 2018, St.Pierre et al. 2019, Halofsky et al. DRAFT).

Approximately 213,000 acres of lakes and ponds are present on Tongass National Forest lands. Of these, approximately 3,300 lakes and ponds are mapped as Class 1 water bodies; these water bodies are defined as anadromous or high-value resident fish habitat. Another 1,000 lakes and ponds are mapped as resident fish habitat (USDA 2016, p. 3-104).

Lakes accessible to salmon are classified as essential fish habitat. Large anadromous lake systems accessible to communities in Southeast Alaska are important for subsistence (Klawock, Redoubt, Sitkoh, + others). Lakes offer high quality spawning, rearing and refugia for a variety of salmonid species and other aquatic organisms. Both fish bearing and non-fish bearing lakes have been used for fisheries enhancement. The 2016 Forest Plan listed 5 lake/stream fertilization projects, and 7 lake stocking projects completed between 1996-2014.

Historically, large lakes accessible by floatplane from surrounding communities were stocked with native and non-native lake species including brown trout, rainbow trout and grayling. Many of these stocking efforts have not persisted to the present day due to lake conditions or competition with native species, though the State of Alaska still stocks sportfish species in lakes across the region. In Yakutat, illegally stocked northern pike were eradicated from ponds due to concerns over their potential to invade the Situk river. No other invasive lake species are of current concern.

Lake temperature can have both positive and negative implications at multiples scales. At the watershed scale lake coverage is an important physical driver for stream temperature (Winfree. et al. 2018). Lake coverage is associated with warming downstream reaches in both summer and winter. Increases in lake temperature are associated with increases in biological production (Kovach et al. 2015) but may also influence the prevalence of hypoxia and fish kills in low gradient reaches downstream (Sergeant et al 2023).

The majority of the hydro-electric projects in Southeast Alaska (on and off NFS lands) are sourced from lakes. In most cases the target lakes are in steep drainages that don't overlap with anadromous habitat – however as most stream systems have some near-saltwater habitat, any flow modification from dams, or penstock/powerhouse development has the potential to alter flow regimes or habitat quality (temperature, dissolved oxygen, nutrient and sediment flux).

Under the 2016 Forest Plan, lakes are protected by a 100' no-cut commercial harvest buffer. The function of the riparian buffer on lakes is like streams as it minimizes excess sedimentation inputs and allows for allochthonous inputs to lakes including large wood (LW) as cover, and leaf litter/insects to support biological production (USDA 2016a, Appendix D). No analysis of lakes affected by riparian harvest was completed for 2016 Plan. Legacy timber harvest extending to lakeshores has converted intact riparian forests to young growth. While there haven't been any habitat (large wood placement) enhancement projects within lakes, thinning treatments to improve lakeside riparian habitat have been proposed and are underway in the Cube Cove priority watershed. Lakes affected by upstream sediment load have been considered for dredging, and shallow lakes have undergone vegetation removal projects (Yakutat). The most recent comprehensive sample of lake condition was undertaken by the Alaska Department of Environmental Conservation (ADEC) in 2017 as part of the Alaska Monitoring and Assessment Program. A statistical sample of 37 lakes were surveyed using a suite of physical and biological parameters and a field report produced (ADEC 2017).

### *Ecosystem Services*

Lakes play several important physical and biological roles within the watershed. Physically, they act to buffer both high and low streamflow and insulate downstream reaches from upstream disturbance effects. Lakes play important roles in spawning, overwintering and rearing of salmonid species, are important habitat for resident and migratory waterfowl

### *Status and Trends*

- Indicators of lake ecosystem health include chemical contaminants, macroinvertebrate community structure and water chemistry.
- Underlying geology, altitudes, and morphometric characteristics of lakes influences water chemistry.
- Trends in water quality can signify chronic or developing watershed issues within Southeast Alaska. The majority of data suggest that no considerable sources of pollution are affecting the health and integrity of this ecosystem.
- Signatures of industrialization are evident in lake sediments, where atmospherically deposited mercury levels are higher than the expected background levels
- Lakes and ponds contribute a great deal to watershed productivity and species diversity.
- Low elevation lakes are often high-quality fish rearing habitat providing for many species of wildlife (e.g. beaver, mustelids, loons, eagles, swans, and other water birds).
- Lakes and ponds mitigate downstream flooding during storms, and are important for surface-groundwater exchange and moderating water temperatures.
- Small ponds, particularly beaver ponds, can be highly productive.
- The size and number of glacier-fed lakes has increased in the last 30 years
- Glacier-fed lakes are significant and previously unrecognized annual CO2 sinks due to chemical weathering.
- As glaciers continue to retreat and feed glacial lakes, the implications for glacial lake outburst floods and water resources are of considerable societal and ecological importance.

## Nearshore

### *Key Takeaways*

- The nearshore ecosystem is a unique and important triple interface between air, land and sea that provides linkages for transfer of water, nutrients, and species between watersheds and offshore habitats.

- The inside coastal waters, where this runoff is concentrated, have estuarine characteristics, whereas the outer coast has greater stability of salinity and temperature, directly influenced by the Gulf of Alaska
- Freshwater runoff for the Gulf of Alaska basin is two- to sixfold higher than that of the Amazon and Congo rivers.
- The nearshore is the base of the food chain. It is a source of primary production for export to adjacent habitats (primarily by kelps, other seaweeds, and eelgrass), as well as a recipient for primary (phytoplankton) and secondary production (zooplankton) transported from offshore systems.
- The nearshore includes a variety of unique habitats for resident organisms (e.g. sea otters, seals, sea lions, shorebirds, seabirds, nearshore fishes, kelps, seagrasses, clams, mussels, and sea stars).
- It provides nursery grounds for migratory marine animals (e.g., crabs, salmon, herring, seabirds, and whales) and feeding grounds for important consumers (e.g., killer whales, harbor seals, sea otters, sea lions, sea ducks, shorebirds and many species of fish.
- Nearshore ecosystems are a source of animals important to commercial and subsistence harvests (e.g. marine mammals, fishes, crabs, mussels, clams, chitons, and octopus).
- Recreational activities including fishing, boating, camping, and nature viewing are important to residents and tourists.

### *Ecosystem description*

Seaward, beyond the tidal wetlands and estuaries (addressed in the Terrestrial Ecosystems Assessment section) lies the nearshore environment. This ecosystem can be defined as the interface between land and ocean, defined by well-known species with well understood ecological relations, where high densities of specialist predators (sea otters, sea ducks, black oystercatchers, sea stars) exist within a diverse and productive system full of kelps and invertebrates that don't occur in any other habitats. Kelps and eelgrasses are "living habitats" that serve as nutrient filters and provide understory and ground cover for planktivorous fish, clams, and urchins, and a physical substrate for other invertebrates and algae. Kelps and eelgrasses also provide spawning and nursery habitats for forage fish and juvenile crustaceans. Nearshore marine ecosystems face significant challenges at global and regional scales, with threats arising from both the adjacent lands and oceans.

Southeast Alaska is a subarctic region where glacial ice and erosion have created an intricate landscape with many islands, deep inlets, fjords, and interconnected channels. The complex coastal topography of Southeast Alaska leads to environmental variability, most notably between inner coast and outer coast regions (Weingartner et al. 2009). We refer to the interior islands and waters adjacent to the Coast Mountain range as the inner coast region, which includes Lynn Canal, the deepest fjord in North America, with depths exceeding 900 meters, and a fault trace that extends the length of Chatham Strait (Martin and Williams 1924; Brew et al. 1991). The outer coast region includes the outermost islands and waters directly connected to the Gulf of Alaska, including Sitka Sound.

Glaciers and ice fields contribute significantly to freshwater discharge to the Gulf of Alaska and are responsible for 47% of the total freshwater discharge to the Gulf of Alaska (Neal et al. 2010). In Southeast Alaska, the gradient of freshwater discharge is from the interior Coast Mountain range to the outer coast (Weingartner et al. 2009). Freshwater runoff is seasonally most pronounced during the spring and autumn, causing water column stratification that is strongest near freshwater discharge sites (Pickard

1967; Royer 1982; Weingartner et al. 2009). The inside coastal waters, where this runoff is concentrated, have estuarine characteristics, whereas the outer coast has greater stability of salinity and temperature, directly influenced by the Gulf of Alaska (Pickard 1967; Murphy and Orsi 1999). Freshwater runoff for the Gulf of Alaska basin is two- to sixfold higher than that of the Amazon and Congo rivers (Neal et al. 2010). This significant force fuels coastal circulation in the Gulf of Alaska (Royer 1981). As a result of significant glacial fluctuations in the last 10,000+ years, marine communities in inner coast regions of Southeast Alaska are glacially influenced, while those on the outer coast are not. Recent studies indicate that levels of glacial coverage can alter the timing and magnitude of freshwater, dissolved organic matter, and nutrient yields to coastal marine communities (Hood and Scott 2008; Hood et al. 2009).

Southeast Alaska has a more diverse macroalgal community than any other Alaska region (Lindstrom 2006, 2009). Large within region diversity differences, in particular greater diversity at the outer coast sites, may be strongly influenced by variation in freshwater discharge to the nearshore marine environment due to glaciation at the inner coast. There exists biogeographic distinction between the outer and inner coast sites of northern Southeast Alaska for shallow subtidal macroalgal, invertebrate, and fish communities. Shallow subtidal invertebrates are understudied in Southeast Alaska, and consequently the ecology of many species is poorly understood.

### *Ecosystem Services*

The nearshore is considered an important ecosystem because it provides:

- A variety of unique habitats for resident organisms (e.g. sea otters, seals, sea lions, shorebirds, seabirds, nearshore fishes, kelps, seagrasses, clams, mussels, and sea stars).
- Nursery grounds for marine animals from other habitats (e.g. crabs, salmon, herring, and seabirds).
- Feeding grounds for important consumers, including killer whales, harbor seals, sea otters, sea lions, sea ducks, shore birds and many fish and shellfish.
- A source of animals important to commercial and subsistence harvests (e.g. marine mammals, fishes, crabs, mussels, clams, chitons, and octopus).
- An important site of recreational activities including fishing, boating, camping, and nature viewing.
- A source of primary production for export to adjacent habitats (primarily by kelps, other seaweeds, and eelgrass), as well as a recipient for primary (phytoplankton) and secondary production (zooplankton) transported from offshore systems.
- An important triple interface between air, land and sea that provides linkages for transfer of water, nutrients, and species between watersheds and offshore habitats.

### *Drivers and Stressors*

Kelps are the major primary producers in the marine nearshore and because they are located in shallow water, they are prone to be more impacted by oil spills and other human-related activities. Other potential stresses include activities that disturb the beds directly, such as dredging and anchor scars, and events that reduce the ability for light to penetrate into the water column, such as runoff (increased turbidity) or nutrient addition (eutrophication).

Southeast Alaska is an understudied region with respect to marine ecological processes. Marine ecosystem shifts are expected for coastal regions of the Gulf of Alaska as a consequence of ocean warming and increased freshwater input to the North Pacific marine environment (Royer 1989; Royer et al. 2001; Weingartner et al. 2005; Royer and Grosch 2006). Given that glaciers and ice fields are responsible for 47 % of the total freshwater discharge to the Gulf of Alaska (Neal et al. 2010) and that Alaskan glaciers are losing mass more rapidly since the 1990s than they were several decades earlier (Arendt et al. 2002), studies are needed along the fjord coast of Southeast Alaska to follow marine community shifts over time with these environmental changes.

### *Status and Trends*

- The major gradient of freshwater discharge from the coast to the open ocean is persistent and has been stable since the 1960s, which is important for sediment and nutrient transport.
- Species diversity, especially invertebrates, increased toward the outer coast and in deeper water.
- Based on long-term monitoring in Icy Bay, juvenile salmon are entering the Gulf of Alaska (GOA) with average to below-average size.
- Smaller fish are less efficient at foraging and more vulnerable to predation. Further growth and survival will be dependent on favorable over-winter conditions in the GOA.
- Plankton community response to temperature indicates bottom-up climate effects.
- Declines in kelp (macroalgae) were observed, which is a critical food source for filter feeders (e.g., mussels), benthic feeders (e.g., kelp greenling) and pelagic feeders (e.g., black rockfish) in the nearshore ecosystem.
- Seabirds, marine mammals, and groundfish experienced shifts in distribution, mass mortalities, and reproductive failures, which they are still recovering from.
- Given anticipated increases in marine heatwaves under current climate projections, it remains uncertain when or if the Gulf of Alaska ecosystem will return to a pre-PMH state.

## Marine

### *Key Takeaways*

- Long-term surface temperatures (1900–2023) show a persistent warming across the Gulf of Alaska shelf, driven largely by increasing temperatures in the summer months (May – October).
- This ecosystem is largely driven by La Niña to El Niño conditions.
- The 2014–2016 marine heatwave (also called The Blob) resulted in ecosystem level effects and the ecosystem is still recovering.
- Salmon have a varied response to marine conditions based on their life histories.
- There is a lag time in observing effects of changing ocean conditions to salmon due to climate change, which are not known until they return to freshwater ecosystems to spawn.

### *Ecosystem description*

The Gulf of Alaska and Inside Passage, which includes the Dixon Entrance, Clarence Strait, Frederick Sound, Chatham Strait and Lynn Canal, are part of the marine ecosystem that salmon use during their adult life stage. The North Pacific Fisheries Management Council reports annually on the status and trends of the Gulf of Alaska ecosystem by measuring 18 indicators in the eastern and western portions of the gulf. The Gulf of Alaska is characterized by topographical complexity, including islands, deep sea mounts, a continental shelf interrupted by large gullies, and varied and massive coastline features such as Cook Inlet, Prince William Sound, Copper River, and Cross Sound, which bring both freshwater and nutrients into the Gulf of Alaska. The topographical complexity leads to ecological complexity, such that species richness and diversity differ from the western to eastern Gulf of Alaska (Ferriss 2023).

### *Ecosystem Drivers and Stressors*

In the Gulf of Alaska, El Niño events typically lead to warmer than average sea surface temperatures, increased storm activity, and a deeper Aleutian low pressure system, resulting in wetter conditions, while La Niña brings cooler waters, higher pressure systems, and generally drier conditions compared to normal; both can significantly impact marine life and weather patterns in the region.

**El Niño:**

- Warmer waters: During El Niño, the Gulf of Alaska experiences warmer ocean temperatures due to the eastward movement of warm water in the Pacific Ocean.
- Increased storms: This warming can lead to more frequent and intense storms, particularly in the fall season.
- Deeper Aleutian Low: The Aleutian Low pressure system, which usually sits over the North Pacific, shifts southeastward and deepens during El Niño, influencing weather patterns in the Gulf of Alaska.
- Potential impacts: This can result in wetter winters and more precipitation overall in the region.

**La Niña:**

- Cooler waters: In contrast, La Niña brings cooler than average ocean temperatures to the Gulf of Alaska due to stronger trade winds pushing cold water up from the deep.
- Higher pressure: A stronger high-pressure system forms over the Gulf of Alaska, leading to generally drier conditions.
- Weaker Aleutian Low: The Aleutian Low tends to be weaker and less pronounced during La Niña, further contributing to drier weather.

### *Ecosystem Services*

The Gulf of Alaska marine ecosystem provides a wide range of ecosystem services including: food production (fisheries), climate regulation by absorbing carbon dioxide, coastal protection from storms, water purification, recreation and tourism, biodiversity support, and nutrient cycling.

### *Status and Trends*

The Gulf of Alaska shelf marine ecosystem had an average year of productivity in 2023, with some declining trends from the highly productive previous year. Some highlights for 2023 include an increase in Pacific cod although still very low population levels) and capelin populations (both had not shown signs of recovery since declines related to the 2014–2016 marine heatwave), and a transition from three consecutive years of La Niña to El Niño conditions.

Despite the generally productive year, some concerns persist around a decline in the zooplankton prey base. Total zooplankton biomass in 2023 was variable, but overall declined to below average, as indicated by multiple zooplankton surveys, low biomass of age-0 pollock and cod (WGOA), and low energy density of juvenile pink and sockeye salmon (eastern GOA; predators of zooplankton). Given the current El Niño status and the associated warming surface waters predicted in winter/spring of 2024, the reduction in zooplankton availability and quality may persist into the coming year. The last El Niño event occurred in 2016, with warming effects augmented by the ongoing 2014–2016 marine heatwave. If we do not experience another separate marine heatwave event, the upcoming El Niño is predicted to be of a strength similar to that in 1997/1998.

Vulnerable groundfish in 2024 (due to warm surface waters and reduced zooplankton quality) potentially include the larval and age-0 juveniles of Pacific cod, walleye pollock, and northern rock sole. Warm surface waters can be favorable for larval rockfish and sablefish. Adult zooplanktivorous groundfish may have reduced prey availability (walleye pollock, Pacific ocean perch, dusky and northern rockfish) but the deeper adult habitat is not predicted to warm unless El Niño related warming persists long enough to be mixed to depth.

## Key Findings

- The integrity of freshwater ecosystems is generally high. Across the Tongass, rivers, streams, lakes and ponds are expected to continue delivering highly functioning conditions and services including biodiversity and productivity without human interference.
- The integrity of glaciers, nearshore and marine ecosystems, however, is moderate. Glaciers are expected to deliver moderately functioning conditions and services including biodiversity and productivity at a reduced level relative to expectations for this ecosystem. Climate change is the primary stressor affecting these ecosystems.
- Extreme weather events and changes in climate have affected water temperature, timing of runoff, flooding, and water chemistry throughout all aquatic ecosystems, and these changes are expected to continue, without all potential effects understood.
- Fish (anadromous and non-anadromous), amphibians and aquatic invertebrates occupy various aquatic habitats throughout their lifecycles.
- Salmon are essential part of the health of freshwater and marine ecosystems.
- When salmon return to freshwater to spawn, they provide marine-derived nutrients that are key for forest health.
- Development, including timber harvest, mining, and roads may alter aquatic ecosystem integrity at a localized scale.
- At a local scale, the legacy effects of timber harvest are observed, particularly where large, productive old-growth was harvested from valley bottoms, so that large wood is no longer recruited into aquatic ecosystems.
- Restoration efforts include installing culverts designed for aquatic organism passage (fish passage) to increase resilience to flooding, maintain connectivity to upstream habitats, and restore habitat quality near roads.

- Threats to freshwater ecosystems include point and non-point source pollution from physical conditions and chemical pollutants including urbanization, mining, timber harvest, and aquaculture practices including hatcheries and shellfish farming.
- Aquatic ecosystems can be degraded as a result of landslides, culvert blockages, water diversions, channelization, and hydroelectric dams.
- Invasive (sometime called nuisance) species may occur in freshwater, estuarine, and marine waters. Invasive species can alter these ecosystems (e.g., Spartina, Elodea, reed canary grass); displace, compete and prey on native species (e.g., northern pike, Atlantic salmon, European green crab); foul infrastructure (e.g., zebra and Quaaga mussels, colonial tunicate *Didemnum vexillum*) and sicken humans by causing diseases (e.g., Norway rat).
- Aquatic ecosystems can be degraded by aquaculture practices
- Fishing practices (e.g., bottom trawling) can cause physical damage to marine habitats like coral reefs and the seafloor.
- Threats to the estuarine ecosystem include point and non-point source pollution, aquaculture, commercial fishing, large vessel traffic, shoreline development, and changes in climate.

*This page intentionally left blank.*

# References

Alaska Department of Environmental Conservation [ADEC]. 2017. 2017 Southeast Alaska Lake Survey Sites. Retrieved December 16, 2024 https://dec.alaska.gov/media/9085/2017-southeast-lakes-survey.pdf.

Aley, T., Aley, C., Elliott, W. R., & Huntoon, P. W. 1993. Karst and cave resource significance assessment, Ketchikan area, Tongass National Forest, Alaska. Report of the Karst Resources Panel, 79.

Arendt, A. A., Echelmeyer, K. A., Harrison, W. D., Lingle, C. S., & Valentine, V. B. 2002. Rapid wastage of Alaska glaciers and their contribution to rising sea level. Science, 297(5580), 382-386.

Arimitsu, M. L., Piatt, J. F., Hatch, S., Suryan, R. M., Batten, S., Bishop, M. A., and von Biela, V. R. 2021. Heatwave-induced synchrony within forage fish portfolio disrupts energy flow to top pelagic predators. Global Change Biology, 27(9), 1859-1878.

Baichtal, J. F. 1996. Karst landscapes and associated resources: a resource assessment (Vol. 383). US Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Baichtal, J. F.; Swanston, D. N. 1996. Karst landscapes and associated resources: a resource assessment. Gen. Tech. Rep. PNW-GTR-383. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 13 p.

Bellmore, J. R., Fellman, J. B., Hood, E., Dunkle, M. R., & Edwards, R. T. 2022. A melting cryosphere constrains fish growth by synchronizing the seasonal phenology of river food webs. Global Change Biology, 28(16), 4807–4818. https://doi.org/10.1111/gcb.16273

Berg, E. E., Hillman, K. M., Dial, R., & DeRuwe, A. 2009. Recent woody invasion of wetlands on the Kenai Peninsula Lowlands, south-central Alaska: a major regime shift after 18 000 years of wet Sphagnum–sedge peat recruitment. Canadian Journal of Forest Research, 39(11), 2033-2046.

Beuchel, F., Gulliksen, B., & Carroll, M. L. 2006. Long-term patterns of rocky bottom macrobenthic community structure in an Arctic fjord (Kongsfjorden, Svalbard) in relation to climate variability (1980–2003). Journal of Marine Systems, 63(1-2), 35-48.

Bidlack, A. L., Bisbing, S. M., Buma, B. J., Diefenderfer, H. L., Fellman, J. B., Floyd, W. C., and Tank, S. E. 2021. Climate-mediated changes to linked terrestrial and marine ecosystems across the Northeast Pacific coastal temperate rainforest margin. BioScience, 71(6), 581-595.

Brahney, J., Bothwell, M. L., Capito, L., Gray, C. A., Null, S. E., Menounos, B., & Curtis, P. J. 2021. Glacier recession alters stream water quality characteristics facilitating bloom formation in the benthic diatom Didymosphenia geminata. Science of the Total Environment, 764, 142856.

Burpee, B. T., Anderson, D., & Saros, J. E. 2018. Assessing ecological effects of glacial meltwater on lakes fed by the Greenland Ice Sheet: The role of nutrient subsidies and turbidity. Arctic, Antarctic, and Alpine Research, 50(1). https://doi.org/10.1080/15230430.2017.1420953

Corliss, K., von Biela, V., Coletti, H., Bodkin, J., Esler, D., & Iken, K. 2024. Relative Importance of Macroalgae and Phytoplankton to Nearshore Consumers and Growth Across Climatic Conditions in the Northern Gulf of Alaska. Estuaries and Coasts, 47(6), 1579-1597.

Curran, J. H., & Biles, F. E. 2021. Identification of seasonal streamflow regimes and streamflow drivers for daily and peak flows in Alaska. Water Resources Research, 57(2), e2020WR028425.

Dean, T. A., Haldorson, L., Laur, D. R., Jewett, S. C., & Blanchard, A. 2000. The distribution of nearshore fishes in kelp and eelgrass communities in Prince William Sound, Alaska: associations with vegetation and physical habitat characteristics. Environmental Biology of Fishes, 57, 271-287.

Dunkle, M. R., Bellmore, J. R., Fellman, J. B., & Caudill, C. C. 2024. Glaciers, snow, and rain: Water source influences invertebrate community structure and secondary production across a hydrologically diverse subarctic landscape. Limnology and Oceanography, 69(2), 232-245.

Engle, V. D., Kurtz, J. C., Smith, L. M., Chancy, C., & Bourgeois, P. 2007. A classification of US estuaries based on physical and hydrologic attributes. Environmental Monitoring and Assessment, 129, 397-412.

Fellman, J. B., Nagorski, S., Pyare, S., Vermilyea, A. W., Scott, D., & Hood, E. 2014. Stream temperature response to variable glacier coverage in coastal watersheds of Southeast Alaska. Hydrological Processes, 28(4), 2062-2073.

Ferriss, B.E. 2023. Ecosystem Assessment. In: Ferriss, B.E. 2023. Ecosystem Status Report 2023: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 1007 West Third, Suite 400, Anchorage, Alaska 99501.

Geist, M., Jarnevich, C., Steer, A., Osnas, J., Carey, M.P., Martin, A.E., Davis, T., and Kelty, R. Modeling, mapping, and measuring the risk of freshwater invasive species across Alaska. 2023. Alaska Center for Conservation Science, University of Alaska Anchorage, AK. 236 pp.

Grierson, B., 2018. The Cavernous World Under the Woods, Hakai Magazine. Retrieved from https://www.hakaimagazine.com/features/the-cavernous-world-under-the-woods/

Halofsky, Jessica E.; Prendeville, Holly R.; Peterson, David L.; Parrish, Robert. eds. DRAFT. Climate change vulnerability and adaptation in the Tongass National Forest. Gen. Tech. Rep. PNW-GTR-XXX. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station

Hamilton, J., & Konar, B. 2007. Implications of substrate complexity and kelp variability for south-central Alaskan nearshore fish communities. Fishery Bulletin, 105(2), 189-196.

Harding, K. A., & Ford, D. C. 1993. Impacts of primary deforestation upon limestone slopes in northern Vancouver Island, British Columbia. Environmental Geology, 21, 137-143.

Helfield, J. M., & Naiman, R. J. 2001. Effects of Salmon-Derived Nitrogen on Riparian Forest Growth and Implications for Stream Productivity. Ecology, 82(9), 2403–2409. https://doi.org/10.2307/2679924

Hock, R., & Huss, M. 2021. Glaciers and climate change. In Climate change (pp. 157-176). Elsevier.

Hood, E., & Berner, L. 2009. Effects of changing glacial coverage on the physical and biogeochemical properties of coastal streams in southeastern Alaska. Journal of Geophysical Research: Biogeosciences, 114(G3).

Hood, E., Fellman, J. B., & Spencer, R. G. 2020. Glacier loss impacts riverine organic carbon transport to the ocean. Geophysical Research Letters, 47(19), e2020GL089804.

Huntoon, P. W. 1992a. Hydrogeologie characteristics and deforestation of the stone forest karst aquifers of south China. Groundwater, 30(2), 167-176.

Huntoon, P. W. 1992b. Exploration and development of ground water from the stone forest karst aquifers of South China. Groundwater, 30(3), 324-330.

Johnson, S. W., Murphy, M. L., & Csepp, D. J., 2003. Distribution, habitat, and behavior of rockfishes, Sebastes spp., in nearshore waters of southeastern Alaska: observations from a remotely operated vehicle. Environmental Biology of Fishes, 66(3), 259-270.

Kiernan, K. 1993. Management under ice. Cave Management in Australasia, 10, 24-31.

Koenings, J.P. and Edmundson, A. 1991. Seechi disk and photometer estimates of light regimes in Alaskan lakes: Effects of yellow color and turbidity. Retrieved December 17, 2024 https://aslopubs.onlinelibrary.wiley.com/doi/10.4319/lo.1991.36.1.0091.

Kovach, R. P., Joyce, J. E., Vulstek, S. C., Barrientos, E. M., & Tallmon, D. A. 2014. Variable effects of climate and density on the juvenile ecology of two salmonids in an Alaskan lake. Canadian Journal of Fisheries and Aquatic Sciences, 71(6), 799-807.

Lader, R., Bhatt, U. S., Walsh, J. E., & Bieniek, P. A. 2022. Projections of hydroclimatic extremes in Southeast Alaska under the RCP8.5 scenario. Earth Interactions, 26(1), 180-194.

Lader, R., Bidlack, A., Walsh, J. E., Bhatt, U. S., & Bieniek, P. A. 2020. Dynamical downscaling for Southeast Alaska: historical climate and future projections. Journal of Applied Meteorology and Climatology, 59(10), 1607-1623.

Larsen, D. J., Crump, S. E., & Blumm, A. 2020. Alpine glacier resilience and Neoglacial fluctuations linked to Holocene snowfall trends in the western United States. Science advances, 6(47), eabc7661.

Lindstrom, S. C. 2006. Biogeography of Alaskan seaweeds. Journal of applied phycology, 18, 637-641.

Lindstrom, S. C. 2009. The biogeography of seaweeds in Southeast Alaska. Journal of Biogeography, 36(3), 401-409.

Littell, J. S., McAfee, S. A., & Hayward, G. D. 2018. Alaska snowpack response to climate change: Statewide snowfall equivalent and snowpack water scenarios. Water, 10(5), 668.

Litzow, M. A., Hunsicker, M. E., Ward, E. J., Anderson, S. C., Gao, J., Zador, S. G., and O'Malley, R. 2020. Evaluating ecosystem change as Gulf of Alaska temperature exceeds the limits of preindustrial variability. Progress in Oceanography, 186, 102393.

Mantua, N., Tohver, I., & Hamlet, A. 2009. Impacts of climate change on key aspects of freshwater salmon habitat in Washington State.

McCoy, G. A., Wiggins, W. W., & Schmidt, A. E. 1976 Limnological investigations of six lakes in southeast Alaska. U. S. Geological Survey Water Resources Investigations Report 76-122. https://doi.org/10.3133/wri76122

McDaniel, Josh; Johnson, Adelaide (Di); Bellmore, J. Ryan; Haught, Stormy; Medel, Ron. 2020. Alaska’s forest fish: Calculating the value of wild salmon from the Chugach and Tongass National Forests. Science Findings 234. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 5 p.

Milner, A. M., Khamis, K., Battin, T. J., Brittain, J. E., Barrand, N. E., Füreder, L., and Brown, L. E. 2017. Glacier shrinkage driving global changes in downstream systems. Proceedings of the National Academy of Sciences, 114(37), 9770-9778.

Molnia, B. F. 2007. Late nineteenth to early twenty-first century behavior of Alaskan glaciers as indicators of changing regional climate. Global and Planetary Change, 56(1-2), 23-56.

Moore J, M. J., Flitcroft, R. L., Tucker, E., Prussian, K. M., & Claeson, S. M., 2024. Same streams in a different forest? Investigations of forest harvest legacies and future trajectories across 30 years of stream habitat monitoring on the Tongass National Forest, Alaska. Plos one, 19(7), e0301723.

Moore, J. W., Pitman, K. J., Whited, D., Marsden, N. T., Sexton, E. K., Sergeant, C. J., & Connor, M. 2023. Mining stakes claim on salmon futures as glaciers retreat. Science, 382(6673), 887-889.

Motyka, R. J., O'Neel, S., Connor, C. L., & Echelmeyer, K. A., 2003. Twentieth century thinning of Mendenhall Glacier, Alaska, and its relationship to climate, lake calving, and glacier run-off. Global and Planetary Change, 35(1-2), 93-112.

Murphy, M. L., Johnson, S. W., & Csepp, D. J., 2000. A comparison of fish assemblages in eelgrass and adjacent subtidal habitats near Craig, Alaska. Alaska Fishery Research Bulletin, 7, 11-21.

Musselman, K. N., Lehner, F., Ikeda, K., Clark, M. P., Prein, A. F., Liu, C., ... & Rasmussen, R. 2018. Projected increases and shifts in rain-on-snow flood risk over western North America. Nature Climate Change, 8(9), 808-812.

Nash, D., Rutz, J. J., & Jacobs, A. 2024. Atmospheric rivers in Southeast Alaska: Meteorological conditions associated with extreme precipitation. Journal of Geophysical Research: Atmospheres, 129(4), e2023JD039294.

O’Neel, S., Hood, E., Arendt, A., & Sass, L. 2014. Assessing streamflow sensitivity to variations in glacier mass balance. Climatic Change, 123, 329-341.

Paustian, S.J., 1992. A channel type user’s guide for the Tongass National Forest, southeast Alaska. Technical Paper 26. Juneau, AK: USDA, Forest Service, Alaska Region. Revised 2010.

Pitman et. al., 2020. Glacier Retreat and Pacific Salmon. BioScience Volume 70, Issue 3

Renaud, P. E., Włodarska-Kowalczuk, M., Trannum, H., Holte, B., Węsławski, J. M., Cochrane, S., ... & Gulliksen, B., 2007. Multidecadal stability of benthic community structure in a high-Arctic glacial fjord (van Mijenfjord, Spitsbergen). Polar Biology, 30, 295-305.

Rinella, D. J., M. S. Wipfli, C. M. Walker, C. A. Stricker, and R. A. Heintz. 2013. Seasonal persistence of marine-derived nutrients in south-central Alaskan salmon streams. Ecosphere 4(10):122. http://dx.doi.org/10.1890/ ES13-00112.1

Rounce, D. R., Hock, R., Maussion, F., Hugonnet, R., Kochtitzky, W., Huss, M., and McNabb, R. W., 2023. Global glacier change in the 21st century: Every increase in temperature matters. Science, 379(6627), 78-83.

Rovellini, A., Punt, A. E., Bryan, M. D., Kaplan, I. C., Dorn, M. W., Aydin, K., ... & Weise, M. T. 2024. Linking climate stressors to ecological processes in ecosystem models, with a case study from the Gulf of Alaska. ICES Journal of Marine Science, fsae002.

Royer, T. C. 1989. Upper ocean temperature variability in the northeast Pacific Ocean: Is it an indicator of global warming?. Journal of Geophysical Research: Oceans, 94(C12), 18175-18183.

Royer, T. C., & Grosch, C. E. 2006. Ocean warming and freshening in the northern Gulf of Alaska. Geophysical Research Letters, 33(16).

Royer, T. C., Grosch, C. E., & Mysak, L. A. 2001. Interdecadal variability of Northeast Pacific coastal freshwater and its implications on biological productivity. Progress in Oceanography, 49(1-4), 95-111.

Schwoerer, T., Little, J. M., & Adkison, M. D. 2019. Aquatic invasive species change ecosystem services from the world's largest wild sockeye salmon fisheries in Alaska. Journal of Ocean and Coastal Economics, 6(1), 2.

Sergeant, C. J., Falke, J. A., Bellmore, R. A., Bellmore, J. R., & Crumley, R. L. 2020. A classification of streamflow patterns across the coastal Gulf of Alaska. Water Resources Research, 56(2), e2019WR026127.

Simon, K. S., & Benfield, E. F. 2002. Ammonium retention and whole-stream metabolism in cave streams. Hydrobiologia, 482, 31-39.

St. Pierre, K. A., St. Louis, V. L., Schiff, S. L., Lehnherr, I., Dainard, P. G., Gardner, A. S., ... & Sharp, M. J. 2019. Proglacial freshwaters are significant and previously unrecognized sinks of atmospheric CO2. Proceedings of the National Academy of Sciences, 116(36), 17690-17695.

Suryan, R. M., Arimitsu, M. L., Coletti, H. A., Hopcroft, R. R., Lindeberg, M. R., Barbeaux, S. J., and Zador, S. G. 2021. Ecosystem response persists after a prolonged marine heatwave. Scientific reports, 11(1), 6235.

Suryan, R. M., Lindeberg, M. R., Arimitsu, M. L., Esler, D., Coletti, H. A., Hopcroft, R. R., & Pegau, W. S. 2023. Gulf Watch Alaska: Long-term research and monitoring in the Gulf of Alaska. Available at https://www.openaccessgovernment.org/article/gulf-watch-alaska-long-term-research-monitoring-ecosystem/156485/

Thoman, R. and H. R. McFarland, editors. 2024. Alaska’s Changing Environment 2.0. Alaska Center for Climate Assessment and Policy, International Arctic Research Center, University of Alaska Fairbanks. uaf-iarc.org/communicating-change.

Tongass National Forest (TNF). 201) Tongass National Forest Monitoring and Evaluation Report – Streams and Fish Habitat, Riparian. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprd3856120.pdf

USEPA [United States Environmental Protection Agency]. 2004. Classification Framework for Coastal Systems, EPA/600/R-04/061. Research Triangle Park, NC, USA: U.S. Environmental Protection Agency, Office of Research and Development, National Health and Environmental Effects Laboratory.

United States Forest Service, Tongass National Forest [USDA]. 2016. Final Environmental Impact Statement: Tongass Land and Resource Management Plan (No. R10-MB-769e,f).

United States Forest Service [USDA]. 2016a. Land and Resource Management Plan. Forest Service Alaska Region, Tongass National Forest R10-MD-769j.

United States Forest Service [USDA]. 2024. Tongass National Forest Salmon Factsheet. Retrieved December 16, 2024 https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd918446.pdf.

Veh, Georg, Lutzow, N., Tamm, J., Luna, L.V., Hugonnet, R., Vogel, K., Geertsema, M., Clague, J.J., and Korup, O. 2023. Less extreme and earlier outbursts of ice-dammed lakes since 1900. Retrieved December 17, 2024 at https://www.nature.com/articles/s41586-022-05642-9.

Walsh, J. E., Thoman, R. L., Bhatt, U. S., Bieniek, P. A., Brettschneider, B., Brubaker, M., and Partain, J. (2018). The high latitude marine heat wave of 2016 and its impacts on Alaska. Bull. Am. Meteorol. Soc, 99(1), S39-S43.

Weathers, K. C., Strayer, D. L., & Likens, G. E. 2021. Introduction to ecosystem science. In Fundamentals of ecosystem science (pp. 3-26). Academic Press.

Weingartner, T. J., Danielson, S. L., & Royer, T. C. 2005. Freshwater variability and predictability in the Alaska Coastal Current. Deep Sea Research Part II: Topical Studies in Oceanography, 52(1-2), 169-191.

Winfree, M. M., Hood, E., Stuefer, S. L., Schindler, D. E., Cline, T. J., Arp, C. D., & Pyare, S. 2018. Landcover and geomorphology influence streamwater temperature sensitivity in salmon bearing watersheds in Southeast Alaska. Environmental Research Letters, 13(6), 064034.

Witherell, D., Pautzke, C., & Fluharty, D. 2000. An ecosystem-based approach for Alaska groundfish fisheries. ICES Journal of Marine Science, 57(3), 771-777.

Young, J. C., Pettit, E., Arendt, A., Hood, E., Liston, G. E., & Beamer, J. 2021. A changing hydrological regime: Trends in magnitude and timing of glacier ice melt and glacier runoff in a high latitude coastal watershed. Water Resources Research, 57(7), e2020WR027404.

Ziemen, F. A., Hock, R., Aschwanden, A., Khroulev, C., Kienholz, C., Melkonian, A., & Zhang, J. 2016. Modeling the evolution of the Juneau Icefield between 1971 and 2100 using the Parallel Ice Sheet Model (PISM). Journal of Glaciology, 62(231), 199-214.

*This page intentionally left blank.*