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science for a changing world

Partners in Research

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Alaska Park Science is the science journal of the National Park Service Alaska Region. Each issue highlights research and scholarship important to the stewardship of Alaska's parks.

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On the Cover: Old Creek (or Ole Creek), Aniakchak National Monument and Preserve.
NPS/LESLIE SKORA

Partners in Research

Sarah M. Laske *is a Research Fish Biologist at the USGS Alaska Science Center. She studies aquatic communities, pursuing questions about how the environment affects biodiversity and food webs. She has studied aquatic ecosystems in the Arctic and subarctic since 2011, studying at the University of Alaska Fairbanks, earning her Ph.D. in 2017. Her science is collaborative to provide information to support decision making.*

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This issue of Alaska Park Science focuses specifically on the National Park Service (NPS)-U.S. Geological Survey (USGS) science partnership. Alaska's national parks protect large, ecologically intact landscapes that are a valuable setting for scientists to understand ecosystem function and change. These "natural laboratories" are ideal settings for researchers from universities and other federal agencies. Together, we build a body of science that informs a variety of disciplines as well as park management.

In this issue, we highlight research on water—in its many forms—frozen water (glaciers), moving water (streams and rivers), still water (lakes), and salt water (intertidal). We explore water as a source of transportation (rivers, lakes, and gulfs), concern (oil spills, permafrost thaw, and erosion), and livelihoods (fish, wildlife, and recreation)—even as a means for conducting science, such as how a river corridor serves as a bear survey transect.

Our research in parks spans the state, from Noatak National Preserve in Northwest Alaska, to Sitka National Historical Park in Southeast, to Katmai National Park and Preserve in Southwest. The researchers themselves are as varied as the places and the studies, led by USGS and NPS scientists in collaboration with science centers, universities, and in remote field stations, and at all career stages from seasoned experts to students and technicians.

The USGS is closely associated with the NPS, both housed within the U.S. Department of the Interior (DOI). Despite its rocky epithet, the USGS employs researchers across the spectrum of science, from biologists and ecologists, to astronomers and astrophysicists, to hydrologists, geologists, and geographers. The mission of USGS is to provide objective and impartial scientific research that benefits resource managers and the public more broadly. Distinct from many other DOI bureaus, USGS does not have a land and resource management base, but contributes strong scientific expertise and partnership.

It is our hope that the articles in this issue serve to underscore the close and abiding ties between USGS and NPS in providing scientific insight that helps park staff to manage and protect Alaska's national parks, for continued and future use by Alaskans and, indeed, all of America.

Waterfall Creek, Aniakchak National Monument and Preserve.
NPS/LESLIE SKORA

Brewing Change in the (Glacier) Percolation Zone

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Michael Loso, Wrangell-St. Elias National Park and Preserve, National Park Service

Alaska's glaciers are losing mass at the fastest rate of any region globally, significantly affecting both the volume and distribution of water across the landscape. While most studies measure mass changes in the ablation and wet snow zones of glaciers, our work also studies the higher-elevation percolation zone to understand how changing processes will influence larger glaciers.

Citation:
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Alaska's glaciers are losing mass at the fastest rate of any region globally (The GlaMBIE Team 2025), significantly affecting both the volume and distribution of water across the landscape. Though glaciers in the Alaska region (as defined by glaciologists this includes both Alaska and portions of adjacent Canada; RGI Consortium 2017) range from sea level to nearly 20,320 feet (6,200 m), most glacier area in the Alaska region is concentrated between 2,950 and 6,890 feet (900 and 2,100 m; Figure 1). The U.S. Geological Survey (USGS) Benchmark Glacier Project provides some of the longest *in-situ* records of glacier mass change in the world (WGMS 2023), with long-term monitoring on three moderate sized glaciers in Alaska. The process-based understanding of glacier change on those benchmark glaciers is robust (O'Neel et al.

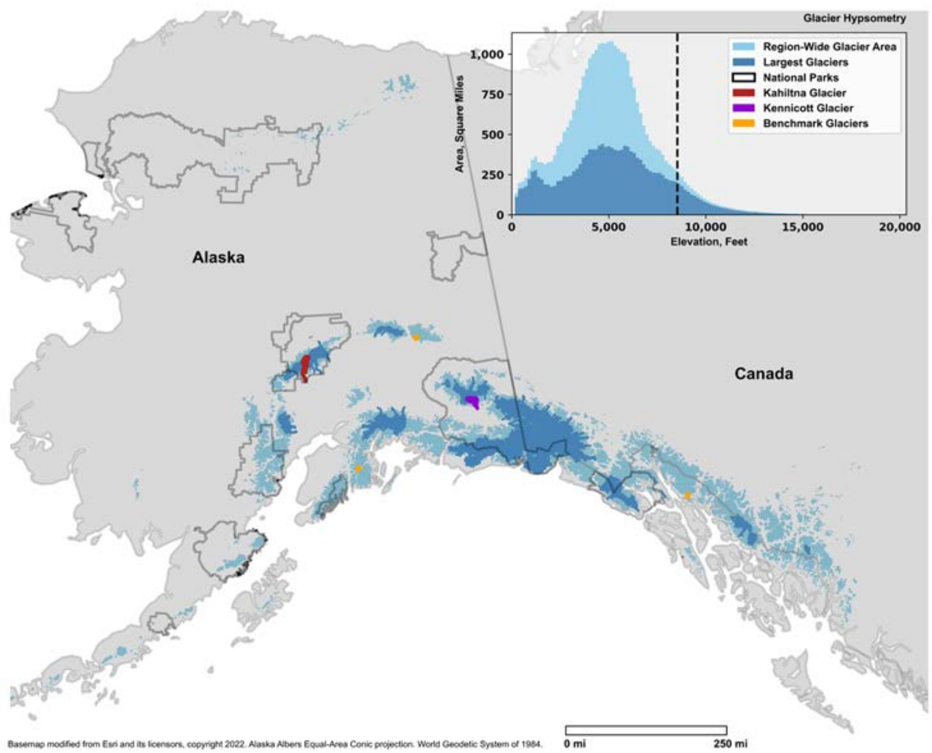

Figure 1. Glacier distribution and National Park Service boundaries in Alaska. Glacier coverage (RGI Consortium 2017) shaded blue with the 100 largest glaciers shown in dark blue.

The inset shows glacier hypsometry (distribution of area versus elevation) of the total glacier area and the 100 largest glaciers, with a dashed vertical line at 8,500 feet (2,600 m).

Flying over Kennicott Glacier on September 29, 2024. These are large glaciers, and even with a helicopter they make you feel very small. Here the scale of the crevasses is illustrated by the small helicopter shadow. This is typical of the complicated topography and significant relief that is common on larger glaciers in Alaska.
USGS/LOUIS SASS

2019, Florentine et al. 2023) but is limited to the range of conditions present on those particular glaciers—at moderate elevations—where large amounts of melt water and rain pass through the glacier and into the downstream ecosystem on an annual basis (Stevens et al. 2024).

The world's largest glaciers outside of Greenland and Antarctica are in the Alaska region (Windnagel et al. 2023). These large glaciers have broad elevation ranges and include large amounts of area at elevations higher than those measured on the USGS benchmark glaciers. Of the more than 27,000 glaciers in the Alaska region, the 100 largest glaciers contain half of the approximately 33,500 square mile (87,000 km^2) total glacier area and over three-quarters of the approximately 2,500 square miles of glacier area above 8,500 feet (2,600 m; RGI Consortium 2017). Hence, behaviors of the largest glaciers are in part driven by high elevation processes not captured by measurements on the smaller benchmark glaciers.

At higher elevations, glacier processes are controlled by high accumulation rates and low melt. At high enough elevations, any liquid water from surface melt or rain refreezes within the cold snow, meaning that none of the precipitation that falls on that portion of the glacier runs off—all of it is converted to ice (Figure 2). This cold high-elevation zone is called the percolation zone (Benson 1962). At the highest elevations, no melt occurs, and this area is referred to as the dry-snow zone. Because warming temperatures increase both the amount of melt and the proportion of precipitation that falls as rain, some glacier areas will transition from percolation zones to wet-snow zones, or from dry-snow zones to percolation zones. The transition from percolation zone to wet-snow zone is particularly important because in the wet-snow zone, melt and rain saturate the snowpack and exit the glacier as runoff. The transition also governs whether a portion of the glacier loses mass at the surface during periods of summer warmth. Understanding where the transition from wet-snow zone to percolation zone occurs and characterizing the interplay between accumulation and runoff at that transition is critical to understanding and forecasting changes in area, mass, and hydrologic behavior for larger glaciers in the Alaska region. A new collaboration with deep historical roots between the U.S. Geological Survey (USGS) Benchmark Glacier Project and the National Park Service (NPS) Glacier Monitoring Program is helping to develop that understanding.

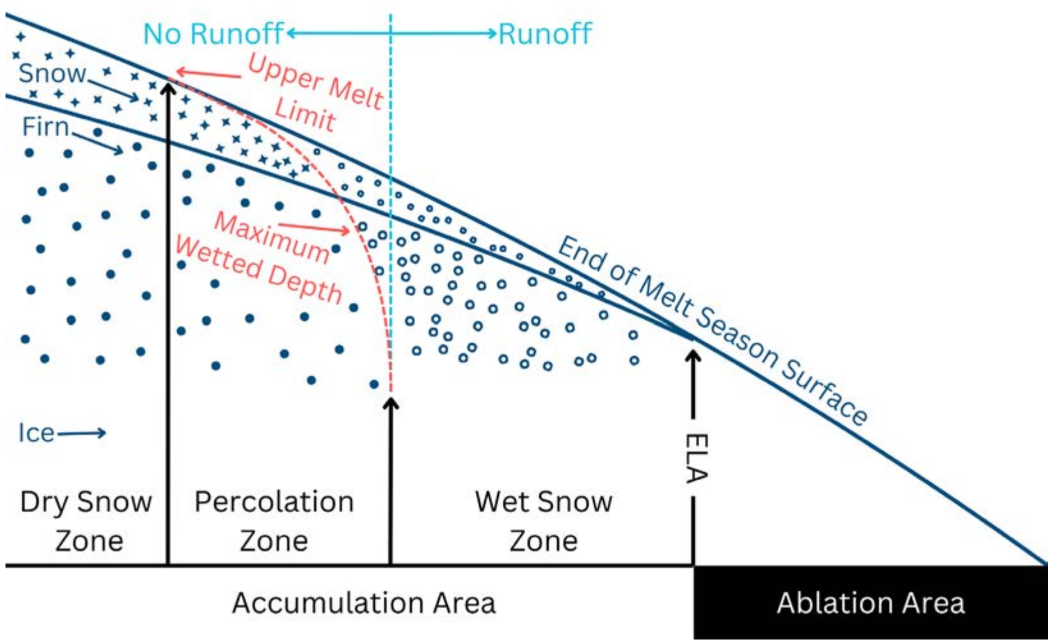

Figure 2. Schematic of glacier processes, showing the dry snow, percolation, and wet-snow zones of the accumulation area. Blue circles represent wetted snow and larger blue circles represent wetted firn. Blue plusses represent dry snow, and blue dots represent dry firn. Below the firn and on the lower portion of the glacier, blank space below the surface represents ice. The percolation zone is defined as the zone where all surface melt refreezes, so no runoff occurs. After Benson (1962).

History

The National Park Service Inventory and Monitoring Program began quantifying glacier change on Kahiltna Glacier (Denali National Park and Preserve) in 1991 as part of the Long-term Ecological Monitoring (LTEM) program (Adema 2003). During the proposal and project development, scientists collaborated with glaciologists from USGS and the University of Alaska Fairbanks. An initial mass-balance measurement site was established near the elevation where annual melt and accumulation are approximately balanced (often called the Equilibrium Line Altitude or ELA). This site and others that have been added over time have been continuously monitored on a seasonal basis for snow accumulation and melt plus surface elevation changes (Loso et al. 2014).

Mass-balance measurements on Kennicott Glacier began in 2016 in recognition of the value in adding a comparable, highly visible, and highly visited glacier in the most heavily glaciated national park: Wrangell-St. Elias National Park and Preserve (Loso 2022). Now, mass balance monitoring efforts on these two glaciers are currently performed in collaboration between the Central Alaska Network (part of the NPS Inventory & Monitoring Program) and the U.S. Geological Survey Benchmark Glacier Program.

These two large glaciers have complex geometries (Figure 3) and extensive areas at higher elevations (Figure 4). The mass balance processes are different at these high elevations than at those measured by the USGS Benchmark Glacier Project or from those typically measured globally (WGMS 2024). Collaboration between USGS and NPS glacier research teams aims to broadly improve the monitoring and research on Kahiltna and Kennicott Glaciers, in part by combining the NPS commitment to monitoring these large glaciers with the workflow and skillsets within the USGS Benchmark Glacier Project. Ultimately the goal is to produce annual glacier-wide mass balance estimates that are corrected to the seasonal mass maximum and minimum and calibrated with geodetic, satellite-measured volume change. This article focuses on the glaciological, field-based mass balance point measurements, and how those measurements are enhancing our understanding of glacier processes at higher elevations—which is particularly critical to understand how larger glaciers in the region are changing.

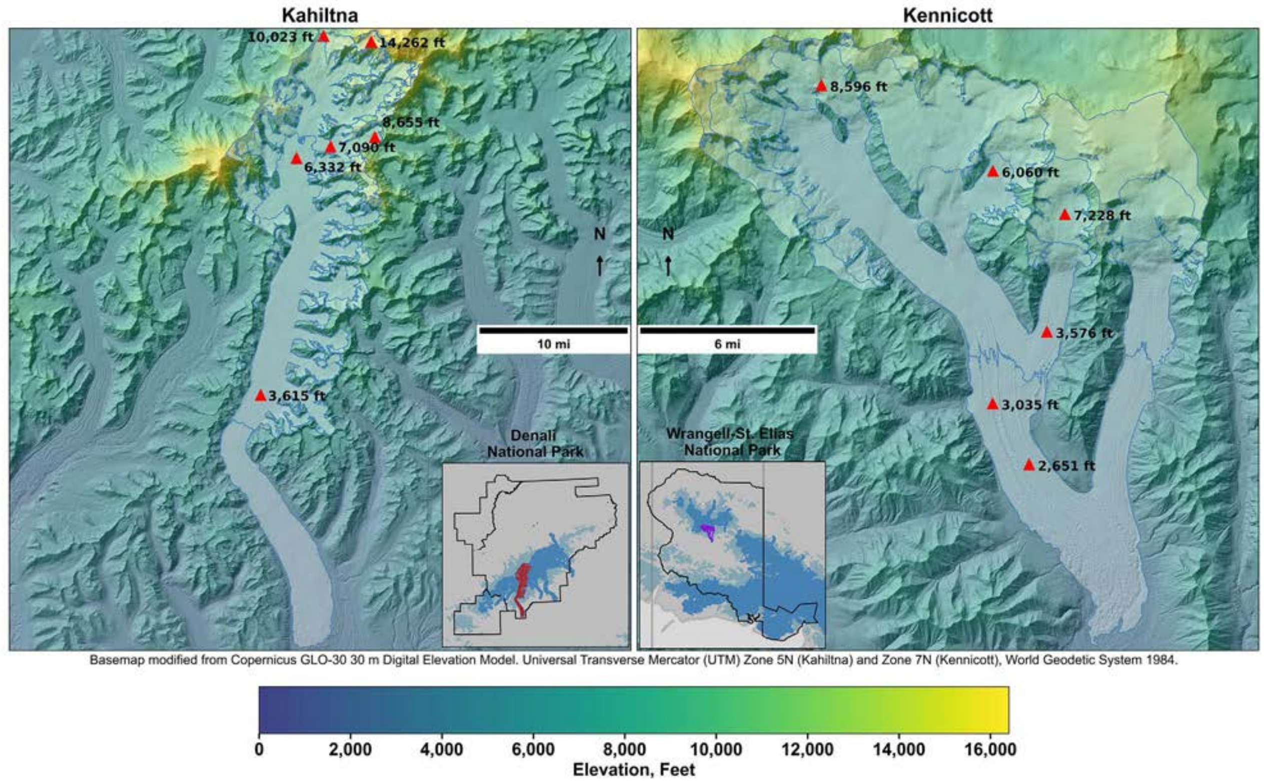

Figure 3. Overview maps of Kahiltna and Kennicott Glaciers.

Insets show glacier outlines (RGI Consortium 2017) within their respective national park boundaries. Mass balance measurement sites are displayed for both glaciers as red triangles, labeled with the elevation in feet (U.S. Geological Survey Glacier Project 2016).

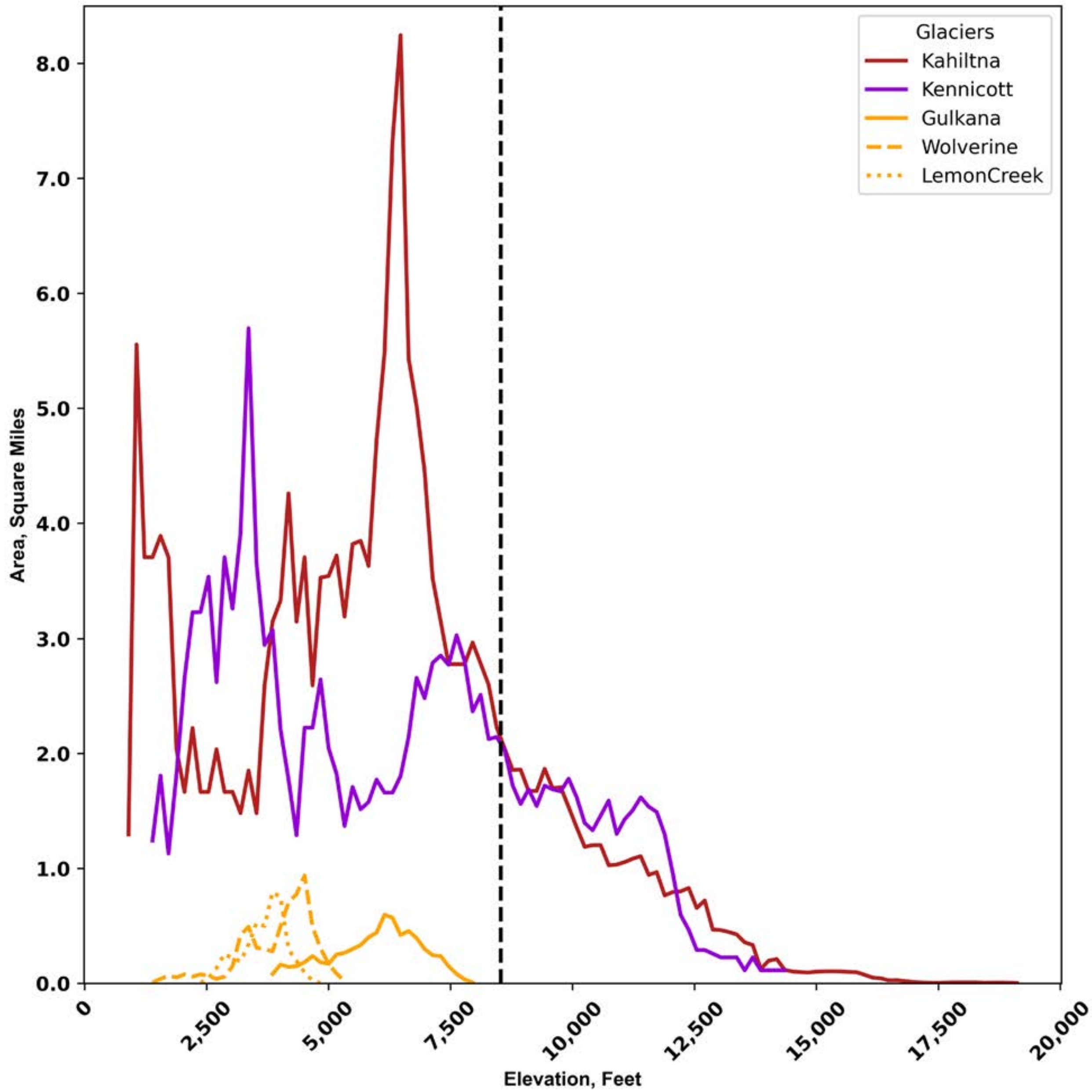

Figure 4. Individual glacier hypsometries (distribution of area versus elevation) for Kahiltna Glacier in red, Kennicott Glacier in purple, and the USGS Benchmark Glaciers in Alaska in gold. The vertical dashed line is at 8,500 feet (2,600 m), the approximate base of the percolation zone (U.S. Geological Survey Glacier Project 2019).

Glacier Processes

Glaciers form when more snowfall accumulates than melts for many years. Snow that lasts for more than one year is subsequently buried by additional snowfall and starts to compress. The transitional material is called firn, which continues to compress over time until it becomes glacier ice. Ice starts to deform and move downhill once it is more than 33 feet (10 m) thick. This deformation allows the ice to flow to lower elevations, where less snowfall and warmer temperatures melt the ice (Cuffey and Paterson 2010).

The size of a glacier is directly related to the interplay between the climate-related physical processes of snowfall (*accumulation*), snow and ice melt (*ablation*), and ice flow (*glacier dynamics*). The climate determines how far and fast the glacier must flow to remove accumulated snowfall via downstream ice melt. These characteristics of glacier flow determine how long it will take the glacier to adjust to changes in temperature and precipitation (Roe et al. 2017).

Glaciers around Alaska are almost all retreating and thinning as they adjust to climate. Satellite remote sensing shows that glacier area within Alaska decreased 8% (from 23,400 square miles to 21,500 square miles, or 60,645 km^2 to 55,652 km^2) during 2000-2020 (Roberts-Pierel et al. 2022). Glaciers in the Alaska region are changing faster than any other region and have thinned by an average of 50 feet (15 m) from 2000-2019 (Hugonnet et al. 2021). Quantifying the physical processes of snow accumulation and both snow and ice melt helps us to understand how those changes in glacier area and elevation are linked to climate, and in turn helps us predict the impacts of these changes on park visitors, infrastructure, and ecosystems.

Direct Measurements of Glacier Mass Balance

Tracking the mass changes on glaciers is commonly referred to as *glacier mass balance*. Direct field-based measurements of glacier mass balance on the surface of glaciers are resource intensive; however, those seasonal measurements inform our understanding of the physical processes, are used to validate regional remote sensing-based measurements of change (e.g., Zemp et al. 2019), and help calibrate models that give us insights into future trajectories for these glaciers (e.g., Rounce et al. 2023, Wells et al. 2025). Globally, most glacier mass balance measurement programs target small to mid-size glaciers and most of the measurement sites are in the ablation zone, where the measurements are less work and the sites are easier to access (WGMS 2023).

Direct measurements of mass balance entail tracking the thickness and density of material gain and loss at specified sites across the glacier's surface through biannual visits conducted in spring and fall, resulting in a seasonal record of mass change. The nature of these measurements depends on the zone of measurement (Figure 2). On the lower glacier's ablation area, where bare ice is exposed by summer snowmelt, spring snow-pits are used to measure the snowfall from each previous winter, and ablation stakes are measured each spring and fall to determine summer melt. Further up-glacier, in the lowest part of the accumulation area (the wet-snow zone), not all the winter snow melts away before it is buried by the snows of the following winter. Measurements are made in similar fashion to measurements in the ablation zone, but a snow-pit in the fall quantifies that remaining snow (the year's positive annual mass balance).

A core section from Kahiltna Glacier at 10,023 feet (3,055 m) on September 30, 2024, showing ice layers in fine-grained snow. These layers form when water from surface melt percolates into the snowpack and refreezes.
USGS/EMILY BAKER

Our collaborative study of Kahiltna and Kennicott Glaciers includes mass balance measurements from higher elevations including the percolation and dry-snow zones. It can be challenging to work in these environments: the accumulated winter snowpack can exceed 20 feet (6 m), and snow frequently continues to accumulate all summer long. Ablation stakes are commonly buried before they can be re-measured, so measurements are limited to extracting a core of snow and firn. In the absence of re-measurement of a stake placed

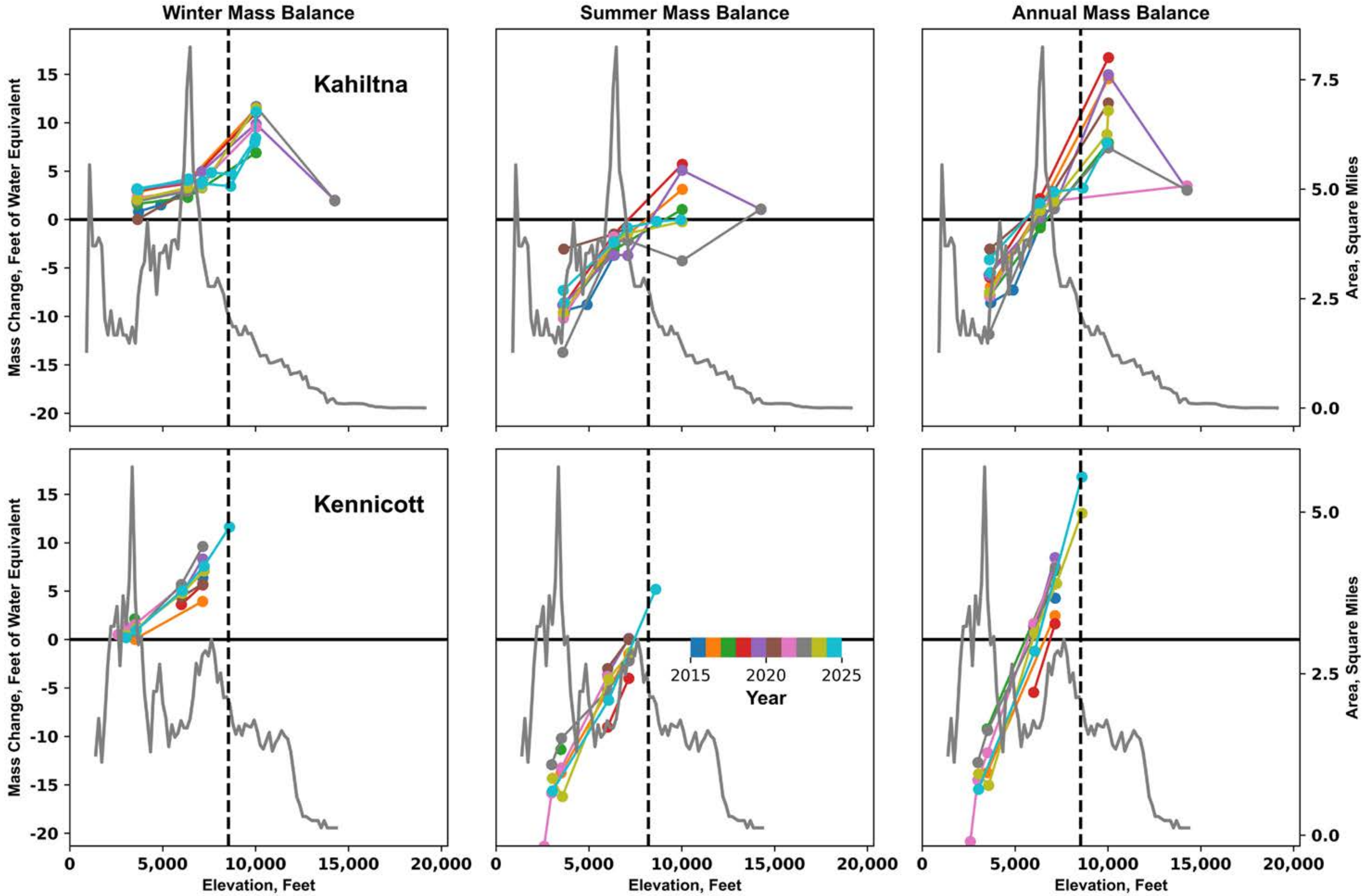

Figure 5. Seasonal mass balance profiles for 2015-2024 (colored dots and lines; U.S. Geological Survey Glacier Project 2016) overlaying glacier hypsometry (distribution of area versus elevation, light grey; U.S. Geological Survey Glacier Project 2019) for Kahiltna (top row) and Kennicott (bottom row) glaciers. Winter balances shown in the first column, summer balances in the middle column, and annual balances are shown in the last column. The horizontal line delineates 0 mass balance, and the vertical dashed line is at 8,500 feet (2,600 m), the approximate base of the percolation zone.

on a previous visit, previous time horizons are interpreted based on the stratigraphy of the snowpack. The grain size and morphology are noted in each core section. While snow initially can have many forms, melting has a distinct effect on morphology: smaller grains melt preferentially, while large grains get even larger as capillary water refreezes, and the grains become very well rounded (Fierz et al. 2009). At these high-elevation high-accumulation sites, melt events do not saturate the entire annual snowpack, leaving sections of cold, fine-grained snow between each summer layer (or layers, as additional snowfall during summer often separates melt layers that form in the same season). Liquid water from melt events pools on the colder snow below and re-freezes into layers of ice. Hence the previous summer surface can be identified by coarser layers of melt-freeze grains with finer grained snow above and below, and sometimes with ice layers below. In other words, subsequent summer surfaces are interpreted by the separation between layers of melt and refreeze by snow (often several meters thick) that remained dry through the summer melt season. In a spring visit, coring to the prior summer surface allows measurement of winter mass balance, combining snow core-derived measurements of depth and density. In the fall, coring through any new snow on the surface, through the melt layers from this summer, and down to the melt layers from the previous summer allows measurement of annual mass balance, including melt, refreeze, and any snowfall that may have occurred mid-summer at these high elevations. In contrast to lower zones, it is common for summer balance to be positive at these sites—meaning annual balance is greater than winter balance.

Results

Measured mass balances on the two glaciers vary both annually and spatially, primarily due to the more than 13,000 foot (4,000 m) elevation spans on both Kahiltna and Kennicott Glaciers. Mass balances during 2015-2024 are displayed on profile plots in Figure 5 and are available in a data release (U.S. Geological Survey Glacier Project 2016). In the figure, the area of glacier within each elevation band is displayed in the background. The mass balance values are plotted at their associated elevations, illustrating the range of measured balances over the elevation ranges of the glaciers. The lowest site with mass balance measurements on Kahiltna Glacier is 3,615 feet (1,102 m), and the highest is 14,262 feet (4,347 m). On Kennicott Glacier, the lowest site with mass balance measurement is 2,651 feet (808 m) and the highest is 8,596 feet (2,620 m). By convention, mass balances are normalized by both area and density and are expressed in specific units of water equivalent (i.e., feet of water equivalent, or m w.e.); hence, the values are equivalent to the thickness of a layer of water. The uncertainties in point measurements of mass balance are poorly constrained and evaluated primarily on the basis of expert opinion (U.S. Geological Survey Glacier Project 2016). Some authors have suggested ±0.10 m w.e. (0.3 feet of water equivalent) for typical measurements of snow and ice ablation (e.g., Heinrichs et al. 1995, Beedle et al. 2014), which is small relative to the unmeasured spatial variability (e.g., Zeller et al. 2023) and does not impact the interpretations here. Measured annual balances range from a minimum of −11.8 feet of water equivalent (−3.6 m w.e.) to maximum of +16.7 feet of water equivalent (+5.1 m w.e.) on Kahiltna Glacier, and minimum of −20.9 feet of water equivalent (−6.4 m w.e.) to maximum of +16.8 feet of water equivalent (+5.1 m w.e.) on Kennicott Glacier. On both glaciers, the negative numbers come from low-elevation sites where there can be a large net loss of ice with summer melting.

On both glaciers, the range of accumulation zone processes varies with elevation in a similar manner. Extrapolating between measurement sites, the annual mass balances are equal to 0 (i.e., the ELA) on both glaciers between 5,900 and 6,230 feet (1,800-1,900 m). Summer mass balances on both glaciers are positive at or above 8,500 feet (2,600 m), meaning that melt refreezes within the snowpack and more snow continues to accumulate even during the summer (Figure 5). In other words, 8,500 feet (2,600 m) is the approximate base of the percolation zone: below that elevation, runoff is generated from melt (Figures 1 and 5; vertical dashed lines). The percolation zone sites have the largest annual balances. On Kahiltna Glacier at 10,023 feet (3,055 m), annual balances range from +7.4 to +16.7 feet of water equivalent (+2.3-5.1 m w.e.), and on Kennicott Glacier at 8,596 feet (2,620 m), annual balances range from +13.1 to +16.8 feet of water equivalent (+4.0-5.1 m w.e.). On Kahiltna Glacier at 14,262 feet (4,347 m), the annual mass balance rates decreased, and the winter balances were smaller than the summer balances, recording a temperature-related decrease in winter precipitation at extremely high elevations.

Filling Knowledge Gaps

The high accumulation rates in the percolation zone are large contributors to the ice flowing through Kahiltna and Kennicott Glaciers; however, these high-accumulation low-melt areas are not well measured in Alaska

Emily Baker (USGS) sampling a snow-pit on Kahiltna Glacier at 10,023 feet (3,055 m) on September 30, 2024.
USGS/LOUIS SASS

or elsewhere. In 2023, more than 1000 mass balance point measurements were submitted to the World Glacier Monitoring Service (WGMS), yet only 250 were from the accumulation zone, and just four of those (0.4%) were taken more than 500 feet (150 meters) above the local equilibrium line altitude (ELA). Several of the observations on Kahiltna and Kennicott Glaciers help to fill this data gap (Figure 5). At lower elevations in the wet-snow zone, glacier mass balance is limited by temperature as melt (and rain) run off the glacier and limit the retention of precipitation. As the elevation increases, temperatures and melt both decrease while precipitation typically increases. The transition to the percolation zone is defined by the upper limit of runoff, where any melt that occurs refreezes locally, and glacier mass balance is limited directly by precipitation. At the highest elevations in the dry-snow zone, there is no melt at all, but there is typically less precipitation, so the accumulation rates are lower than the percolation zone. At the transition between wet-snow and percolation zones, the process can be sensitive to precipitation amounts: dry snow acts as a sponge and a thermal sink, so more accumulation refreezes a larger quantity of melt, and less accumulation may result in runoff (Pfeffer et al. 1991). Hence, observations through the wet-snow to percolation zone transition quantify the relationship between mass-balance, precipitation, and temperature, a critical balance where changes in precipitation and temperature could have competing effects. These observations on Kahiltna and Kennicott Glaciers offer insights into the physical processes on these and other large glaciers and can provide calibration and validation for both remote sensing and modeling.

Almost all prior research on the percolation zone has been in Greenland, where Benson (1962) defined and pointed out the importance of the zone to the overall mass balance of the Greenland Ice Sheet. Recent research in Greenland has shown that the percolation zone can either attenuate or exacerbate mass losses due to anomalous melt seasons. The percolation zone can attenuate mass losses by storing large amounts of water in persistent aquifers within the firn (Miller et al. 2020, Montgomery et al. 2017, Horlings et al. 2022), but refreezing of those aquifers into ice slabs makes the surface more prone to runoff in subsequent melt seasons (Machguth et al. 2016, Jullien et al. 2023). The associated changes in density increase the variability in the firn air content, limiting the utility of surface elevations for tracking mass changes (Vandecrux et al. 2019).

The extensive relief and very rugged topography of the Alaska region result in extensive crevassing and higher and more variable accumulation rates compared to the Greenland Ice Sheet. This limits the transferability of mass balance process understanding between the two. Any aquifer and ice-slab formation in Alaska will have limited spatial extents, due to the flow pathways provided by crevasses. Similarly, the competing relationship between accumulation rates (precipitation) and melt (or temperature) will be different in the Alaska region: Kahiltna and Kennicott Glaciers both have mass balance sites where the average is more than +10 feet of water equivalent (+3 m w.e.) accumulation per year, whereas almost the entirety of the Greenland Ice Sheet has accumulation rates less than +4 feet of water equivalent (+1.2 meters) per year (Montgomery et al. 2020).

The rugged topography and high relief that give rise to exceedingly steep gradients in accumulation with respect to elevation across the Alaska region also result in high spatial variability of accumulation (McGrath et al. 2015). Consequently, the location of the wet-snow to percolation zone transition varies spatially based on accumulation rates. Non-elevation dependent variability of accumulation rates and ELAs in the Alaska region have been previously documented as fundamental components of the mass balance processes on individual glaciers (e.g., McGrath et al. 2017) and regionally (Zeller et al. 2025). An example of this non-elevation dependent spatial variability in the measurements presented here are from Kahiltna Glacier at 8,655 feet (2,638 m) and Kennicott Glacier at 8,596 feet (2,620 m) in 2024. For Kahiltna Glacier at 8,655 feet (2,638 m), the winter balance was +3.4 feet of water equivalent (+1.1 m w.e.) and the summer balance was negative. In autumn, +3.2 feet of water equivalent (+1.0 m w.e.) of snow remained but was wetted out, suggesting liquid water likely drained out of the snowpack. In contrast, for Kennicott Glacier at 8,596 feet (2,620 m), the fall core showed an annual balance of +13.1 feet of water equivalent (+4.0 m w.e.), and the stratigraphy preserved meters of fine-grained dry snow with no evidence of water percolation below the summer sun-crusts. Kahiltna Glacier at 8,655 feet (2,638 m) is in a precipitation shadow with ~13,000-foot (4,000 m) ridgelines in both southerly and easterly directions (Figure 3, easternmost site on Kahiltna Glacier). This area receives less precipitation than sites on the main trunk of the glacier, which reduces the

This is a 52.5-foot (16 m) core from Kahiltna Glacier at 10,023 feet (3,055 m), May 26, 2023. Kakiko Ramos-Leon (NPS, on the left) is standing where the core intersected the surface. Eric Ridington (pilot, in the middle) is pointing to the melt layers from summer 2022. The melt layers barely visible in the foreground are from summer 2021.
USGS/LOUIS SASS

capacity to hold and re-freeze melt, resulting in runoff. Despite almost identical elevations, the Kennicott Glacier site with a deeper snowpack is in the percolation zone, while the Kahiltna Glacier site with a shallower snowpack is in the wet-snow zone. Given the overall similarity of the balance profiles between the two glaciers it seems likely that similar elevations at other locations on Kahiltna Glacier are in the percolation zone. The wet-snow zone result at this site illustrates how areas of low accumulation may influence the wet-snow to percolation zone transition.

Deep firn and ice cores collected for climate records, while not part of the USGS/NPS monitoring project described here, provide a baseline for comparison of prior conditions with current observations. Cores collected in the Alaska region from above 13,120 feet (4,000 m) all show evidence of either very limited or no melt, and of modest accumulation rates of +3.3 to +4.6 feet of water equivalent (+1.0-1.4 m w.e.; Mount Wrangell-Yasunari et al. 2007, King Col-Fisher et al. 2006, Bona-Churchill ice divide-Porter et al. 2019). Cores from 9,300 to 12,800 feet (2,830-3,900 m) are interpreted as percolation zone with evidence of more melt but no evidence of melt exiting the system as runoff, and higher accumulation rates of +4.6 to +6.6 feet of water equivalent (+1.4-2.0 m w.e.) per year (Aurora Peak-Tsushima et al. 2015, Eclipse site in Canada-Yalcin et al. 2007, Mount Hunter-Winski et al. 2017). In contrast, a scouting mission for ice cores on the Yentna Glacier at 8,700 feet (2,650 m) estimated the accumulation rate at +5.2 feet of water equivalent (+1.6 m w.e.) per year and found evidence of significant water movement through the firn and possible runoff, suggesting that site may be below the wet-snow percolation zone transition (Campbell et al. 2012). Of all those sites, only the Eclipse site in Canada has been revisited, and those repeat measurements showed more melt and warmer firn temperatures (Kindstedt et al. 2025).

Year-to-year variations in processes within the accumulation area are challenging to quantify in part because the transition from the wet-snow zone to percolation zone and the upper limit of runoff is defined by the processes at the base of the snowpack rather than the surface. This makes it particularly difficult to quantify without digging or coring through the full depth of the seasonal snowpack. The site on Kennicott Glacier at 7,228 feet (2,203 m) had +0.0 feet of water equivalent summer mass balances in both 2020 and 2021, although in other years it has had negative summer mass balances (as low as −4.0 feet of water equivalent or −1.2 m w.e.). In other words, a single measurement at this site in 2020 or 2021 might have concluded that this site is at the transition to the percolation zone, but the full time series of measurements shows that it is in the upper elevations of the wet-snow zone and usually produces runoff. Many other important characteristics about glaciers, such as terminus position, ELA, surface elevations, and even the extent of surface melt can all be observed through remote sensing, but direct measurements of glacier mass balance are currently the only way to quantify the transition to the percolation zone.

Characterizing the glacier mass balance processes as they occur in the high accumulation and complicated topography of Kahiltna and Kennicott Glaciers provides a baseline to understand these and other large glaciers in the Alaska region and can be used to constrain future projections. The global distribution of glacier mass balance measurements is heavily skewed toward ablation zone processes, and those few measurements made in the accumulation zone are almost entirely made in the wet-snow zone where large amounts of melt and liquid water run off the glacier each year. Furthermore, we know that the high-elevation percolation zones of today's glaciers will be among the last remaining glaciated areas in Alaska after many decades of persistent glacier retreat—further amplifying the utility of monitoring their changes over time. Understanding the full range of processes on these large glaciers is critical for understanding how these and other glaciers in the Alaska region will respond in the future.

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Monitoring for the Future of Central Alaska Streams

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Streams are good indicators of change and the health of watersheds. By monitoring stream chemical composition and the kinds of life they support, we can learn about how they are being stressed (by activities such as mining or climate change) or recovering from a stress (after restoration efforts). But Central Alaska watersheds and the natural stream conditions they produce are diverse. From long-term monitoring, and repeat measurements, we can start to understand the related baselines and fine-tune our understanding of changes.

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The National Park Service's Central Alaska Network includes Denali National Park and Preserve, Wrangell-St. Elias National Park and Preserve, and Yukon-Charley Rivers National Preserve—nearly 22 million acres stretching from coastal rainforest to interior boreal forest. Streams within these parks and preserves are chemically and biologically diverse, reflecting the topography and hydrology of watersheds shaped by glaciers, permafrost, and wetlands (Figure 1).

These watersheds are changing rapidly:

- Shifts in the timing and amount of precipitation over the past half-century have altered many stream flow regimes and are projected to increase the frequency of flooding (Crossman et al. 2013, Bennett et al. 2015).
- Shallow permafrost underlaid nearly 50% of Denali and Wrangell-St. Elias national parks and preserves at the beginning of this century, but is projected to cover 30% of Wrangell-St. Elias and only 6% of Denali by 2050 (Panda 2017).
- Repeat photography over the last few decades has revealed changes in vegetation, shrinking ponds, and receding glaciers in Denali (Roland and Stehn 2013).
- Thawing permafrost and warmer temperatures more broadly have enabled invasions of woody vegetation like alder into formerly treeless areas such as tundra, wetlands, and unvegetated floodplains (Panda et al. 2014, Brodie et al. 2019, Frost et al. 2023).

More direct human impacts are also occurring. Although roads and trails exist at very low densities by Lower-48 standards, they still influence watersheds and their streams within parks:

- Gravel extraction for road maintenance, bridges, and off-road vehicle trails may alter both up- and downstream hydrology and morphology (Arp and Simmons 2012, Richards 2016).
- On roads, dust suppression applications such as calcium chloride sprays ($CaCl_2$) could elevate salt concentrations in some watersheds (Stehn and Roland 2018).
- Culverts, which are necessary when roads cross small streams, may impede the movement of salmon and other fishes if not properly maintained or installed (Davis and Davis 2011).

"McKinley Bar Trail creek" is a small, otherwise unnamed stream flowing through wetlands near Wonder Lake in Denali. This is one example of the diverse stream sites we monitor.
NPS PHOTO

Figure 1. Selected photos of sampling sites illustrating the diversity of characteristics.

(A) East Fork Toklat River is a large, braided glacial river on the north side of the Alaska Range in Denali National Park and Preserve.
(B) Alder Creek is a large, glacially influenced stream on the south side of the Alaska Range in Denali; site elevation is 1,608 feet (490 m).
(C) Beaver Creek is a small, high-elevation lake outlet stream in the Nutzotin Mountains in Wrangell-St. Elias National Park and Preserve; site elevation is 4,495 feet (1,370 m).
(D) The Nadina River is a moderately sized glacial river on the west side of the Wrangell Mountains in Wrangell-St. Elias; site elevation is 2,690 feet (820 m).
(E) "Seventymile tributary" is an otherwise unnamed headwater stream in the White Mountains in Yukon-Charley Rivers National Preserve; site elevation is 4,000 feet (1,220 m).
NPS PHOTOS

- Even seemingly innocuous activities have far-reaching implications; for instance, fecal microorganisms from climbers in Denali National Park and Preserve can be detected far downstream of glaciers (Goodwin et al. 2012, Loso and Chenoweth 2025).

An additional direct human impact is mining, which has a long history across Alaska. Much of this activity, both historically and today, is placer mining, in which stream beds and adjacent ground are excavated to access gold-bearing gravels underneath. Placer mining reduces habitat complexity, replacing winding vegetation-lined streams of alternating riffles and pools with straightened, channelized, homogenous flow channels that have exposed, rocky banks (Madison 1981, Weber and Post 1985, Gilvear et al. 1995, Wohl 2015). Upstream mining activities can deposit fine sediments that clog the space between stream gravels, reduce algal production at the base of food webs through scouring and light reduction, and carry potentially toxic heavy metals (LaPerriere and Reynolds 1997). Antimony lode mining in Denali's Kantishna Hills likely reduced downstream periphyton (algae) biomass and the abundance of macroinvertebrates (stream insects and their relatives; Brown 1987, Wedemeyer 1987). Although many older mines are now inactive, stream morphology, riparian vegetation, and invertebrate communities can take decades to recover, especially if mine tailings are left in active floodplains where they continue affect stream chemistry and sediment loads (Weber and Post 1985, Gilvear et al. 1995, Milner and Piorkowski 2004).

Stream Monitoring in the Central Alaska Network

The National Park Service has been consistently monitoring streams in Central Alaska parks for water quality and benthic macroinvertebrate communities for almost two decades (Figure 2, Simmons 2017). Macroinvertebrate communities are a critical food base for juvenile salmon and other fish and also are well-known indicators of water quality because they respond to changing water chemistry, sediment loads, and temperature and flow regimes (Simmons et al. 2021). Sampling occurs primarily in June, July, and August, when streams are at summer base flows after the seasonal snowmelt peaks. In addition to on-site measurements of dissolved oxygen, pH, and specific conductance (related to salts and other compounds in the water), water samples are collected and preserved for later laboratory analyses. A contracted laboratory quantifies many analytes from these samples, such as different organic and inorganic forms of nitrogen and phosphorus, dissolved forms of organic carbon, and multiple cations that indicate watershed soil and rock weathering patterns. Macroinvertebrates are collected by systematically disturbing targeted streambed habitat using fine nets to capture them (Simmons et al. 2021). Once collected, they are preserved, identified (usually to genus level), and counted, allowing densities of each group to be estimated at the stream site based on the stream area sampled.

Monitoring can establish baseline conditions for changing watersheds and aquatic resources. Here, a baseline refers to the current spatial, watershed-driven patterns in natural variation in water chemistry and invertebrate community composition, particularly where there is no or little direct human impact. Setting baselines is a critical outcome of ecological monitoring and is needed now more than ever at high latitudes: opportunities for understanding current and past conditions as frames of reference are dwindling as the climate rapidly warms (Culp et al. 2022).

In Central Alaska parks, we monitor sites that span the diversity of permanently flowing, wadable streams. The sites extend from near sea level to nearly 5,000 feet (1,500 m) in elevation, and cover the dominant landcover types from forested streams at lower elevations to shrubby or tundra-dominated watersheds at higher elevations. The streams encompass wide ranges of permafrost extent, glacial influence, and wetland extent. Water chemistry and benthic invertebrates are partially controlled by watershed characteristics, so understanding how streams might be responding to factors such as climate change requires understanding how their watershed characteristics, water chemistry, and macroinvertebrate are currently related to each other. We measure water chemistry and macroinvertebrates in the field, and quantify other watershed variables (e.g., elevation, slope, woody vegetation coverage) using satellite imagery (Simmons 2017).

Additionally, many streams in the Central Alaska Network are regularly resampled. Some have been sampled for macroinvertebrates and water chemistry more than 10 times over the past 18 years, creating an important dataset to detect change across multiple kinds of watersheds. Natural systems exhibit year-to-year variability, but frequent monitoring yields better certainty about whether and where directional ecosystem change is occurring. For

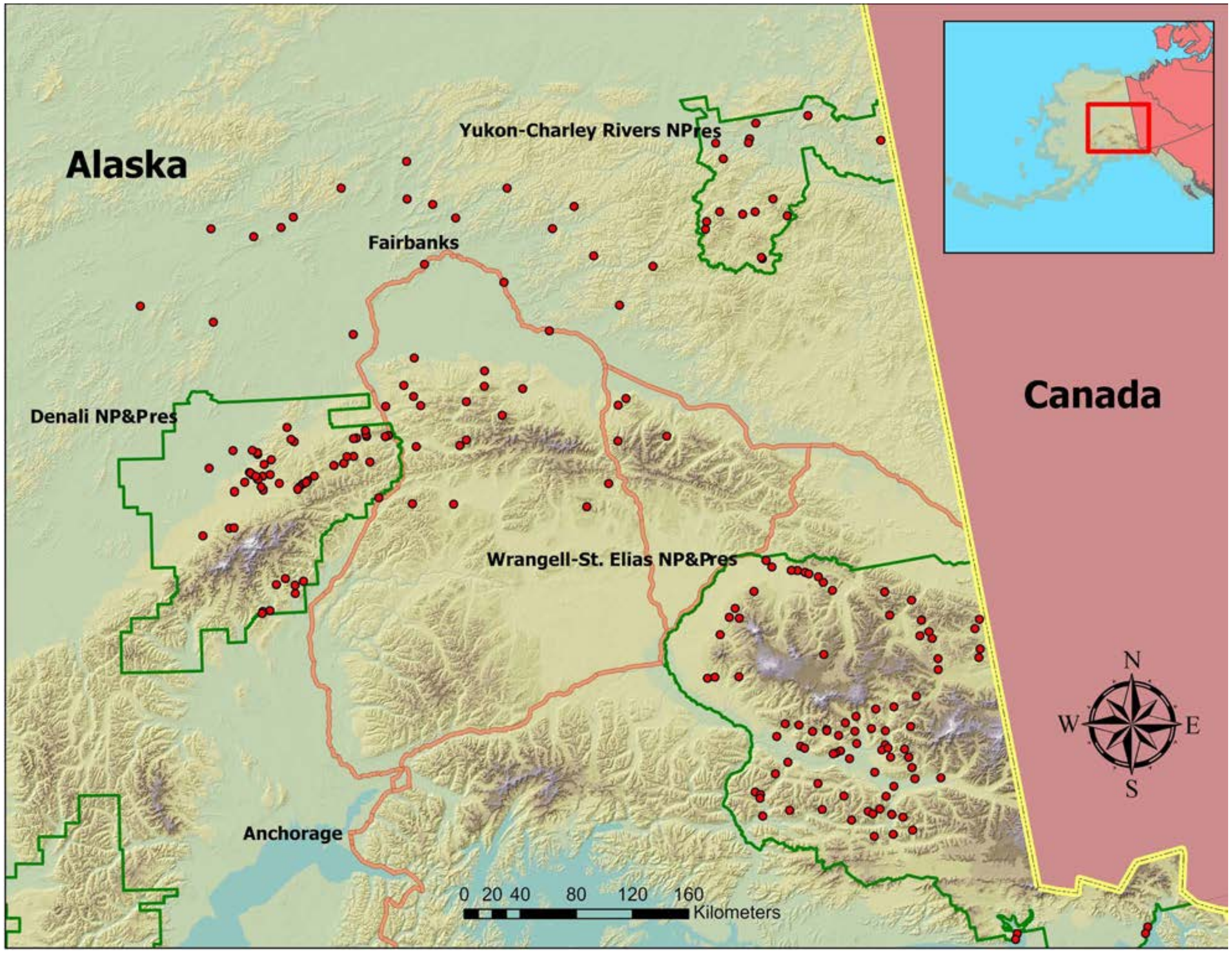

Figure 2. Map of sites (red dots) monitored for benthic macroinvertebrates within and near the Central Alaska Network. These sites comprise Denali National Park and Preserve (NP&Pres), Yukon-Charley Rivers National Preserve (NPres), and Wrangell-St. Elias (NP&Pres; park boundaries as green lines, highways as orange lines). Water chemistry is measured at a subset of these sites primarily within park boundaries.

example, sampling multiple times over wet and dry years, an important factor determining how the stream water reflects its watershed, could yield longer-term trends that are otherwise masked by the Pacific Decadal Oscillation, associated El Niño events, and other year-to-year climatic variations.

Trends from Monitoring Data

Data records from 16 of the stream sites, located in two of the parks (Denali National Park and Preserve and Wrangell-St. Elias National Park and Preserve), contain a sufficiently long record of high-quality continuous temperature data that they can be assessed using non-parametric trend analysis (Simmons and Sendek in prep). Statistically significant trends in annual temperatures were identified for 4 of the 16 streams, with trends in seasonal temperatures (May to October) for 4 other streams. This analysis also revealed significant trends in at least one month for 15 of the 16 sites. Half of the sites (8 of 16) showed an increase in at least one temperature parameter of over 0.1°C per year (1°C, or 1.8°F, per decade) and almost half of the sites (7 of 16) showed an increase in temperature in at least 3 months over the duration of the data record.

Using a combination of standard taxonomic techniques that rely on morphological characteristics, along with DNA sequence analysis, we have identified 239 unique taxa in samples of macroinvertebrate communities in the streams, nearly all of which we have been able to identify to the genus or species level. Because most aquatic macroinvertebrates are collected at the larval stage, identification to species can be challenging using only morphological characteristics. Accordingly, our collaboration with the Canadian Centre for DNA Barcoding in sequencing DNA from hundreds of specimens has been vital in expanding the number that we are able to identify to species. Another result of this DNA sequencing work has been the documentation of 28 insect species that had not been previously reported in Alaska, including 21 species that are new records for the United

States, and 7 that are new records for North America (Webb et al. 2022).

To assess how mining history has affected streams, we developed a multimetric index (MMI) in collaboration with the U.S. Bureau of Land Management National Aquatic Monitoring Center, using macroinvertebrate data from 200 Central Alaska streams as well as additional data from streams across the region collected by other organizations. An MMI can be used to assess the condition of streams by combining various metrics that describe the macroinvertebrate community (e.g., predator abundance) that differ between relatively pristine "reference" streams and streams that have been disturbed by human activity (Schoolmaster et al. 2012). The resulting Alaskan Interior MMI, which relied on five invertebrate metrics (dominant taxon abundance, non-insect abundance, the number of collector-filterer taxa, collector-filterer abundance, and the number of shredder taxa) was successful in separating reference streams from disturbed streams ($p<0.001$). We used this MMI to evaluate the degree to which mined sites in and near the parks differed from the distribution of reference sites, which provides a surrogate measure of the severity of the ecosystem impact.

Restoration Planning

The water quality and macroinvertebrate data can be particularly useful in addressing not only the impacts of disturbance such as mining, but also in assessing ecosystem recovery after a disturbance. The Alaskan Interior MMI has been incorporated into the Alaskan Interior Stream Quantification Tool (Alaska Stream Quantification Tool Steering Committee 2021a, 2021b). This tool can be used to assess overall stream function in the context of stream restoration and provides a repeatable method for quantifying the degree to which stream restoration projects succeed.

A good example that pulls all these data uses together is Coal Creek in Yukon-Charley Rivers National Preserve (Figure 3). Coal Creek was heavily mined throughout much of the 20th century and is the target of an ongoing stream restoration effort. Applying the MMI to Coal Creek shows that it is well outside the distribution of reference sites, suggesting that the ecosystem is significantly disturbed (Figure 4). If stream restoration takes place in future years, the MMI will be useful in tracking stream recovery post-restoration. In addition, by using these data along with new food web and stream habitat assessments carried out as part of a graduate thesis at the University of Alaska Fairbanks, we are exploring the extent to which Coal Creek may support growth for juvenile chinook salmon (*Oncorhynchus tshawytscha*). Yukon River chinook salmon have undergone a recent population crash (Schoen et al. 2023), resulting in a moratorium on fishing throughout the river basin. We are comparing Coal Creek to nearby, less-disturbed streams in Yukon-Charley Rivers National Preserve to understand how stream restoration, if implemented, may improve growth conditions for juvenile fish through changes in stream temperature, refuge habitat, and food availability. If stream restoration provides more favorable bioenergetic conditions for juvenile chinook salmon entering Coal Creek, this may improve their condition for their long journey to the Bering Sea.

Figure 3. Aerial view of Coal Creek, in Yukon-Charley Rivers National Preserve. The photo shows the extensive mine tailings in the active corridor of the creek, which is proposed as a site of stream restoration.

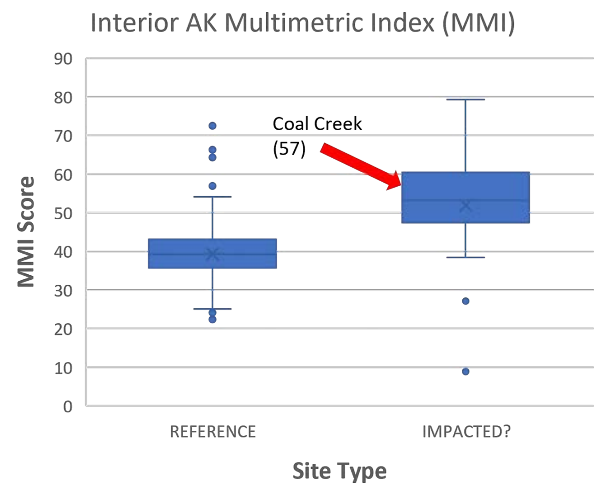

Figure 4. Multimetric index (MMI) results based on Central Alaska Network macroinvertebrate sampling across relatively pristine reference sites and other potentially impacted or degraded sites. The high MMI score recorded for Coal Creek demonstrates that it is divergent from reference sites and therefore likely to be significantly degraded.

Forecasting Future Conditions

Through a collaboration between the U.S. Geological Survey (USGS), National Park Service, and the University of Alaska Fairbanks, we have also been exploring the rich Central Alaska Network monitoring dataset through the lens of ecological forecasting. Ultimately, these data provide opportunities to model patterns and changes in stream variables as a function of measured watershed variables and time. If we can relate patterns in stream water chemistry, for example, to the types of land cover in a watershed (e.g., wetlands, permafrost coverage), we may be able to predict how water chemistry will change as temperatures rise, permafrost thaws, wetlands dry, and woody vegetation moves upslope. For example, elevation correlates strongly with total dissolved nitrogen (TDN; Figure 5; Robbins et al. in prep(a)). We may similarly tie whole macroinvertebrate communities to the changing landscape via statistical methods.

Elevation is also correlated with the number of macroinvertebrate taxa observed (richness) at a site (Figure 6; Robbins et al. in prep(b)). Newer methods such as joint species distribution models and artificial intelligence (machine learning) enable modeling of how each species responds to environmental factors such as watershed cover, and also capture how community members respond collectively to changing environments (Olden et al. 2006, Harris 2015, Niku et al. 2019). This will allow us to predict the composition of entire communities rather than just the abundance of individual species, based on a set of watershed characteristics.

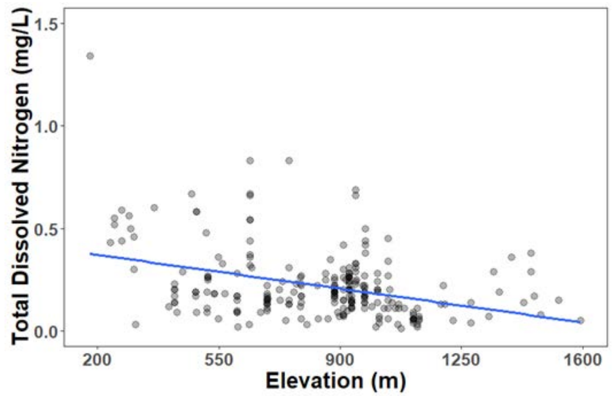

Figure 5. Total dissolved nitrogen (mg/L) measured in Central Alaska stream water plotted against the site's elevation. Blue line is the predicted fit from a simple linear regression.

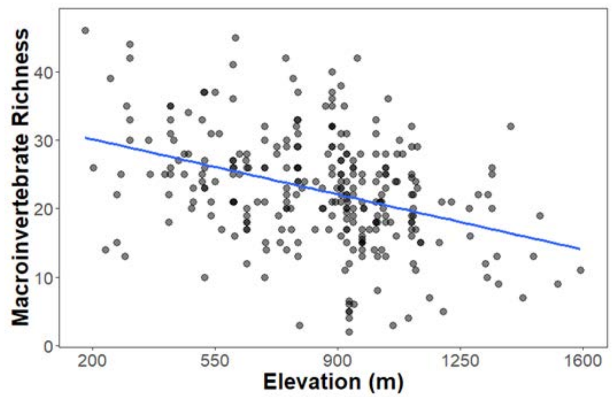

Figure 6. Macroinvertebrate richness (number of taxa found during a site visit) for Central Alaska sites plotted against the site's elevation. Blue line is the predicted fit from a simple linear regression.

These models of watershed water quality and macroinvertebrate communities can help project future expectations and priorities for monitoring and stream assessment. This is especially important because some streams are actively changing. We have observed TDN concentrations or richness up to doubling in some streams over the monitoring period (Figures 7 and 8; Robbins et al. in prep(a), in prep(b)). Given the inverse relationship between elevation and richness, we speculate that richness may be increasing in response to warming water temperatures. We can also use models as bioassessment tools to compare the observed invertebrate communities to an expected, model community based on the stream's watershed characteristics (Hawkins 2006, Vander Laan et al. 2013). If the observed community looks different than expected, it could indicate impairment, including from human impacts.

Shifted baselines occur when the future does not function like the past. In these cases, our statistical models, built on past patterns, can be inaccurate for predicting present patterns. However, by making comparisons between models and collected data, we have the opportunity to critically understand how and why we are wrong. This allows us to continually improve our understanding, models, and forecasts, reducing the guesswork in how current model results apply to the future (Dietze et al. 2018). This approach is critical to adapting expectations and management strategies in a rapidly changing world (Bodner et al. 2021).

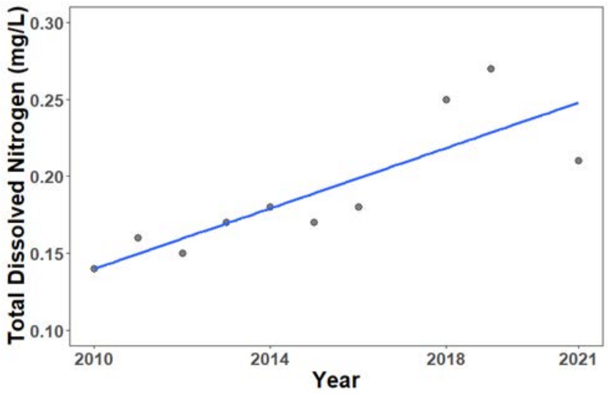

Figure 7. Total dissolved nitrogen (mg/L) measured in stream water at Moose Creek at Park Road bridge in Denali National Park. Blue line is the predicted fit from a simple linear regression.

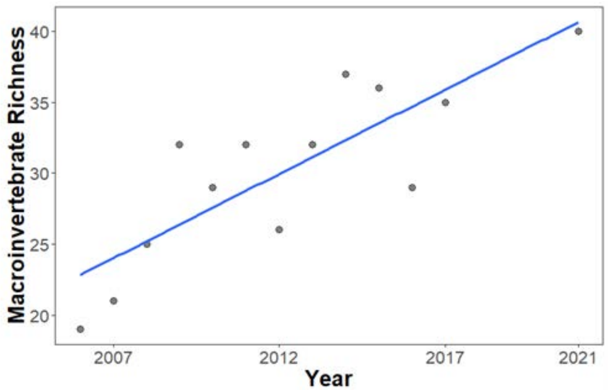

Figure 8. Macroinvertebrate richness (number of taxa found during a site visit) measured through time at Jack Creek at Nabesna Road bridge in Wrangell-St.Elias National Park. Blue line is the predicted fit from a simple linear regression.

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Understanding Flooding and Channel Dynamics Along the Taiya River: Providing Context for Resource Management

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Flooding and channel change in the Taiya River Basin in recent decades have directly affected park infrastructure and cultural resources. The complexities of flooding and channel change are compounded by the changing sediment and flow regime from a changing climate and shrinking glaciers, which will continue to drive dynamic riverine change. Streamflow data and geomorphic interpretation helped us place these events in context to inform decision making that takes dynamic natural processes into account.

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Curran, J. H. 2026. Understanding flooding and channel dynamics along the Taiya River: Providing context for resource management. Alaska Park Science 24 (1): 26-35.

Many coastal basins in southeast Alaska, where rainfall and glaciers abound, support dynamic riverine environments. Shrinking glaciers (Rounce et al. 2023, Hugonnet et al. 2021) and changing precipitation amounts, type (rain or snow), and timing associated with changing climate conditions (Thoman and McFarland 2024) also generate adjustments in riverine systems. As water and sediment supplies vary, rivers respond with changes to streamflow and channels. Streamflow can change in volume or seasonal timing, and channels can change patterns, erode banks, and fill or incise. This complicates efforts to manage a national park responsible for providing visitor access and preserving cultural and natural resources along an active river corridor.

Along the Taiya River near Skagway, Alaska, Klondike Gold Rush National Historical Park, Chilkoot National Historic Trail, and Dyea-Chilkoot National Historic Landmark (hereafter referred to as "the park") infrastructure, visitor safety, and cultural and natural resources can be affected by interwoven threats from flooding, channel movement, and bank erosion. Taken individually, striking flooding and episodes of channel change can be difficult to respond to in a meaningful way that aligns with the park's mission, which includes balancing protection of a dynamic natural environment and preserving static park resources. Park managers are confronted with decisions about siting new infrastructure, protecting, repairing, replacing, or relocating existing park resources, and protecting public safety that require balancing the likelihood of a damaging hydrologic event with the impacts to possible alternate locations that can also be ecologically or culturally sensitive. Similarly, park archeologists need to know where erosion might occur and how fast it could progress to guide priorities for excavation and documentation or relocation of artifacts. How can managers create resilient solutions in this case? Data and scientific interpretation can help place these events in context to inform decision making that takes dynamic natural processes into account.

In 2020, the U.S. Geological Survey (USGS) completed a study to provide an improved understanding of the formative geomorphic processes, hydrologic conditions, and hydrologically dependent resources in the lower 5 miles (7.5 km) of the Taiya River valley bottom (Curran 2020). Geomorphic processes are the processes that shape the land surface, including geologic, hydrologic, and biologic factors, and understanding formative geomorphic processes is an important starting point for understanding and managing potential future changes. In 2022, back-to-back floods from rainstorms in

In this photograph from August 2017, the banks of the Taiya River at the historical Dyea downtown area, an area rich with 1897-1898 gold rush archeological resources and other cultural sites, showed signs of erosion after more than a decade of stability. Since then, meander migration caused this bank to retreat several hundred feet (about 100 m) into the historical downtown area.
USGS/JANET CURRAN

late September and October swelled the Taiya River to the highest levels since 1967 (USGS 2025), eroding sections of the park's Chilkoot National Historic Trail, flooding a campground, and washing out critical trail bridges. To help the park respond to this and extensive erosion and channel change damaging park resources near the historic ghost town of Dyea and elsewhere along the Chilkoot Trail, the USGS began a supplement to the 2020 study to document new channel conditions, update flood frequency information, and provide a more basin-wide hydrologic context. This article summarizes some of the key elements of the 2020 USGS report (Curran 2020) and describes the post-report flooding, bank erosion, and data acquisitions to be considered in the new study.

A Dynamic Watershed in a Historic Setting

The Taiya River drains a 186-square-mile (481 km^2) basin at the end of a long fjord deep in the Coast Mountains of southeast Alaska. The Dyea and Chilkoot Trail National Historic Landmark and the Chilkoot Trail Unit of the park surround the Taiya River in a narrow strip from Taiya Inlet to Chilkoot Pass (Figure 1). Although the park is not typically perceived as a glacial park because its narrow footprint only contains a sliver of one glacier (Chambers et al. 2023), glaciers cover 29% of the Taiya River Basin and create the glacial character of the Taiya River and many side streams.

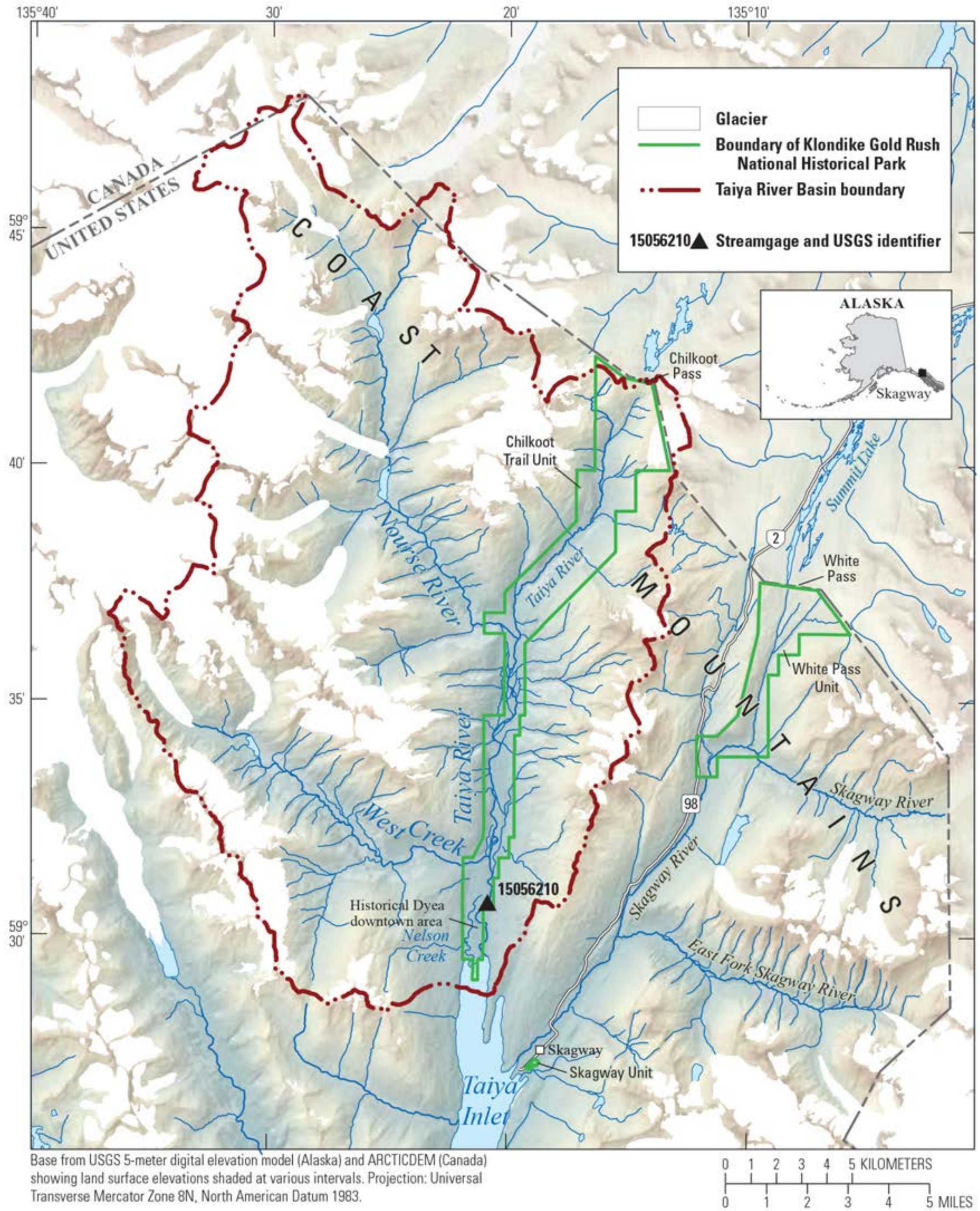

Figure 1. The Chilkoot Trail Unit of Klondike Gold Rush National Historical Park forms a narrow corridor around the Taiya River near Skagway in southeast Alaska. The Taiya River is fed by two large glacial tributary streams, West Creek and the Nourse River, and numerous smaller glacial and non-glacial tributaries, many of which cross the Chilkoot Trail. This figure is modified from Curran (2020).

The Taiya River main stem extends about 8 miles (14 km) from the tidal flats of Taiya Inlet to the confluence with the Nourse River, stretching along a low, narrow valley bottom less than 1 mile (1 km) wide. This sediment-filled valley bottom contains the most developed parts of the basin, including the Dyea area and the start of the Chilkoot Trail. Three major tributary valleys and numerous smaller, steep streams drain to the main-stem valley bottom. Of these, the Nourse River valley is the largest and most glacier-rich, forming the headwaters of the Taiya River Basin and dominating the tributary network. West Creek drains another substantial and glacier-rich tributary basin, joining the main stem just upstream of the Dyea area. The third and smallest tributary valley bears the Taiya River name and extends about 6 miles (10 km) upstream from the Nourse River confluence. The Chilkoot Trail continues up this valley, which contains scattered, smaller glaciers, to Chilkoot Pass. This low-elevation pass, used as a trade route by Alaska Natives (Thornton 2004) and later made famous as a route for Klondike gold rush miners in 1897–1898, also creates an ecologically important corridor linking coastal temperate rainforest ecosystems with interior boreal forest ecosystems in the Coast Mountains (Bernatz et al. 2011).

Founded in 1976 to preserve historic structures, trails, artifacts, and landscapes and stories associated with the Klondike Gold Rush, Klondike Gold Rush National Historical Park is charged with meeting the National Park Service mission to preserve unimpaired the natural and cultural resources and value for future generations. The park's planning documents identify the Taiya River, the surrounding landscape, and the dynamic environmental processes as both cultural and natural resources, and the Dyea and Chilkoot Trail National Historic Landmark designation further identifies the cultural and natural importance of the Taiya River to the park (NPS 2009). The Chilkoot Trail Unit of the park contains the historic Dyea townsite, a short-lived boom town where thousands of would-be gold rush miners acquired and staged supplies, the Chilkoot Trail, a cultural, historical, and recreational resource that parallels the Taiya River from Dyea to Chilkoot Pass, and numerous archeological sites.

Flooding and channel change active in the Taiya River Basin in recent decades have directly affected park infrastructure and cultural resources. In 2002, a moraine collapsed in the West Creek Basin, generating a glacial lake outburst flood on the Taiya River that forced an emergency evacuation of the Dyea campground and area residents (Capps 2004, Bernatz et al. 2011). At the historical Dyea downtown area, where bank erosion had been minimal for more than a decade, substantial new bank erosion claimed historical cemeteries and archeological sites along a 1,300-foot (400-m) length of bank between about 2017-2023 (Figure 2), and continued erosion left the river positioned to potentially cut through banks and inundate part of a long-abandoned channel known as Nelson Slough. This slough, which runs immediately adjacent to and through a portion of the historical Dyea downtown area, was a main-stem channel near the time of the gold rush but was cut off and currently supports wetlands, locally conveys minor streamflow, and traverses local access roads not necessarily designed to withstand main-stem amounts of streamflow. The late-fall, rain-generated 2022 floods washed away Chilkoot Trail bridges and sections of trail, flooded the Dyea campground, and accelerated erosion of the historical Dyea downtown area. The 2022 flooding also damaged private properties and structures and public roads and facilities within the park boundary. In 2021, a landslide-like release along a glacial side stream near Chilkoot Pass redirected the stream and damaged park infrastructure there. Additional potential slough capture and erosion hotspots in the lower valley bottom threaten park trail sections and bridges and cultural and historical resources. While the 2020 USGS report (Curran 2020) provides historical hydrologic and geomorphic context through about 2018, the new USGS data will consider channel change

Visitors view salmon gathered during spawning season in August 2017 near the confluence of Nelson Creek (left) and the abandoned Nelson Slough (right), now partly a wetland environment that supports western toad (*Anaxryus boreas*; sometimes referred to as boreal toad) breeding sites. The people in this photograph are not USGS employees.
USGS/JANET CURRAN

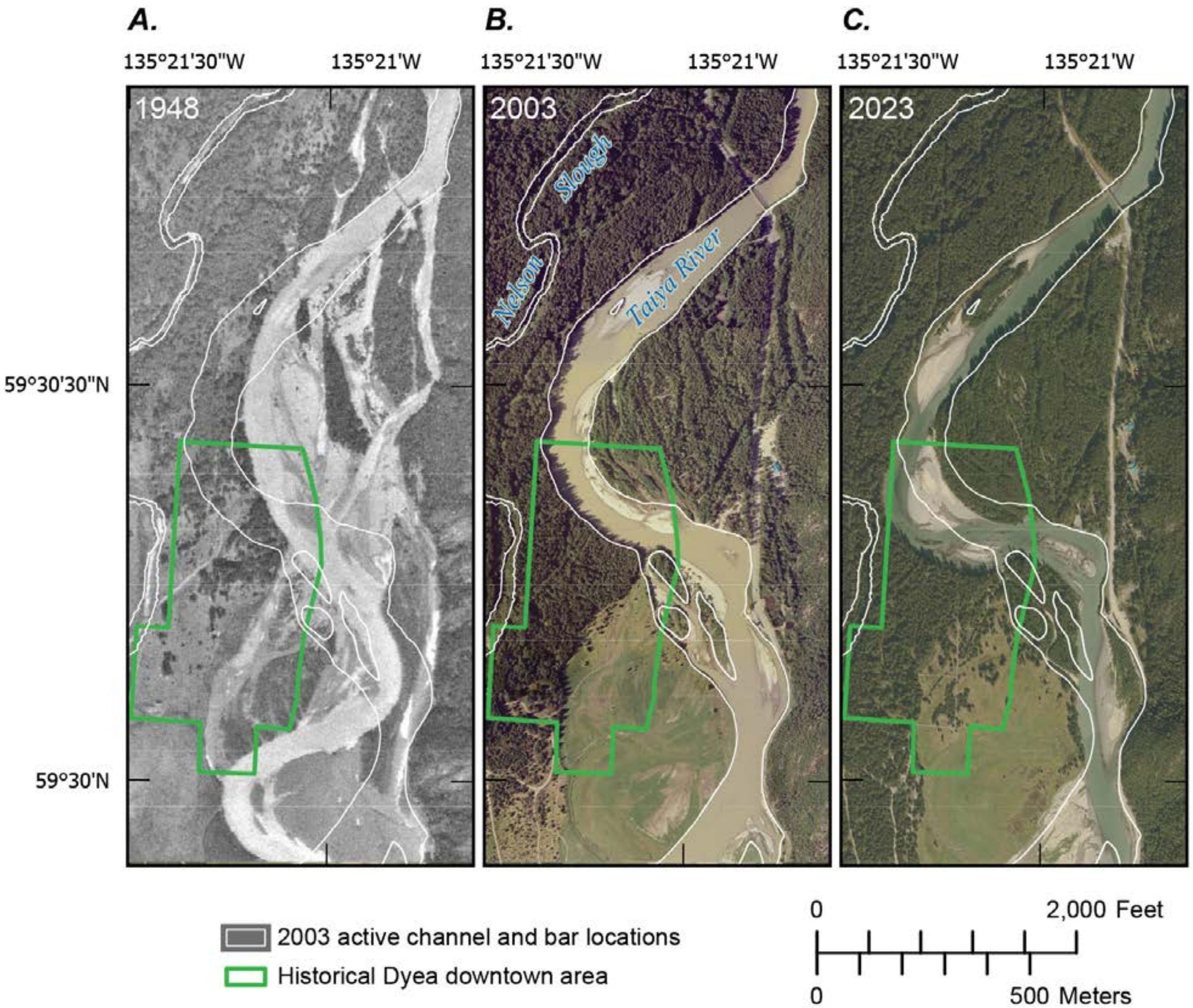

Figure 2. (A) Near the historical Dyea downtown area, channel scars visible in 1948 aerial imagery, the earliest widespread imagery available, illustrate pre-1948 complex channel change that eroded away part of the historical downtown area and reconfigured the path of the Taiya River. (B) Between 1948-2003, as much as 450 feet (140 m) of bank erosion then pushed a meander farther into the downtown area. (C) Although bank position measurements and isolated aerial images (not shown) showed that the meander position was relatively stable until about 2017, bank erosion between 2017-2023 cut up to another 300 feet (100 m) into the historical downtown area, pushing the channel to within 100 feet (30 m) of adjacent abandoned Nelson Slough, a parallel off-main-stem channel that runs through a part of the historical downtown. For reference, the 2003 channels and historical Dyea downtown boundary are shown in each image.
IMAGERY SOURCES: (A) NATIONAL PARK SERVICE (2004); (B) AEROMAP U.S. (2008); (C) DEWBERRY (2025).

through 2023 (the date of new aerial imagery) and flood information through 2025.

Documenting and Understanding Formative Processes of a River Valley

The 2020 USGS study (Curran 2020) used streamflow data through 2017; 2003 lidar data (laser-derived, high-resolution elevation data); bank surveys by the National Park Service from 1979-2017; historical aerial imagery from 1948, 2003, 2014, 2017, and 2018; and historical photos from 1894 (before the gold rush) to detail active and historical channels and describe major valley bottom features and changes since the Klondike Gold Rush (Figure 3). The Taiya River valley bottom owes its general form to ancient faulting that set valley orientation and Pleistocene (Ice Age) glacier occupation and retreat. Riverine processes, including glacial lake outburst floods, have reworked the glacial outwash filling the valley bottom since then. Notably high rates of isostatic rebound from glacier retreat (Larsen et al. 2005, Bernatz et al. 2011) have generated nearly 6 feet (2 m) of uplift since the gold rush, and emergent tidal flats have extended the river mouth more than 1,600 feet (500 m) coastward from Dyea, the gold rush-era high tide line. Modern valley bottom processes are a dynamic mix of glacially controlled delivery of water and sediment, river movement and transport of sediment, and uplift, which can generate river incision and extension near the river mouth. The Taiya River is currently mostly contained in a single main channel with mid-channel bars and a few sloughs (long channels separated from the main part of the river). However, in the gold rush era, the river sustained multiple paths and long, large sloughs, including the prominent West Branch Taiya River, now the abandoned Nelson Slough.

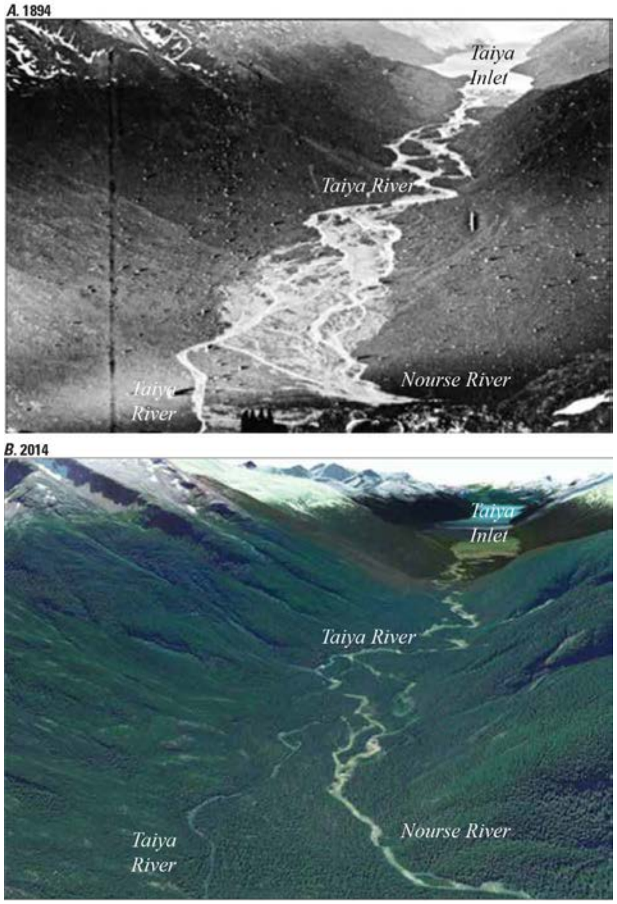

Figure 3. The downstream views in (A) a photo from just before the gold rush (McArthur 1894) and (B) 2014 aerial imagery (base image from Google, copyright 2018) show channel changes along the main-stem Taiya River. Although many of the 2014 channels are in the same approximate location as they were in 1894, there are fewer channels in 2014 and most are narrower. The poor quality of the 1894 photo produced artifacts that appear as small bumps and shadows and makes the side slopes erroneously appear deforested. This figure is reproduced from Curran (2020).

Coupling repeat imagery with detailed information from lidar elevation data created an effective method for visualizing the river's history, which forms a first-order assessment of likely future conditions, and identifying critical locations including recent bank erosion and habitat features (Curran 2020). When processed to show the land elevation relative to the river surface, lidar reveals active and abandoned channel forms (Figure 4A). A geomorphic map created using the imagery and lidar data showed where the Taiya River was active in 2003 and where it had abandoned channels, both before and after the 1940s (Curran 2020, Figure 4B). It also showed where erosion occurred between 2003 and 2018 (mostly related to an episode of more rapid erosion that began in 2017), creating small new areas of active main-stem channel. The mapping exercise also identified the locations of off-main-stem channels consisting of abandoned valley bottom main-stem channels and a few small tributary streams (Curran 2020). These features form important habitats for fish and wetland breeding sites for the western toad, an ecologically important sentinel species (ADFG 2015).

The geomorphic map (Figure 4B) and photographs from 1894 (Figure 3) showed that although the channel has progressively narrowed and stabilized since the gold rush, channel migration eroded away about one-third of the historical Dyea downtown area by 1948, and several complex channel changes between the 1940s and 2003 fundamentally altered the course of the river nearby. Between 2003 and the last date of imagery used (2018), channel change was limited to smaller amounts of local channel migration (mostly beginning in 2017) that nonetheless caused damage to park cultural resources. The new USGS study is updating this history using new lidar elevation data and aerial imagery from 2023, along with repeat bank surveys by the National Park Service, which show more substantial channel migration and modification of slough entrances but still no comprehensive channel relocation (Figure 2). Importantly, these studies show that bank erosion along the lower part of the Taiya River has been episodic, with periods of stability followed by swift bank retreat. Recent measurements by the park show that a series of large floods like those in September–October 2022 or a single season of active erosion can generate tens to hundreds of feet (tens of meters) of erosion, and historical imagery shows that banks can be stable for several decades.

This more-than-100-year historical geomorphic perspective, synthesized from multiple lines of evidence, demonstrates that the primary concern along most of the Taiya River main stem is likely localized, episodic bank erosion, and that there is little likelihood of consistent annual reworking of channels as might occur in a braided river. However, localized channel change has been substantial and has often persisted over multiple years, and this pattern is likely to continue. Where bank erosion since the 2020 study has advanced so far that the mainstem channel has the potential to break through and capture smaller sloughs, the historical context for episodic, complex channel change helps managers prepare nearby and downstream bridges, trails, and cultural and ecological sites for impacts from large increases in streamflow in smaller channels and new bank erosion hotspots, along with potential abandonment or decreased streamflow in existing mainstem channels.

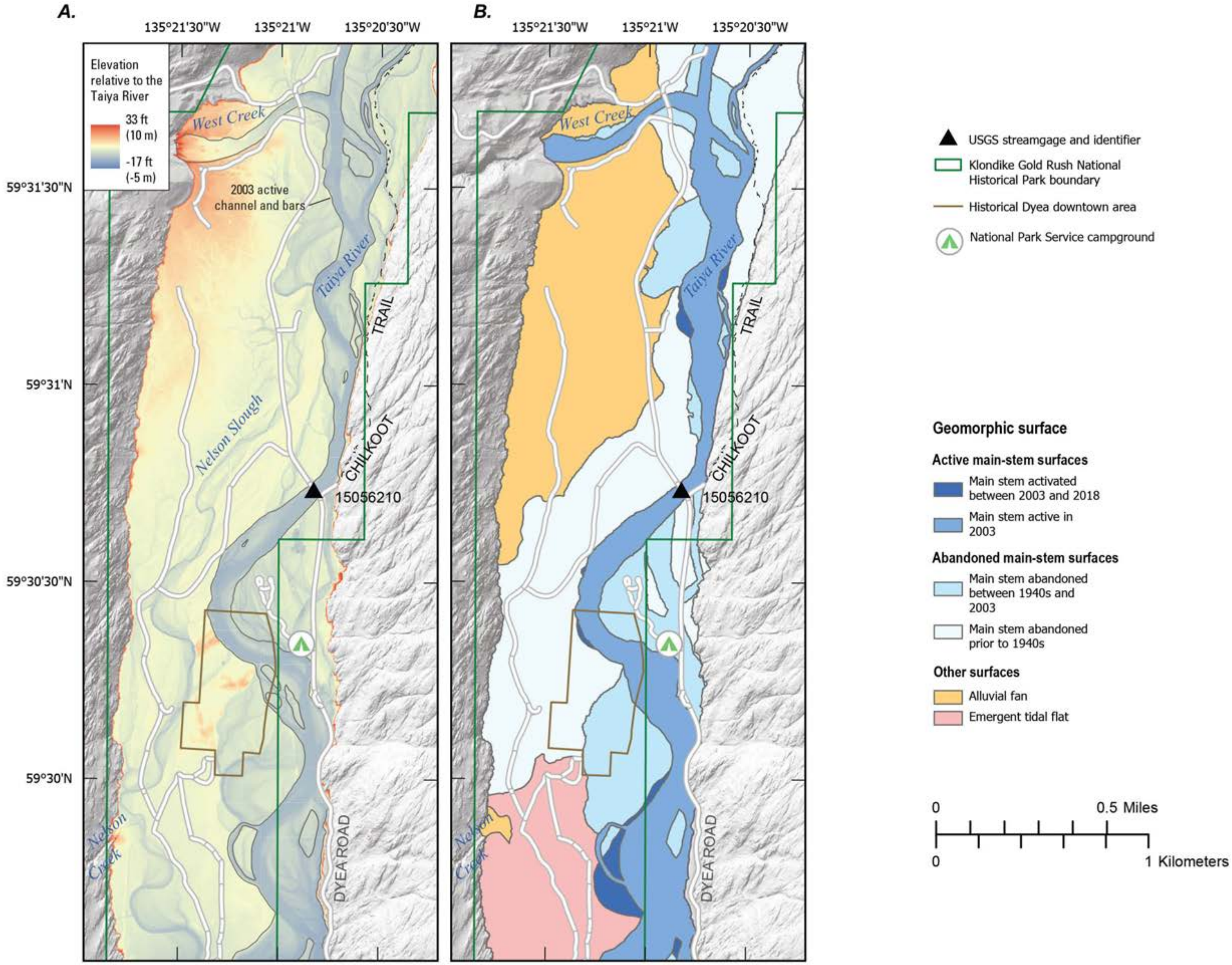

Figure 4. (A) The 2003 lidar elevation data, reprocessed to show the elevation relative to the river surface, highlights existing and former channels in the Taiya River valley bottom. (B) Using the surface textures from the elevation data and channel occupation dates from historical imagery through 2018 helped prepare a geomorphic map that identified the extents of main-stem channel locations for various periods from prior to the 1940s until 2018. This figure is modified from Curran (2020).

Streamflow and Flooding in a Glacier-fed River

Streamflow statistics compiled from multiple years of data can be used to gain perspective on floods and seasonal streamflow patterns. The USGS monitors Taiya River streamflow at a streamgage near the Dyea Road bridge (USGS station 15056210, USGS 2025) as part of a nationwide streamgage network. In addition to providing data to support statewide analyses, the streamgage documents local floods and provides detailed real-time information for users from park managers to recreational rafting companies. The stream gage data include 2 large floods documented outside the period of routine operation: a 1967 rainstorm-driven (Boning 1972) flood estimated at 25,000 ft^3/s and a 2002 flood of 18,600 ft^3/s that was affected by the glacial outburst flood in West Creek. These floods were recorded as annual peak streamflows, or the largest flood of the water year, which runs from October through September. The streamgage data also include routinely monitored annual peak streamflows and daily streamflows from water years 1970-1977 and a second period that started in water year 2004.

Daily streamflow records for the Taiya River show a pattern of lower cold-season flows and higher warm-season flows that peak in summer (Figure 5). The Taiya River exhibits a high-elevation-melt-dominated pattern that is typical of streams in glacier-rich basins in Alaska (Curran and Biles 2021). This seasonal pattern is driven first by spring snowmelt, and later by high-elevation snowmelt and glacier ice melt that is augmented by rainfall at any time (most commonly in autumn). However, as is the case for many other streams in Alaska (Blaskey et al. 2023), when the earlier (1970-1977) part of the gaged period is compared to more recent years (2004-2024), winter flows have increased, and spring high flows arrive an average of two weeks earlier (Curran 2020), in response to changes in climate in this region.

Annual peak streamflows on the Taiya River are most common in August and September, coinciding with the overlap of the rainiest season and the highest meltwater runoff season. The Taiya River reached 20,300 ft^3/s from the rainstorm on October 13, 2022 (USGS 2025), less than the 1967 flood but more than the 2002 outburst-flood-affected flow.

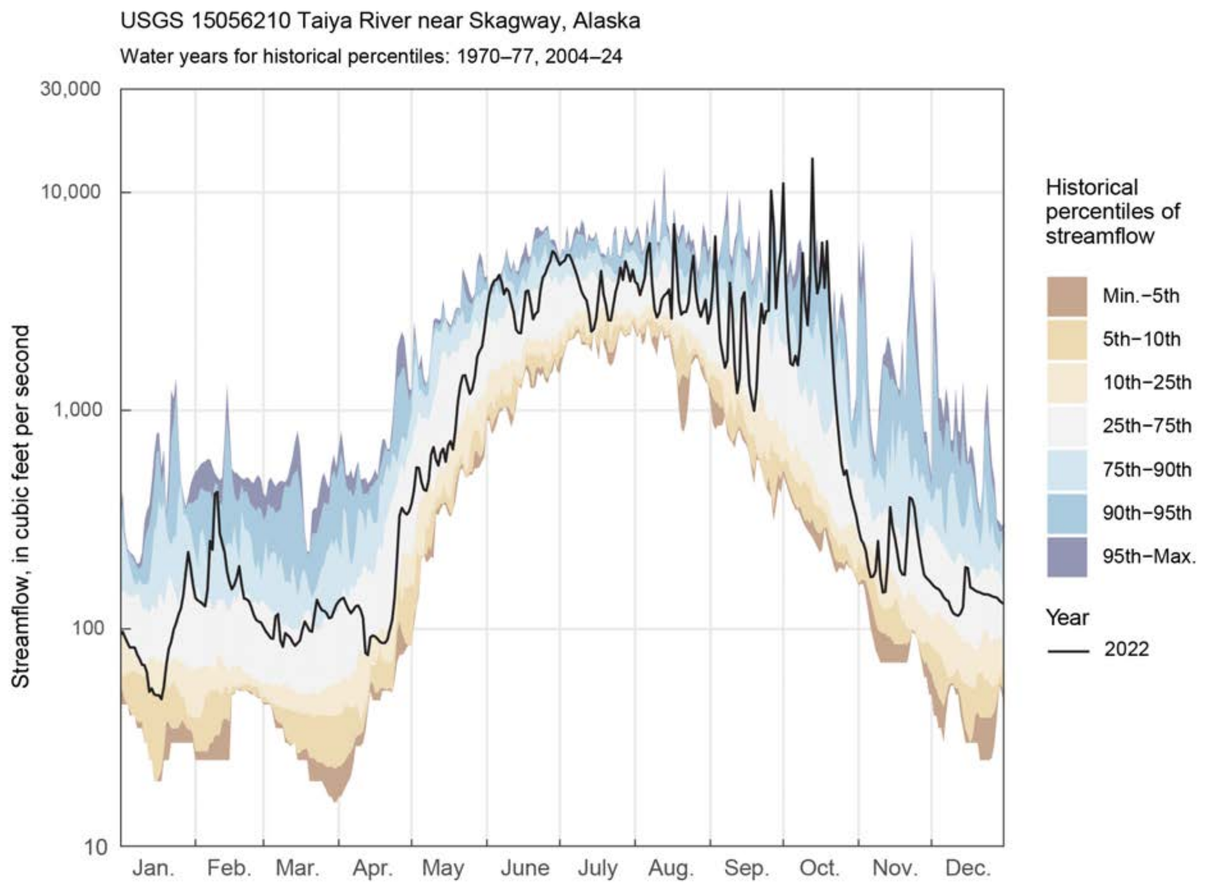

Figure 5. The annual hydrograph for 2022 (black line) shows how daily streamflow that year compared to the historical daily streamflow percentiles, or long-term streamflow statistics, shown on a logarithmic scale. The historical data form a summer-dominated curve typical of streams in glacier-rich basins in Alaska. The flood in October 2022 created new record daily highs for the available data since 1970 (USGS 2025).

Although large floods such as those in 2022 can be damaging, placing them in context can help understand how to manage responses to them. The 2020 USGS study (Curran 2020) noted that in addition to the large 1967 flood, earlier ungaged but large and damaging rain-generated floods after the gold rush, described in modern and historical reports, could have approached these magnitudes. Earlier glacial lake outburst floods in the Taiya River Basin (Curran 2020) include a documented 1897 flood in the upper part of the Taiya River Basin (Gurcke 2010) and evidence for older floods from the Nourse River Basin. The 1967 and 2022 floods and other gaged, non-outburst data will be included in the next USGS update of flood frequency statistics for the Taiya River to provide technical design data, but the pre-streamgage flood history reinforces the potential for large floods and related damage to occur along the Taiya River. An important consideration is that flood levels at the streamgage do not necessarily correspond to slough flood levels. One of the trail bridges that washed out in 2022 spanned a slough of the Taiya River, where flow levels depend on how much flow is in the Taiya River and how much of the flow enters the slough. Slough entrances on the Taiya River have been controlled by log jams and main-stem channel migration (Curran 2020) that have collectively resulted in progressive to abrupt streamflow increases or decreases, creating higher uncertainty for making management decisions in sloughs than would exist in areas where the flow is currently and was historically confined to a single channel.

Moving Forward

The park is tasked with preserving cultural and natural resources, which necessitates an understanding of natural processes in a dynamic riverine park setting. The 2020 USGS study (Curran 2020), mostly focused on the lower Taiya River, provided historical hydrologic and geomorphic considerations for management of park infrastructure, cultural and natural resources, and public safety. The river history indicates long-term channel stabilization and narrowing since the Klondike Gold Rush but likely continued localized and episodic channel change and bank erosion, and the flood history shows that large damaging floods are infrequent but not unprecedented. However, the complexities of flooding and channel change are compounded by the changing sediment and flow regime from a changing climate and shrinking glaciers, which will continue to drive dynamic riverine change (Beamer et al. 2017, Young et al. 2021). Ongoing studies by the USGS are providing documentation of recent changes and support as park managers address effects of hydrologic and geomorphic processes, some of which occur outside park boundaries, to continue curation of this historically and ecologically important area.

Acknowledgements

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Using Long-term Monitoring Data to Understand Lake Water Quality Trends in Southwest Alaska National Parks

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Lakes are vital ecosystems in southwest Alaska, supporting Pacific salmon, wildlife, and people. The diverse landscapes of Southwest Alaska include volcanic uplands, glacier-fed valleys, and tundra, all of which combine to influence temperature, water quality, and critical uses of regional lakes. Through long-term sampling of lakes from the surface to deep waters, we track how the environment governs lake water quality.

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Lakes are vital cultural, ecological, and aesthetic resources, supporting fish, wildlife, and human communities. In southwest Alaska, vast landscapes of volcanic mountain ranges, glaciers, and tundra influence the physical and chemical conditions of large (>3,000 acres; >450 feet deep) and small (300-3,000 acres; 100- 450 feet deep) lakes. In this region, the National Park Service manages Lake Clark and Katmai national parks and preserves (NP&Pres). Each park comprises a landmass of over 4 million acres—an area greater than the states of Rhode Island and Connecticut combined.

These parks contain an astounding amount of freshwater in the form of glaciers, wetlands, rivers, and lakes. In fact, the many lakes in Katmai NP&Pres and Lake Clark NP&Pres hold over 20% of the lake surface area in the National Park System nationwide (Messager et al. 2016). The Alaska National Interest Lands Conservation Act (ANILCA) created or expanded these parks in 1980 to preserve the watersheds, lakes, and rivers that support Bristol Bay Sockeye Salmon (*Oncorhynchus nerka*) and the bears that rely on them.

Lakes in these parks are as diverse as the landscapes they inhabit, shaped by key watershed characteristics such as elevation, permafrost, snowpack, glaciers, and volcanic activity. As sentinels of change, lakes reflect the combined influences of watershed hydrology, geology, and climate—including air temperature, wind, and solar radiation—on their physical and chemical conditions (Schindler 2009). In doing so, they capture and record environmental change, revealing shifts in climate, vegetation, and watershed processes (Adrian et al. 2009, Williams et al. 2009).

To understand how lakes are changing over time, we need to study depths below the lake surface. Sampling water temperature along a vertical profile from the lake surface downward illuminates the thermal structure of lakes, which influences ecological processes and lake-dwelling organisms. Lakes support diverse biological communities and provide critical resources for surrounding ecosystems. The thermal and chemical properties of lakes influence aquatic life, from microorganisms to fish. In southwest Alaska, lakes often support economically, ecologically, and culturally important fish populations. Lake ecosystems in both parks support all five species of Pacific salmon: sockeye salmon, chinook salmon (*O. tshawytscha*), chum salmon (*O. keta*), coho salmon (*O. kisutch*), and pink salmon (*O. gorbuscha*). These lakes also support resident populations of rainbow trout (*O. mykiss*), arctic char (*Salvelinus alpinus*), Dolly Varden (*S. malma*), lake trout (*S. namaycush*), arctic

A plume of suspended sediment from two glacial tributaries enters the upper basin of Lake Clark. This input of sediment creates a turbidity gradient from the headwaters to the outlet of the lake.
NPS/EVAN BOOHER

National Park Service technician Paul Gabriel uses a hand-held device to track the depth of the water quality meter as it descends down the lake profile in Kontrashibuna Lake, Lake Clark National Park and Preserve.
NPS/TROY RILING-ANDERSON

grayling (*Thymallus arcticus*), burbot (*Lota lota*), and northern pike (*Esox lucius*). Lakes are sensitive to their surrounding climate. Over the last century, high-latitude ecosystems, such as those in southwest Alaska, have experienced ongoing warming and changing precipitation regimes (Littell et al. 2023). Changes in watershed characteristics that alter thermal and chemical conditions of lakes, in turn, will shape the productivity and capacity of the lakes to support these fish. Warmer and more nutrient-rich waters can increase the primary production of aquatic algae. Which, in turn, provide a dominant control on the daily dynamics of dissolved oxygen and pH dynamics as they photosynthesize during the day and respire at night.

Vertical Lake Profile Monitoring Program

Long-term monitoring by the Southwest Alaska Inventory & Monitoring Network focuses on five main indicators of lake water quality: temperature, dissolved oxygen, specific conductance, pH, and turbidity. These indicator data are collected along a vertical profile of the water column at fixed depths from the surface to around 165 feet (50 m) deep or the lake bottom, whichever comes first. Since 2008, the Southwest Alaska Inventory & Monitoring Network has collected a series of vertical profiles of 37 lakes spread across Lake Clark NP&Pres and Katmai NP&Pres (with an additional two in Kenai Fjords National Park that are not included here) either annually or on a rotating basis (Figure 1). Four lakes are revisited every year typically by boat and, in the case of the two largest lakes, Lake Clark and Naknek Lake, at multiple points within each basin. The remaining lakes are sampled every 3-5 years typically by float plane as time and conditions allow. This approach helps managers and scientists to understand processes occurring across lakes, whether these processes are changing over time, and the ensuing effects on fish and other aquatic organisms. Data used in this study may be found via the NPS Aquarius WebPortal.

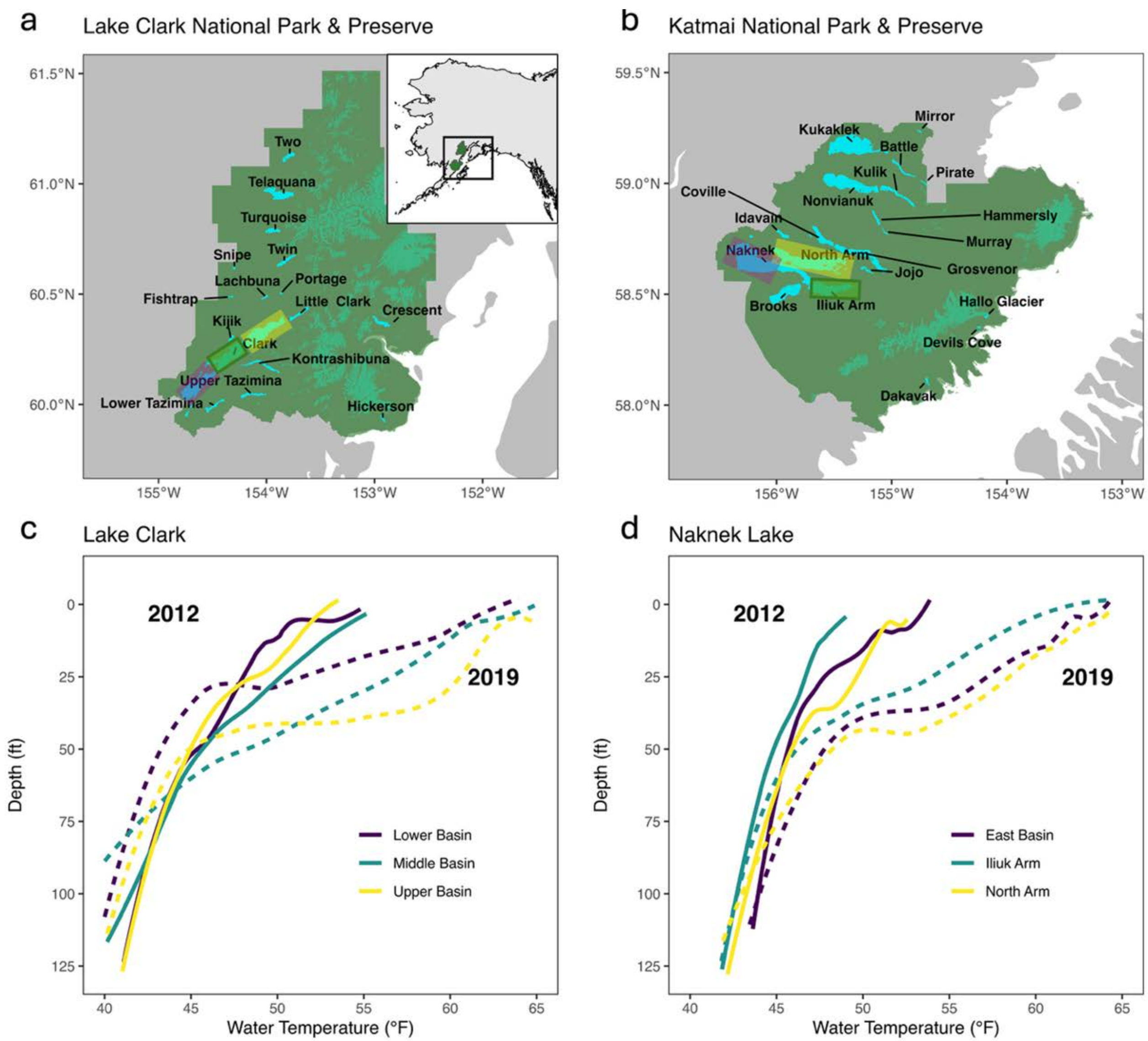


Figure 1. Map of lakes sampled for vertical lake profile data in Lake Clark (a) and Katmai (b) national parks and preserves. Glacier coverage from the Randolph Glacier Inventory (RGI 6.0) is shown in light green. Vertical temperature profiles of the two largest lakes—Lake Clark (c) and Naknek Lake (d)—illustrate how strongly thermal structure responds to interannual climate variability, contrasting a relatively cool, wet year (2012; solid lines) with a relatively warm, dry year (2019; dashed lines). In both lakes, 2019 profiles show substantially warmer surface waters and deeper thermal stratification across all basins, indicating that warm, dry years drive stronger and deeper thermoclines. This has direct implications for habitat availability for cold-water species: deeper stratification compresses the cold, well-oxygenated water that salmon and other cold-water fishes depend on during summer.

What We Measure

Temperature. If we swim in a lake that is warm near the surface but dramatically cools as you put your feet deeper in the water, we are feeling the layering of temperature zones, which is referred to as *thermal stratification*. Water temperature is a major factor controlling ecological processes in lakes (MacIntyre and Hamilton 2024). In high-latitude regions, lakes freeze during winter. During the summer, sunlight and warm air heat the water surface. This light and heat cannot penetrate deep into the water; hence lakes are often colder at greater depths. Interestingly, water is most dense at 39°F (7 degrees above its freezing point at 32°F) allowing cold, but not quite freezing, water to stay liquid below the frozen lake surface. This unique physical property of water is what allows many lakes to ice over without freezing solid and is critical for freshwater life.

The zone of rapid change in temperature is referred to as the *thermocline*. As the difference in temperature between surface water and deeper water increases, the amount of energy required to mix the two layers also increases. The layer above the thermocline is referred to as the *epilimnion* and the layer below the thermocline is referred to as the *hypolimnion*. The depth of the thermocline can tell us about the physical and chemical structure of the lake and the conditions organisms experience at different depths. Using a combination of routine vertical profile sampling of lake thermal structure across parks, we can track how lakes with different elevations, watershed conditions, and physical characteristics respond to variation in weather year to year.

Dissolved oxygen. Dissolved oxygen (DO), measured in milligrams per liter (mg/L), is the amount of oxygen in water that is readily available for respiration by aquatic organisms. In the epilimnion, DO originates from a variety of sources; for example, from air mixing with surface water due to wind or turbulent flow, and from aquatic plants and algae producing oxygen (O_2) during photosynthesis (Marcé et al. 2024). When rates of photosynthesis are very high, such as those observed during algal blooms, the epilimnion may be at maximum oxygen holding capacity. As photosynthetic algae die, they drift lower in the water column toward the hypolimnion, where they are decomposed by bacteria and other microorganisms that consume oxygen and release carbon dioxide, leading to lower levels of DO. Temperature influences oxygen concentration in water colder water can hold greater amounts of DO.

Specific conductance. Specific conductance, or *electrical conductivity*, is a measure of the capacity of electricity to flow through water, which is influenced by the concentration (microsiemens per centimeter, µS/cm) of dissolved ions in water standardized at 25°C. These ions are derived from dissolved electrolytes (like those in sports drinks), which include salts, organic matter, and compounds of chloride, sulfide, and carbonate. Greater concentrations of ions result in higher values of specific conductance (e.g., these values range from ~0-2,000 µS/cm in freshwaters to over 50,000 µS/cm in sea water). In freshwaters, specific conductance is commonly used to estimate either salinity or total dissolved solids (Thomas 1986, McCleskey et al. 2023, Dugan 2024).

pH. Another fundamental water quality parameter we measure is pH, which indicates how acidic or basic water is. The pH metric is unitless and reflects the ratio of free hydrogen ions (H^+) to hydroxide ions (OH-) in water on a negative logarithmic scale ranging from 0 (very acidic) to 14 (very basic), with 7 being neutral. Extreme pH values influence the bioavailability and solubility of nutrients like phosphorus. Watershed geology may impact pH, with carbonate-heavy bedrock (such as limestone) increasing pH. Dissolved carbon dioxide (CO_2) concentrations in water also influence pH, with higher levels of CO_2 dissolved in water causing more acidic conditions. Gases also exchange across the air–water interface and atmospheric CO_2 concentrations dissolved CO_2 concentrations in surface waters. Watersheds in Katmai NP&Pres and Lake Clark NP&Pres may be influenced by the presence of tundra, peatland, volcanic ash, and decomposing organic matter, all of which can decrease pH of rivers and lakes. However, the presence of carbonate-rich soils and bedrock, such as those in the northern part of Lake Clark NP&Pres, can increase pH, particularly if erosion by glaciation introduces substantial carbonate-rich sediment to waterbodies.

Water clarity and turbidity. Water clarity has been measured routinely since monitoring began. Despite widespread use and common methods to measure water clarity, it remains a somewhat subjective measurement (e.g., relying on the observer to visually identify depth at which a *Secchi* disk is no longer visible in the water column). The most recent parameter added to our vertical lake profile monitoring is turbidity. Turbidity is a measure of how effectively light penetrates the water

A Secchi disk (used to measure water clarity) is lowered into Portage Lake, Lake Clark National Park and Preserve, by pilot Andy Mankus.
NPS/PAUL GABRIEL

column (Kitchener et al. 2017, Matos et al. 2024). Because light penetration is largely controlled by the presence of suspended solids (e.g., organic matter, sediment), turbidity is an efficient, indirect way of estimating the total suspended solid loads in lakes. In the lakes of Katmai NP&Pres and Lake Clark NP&Pres, turbidity is typically influenced by the presence of glacial till and volcanic ash. Tracking turbidity across the water column and over time allows us to detect general trends in particulate matter flowing into lakes.

Water Quality and the Ecology of Lakes in Southwest Alaska

Water temperature records allow us to estimate the growth potential of fish in different lake habitats. Coldwater species, such as Pacific salmon, trout, and char, require cool temperatures for efficient growth and survival. When temperatures are too warm, negative effects can be observed in swimming speed, immune responses, growth, and other variables (Brett 1971, Reed et al. 2010, Chen et al. 2013, Sparks et al. 2019). Thermal stratification controls the mixing of water, which influences other water quality conditions, such as DO, conductivity, and pH, at different lake depths.

Dissolved oxygen plays a critical role in supporting cold-water fishes, which require cold, well-oxygenated water. Negative effects of low DO have been noted for char when DO falls below 2.18 mg/L, for rainbow trout at 7.3 mg/L, and for sockeye salmon at 9.2 mg/L (Davis 1975). When DO levels are low, fish may experience decreased swimming speed, lower metabolic efficiency, and elevated blood pressure and respiration rates, all signs of stress. When oxygen levels fall near zero, *hypoxia* occurs and can lead to fish kills and other negative effects on lake ecosystems.

Similar negative issues occur when water chemistry varies outside an optimal range for aquatic organisms. For example, high salinity, as identified by changes in specific conductance, can have harmful effects on fish and other aquatic life (Stekoll et al. 2009, Larsen et al. 2023). Higher salinity can decrease the capacity of water to hold DO. Similarly, for most

National Park Service technician Evan Booher taking a vertical profile sample near the water surface in Lake Clark, Lake Clark National Park and Preserve in 2014.
NPS/JEFF NELSON

freshwater organisms, a pH range of ~6.5-9.0 is tolerable. When pH becomes greater than ~11 or less than ~4, fish and other organisms may suffer or die. However, even marginally acidic (e.g., pH = 5.5) conditions can limit growth in salmonids, both through direct effects on fish and negative effects on their invertebrate prey (Magnuson et al. 1984). Additionally, turbidity and water clarity inform how deeply light can penetrate the water column to support photosynthesis and can influence the ability of visual predators, like Pacific salmon or birds, to find resources.

Depth of Summer Stratification

Vertical profile samples of lake water temperature can be used to identify the depth below the surface of the *thermocline* (Figure 1), the depth at which water temperature changes more than 0.55 °F/foot (1 °C/m) and how it relates to air temperatures. Examining data from two years with notably different summer conditions (cool and wet in 2012 and warm and dry in 2019), we were able to identify that thermocline depth among the three basins in Lake Clark ranged between 23-31 feet in 2012 and 20-46 feet in 2019 (Figure 1c). During this same period, the thermocline depth of the three deepest basins of Naknek Lake ranged between 25-40 feet in 2012 and 5-38 feet in 2019 (Figure 1d). Typically, in a warm and dry year like 2019, thermocline depths are expected to be much deeper. However, both the upper basin of Lake Clark and the Iliuk Arm of Naknek Lake receive substantial inputs of cold, turbid glacier meltwater, which likely contributed to the greater range in thermocline depths observed in 2019 versus in 2012. These differences in thermocline depth show how lakes are sensitive not only to climate and weather drivers, but also local watershed variation. Understanding this variation is important because it influences how heat, oxygen, and nutrients are distributed in the lake and the habitat conditions for aquatic organisms.

Temperature and Water Quality Over Time

We show the temporal dynamics of water temperature (Figure 2) and air temperature and water quality indicators (Figure 3) in the epilimnion and hypolimnion using a loess smoothing function that reflects the moving average condition over time. We compared values across large and deep lakes (>3,000 acres; >450 feet deep) versus small and shallow lakes (300-3,000 acres; 100-450 feet deep) in the two parks using simple linear models of response over time. Linear trend analyses confirmed significant warming in surface waters of large/deep lakes in both parks (slopes = +0.17–0.24°F/year, $p<0.001$, $R^2=0.11–0.18$), concurrent with significant increases in air temperature across all lake types (slopes=0.08–0.17°F/year, all

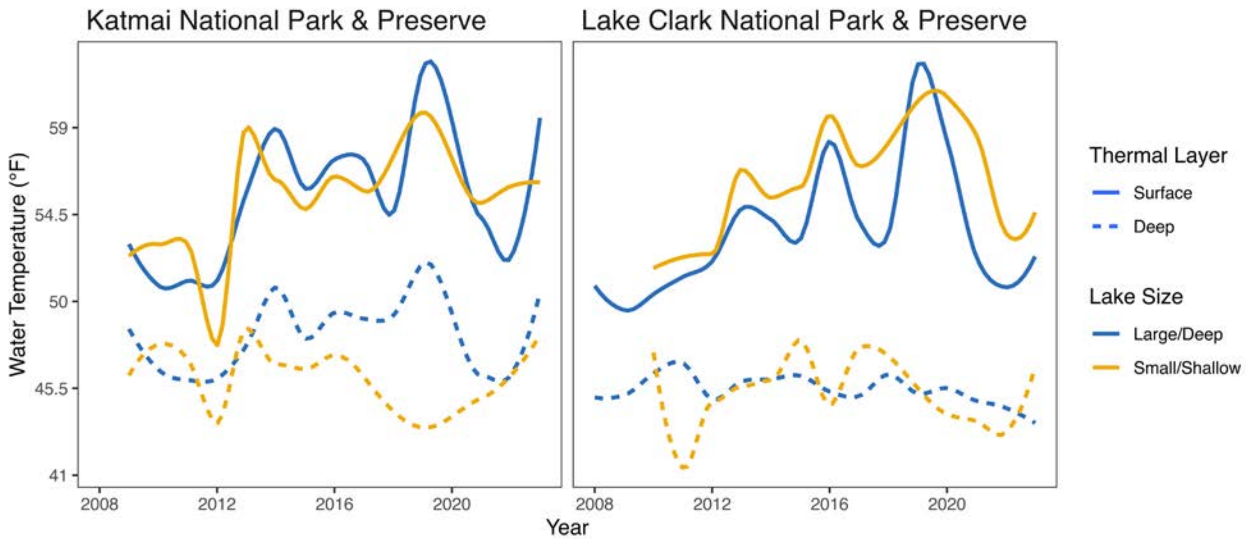
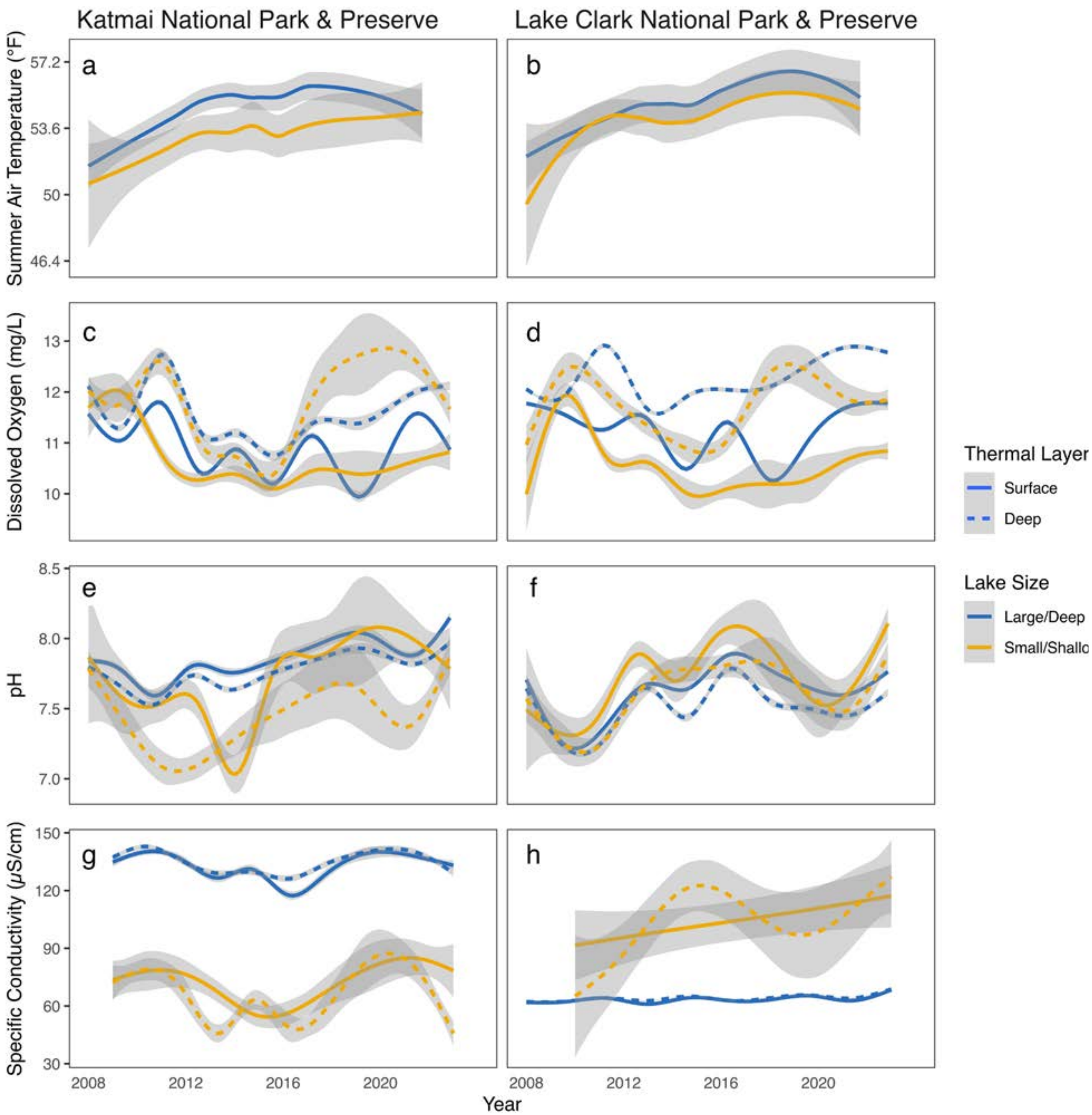


Figure 2. Changes over time in average water temperature in the surface (epilimnion) and deeper (hypolimnion) layers for consistently stratified lakes in Katmai and Lake Clark national parks and preserves.

Surface waters of large/deep lakes show the strongest and most consistent warming trends over the monitoring period, particularly in Lake Clark where surface temperatures rose markedly after ~2016. Deep water temperatures remain cooler and more stable but show subtle warming in large/deep lakes, suggesting heat is penetrating below the thermocline over time.

Small/shallow lakes show greater interannual variability with less directional trend, reflecting their greater sensitivity to year-to-year climate fluctuations rather than sustained warming. Together, these patterns indicate that large/deep lakes are experiencing progressive thermal change that may reduce the volume of cold, deep-water habitat over time.

Large and deep lakes in this time series include Lake Clark and Naknek Lake, as well as Crescent, Upper Twin, Upper Tazimina, Turquoise, Telaquana, and Kontrashibuna (Lake Clark NP&Pres) and Grosvenor, Kukaklek, Kulik, and Nonvianuk (Katmai NP&Pres). Lakes that were mixed or lacked a clear thermocline are excluded.



p<0.001, R^2=0.07–0.42). Warming trends in small/shallow lake surface waters were weaker and non-significant in Katmai (p=0.105), and deep-water temperatures showed no consistent directional trend. Dissolved oxygen showed significant declining trends in surface waters (slopes=−0.02 to −0.06 mg/L/year, p<0.05, R^2=0.03–0.07), though low R^2 values indicate substantial interannual variability, consistent with the dynamic patterns visible in Figure 3. pH increased significantly across nearly all groups in both parks (slopes=+0.019–0.036 pH units/year, p<0.05, R^2=0.02–0.18). Specific conductivity trends were variable and inconsistent in direction across groups (slopes = −0.89 to +2.57 μS/cm/year), with uniformly low R^2 values (< 0.05) suggesting lake-specific rather than regional drivers.

Figure 3. Moving average (mean ± 95% confidence bands) of summer air temperature for lakes in Katmai National Park and Preserve (a) and Lake Clark National Park and Preserve (b), with subsequent panels showing dissolved oxygen (c–d), pH (e–f), and specific conductivity (g–h). Solid and dashed lines reflect surface (epilimnion) and deep (hypolimnion) thermal layers, respectively; blue lines represent large/deep lakes (>3,000 acres, >450 feet deep) and yellow lines represent small/shallow lakes (300–3,000 acres, 100–450 feet deep).

Despite broadly similar warming trends in air temperature across both parks, water quality parameters diverged markedly by lake size and depth. Large/deep lakes showed greater thermal stratification and more stable dissolved oxygen and pH over time, while small/shallow lakes exhibited greater variability and more pronounced long-term shifts in specific conductivity and pH, patterns consistent with heightened sensitivity to climate forcing in lakes with less thermal buffering capacity.

Conclusions and Future Directions

Lakes in southwest Alaska national parks are sentinels of ongoing environmental change, offering key insights into shifting climate and watershed processes. Ongoing long-term monitoring of lake temperature and water quality across the water column provides critical insights into lake health and function. Specifically, monitoring temperature and stratification patterns informs our understanding of habitat quality for important aquatic organisms, like juvenile sockeye salmon that depend on cold, well-oxygenated waters. Changes in water chemistry, such as salinity and pH, reflect both natural watershed geology and broader environmental shifts.

Using a combination of mechanistic models and future climate predictions, we are working to predict future changes in ice coverage, lake thermal structure, and summer maximum water temperatures. Preliminary findings corroborate those of other studies in high-latitude lakes (Gillis et al. 2021, 2024, Kirchner and Hannam 2024), which suggest decreased duration of ice cover, warmer and often wetter summer conditions, and a general warming trend within the epilimnion of lakes. We will combine these approaches with knowledge of the relationship between temperature, DO, and other water quality characteristics to predict future habitat suitability for fish, supporting the sound management of iconic species such as sockeye salmon. Long-term lake monitoring in Lake Clark and Katmai national parks and preserves is vital for managing these globally significant ecosystems, as well as supporting fisheries, biodiversity, and the cultural and ecological integrity of southwest Alaska.

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Wetlands and forests are important components for water quality of the freshwater systems of Katmai National Park and Preserve.
UAF/MATT DUNKLE

Investigating the Role of Lake Environments and Food Chains on the Transfer of Mercury to Lake Trout

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Mercury contamination can pose threats to fish, wildlife, and people. Methylmercury, found in fish, can be particularly detrimental, especially to children. This study explores the sources and concentrations of mercury and proposes how people can become aware and limit their exposure.

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Lake trout from Lake Clark, Lake Clark National Park and Preserve.
NPS/W. HARMON

Mercury contamination can pose threats to fish, wildlife, and humans. A highly toxic form, methylmercury, can cause a range of negative health effects that are detrimental particularly to infants and children because it affects their growing brains and nervous systems (USEPA 2024). Exposure is most common from consumption of fish that contain methylmercury, which comprises nearly all the total amount of mercury found in fish (Jewett et al. 2003). Therefore, gaining an understanding of where and which fish may have harmful methylmercury levels could provide relevant information about potential exposure to mercury contamination that could be used by fisheries managers and the public.

Prior research in lakes of Alaska's national parks has found large differences in fish mercury concentrations and, therefore, exposure for human consumers (Allen-Gil et al. 1997, Eagles-Smith et al. 2014, Kowalski et al. 2014, Lepak et al. 2022, Bartz et al. 2023). In all studies, researchers implicate fish diet and food chains as a factor and call for further study, providing motivation for our investigation (outlined below). We undertook this study because of the importance of lakes and fish to the public, and to better understand how mercury is processed and bioaccumulated in fish in northern lake ecosystems (Figure 1).

Why Mercury is a Problem

Alaska's national parks are seemingly pristine places that are largely untouched by direct human development, but the parks are not immune to global stressors (Trammell et al. 2022). Pollutants like mercury are widespread and prevalent at great distances from their sources through atmospheric transportation. In fact, due to global circulation patterns, more than 98% of atmospheric mercury in the Arctic is transported there from distant locations and is largely derived from human-induced sources, either through current emissions or remobilization from the land and ocean (Outridge et al. 2018, Dastoor et al. 2022).

Mercury concentrations in lake trout (*Salvelinus namaycush*) from several of Alaska's national parks were among the highest measured in the western United States, often exceeding ecological and human health benchmarks (Landers et al. 2008, Eagles-Smith et al. 2014, Bartz et al. 2023). These benchmarks are used by federal and state agencies to provide guidance and issue advisories on contamination levels and food safety for those who are pregnant or breastfeeding and for children that consume fish (USEPA 2024, Hamade 2014). The U.S. Food and Drug Administration and Environmental Protection Agency classify freshwater trout as a "best choice," a category that permits consumption of three 4-ounce (113-g) servings

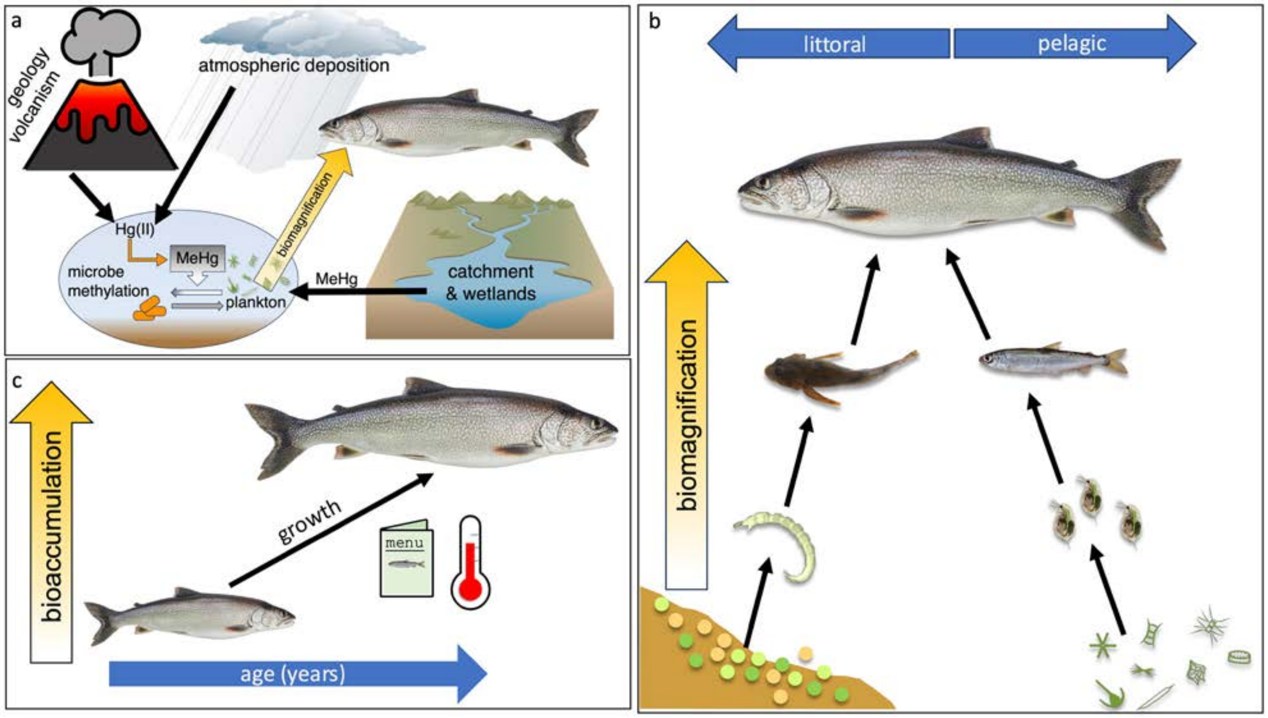

Figure 1. Production, bioaccumulation, and biomagnification of mercury.

(a) Mercury is deposited to northern lakes mainly from atmospheric deposition. Other local sources include adjacent wetlands, volcanoes, glaciers, and bedrock (e.g. cinnabar deposits). Elemental mercury (Hg(II)) is transported to lake and wetland habitats where it is converted to its bioavailable form, methylmercury (MeHg), which is taken up into the food chain by primary producers (plankton) and then biomagnified to predators like lake trout. Yellow shading in the arrows of bioaccumulation and biomagnification represents the concentration of methylmercury. Panel a is modified from Lepak et al. (2022).

(b) Biomagnification is the increase in concentration of methylmercury with each successive step in a food chain. Biomagnification varies depending on the prey and the consumer. In lakes, multiple food chains may provide energy to a top predator. Here, we depict a littoral (shallow water) and a pelagic (open water) food chain converging at the lake trout. The methylmercury concentration in the lake trout will depend on the biomagnification of methylmercury in each individual chain and the proportion of the diet each chain represents.

(c) Bioaccumulation is the gradual increase of methylmercury concentration in fish tissues over time. Methylmercury bioaccumulates over the lifespan of a fish as more is taken in than excreted. The rate of fish growth, which is controlled by food choice and temperature, can affect concentrations. If fish gain weight faster than they accumulate methylmercury, it can dilute the concentration in their tissues. This dilution can reduce the level of exposure associated with methylmercury.

Symbol artwork (Daphnia, Kim Kraeer and Lucy Van Essen-Fishman; diatoms, Diana Kleine, Marine Botany UQ; watershed and rain, Tracy Saxby) is from the University of Maryland, Center for Environmental Science, Integration and Application Network.

per week (USEPA 2024). Guidance provided by the State of Alaska Department of Health uses a point system, where a 6-ounce serving of lake trout counts as 2 of 12 allowed weekly points for consumption of fish (AKDH 2025). However, elevated levels of mercury are often found in large-bodied, long-lived species like lake trout that occupy space at the top of the food chain (Barst et al. 2022). Lake trout can grow to 47 inches (1.2 m) in length and weigh 66 pounds (30 kg), living up to 60 years. Within the species, individuals can display variable body shapes and colors, consume a wide variety of prey, and live in varied habitat types (Riley et al. 2021). The characteristics that cause them to be high in mercury, primarily size and age, are also what make them appealing to subsistence fishers and sport anglers. Large fish provide more meat and are fun to catch.

Mercury finds its way to lake trout via various pathways, all the while bioaccumulating and biomagnifying to these higher trophic level species (i.e., top predator in the food chain), but location-specific differences appear to play an important role in determining levels in fish (McKinney et al. 2022). Through a collaborative U.S. Geological Survey (USGS) and National Park Service (NPS) project, we aim to investigate how diet and food chain pathways affect mercury transfer to lake trout. Our study objectives were to (1) examine effects of the lake environment on availability and bioaccumulation of mercury, (2) understand the transfer of mercury from prey to predator, and (3) identify lake trout characteristics that provide information about mercury exposure to anglers.

Where We Went and What We Sampled

We included a variety of locations and parks when designing the study, in order to best capture and help explain variation of fish mercury concentrations. Lakes from four national parks across Alaska were selected for inclusion in the study: Gates of the Arctic National Park and Preserve, Lake Clark National Park and Preserve, Noatak National Preserve, and Wrangell-St. Elias National Park and Preserve (Figure 2). These parks are situated across multiple ecoregions (land areas with similar ecology, geology, and climate) including Arctic tundra, mountain ranges, and interior forests (Gallant et al. 1995). We chose lakes that would provide information to federal agencies and decision makers, focusing on lakes commonly used for subsistence or recreational fisheries.

In early fall of 2020, during the first year of the COVID-19 pandemic, we downsized our initial sampling plan, and NPS biologists from Lake Clark National Park and Preserve collected data only from Kontrashibuna Lake. NPS also sampled Crescent Lake, Lake Clark, and Telaquana Lake in summer 2021. Over the summers of 2022 and 2023, USGS, NPS, and Alaska Department of Fish and Game staff sampled six more lakes: Copper, Tanada, and Chelle lakes in Wrangell-St. Elias National Park and Preserve; Feniak Lake in Noatak National Preserve; and Chandler and Nutuvukti lakes in Gates of the Arctic National Park and Preserve. This team effort collectively relied on 24 field biologists, 8 pilots, and multiple landowners and support staff. To trace mercury through the lake food chains, biologists collected samples and data on water quality, algae, zooplankton, benthic (bottom-dwelling) invertebrates, prey fish, and lake trout (Figure 3).

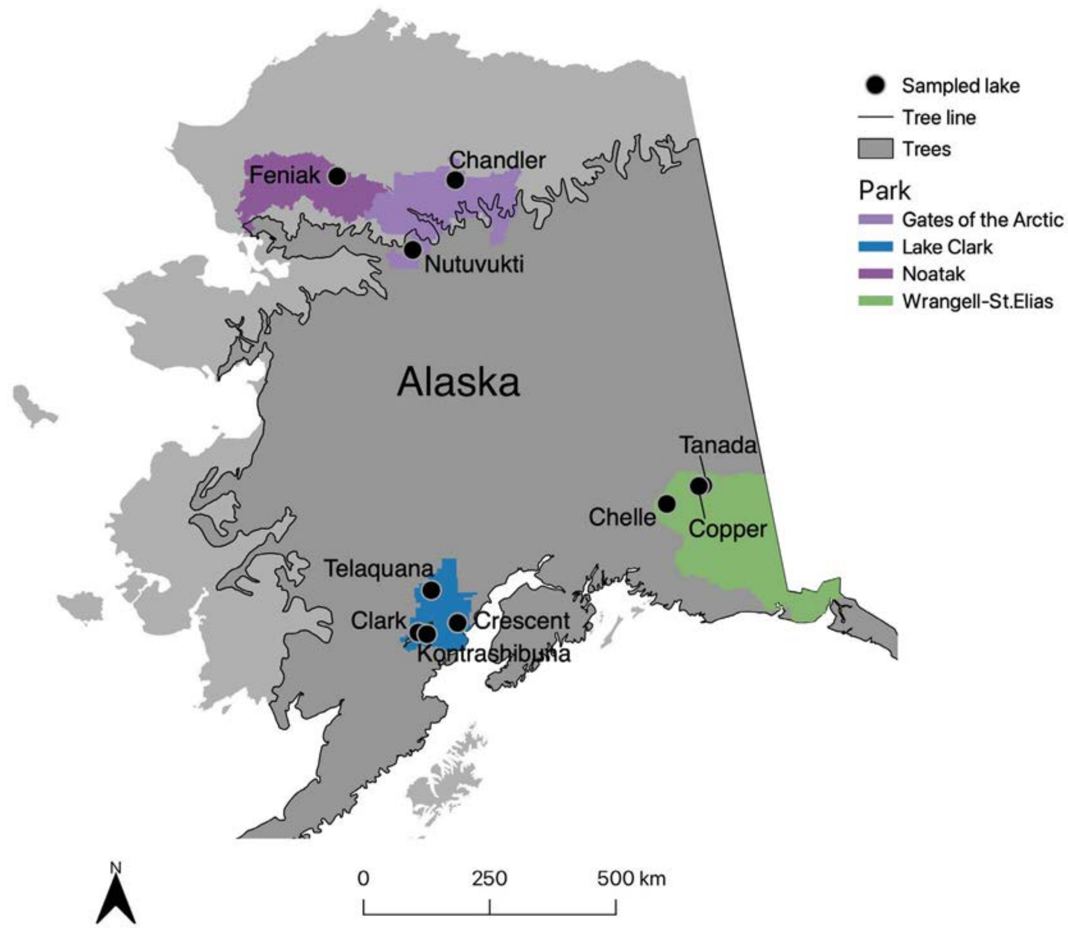

Figure 2. Map of 10 Alaskan lakes across four national park units included in our evaluation of lake trout mercury concentrations. Samples were collected 2020-2023.

Tree line and tree covered area are from the Alaska Geobotany Center (2020), Alaska outline and National Park boundary layers are available from the U.S. Geological Survey.

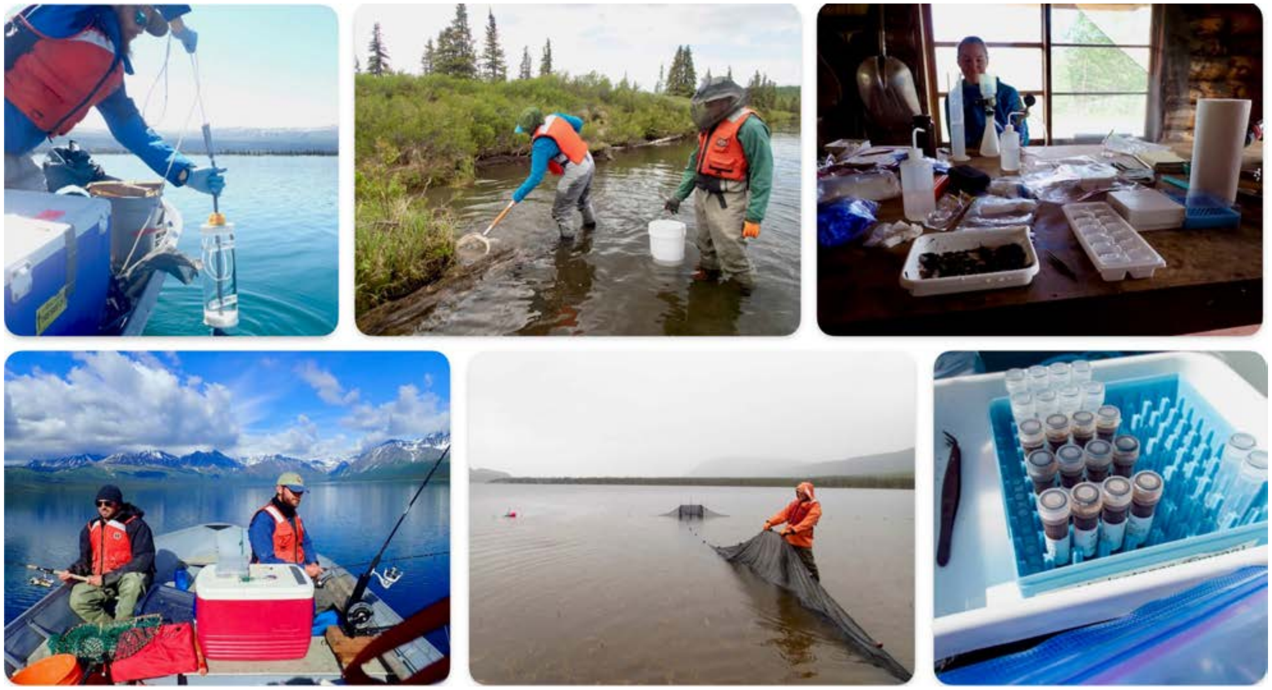

Figure 3. Sample collection targeted animals along the food chain, from algae to fish.

Clockwise from top left: Collecting water from below the surface of Telaquana Lake (NPS/W. Harmon). Sampling benthic invertebrates from the shoreline of Copper Lake (USGS/A. Stanek). Filtering phytoplankton and sorting benthic invertebrates inside the Chelle Lake cabin (USGS/S. Laske). Prepared vials of zooplankton ready for the cryogenic shipper, a storage solution when freezers are unavailable (USGS/S. Laske). Setting up the lead line of a trap net used to capture prey fish (USGS/A. Stanek). Trolling for lake trout in Telaquana Lake (NPS/J. Kramer).

Meeting Study Goals

1. Effects of lake environment on availability and bioaccumulation of mercury.

By comparing across lakes, we are investigating how the environment, including in the lake and its surrounding catchment (Figure 4), affects the availability of mercury and biomagnification of mercury to lake trout. Analysis of factors such as lake surface area, internal (e.g., algae) and external (e.g., leaf litter) carbon sources, and presence of aquatic plants/algae help us understand the relative importance of those and other factors to an aquatic organism's mercury concentration (Branfireun et al. 2020). Studies that look at in-lake processes have shown the importance of lake productivity, where lakes with high nutrient levels tend to have aquatic organisms with lower mercury concentrations (Lescord et al. 2019, Hudelson et al. 2019).

Characteristics of the lake environment that affect productivity are what control fish growth and mercury bioaccumulation, ultimately helping to explain why fish in some locations have higher concentrations than others. If a fish gains more body mass in a growing season than they accumulate mercury, then they can effectively dilute their mercury concentrations (Sandheinrich and Drevnick 2016, Keva et al. 2017), lowering the amount in their tissues and potentially reducing mercury burdens for themselves and consumers. However, over the lifespan of a fish, especially one as long-lived as a lake trout, there can be considerable lifelong bioaccumulation (Chételat et al. 2021). Other studies of lake trout mercury concentrations in Alaska's parks have indicated high mercury concentrations in older populations, but with considerable lake-to-lake variation (Kowalski et al. 2014, Bartz et al. 2023). We will determine the ages of captured lake trout using established methods of counting annual growth from otoliths (ear bones) and then account for their lifespan in our analyses of environmental factors (Figure 5).

2. Transfer of mercury from prey to lake trout.

We can determine how much mercury is bioavailable and can bioaccumulate in lake trout by collecting and analyzing tissue samples from lake trout and their food resources (Figure 6). Mercury biomagnifies, with the smallest concentrations in plankton, moderate concentrations in small prey fishes, and highest concentrations in apex predators like lake trout (Sinclair et al. 2024). Within lakes, we can determine how an organism's trophic position (i.e., location in the food chain) and dietary habits (i.e., which food chain) are related to its

Figure 4. Lake environments are shaped by their catchments, size, and productivity.

From left: Aerial view of Kontrashibuna Lake and its surrounding mountainous catchment; Kontrashibuna Lake is about 13 miles (21 km) long and 380 feet (116 m) deep (NPS/D. Young). A stream drains into Nutuvukti Lake from the fen (NPS/D. Young); a fen is a peat wetland of groundwater rich in dissolved mineral nutrients (NPS 2023). Large freshwater mussels (*Beringiana beringiana*) live on the sandy bottom of Nutuvukti Lake and filter phytoplankton out of the water column (USGS/S. Laske).

Figure 5. Age and growth affect mercury bioaccumulation in fish.

Clockwise from top left: A lake trout otolith from Chandler Lake in Gates of the Arctic National Park. Age can be determined by counting the dark rings of an otolith, much like one would count tree rings (USGS/M. Hendon). A National Park Service biologist processes a lake trout for length and weight; biologists also remove muscle, otoliths, and stomach contents (NPS/J. Kramer). Some of the smallest fish were captured from Chelle Lake, which happens to be the smallest lake, by surface area and depth, included in the study (USGS/S. Laske).

Figure 6. Lake conditions and food availability influence the biomagnification of mercury to top predators.

Clockwise from top left: An Alaska Department of Fish and Game biologist holds a 25-inch (63 cm) lake trout collected from the clear waters of Feniak Lake (USGS/S. Laske). Algae are removed from rocks gathered from Chandler Lake (USGS/S. Laske). Gill nets set for lake trout and their fish prey are retrieved from glacially influenced Kontrashibuna Lake (NPS/J. Kramer). Kokanee—freshwater resident sockeye salmon (*Oncorhynchus nerka*)—are a food resource for lake trout in Copper Lake, the only lake in our study with a population (USGS/S. Laske). Lake trout from Copper Lake with muscle plug removed and stomach opened to evaluate contents, which included 12 slimy sculpin, *Cottus cognatus* (USGS/A. Stanek).

mercury concentration. We can also compare these biomagnification rates across lakes and relate them to the lake environment (Kozak et al. 2021).

By examining the diets of lake trout, we can determine what food items are likely sources of mercury and how much individual dietary variation contributes to mercury concentrations. In the field, biologists evaluated lake trout stomach contents to rapidly evaluate their food items so that lake-specific prey could be targeted for collection. Using stable isotopes of carbon and nitrogen as diet tracers, we will be able to determine from what lake zone (e.g., littoral or pelagic) lake trout get their energy and mercury. Variation in diet and foraging location can affect the concentrations of mercury in lake trout (Chételat et al. 2021, Lepak et al. 2022).

3. Identify lake trout characteristics that provide information about exposure.

We will evaluate the potential use of visible characteristics of lake trout or their habitat as a means of identifying mercury exposure to human consumers (Figure 7). State and federal agencies provide guidance or issue advisories to warn people about the potential of mercury contamination, but guidance is often issued on a taxa-specific level (either by species or groups, like trout) for freshwater fish. Advisories are often based on mean values of collected data, which may not be representative of a given fishing location. When an issue is known, guidance can be provided for specific lakes, as was done in Wrangell-St. Elias National Park and Preserve based on the findings of a previous USGS study (Kowalski et al. 2014). However, mercury levels in fish are generally unknown for unstudied lakes in remote locations.

There are several potential indicators—fish length, weight, and body condition or morphology, and habitat of capture (e.g., deep versus shallow water)—that may be used by anglers and subsistence fishers to assess their level of exposure. Length and weight are often correlated with age and can serve as strong indicators of mercury concentration (Thomas et al. 2020, Johnston et al. 2022). Studies have found that skinny fish (poor body condition) have higher mercury concentrations (Bartz et al. 2023). The habitat use of fish may also influence their diet and body morphology (Chavarie et al. 2013) and, therefore, their mercury concentrations. There is little consistency, however, across locations for the role habitat plays, with predator fish sometimes having higher concentrations when using open-water habitats, while others have higher

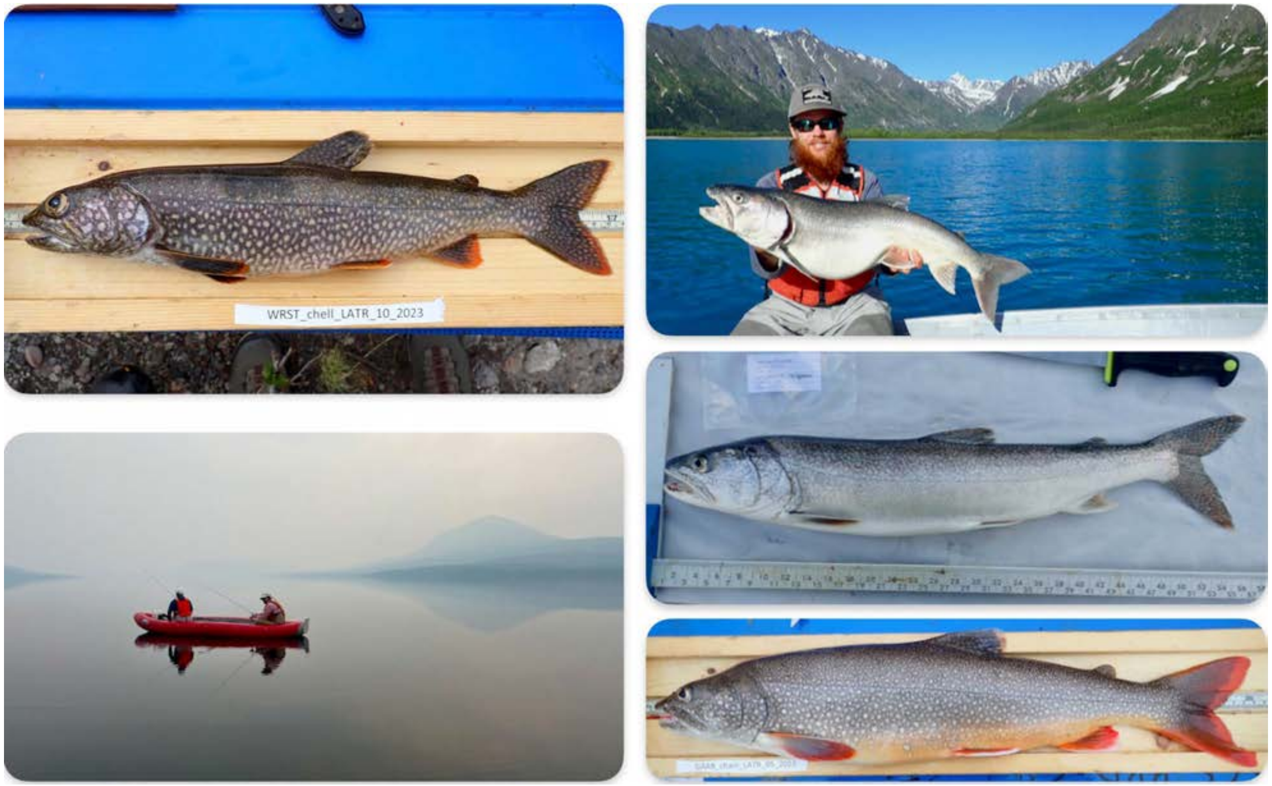

Figure 7. Potential indicators of lake trout mercury concentration include length, weight, body condition or shape, or their habitat.

Clockwise from top left: A lake trout captured from Chelle Lake (USGS/A. Stanek); Chelle Lake is shallow, with a maximum depth less than 33 feet (10 m). A National Park Service biological technician holds a 33-inch (83 cm) lake trout from Telaquana Lake that weighed in at 15 pounds (6.8 kg; NPS/D. Forster). A skinny, 23-inch (58 cm) lake trout captured from Telaquana Lake weighed just under 3 pounds (1.4 kg; NPS/J. Kramer). A lake trout from Chandler Lake shows body morphology characteristics that are known to bottom foraging fish: a deeper head, eyes high on the head, thick tail, and red coloration on the fins (Chavarie et al. 2013; USGS/S. Laske). Biologists jig for lake trout 100 feet (30 m) below the surface of Nutuvukti Lake (NPS/D. Young).

concentrations when using bottom habitat (Chételat et al. 2013, Thomas et al. 2016).

What's Next

Now that samples have been collected and analyzed, our focus is on interpreting our findings and sharing information with resource managers and the public by publishing open-source (free to the reader) data and articles and presenting findings to communities in and around the parks. Information on the project and links to data and publications can be found online as they become available (USGS 2024).

Acknowledgements

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Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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Hyperabundance of a Native Species: Pink Salmon in Sitka National Historical Park

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Hyperabundance of native species within their natural range can pose a difficult management challenge. This study examines the case of pink salmon in Sitka National Historical Park's Indian River. Though native to the river, numbers of pink salmon returning to spawn in late summer have grown exponentially in recent decades, putting other fish species that are reliant on the river at risk. This article explores the drivers and context of this hyperabundance.

Citation:
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Since its inception, the National Park Service (NPS) has operated under a mandate to "preserve unimpaired the natural and cultural resources" under its stewardship. For fish, wildlife, and other natural resources, this mandate calls for maintaining abundances within a "natural range of variation" (NPS 2025a). Pursuant to this, park managers are often confronted with either the scarcity of native plant or animal species or an abundance of non-native (exotic, invasive) species that may damage park ecosystems. However, ecosystems can also experience the hyperabundance (i.e., abundance far beyond the established range of densities) of a native species, due to shifting regional trends in habitat suitability, direct (and often anthropogenic) intervention, or a combination of the two.

For example, in Yellowstone National Park, native mountain pine beetles (*Dendroctonus ponderosae*) have recently decimated coniferous forests due to a lack of cold winter temperatures, which have traditionally limited the insects' numbers and, by extension, their impacts on forests (Gibson et al. 2008). Likewise, in many midwestern and eastern parks, habitat alterations and the extirpation of natural predators outside park boundaries have led to unprecedented densities of white-tailed deer (*Odocoileus virginianus*), capable of intense foraging on vegetation and the depletion of resources on which other species depend (Miller et al. 2023).

The question of when a species exceeds their natural range of abundance can be difficult to ascertain. In the case of the mountain pine beetle, numbers of the insects are on the rise throughout the Rocky Mountains due to shifting climate patterns (Gibson et al. 2008). Is this then an "unnatural" hyperabundance, or is it representative of a new natural state? Numbers of white-tailed deer in midwestern and eastern parks have risen precipitously due to direct human interactions with local ecosystems (vis-à-vis the depletion of natural predators). When confronted with these and similar issues, park managers across the NPS must make careful and informed decisions using the best scientific information available to preserve natural resources. Ideas regarding the drivers of native species exceeding their natural range of abundance are central to the research presented in this article, with specific consideration given to how the effect of broad regional shifts and the effect of direct anthropogenic interventions might be distinguished and disentangled. At the Indian River in Sitka National Historical Park, recent decades have seen annual abundances of native pink salmon (*Oncorhynchus gorbuscha*, Cháas' [Tlingit]) increase dramatically. These

Pink salmon spawning at Indian River, Sitka National Historical Park, Alaska.
UNIVERSITY OF WASHINGTON/BRIAN MCGREAL

large salmon runs can put other resident aquatic species at risk by depleting in-stream dissolved oxygen concentrations. This risk is especially pronounced when these runs coincide with periods of low river flows. A large pink salmon run in 2013 led to a 37-day period in which dissolved oxygen concentrations in the Indian River were well below the threshold required for healthy physiological function in most freshwater species (Sergeant et al. 2017). These highly abundant runs may be influenced by the operations of a nearby hatchery, which rears and releases millions of pink salmon annually. Upon their return as adults, some of these hatchery-origin fish inevitably stray into the Indian River, thereby supplementing the abundance of wild-born fish (May and Westley 2024). However, monitoring efforts from the Alaska Department of Fish and Game (ADFG) show pink salmon abundances on the rise throughout Southeast Alaska, indicating that the conditions in the Indian River may not be due to the influence of the hatchery and instead may reflect the current state of nature in the wider region (ADFG 2025). The intention of this study is to parse this question, and to determine if hatchery releases effect Indian River pink salmon abundances in the context of broader regional trends.

Sitka National Historical Park is a 113-acre coastal park in southeast Alaska. It was designated a national monument in 1910 and a national historical park in 1972 to conserve the site of an 1804 battle between the Native Tlingit Tribe and Russian settlers. The park receives nearly 400,000 visitors each year who learn about the history of the Sitka Tribe of Alaska and Tlingit culture. Along with the preservation of cultural resources related to the site, the park is also managed to conserve its mature spruce-hemlock forest, riparian ecosystem, and the Indian River, which includes a section of the main reach and the intertidal area that falls within the park boundaries (NPS 2025b).

For perhaps 5,000 years, the Indian River (Kaasda Héen [Tlingit]) has been the location of a fishing camp and harvesting site for one of the Tlingit clans (Thornton 1998). The river was particularly valued for its proximity to the clan's permanent and winter villages, as well as for hosting runs of Pacific salmon species, including chum (*Oncorhynchus keta*, Téel [Tlingit]), coho (*O. kisutch*, L'ook [Tlingit]), chinook (*O. tshawytscha*, T'á [Tlingit]), and pink salmon (Thornton 1998). Pink salmon, the most abundant species of salmon, typically return to spawn in late summer (Ruggerone et al. 2025). When the eggs hatch in the spring, juvenile pink salmon emerge from the river gravel and immediately migrate to the ocean, with all members of a brood returning to spawn as adults two years later (Quinn 2018). This leads to two genetically distinct runs occurring in even numbered and odd numbered years, each with its own characteristic abundance (ADFG 2024a).

Pink salmon in Southeast Alaska are an important food resource for predators and scavenging wildlife, providing a vector for marine-derived nutrients to make their way into riparian ecosystems (Brandt et al. 2024). Historically, Indian River pink salmon held special importance for Tlingit fishers, as they were the first salmon to appear each year (Thornton 1998). Today these fish provide an opportunity for visitors to the park to connect with ideas of stewardship and conservation by observing the spawning salmon from a footbridge that spans the river. Although pink salmon have always been abundant in the Indian River, their numbers have increased rapidly in the last several decades (Figure 1). The ADFG

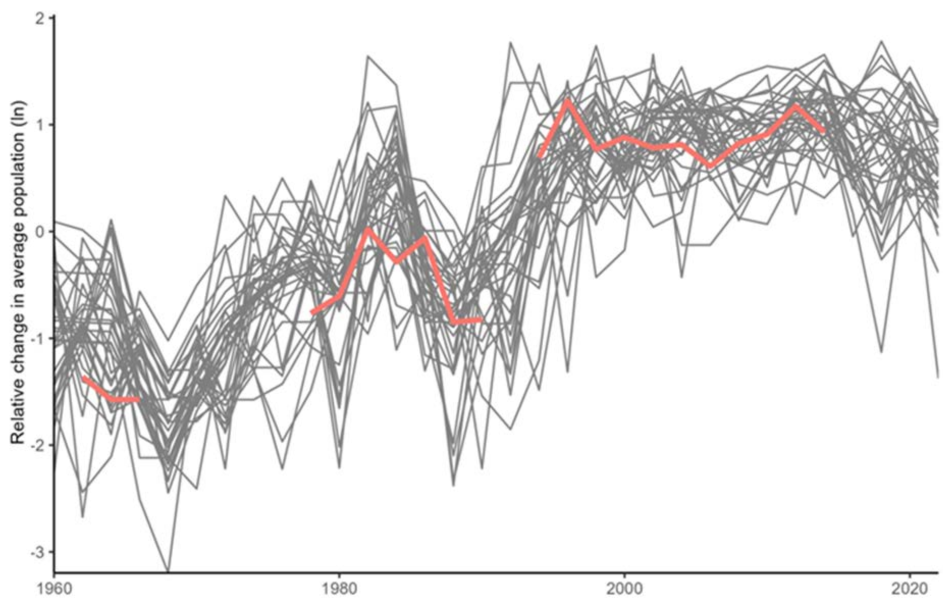

Figure 1: Pink salmon population abundance at 35 index streams in southeast Alaska and Indian River (even year runs). Data is sourced from Alaska epartment of Fish and Game. bundance estimates are scaled by stream length and tatistically standardized for ease of comparison. Therefore, a positive value is above a particular stream's average abundance, and a negative value is below. Indian River highlighted in pink.

peak escapement surveys (numbers of fish that have "escaped" the fishery and returned to spawn in the river) demonstrate that since 1980, pink salmon abundance has increased from several thousand to regularly exceeding 100,000 fish annually (Stopha 2015). Moreover, there are indications that the duration of pink salmon spawning, formerly limited to August and September, now regularly spans July through October.

High salmon densities in the river may be naturally occurring phenomena, influenced by variation in stream conditions, ocean productivity, predation intensity, and commercial harvests, among other factors (Manhard et al. 2017). However, salmon hatcheries can also influence the abundance of salmon (Knudsen et al. 2021). As part of typical hatchery operations, fish embryos are protected from natural mortality during incubation, and juvenile salmon are reared in relatively low-mortality raceways and net pens before they are released into the ocean to feed, grow, and later return (Stopha 2015). Due to the natural homing ability of salmon, adult fish, having imprinted on the chemical signatures of the water in which they were reared, return to their hatchery of origin when they are prepared to spawn. Therefore, if all salmon reared in a hatchery returned to that hatchery as adults, then population dynamics of salmon in adjacent stream systems would be independent of hatchery operations. In practice, however, homing by salmon is not perfect, and some fish produced in the hatchery will inevitably stray into nearby streams and rivers when returning as adults. Although it is difficult to infer whether straying is more or less likely in hatchery-origin fish, homing imperfection is likely an evolved trait as it allows a few fish to colonize new habitats when they become suitable for spawning (Quinn 2018). Nevertheless, hatchery and fishery managers typically aim to minimize straying rates, both to maximize the returns to the hatchery and to reduce the chances of hybridizing hatchery and wild fish, as hybridization can produce offspring that are less adapted to local conditions and thus have lower fitness (May and Westley 2024).

At Sitka National Historical Park, the possibility of hatchery pink salmon straying into the Indian River is particularly high. The not-for-profit Sitka Sound Science Center operates a hatchery immediately adjacent to the park boundary, less than a mile from the Indian River estuary (Figure 2; Sitka Sound Science Center 2025). In general, the likelihood of hatchery raised pink salmon straying into nearby streams is influenced by the spatial proximity of those streams to the hatchery. The closer a hatchery is to a stream, the greater the chance hatchery fish will stray into that stream (Knudsen et al. 2021). Sitka Sound Science Center's hatchery has been in operation since 1975, a timeline which coincides with the increases in Indian River pink salmon abundances observed in the 1980s. The hatchery initially was permitted to rear and release 1 million pink salmon annually, a number that was increased to 3 million in 2010. The hatchery uses the Indian River, via a diversion upriver of the park's boundary, as the source of water for operations. This water is used to rear salmon fry, which imprint on its chemical signature, and is also released into the bay near the hatchery to attract returning adult fish, only a few hundred meters from the mouth of the Indian River. Some portion of returning adults are retained each year by hatchery technicians

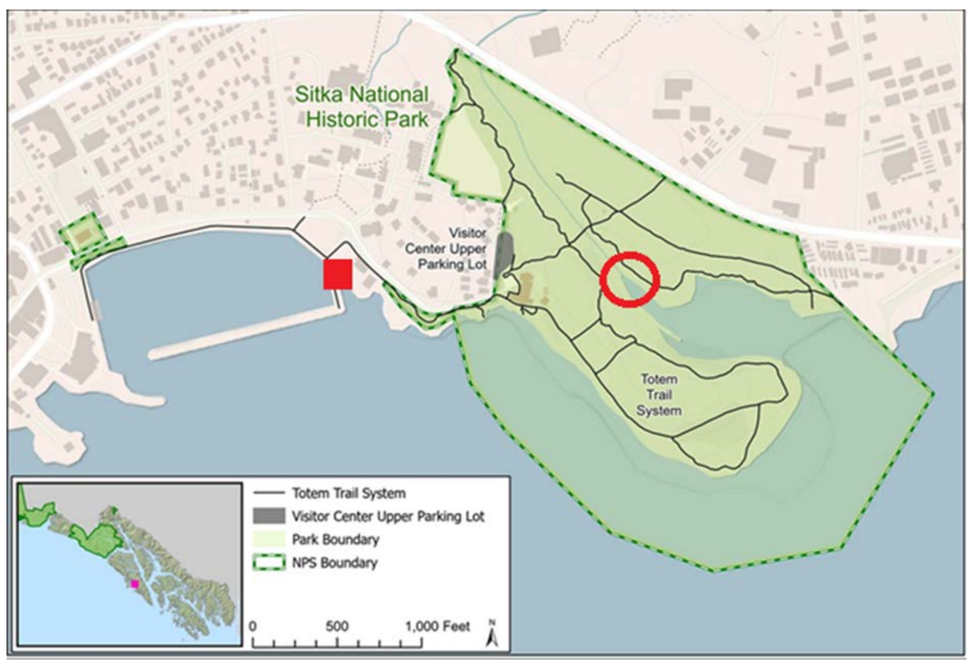

Figure 2: Location of Indian River mouth (red circle) and Sitka Sound Science Center (red square).
NATIONAL PARK SERVICE (NPS 2025C), MODIFIED.

as broodstock, from which the eggs that will grow into the next year's cohort of juveniles are extracted. Initial broodstock at the onset of hatchery operations came from the Indian River (even years) and nearby Starrigavan Creek (odd years; Stopha 2015).

Fisheries managers and biologists identify hatchery-produced salmon by otolith marking, a process in which small carbonate bodies located in the inner ears of fish are marked with a distinct pattern produced during incubation. To produce these markings, hatchery technicians expose salmon eggs to carefully controlled regimes of dry periods and periods submerged in water (Figure 3; ADFG 2024b, Stopha 2015). When salmon return to spawn as adults, the otoliths from the carcasses can be collected and sent to a lab to determine whether the adult fish sampled are of hatchery or wild origin. Surveying efforts in Indian River have at times noted high numbers of stray pink salmon from the hatchery, however, these rates vary depending on year and sampling period. For example, in 2015, hatchery strays made up approximately 33% of all individuals pink salmon sampled, while in 2011 hatchery strays represented less than 5% (Gende and Carter 2015). Likewise, large percentages of fish sampled returning to the hatchery are wild born, and, based on the proximity and linkages between the two sites, it is likely that these wild fish with no otolith marks may have originated in the Indian River.

Given the proximity of Sheldon Jackson Hatchery to Indian River, and given pink salmon's propensity for straying, the question of whether pink salmon originating from the hatchery but spawning in the Indian River are significantly contributing to the high densities

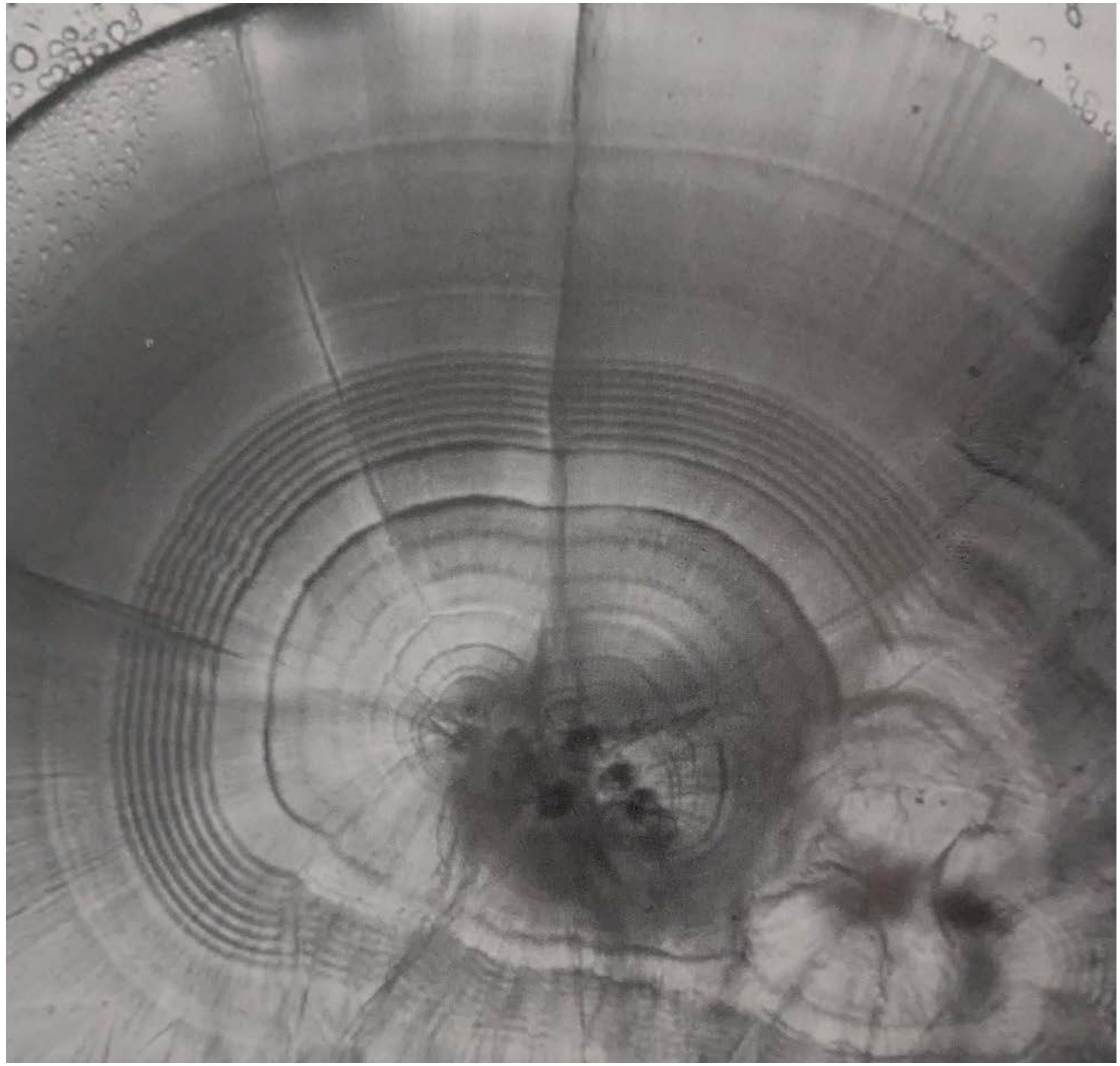

Figure 3: Otolith of a pink salmon fry from Wally Noerenberg Hatchery in Prince William Sound, Alaska, showing the regular rings produced by systematic changes in temperature to mark the fish.
ADFG/DION OXMAN

observed in recent years becomes germane. When salmon spawn, they remove dissolved oxygen from the water both through the direct consumption of oxygen while alive and through the respiration of decomposing microbes following their death (Sergeant et al. 2023). High salmon abundances occurring during periods of low river flows can reduce dissolved oxygen concentrations to levels below what is needed for resident fish and other aquatic life to survive, especially if these low flows coincide with warm temperatures (Sergeant et al. 2017). In stream systems free of hatchery influence, there are natural regulators (density dependence) that bring the population back into balance when the number of returning spawners exceeds a stream's carrying capacity. For example, at very high densities, females arriving later in a spawning season dig up nests (redds) made by early arriving females, so the stream has a natural limit to production (McNeil 1964). Hypoxia events are also not limited to stream systems in which natural abundances are supplemented by hatchery strays. In such an instance, females may die before spawning due to lowered oxygen levels (Tillotson and Quinn 2017). In either of these scenarios, the numbers of spawners returning in subsequent years would be constrained. These constraints weaken with the introduction of straying fish from hatcheries, and the question becomes whether these natural processes and resulting swings in salmon abundance, are exaggerated by strays from nearby hatcheries to the point where the stream ecosystem is disturbed.

Although fish originating from the hatchery may be contributing to the great abundance of pink salmon observed in recent decades at Indian River, it is also possible that the relatively low numbers of spawning pink salmon observed before 1980 may have been historically atypical, and current densities are within the natural range. During World War II, U.S. Navy contractors began dredging sand and gravel from the riverbed, as well as from a wooded island at the river's mouth, to build fortifications and an airport on nearby Japonski Island. National Park Service officials at the time believed that the removal of gravel contributed to several severe floods between 1940 and 1960 (Antonson and Hanable 1987). Even with the completion of those fortifications, gravel removal continued in the Indian River delta intermittently until 1960, and anecdotal accounts suggest the river may at times have been restocked with fish from other streams during this period. This gravel removal and the accompanying floods affected the geomorphology of the reaches of Indian River in what is now Sitka National Historical Park, shifting the mouth of the river and stripping away lowlands near the river's banks, impacting the quality of riparian habitat. Tlingit Elders have recalled that, before these dredging operations, the pink salmon runs at Indian River were so numerous that "it seemed like you should just be able to walk across the river on the humpies [pink salmon]" (Thornton 1998). It is possible that high pink salmon abundances observed in recent years are not an exception but a return to historical levels.

With all this in mind, how might park managers determine whether the abundances of pink salmon observed in recent years at Indian River are within some natural range of variation? Building a baseline picture of pink salmon abundance in the wider region could provide a useful basis of comparison. ADFG has monitored pink salmon streams in Southeast Alaska as far back as 1960 to manage escapement and regulate fisheries. It is worth noting that 1960 was the first year following the banning of salmon fish traps in Alaska, suggesting that salmon abundance may have been at a historical low point throughout the region (Colt 1999). This monitoring effort surveys 714 pink salmon index streams annually throughout Southeast Alaska via fixed-wing aircraft. A subset of these streams surveyed are subject to validation by foot counts to assess the accuracy of ADFG's aerial survey efforts (A. Dupuis – Alaska Department of Fish and Game, personal communication, August 19, 2024). Of these 714 index streams, ADFG places 35 within the "Northern Southeast – Outside" subregion—the ocean-facing coasts of Chichagof and Baranof islands (where the city of Sitka is located), as well as a few smaller islands in the vicinity. Abundances of pink salmon observed both in these 35 index streams as well as in the Indian River are displayed in Figure 1.

In 2023, the NPS entered into a partnership with U.S. Geological Survey and the University of Washington to evaluate Indian River pink salmon populations in the context of the broader region. Using statistical modeling, it is possible to estimate the annual abundance of pink salmon in the Indian River and to compare those estimates to pink salmon abundance in neighboring streams. The project will also explore the Indian River system in greater detail, with the goal of identifying what if any measurable impact hatchery releases have on abundances of spawning pink salmon entering the stream each year.

Part of the management challenge when confronted with hyper-abundant native species is assessing whether the abundances observed occur within some natural range of variation. The cases of the pine mountain beetle and white-tailed deer indicate that both local and global factors may drive the proliferation of native species within a park. Understanding whether the density of spawning pink salmon observed in recent years at Indian River is exceptional requires understanding both the general behavior of pink salmon in the region as well as the potential impact of direct influences such as hatchery releases. The intent of this research is to provide context and clarity to park officials regarding the pink salmon population in the Indian River to help maintain the healthy riverine ecosystem on which so many other resident species depend.

Acknowledgements

The work presented would not have been possible without support from Sitka National Historical Park management and biologists. Mary Miller, Olivia Magni, Jordan Tanguay, and Zachary Jones have provided substantial guidance in understanding the ecological and cultural history of the park and its neighbors. Lauren Bell, Bill Coltharp, and Haley Jenkins of the Sitka Sound Science Center have likewise offered invaluable perspectives and background regarding the history and current state of hatchery operations. Finally, collaboration from Alaska Department of Fish and Game biologists Aaron Dupuis and Justin Priest has enabled this work to compare Indian River pink salmon abundances to those seen elsewhere in the vicinity of Sitka, a vital component of this research. This research has occurred on the ancestral homeland and with the approval of the Sitka Tribe of Alaska.

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Exploring How Dolly Varden in Arctic Streams Respond to Changes from Permafrost Thaw

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The influence of permafrost thaw on aquatic ecosystems is complex. Carbon, nutrients, and metals in stream discharge result in changing stream color, chemistry, and temperature. These different processes create a mosaic of spatially and temporally dynamic disturbances across the landscape with complex effects on the ecology.

Citation:
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Arctic rivers and streams provide habitat for resident freshwater fish and fish that spend different life stages in freshwater and saltwater. Many of these fish species are important for subsistence and recreational harvest, such as Dolly Varden (*Salvelinus malma*). Due to the importance of Dolly Varden to aquatic ecosystems and people, it is imperative to understand what environmental factors influence their populations and anticipate future changes. One of the most pervasive disturbances occurring in the Arctic is permafrost thaw (Smith et al. 2022). *Permafrost* is ground that remains frozen year-round and is common in cold, high-latitude environments such as Alaska. Here, we discuss how disturbances from permafrost thaw affect fish in streams and rivers based on our research in Alaska's Arctic national parks.

Permafrost thaw influences Arctic streams and rivers by altering how water flows from terrestrial to aquatic ecosystems. Specifically, permafrost can limit water infiltrating into soils and control the depth of subsurface flow that the water follows before entering a stream (Toohey et al. 2016, Sjöberg et al. 2021, Koch et al. 2022). When permafrost soils thaw, water can infiltrate deeper in the soil and travel through deeper, longer flow paths. This shift in subsurface hydrology due to thaw has an impact on stream discharge, temperature, and chemistry (Vonk et al. 2015, Walvoord and Kurylyk 2016, Sjöberg et al. 2021, Koch et al. 2022). By modifying the hydrology, temperature, and water quality of Arctic rivers and streams, thawing permafrost is likely to have consequences for fish.

Dolly Varden use Arctic streams and rivers at multiple stages of their life history (Carey et al. 2021 and references therein) and can be affected by permafrost characteristics of watersheds (Carey et al. 2025). Dolly Varden is a cold-water, salmonid fish that lives in the north Pacific and Arctic oceans in Asia and North America. Migratory Dolly Varden spawn in freshwater streams, and young fish rear for two to five years before migrating out to productive coastal areas that allow them to grow rapidly. Thereafter, Dolly Varden feed annually in saltwater during summer and migrate to freshwater systems each fall to overwinter or spawn, following an amphidromous life history strategy. While this amphidromous life history is common, Dolly Varden have other life history strategies that rely on Arctic rivers and streams for habitat (Carey et al. 2021). For example, Dolly Varden can exhibit partial migration (where only part of the year class migrates), skip spawning (after entering freshwater, adult fish spend a year in freshwater before spawning), or complete their life cycle in freshwater (i.e., resident populations). Therefore, many Arctic streams are continuously inhabited by Dolly Varden in various life stages.

An orange tributary flows into the Kugururok River, Noatak National Preserve.
USGS/JOSHUA KOCH

Arctic landscapes in Noatak National Preserve.

Polygonal ground in the Cutler River watershed indicating the presence of ice-rich permafrost (above left).
USGS/JOSHUA KOCH

A headwater stream in the Agashashok River watershed (above right).
USGS/MICHAEL CAREY

Dolly Varden caught in Cape Krusenstern National Monument.
NPS/JONATHAN O'DONNELL

How Dolly Varden respond to changes in stream hydrology and chemistry from permafrost thaw is difficult to predict due to the complex changes in physical, chemical, and ecological conditions (Carey et al. 2025). Moreover, changes driven by permafrost thaw could be experienced differently across life history types and stages making it more difficult to predict the outcomes for Dolly Varden populations. By altering stream conditions, thawing permafrost creates different types of disturbances including press disturbances that occur continuously over time, pulse disturbances that are discrete and often abrupt events, and ramp disturbances that are increasing in severity and spatial scale (Figure 1; Lake 2000). Categorizing the different disturbances depends on the spatial and temporal scope of interest. Regardless of the type of disturbance, differences in permafrost create a mosaic of disturbances across the landscape with complex effects on Dolly Varden that we are currently researching on park lands.

Stream Temperature and Productivity Acting as Press Disturbances

Stream temperatures are influenced by permafrost characteristics at the catchment scale. Permafrost thaw creates a press disturbance by altering the thermal regime for Dolly Varden. Groundwater that enters streams from longer and deeper flow-paths due to less permafrost reduces stream temperatures in the open-water season by keeping the water colder as the groundwater moves to the stream (Sjöberg et al. 2021). Furthermore, catchments with less permafrost often have more vegetation that cools streams through shading. Thus, as permafrost thaw increases, streams may become cooler during the open-water season for fish. Conversely, permafrost characteristics that restrict water to shallow subsurface flow paths lead to warmer stream water.

In recent work in Noatak National Preserve, water temperatures of Arctic streams have a strong relation with Dolly Varden abundance and biomass (Carey et al. 2025). The importance of temperature is expected because water temperature influences fish metabolism, energetic content, and growth (Magnuson et al. 1990); however, the direction of the relationship was surprising because headwater streams that were warmer on average have less Dolly Varden biomass (Carey et al. 2025). In cold Arctic streams, warmer water was expected to be beneficial to Dolly Varden by supporting more fish growth and increasing food web productivity by increasing water temperatures closer to optimal temperature (Armstrong et al. 2021, Thomas et al. 2025). We suspect the counterintuitive relationship between Dolly Varden biomass with water temperature in these headwater streams is driven by differences between the optimal temperature for Dolly Varden growth and the range of temperatures fish experience during the open water season (Takami et al. 1997, Bozeman and Grossman 2019).

The relationship of Dolly Varden with water temperature raises the questions of whether food resources are sufficient to support the elevated metabolism of fish in warmer water and if cooler waters may be more bioenergetically favorable in low-productivity streams. Sorting out the effect of temperature and productivity is complicated by the fact that permafrost thaw can also increase productivity. Again, by affecting the subsurface flow-paths, permafrost influences the transport and

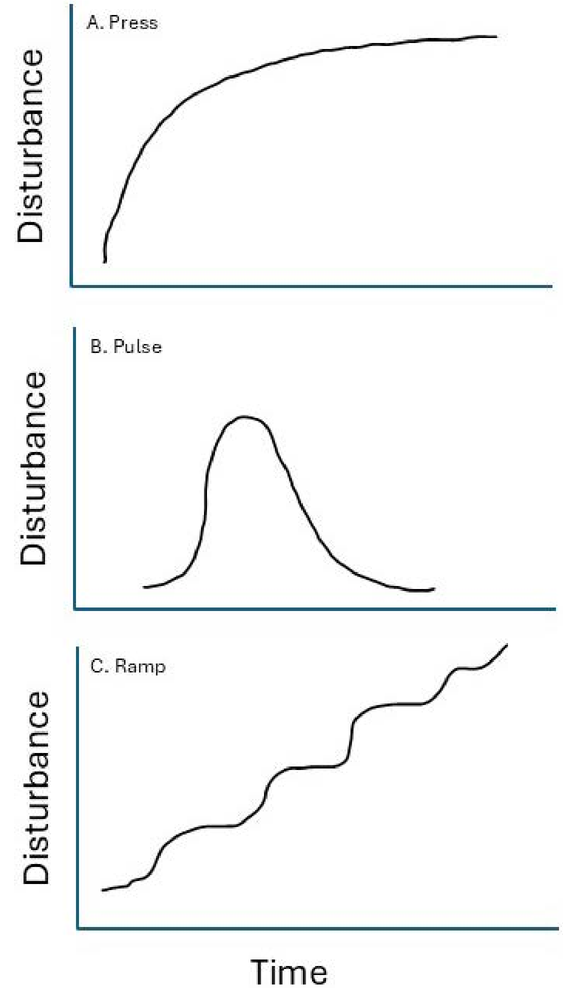

Figure 1. Examples of temporal patterns for (A) press, (B) pulse, and (C) ramp disturbances. A press disturbance occurs continuously over time, pulse disturbances are discrete and abrupt events, and ramp disturbances increase in severity and spatial scale. There are other temporal patterns for each type of disturbance.

A tributary of the Salmon River, Kobuk Valley National Park.
USGS/MICHAEL CAREY

cycling of carbon (both organic and inorganic), nutrients (nitrogen, phosphorus), and other elements as they move through soils to streams (Koch et al. 2013, O'Donnell et al. 2016). The depth of the subsurface flow paths determines whether lateral flow is routed through shallow organic soils or deeper mineral soils, thereby determining what solutes are transported to streams. Carbon and nutrients can also be sourced from the thawing permafrost itself (e.g., Wickland et al. 2018). Permafrost thaw can then create a bottom-up effect on the aquatic food web by more carbon and nutrients increasing the amount of benthic biofilm that supports more macroinvertebrates. A larger forage base for macroinvertebrates may then support a higher biomass of Dolly Varden. More carbon and nutrients entering streams from permafrost thaw have been observed propagating up through aquatic food webs in Arctic streams of Alaska (O'Donnell et al. 2020, Carey et al. 2025). The interacting effect of temperature and productivity of Arctic rivers and streams driven by differences in permafrost characteristics is a topic that we are actively researching.

Streamflow Variability Can Create Pulse Disturbances

Variability in Arctic streamflow is influenced by permafrost characteristics of the surrounding watershed and can create pulse disturbances affecting multiple life history stages of Dolly Varden. Specifically, as permafrost thaws and vegetation grows, water can percolate into deeper soil layers or be lost to evapotranspiration, reducing the amount of water reaching headwater streams and influencing stream hydrology, a phenomenon recently documented in headwater streams of Arctic Alaska (Koch et al. 2022). Low streamflow or drying reduces habitat for Dolly Varden and limits connectivity to critical habitat for rearing or spawning fish potentially reducing populations. Low streamflow and drying impact macroinvertebrate communities with potential negative effects on Dolly Varden populations due to a reduced forage base. Low streamflow can also influence water temperatures leading to warmer and more variable water temperatures interacting with the cooling effect mentioned above. Conversely, permafrost presence may result in high runoff rates, when high streamflow can scour stream beds after fish spawn and during the egg incubation period resulting in egg mortality. High streamflow can also increase the amount of sediment deposition on eggs, again leading to mortality. At the juvenile stage of Dolly Varden, high stream flow that affects water velocity can alter drift feeding success, energetic costs of feeding in the stream, and directly impact the macroinvertebrates themselves creating differences in prey availability. Overall, in Arctic headwater streams, higher variability in streamflow creates a harsher environment that is more energetically costly for juvenile fish (Carey et al. 2025).

Metals Derived from Thawing Permafrost Generate a Ramp Disturbance

The recent, emergent phenomenon of rusting rivers driven by metals, previously immobilized in frozen ground, being transported to streams from thawing permafrost is creating a ramp disturbance in the chemistry of Arctic rivers (O'Donnell et al. 2024). An increasing number of watersheds have been identified in the last decade with impaired, metal-laden water that often deposits iron oxides on stream beds, passivating the hyporheic zone. Metal seeps are hypothesized to be a result of thawing permafrost and deeper subsurface flow paths that can promote chemical weathering of minerals and groundwater transport of metals to streams including iron and many other metals such as aluminum, selenium, zinc, and copper. Within a watershed, these localized changes occur abruptly and can present as a press or pulse disturbance that combine across the landscape as a ramp disturbance.

The occurrence of a rusting river has led to the loss of fish habitat for Dolly Varden and speculation on possible toxic effects (O'Donnell et al. 2024). In a small tributary of the Akillik River in Kobuk Valley National Park, there was an abrupt shift from clear to rusting waters with an increase in total iron concentrations from below detection (<50 µg/L) to 500 µg/L, and concurrent decreases in pH (7.5 to 6.7; O'Donnell et al. 2024). Food web changes were observed from the degraded water quality including the loss of juvenile Dolly Varden, a reduction in macroinvertebrates, and a decrease in primary producers in the tributary (O'Donnell et al. 2024). The degraded water quality coincided with the loss of macroinvertebrates from the orders of Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies; Carey et al. 2024). Under the degraded water quality conditions, the primary producers were covered in an iron precipitate making them difficult to measure reliably.

Key questions remain about the processes driving the short- and long-term effects of elevated iron and other co-mobilized trace metals on Dolly Varden. In particular, could the negative effects of iron toxicity for fish that have been observed in laboratory studies (Egnew et al. 2021) occur in these Arctic streams and rivers? For example, iron accumulation in gills, liver, and muscle tissue of fish has led to structural impairment of the gills, DNA damage, and decreased survival (Egnew et al. 2021). Metal can also affect fish that spawn in these rivers by limiting water, heat, and nutrient transport through the hyporheic zone in which eggs are laid and develop. Moreover, assessing the downstream fate of more mobile elements released, for example selenium, zinc, and nickel, will be critical to identify the spatial extent of the impact. Scientists and park managers are concerned that the rusting of Arctic rivers may reduce habitat for Dolly Varden and threaten subsistence activities.

Summary

Permafrost thaw is one of the most pervasive changes occurring in the Arctic, and these changes on the landscape influence Arctic streams and rivers by altering how water flows from terrestrial to aquatic ecosystems. By altering the characteristics of Arctic streams, permafrost thaw has consequences for aquatic food webs including fish. Dolly Varden is an important subsistence fish that uses Arctic streams during different stages of its life history and is influenced by changes to aquatic ecosystems. The influence of permafrost thaw on aquatic ecosystems is complex, resulting from disturbances such as changing stream discharge and temperatures, as well as modified delivery of carbon, nutrients, and metals to streams (Table 1). These different processes create a mosaic of spatially and temporally dynamic disturbances across the landscape with complex effects on Dolly Varden. Developing a mechanistic understanding of how these changes interact to influence Dolly Varden can help predict the outcome of the rapid changes occurring in these ecosystems and fulfill the mission of the Arctic parklands to protect habitat for subsistence activities.

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Table 1. Examples of disturbances resulting from permafrost thaw that can alter Arctic streams. The thaw-driven processes change stream conditions that govern Dolly Varden growth, productivity, and habitat use. The spatial and temporal scope of interest influences a researcher's perception of the disturbance type.

Type	Thaw-driven Process	Key Stream Changes	Dolly Varden Effects
Press	Deeper flow paths	Colder water temperatures	Optimal growth conditions
Press	Deeper flow paths	Increased carbon and nutrients	Higher fish biomass
Pulse	Infiltration, evapotranspiration	Decreased stream flow	Reduced connectivity and habitat loss
Ramp	Metal mobilization	Impaired water quality*	Habitat loss and toxicity

*Water quality is an example that could also be classified as a pulse disturbance depending on spatial and temporal scale of interest.

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Investigating the source of an orange stream.
USGS/JOSHUA KOCH

Intertidal Community Responses to Perturbations Along Alaska Park Coastlines

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Nearshore ecosystems are highly productive zones with strong connections to both terrestrial and open ocean ecosystems. The rocky intertidal is a highly dynamic ecosystem and changes over a variety of spatial and temporal scales depending on the factors contributing to the change. Here we summarize how nearshore communities and species responded to several perturbations to intertidal communities within Alaska's coastal national parks.

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Nearshore ecosystems are highly productive zones with strong connections to both terrestrial and open ocean ecosystems. Within the nearshore, the intertidal zone, defined as the area uncovered during low tide, is a valued and recognized area by visitors to many coastal parks. Macroalgae (seaweeds) and invertebrates, including mussels, barnacles, and sea stars, are important members of the intertidal community and tend to be well adapted to stressful conditions, including desiccation and highly variable temperatures. Intertidal communities can be shaped by predation and competition for food and space can be intense in the intertidal zone. Vertebrate predators also use this zone, including many fishes, birds, sea otters (*Enhydra lutris kenyoni*), bears, and humans, all of which may look to intertidal habitats for easy-to-access food. In the Gulf of Alaska, the intertidal zone includes stretches of rocky and mixed-substrate coastline, where primary producers like rockweed (*Fucus distichus*) and primary consumers like mussels form the base of a complex food web. The rocky intertidal, a highly dynamic ecosystem, changes over a variety of space and time scales depending on the factors contributing to the change.

Here we summarize how nearshore communities and species responded to several perturbations to intertidal communities within Alaska's coastal national parks, which have been documented by teams of U.S. Geological Survey (USGS) and National Park Service (NPS) scientists, as well as collaborators such as the University of Alaska Fairbanks, over decades of research and monitoring efforts.

The Exxon Valdez Oil Spill

One significant, human-caused disturbance to intertidal communities was the *Exxon Valdez* oil spill (EVOS). In the spring of 1989, the oil tanker Exxon Valdez ran aground in Prince William Sound, spilling 11 million gallons of crude oil (Spies et al. 1996). The oil spread throughout the Gulf of Alaska and the Alaska Peninsula, including coastlines of Kenai Fjords National Park and Katmai National Park and Preserve. Intertidal communities were particularly affected by initial, direct effects of the spilled oil, as well as by intensive clean-up efforts such as washing the intertidal with pressurized hot water. For example, rockweed was damaged by the oil spill, with reduced abundance and reproductive potential, particularly at higher tidal elevations (Stekoll and Deysher 2000). Reductions in rockweed in combination with loss of invertebrate grazers such as limpets and periwinkles led to increases in ephemeral algae and barnacles in years following the spill (Peterson et al. 2003). Though rockweed had appeared to recover from the spill by the 1990s, because the recovered rockweed were all the same age, they senesced simultaneously, leading

Pressure cleaning rocks in the Prince WIlliam Sound intertidal zone.
EXXON VALDEZ OIL SPILL TRUSTEE COUNCIL

to a synchronous die off, and recovery to pre-spill cover was delayed (Peterson et al. 2003). Predators that feed in the intertidal zone also had delayed recovery because of continued exposure to lingering oil and because their prey were still recovering. Most of the lingering oil was sequestered in intertidal sediments. The slow recovery of sea otters in western Prince William Sound, which was heavily oiled, was related to reduced survival rates (Monson et al. 2000, 2011) and food limitation (Dean et al. 2002). Sea otters spend a lot of time foraging in the intertidal zone (Bodkin et al. 2012) and in some of the most heavily oiled areas, may have been exposed to lingering oil for 20 years following the spill. Harlequin ducks (*Histrionicus histrionicus*), whose prey includes invertebrates that live in sediments, had higher levels of a biomarker indicating exposure to hydrocarbons for decades, with no apparent decline in exposure until 24 years after the spill (Esler et al. 2016). For the duck Barrow's goldeneyes (*Bucephala islandica*), it took up to 20 years for oil exposure to decline to levels similar to non-oiled sites (Esler et al. 2011). Barrow's goldeneyes feed on mussels, which had decreasing hydrocarbon amounts 20 years after spill. Due to the large volume of the spill and the deposition of oil along the shoreline, the EVOS impacted intertidal and nearshore resources for decades, with only recent recovery of some injured resources (Esler et al. 2018). In response to the oil spill, federal agencies and Universities built off existing long-term datasets to begin a long-term monitoring program called Gulf Watch Alaska funded by the *Exxon Valdez* Oil Spill Trustee Council to track recovery of injured resources and ecosystems. This long-term monitoring program has also enabled scientists to analyze the effects of other changes in intertidal ecosystems, including heatwaves, disease outbreak, and changes in predator abundance.

The Pacific Marine Heatwave

The Pacific Marine Heatwave lasted from 2014 to 2016, 2-10 times longer than any other marine heatwave across the globe in the last decade, and was the only marine heatwave, globally, to last through all four seasons (Hobday et al. 2018) resulting in a significant perturbation to the marine ecosystem. Sea surface temperatures reached 2.5°C above normal (Amaya et al. 2020). The pelagic ecosystem in many areas of the Gulf of Alaska was negatively affected by the heatwave, with declines in forage fish leading to mass die-off of birds and declines in whales (Arimitsu et al. 2021, Suryan et al. 2021). However, intertidal communities responses were more mixed (Figure 1). For example, high temperatures during the heatwave led to declines in rockweed and other macroalgae, which created open space that was colonized by barnacles and mussels (Weitzman et al. 2021). This represented a regime shift because it changed the type of cover and thus habitat and prey available to higher trophic levels in the intertidal. This pattern was also documented in other north Pacific rocky intertidal systems (Meunier et al. 2024). In sharp contrast to the large scale die-offs of pelagically foraging seabirds owing to drops in forage fish, nearshore benthivorous birds, including sea ducks and shorebirds, did not have strong negative responses to the heatwave (Robinson et al. 2023). This is likely because their prey taxa, including mussels, clams, and limpets, did not decline during and after the heatwave, and even increased in some cases (Robinson et al. 2023). Marine heatwaves are predicted to increase in frequency and intensity (IPCC 2019), and shifts in community structure should continue to be monitored over time as warming and other climate driven perturbations continue.

Sea Star Wasting Disease

Around the same time as the Pacific Marine Heatwave, another large-scale perturbation was affecting intertidal communities in the Gulf of Alaska—the sea star wasting disease epidemic. Sea stars with wasting disease develop lesions on their bodies, their arms detach, and the stars die (Figure 2). Onset of the disease is associated with changing microbial assemblages on the stars' surface and elevated organic matter in the water (Aquino et al. 2021) and is caused by the bacterium *Vibrio pectenicida* (Prentice et al. 2025). While the sea star wasting epidemic began in 2013 in California and Oregon, it reached Alaska later, between 2014 and 2016 in different parts of Alaska (Dawson et al. 2023). The sea star wasting epidemic resulted in dramatic declines in sea star abundance across the Gulf of Alaska, including coastal national parks (Konar et al. 2019). Affected species included the mottled star (*Evasterias troschelii*), the sunflower star (*Pycnopodia helianthoides*), and the ochre star (*Pisaster ochraceus*). These are important predators of invertebrates in the intertidal zone, particularly on taxa that can dominate space, including mussels and barnacles. Sea stars sometimes can act as keystone species in the intertidal, meaning that they have a strong effect on community structure, even though they are not the most abundant member of the community. Predation from sea stars can prevent mussels from taking over intertidal habitat and excluding other species. Reduced predation from sea stars due to the epidemic likely benefited mussels, allowing better

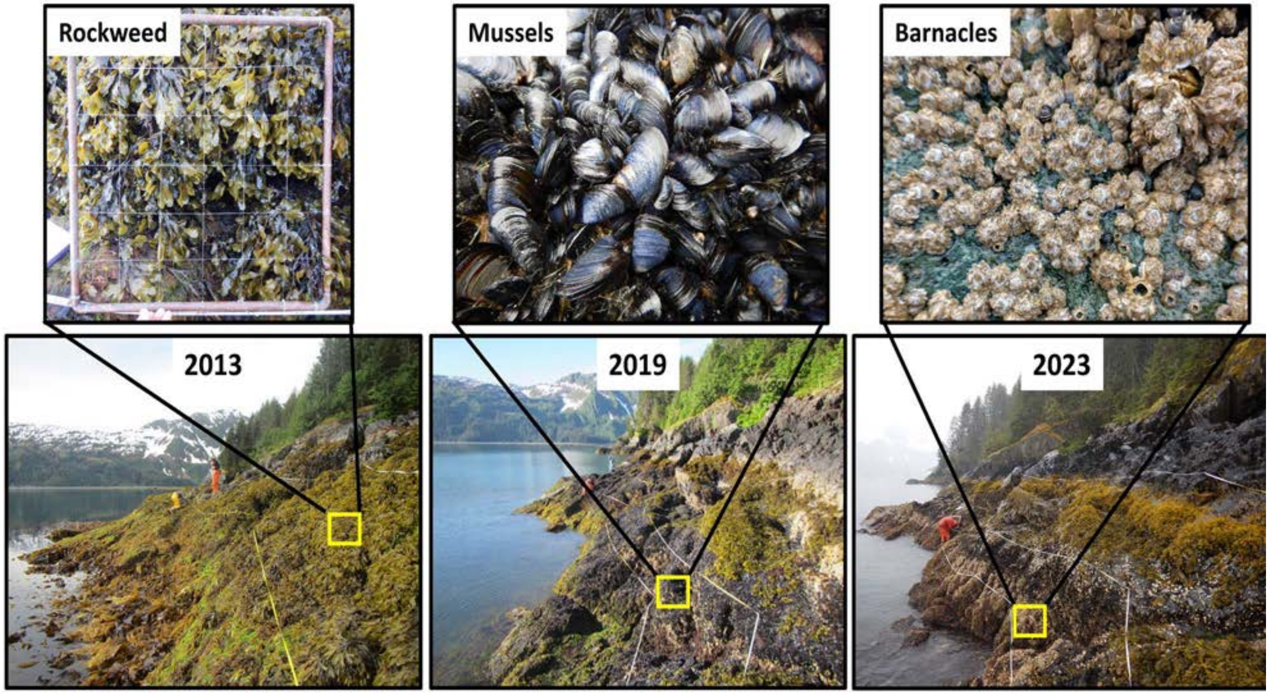


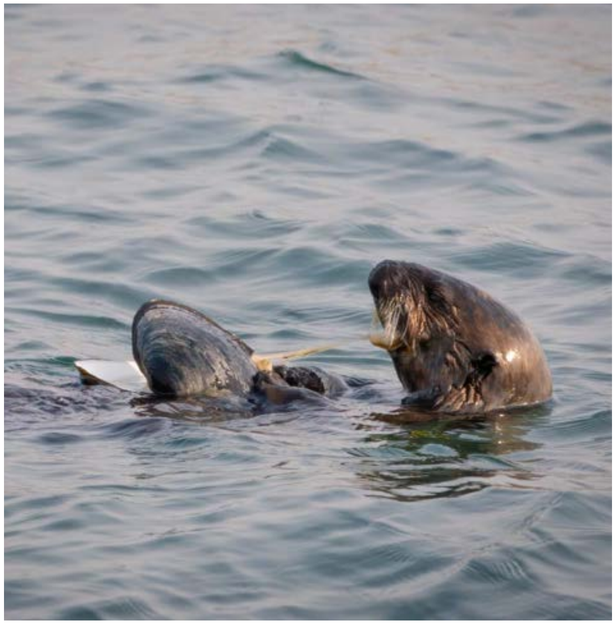
Figure 1 (above). Changes in the intertidal community at Harris Bay in Kenai Fjords National Park over several years demonstrating a regime shift that occurred as a result of the Marine Heat Wave (2014-2016) whereby intertidal communities shifted from dominance by a macroalgae to invertebrates (Traiger et al. 2023). The yellow box in each photograph indicates a location at approximately the same tidal height, between 0.5 m and 1.5 m above mean lower low water.

Figure 2 (right). A wasting sunflower star in Katmai National Park and Preserve in 2023.
USGS

survival. At the same time, more space was available in the intertidal for mussels to expand, due to declines in macroalgae during the Pacific Marine Heatwave (Weitzman et al. 2021). Thus, these two large-scale perturbations combined to result in increased mussel abundance across the Gulf of Alaska (Traiger et al. 2022).

Changes in Sea Otter Populations

Changes to sea otter populations are another source of perturbation to intertidal communities. By the beginning of the 20th century, the maritime fur trade resulted in the near extinction of sea otters across the north Pacific (Kenyon 1969). In many areas of coastal Alaska, including several national parks, sea otter populations have successfully recovered in the past few decades. As another keystone species, sea otters are well-known to have strong top-down effects on nearshore marine communities (Estes and Duggins 1995). Through a strong collaboration among agency and academic scientists, researchers have been documenting effects of this keystone predator on intertidal communities for over 50 years. The general pattern that emerges is that during initial reestablishment of a sea otter population, sea otters first target the most profitable prey, i.e., those that are large (high calorie) and easily accessible (Ostfeld 1982, Leach et al. 2024). This can have strong effects on the size and abundance of invertebrate prey, including intertidal and subtidal clams (Kvitek et al. 1992, Hale et al. 2019). In turn, reductions in prey abundance and size affect how hard otters must work to meet their energetic needs (Coletti et al. 2016). Sea otters can also adjust their consumption of intertidal prey, like mussels, following changes in abundance (Smith et al. 2025). Sea otters can offer numerous ecosystem services through their foraging behaviors, such as increasing genetic diversity of eelgrass (*Zostera marina*) through disturbance (Foster et al. 2021), increased climate resilience for kelp forests and temperate reef systems (Rasher et al. 2020, Nicholson et al. 2024), and increasing abundance of kelps by reducing grazing invertebrates (Estes and Palmisano 1974) which allows for increased biodiversity (Estes and Duggins 1995). Overall, studies have led to significant insights into relationships between sea otters and their prey, and the ecosystem consequences of those relationships in coastal areas, including parks. As sea otters continue to recover from the maritime fur trade throughout their historical range, long-term monitoring will provide additional insights into how ecosystems function and intertidal taxa are affected once the presence of sea otters is restored.



Sea otter eating a clam.
PHOTO COURTESY OF NICOLE LAROCHE

Long-term research and monitoring conducted by USGS and the NPS Inventory & Monitoring Program, in collaboration with scientists from University of Alaska Fairbanks, U.S. Fish & Wildlife Service, and National Oceanic and Atmospheric Administration (NOAA), within Alaska's coastal National Parks has described and quantified changes in nearshore ecosystems over multiple decades, spanning several perturbations. This long-term monitoring provides a basis for interpretating how these systems function and allows predictions about how they will respond to future perturbations of varying types, from large-scale climactic perturbations to smaller-scale point source disturbance. These research and monitoring efforts contribute to the responsible management of nearshore resources within parks and provide broader perspective on the scale of various perturbations and potential timelines to recovery.

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Mussels, seaweed, and barnacles in Katmai National Park.
USGS/SARAH TRAIGER

Connecting the Dots: Using Multiple Datasets to Monitor the Brown Bear Population in Katmai National Park and Preserve

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Monitoring wide-ranging wildlife populations is challenging. Surveys are time consuming, expensive, and observation conditions need to be just right. But confidently assessing the number of animals, and if their numbers are increasing or decreasing is important for park management and ecological understanding. This article describes survey methods and how they can be combined for the most accurate estimates.

Citation:
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Measuring and monitoring wildlife populations can be challenging. Species can be wide ranging, and difficult to observe making studies costly and time consuming. These issues are even more challenging in remote places such as Katmai National Park and Preserve (Katmai), in Southwest Alaska. Katmai supports one of the largest brown bear (*Ursus arctos*) populations in the world and its mission is to protect the high concentration of brown bears, their habitat, and the salmon (*Oncorhynchus* spp.) spawning streams that sustain them. Researchers in this vast rugged region face numerous challenges while measuring ecosystem vital signs—indicators of the health and function of the environment.

Katmai, located in the Bristol Bay region of Southwest Alaska, protects over 4 million acres (1.6 million ha; an area larger than Connecticut) of prime brown bear habitat. Katmai is mostly a roadless and trailless wilderness that is only accessible by plane or boat. The remote location, lack of accessibility, harsh weather, and limited staff and funding make it difficult to measure and monitor wildlife populations, especially species such as brown bears whose ecology is complicated by long lives and multiple life stages.

Despite these challenges, staff at Katmai have collected and maintained several long-term non-invasive datasets of counts and observations. Each dataset monitors a different aspect of the brown bear population. However, many of these projects have yet to be contextualized as to how they relate to trends in the bear population. Now, researchers from Katmai, the U.S. Geological Survey Massachusetts Cooperative Fish and Wildlife Research Unit (MACRU), the National Park Service Southwest Alaska Network (SWAN), and the Katmai Conservancy are working together to estimate the status and trends of the brown bear population within the park. The resulting population, survival, and movement trends help managers ensure the park is successful at maintaining its mission to preserve and protect a high concentration of brown bears (ANILCA 1980).

About Katmai National Park and Preserve

Katmai National Park and Preserve is located along the Alaska Peninsula, with Bristol Bay and the Bering Sea to the west and the Pacific Ocean to the east. The area was established as Katmai National Monument in 1918 to preserve the site of the largest volcanic eruption of the 20th century. It was expanded in 1931 to protect brown bears and other wildlife (Norris 1996). In 1980, the monument was significantly expanded again and designated a national park and preserve as part of the Alaska National Interest Lands Conservation Act. Bear hunting is not allowed within the national park portion

Brown bears feeding in salmon streams in Katmai National Park and Preserve are counted by biologists in small aircraft like the one pictured here.
NPS/LESLIE SKORA

but is allowed in adjacent lands through state and federal hunting seasons and in the 308,000-acre (160,000 ha) Katmai National Preserve.

Most visitors access the park through commercial operators using small fixed-wing aircraft. Much of Katmai's visitation occurs where and when bears are congregating at food sources, which can lead to potential negative human-bear conflict. Katmai does not have permanent staffing in many areas, but staff may be sent out at key times to specific areas to help manage human-bear interactions.

There are three major drainages within Katmai: the Alagnak, Naknek, and Egegik rivers (north to south). Vegetation around these rivers varies from forest cover of alder (*Alnus* spp.), spruce (*Picea* spp.), birch (*Betula* spp.), and willows (*Salix* spp.) to tundra and open marshes and wetlands. During July, the temperature averages 55 degrees Fahrenheit (13.1 degrees C). Average precipitation is 2.3 inches (5.8 cm). During September, the temperature averages 47 degrees Fahrenheit (8.7 degrees C) with an average of 3.2 inches (8.1 cm) of precipitation (NOAA 2018).

Counting Bears

One of the ways Katmai has monitored brown bear abundance in remote areas is by counting bears during slow, low-altitude aerial reconnaissance surveys in fixed-wing aircraft. Katmai conducts two types of aerial surveys, distance sampling and stream surveys, that take advantage of different periods in the bears' life cycle. Katmai also gathers population information based on the recognizable bears that frequent Brooks Camp, a popular bear-viewing area.

Distance Sampling

Line transect surveys are used to estimate population density and size. Transects are randomly placed along contours throughout the study area. Researchers fly along the transects for set distances and note when bears are spotted. After passing the bear, they mark it with a Global Positioning System unit (GPS) so that they can measure the distance that animal was from the transect. Distance sampling analysis then allows researchers to estimate the proportion of animals present along the transect but missed during the survey because they were not detected. Animals that are farther away from the transect are usually more difficult to detect, so the number of bears seen will decline steadily if they are farther from the transect. By modelling the number of animals seen at different distances from the transect, researchers can estimate the number of animals that, on average, should have been seen at each distance. Researchers can then extrapolate the number of individuals seen and not seen in a search area to estimate total population size in the entire study area.

In 2004 and 2005, biologists from Katmai and SWAN began conducting distance sampling surveys (Olson and Putera 2007). They conducted surveys during late May through early June after bears had emerged from their dens but before leaves fully emerged each spring. During this period, bears are not congregated at salmon streams and are assumed to be more randomly distributed, reducing bias in abundance estimations. Researchers randomly selected 20-km-long transects following contours below 3,000 feet, an elevation at which snow and ice limit habitat availability. A pilot and observer team conducted surveys by flying a small tandem-seat, fixed-wing aircraft along each transect. The planes flew about 300 feet above ground level (agl). When bears were spotted, the plane left the transect to fly over the bears so a GPS point could be taken and perpendicular distance from the transect measured. The line transect surveys were conducted throughout Katmai. It required 5 planes flying simultaneously over a 2-week period with exceptional weather. The survey of Katmai (including Katmai Preserve) took 2 years to complete. Because it can be so challenging to complete surveys and bears can be hard to see, researchers combined survey years and assumed the bear population was closed to deaths, births, immigration, and emigration between those two study years. This assumption, while not perfect, allows researchers to gather enough detections for the analysis and can be used over short time periods while population level change is considered small.

During 2009, the aerial line transect surveys were repeated but just in Katmai National Preserve—a smaller portion of the park (308,000 acres). Only 2 aircraft were used to complete surveys during the 2-week period. The Katmai Preserve was chosen because there is a managed brown bear hunt, so estimating brown bear population size in this area is of particular interest to managers.

The next bear density estimate was completed in 2022, due to gaps in funding and staffing and the Covid-19 pandemic. Researchers from Katmai, SWAN, and MACRU coordinated efforts to conduct line transect surveys in the Katmai Preserve. The distance sampling data collected in Katmai Preserve from all 3 studies can be used to estimate, for the first time, trends in brown bear density in the Katmai Preserve.

Aerial Stream Surveys

Line transect surveys offer a standardized method to estimate population size and density, but this type of survey is costly and time-consuming, which leaves gaps in how often the surveys can be conducted (Thompson et al. 2010). Beginning in the 1970s, biologists at Katmai have opportunistically flown surveys and counted brown bears congregating along salmon spawning streams. Bears are relatively easy to spot along larger, open streams and survey efforts can be targeted to specific streams during times when bear abundance is expected to be highest. This reduces the need for multiple aircraft, and scheduling surveys can be more flexible when weather, pilot, observer, and aircraft availability align. Because of these factors, aerial stream surveys are easier to conduct and can be conducted more frequently. Katmai staff have regularly counted bears on specific spawning streams from 2013 onward with several decades of surveys done prior. The pilot of a small, fixed-wing aircraft and observer work together to spot bears congregating along salmon spawning streams and count how many bears they see. Surveys are flown, usually heading upstream, at around 300 feet agl.

Although these surveys allow for more flexibility in scheduling, the bear counts along salmon spawning streams have yet to be contextualized. Counts of bears can vary from week to week and from stream to stream relative to variations in the timing of salmon runs. The number of bears can also vary from year to year, which leads researchers to ask if there are differences in counts reflective of changes in bear population or of resource availability? In other words, if fewer bears were observed during a survey, was it because the population

Biologists preparing to fly transects during 2022 surveys of Katmai National Preserve.
NPS/LESLIE SKORA

Leslie Skora records data during a stream survey flight in Katmai National Park and Preserve.
NPS/LESLIE SKORA

Brown Bears feeding on salmon at Brooks Falls in Katmai National Park and Preserve.
NPS/LESLIE SKORA

decreased or because fewer salmon were spawning and fewer bears were fishing?

Biologists at Katmai and MACRU are using N-mixture modelling techniques (replicate counts, while the population of bears can be considered closed to changes in population abundance) to estimate the proportion of bears potentially missed during surveys and using decades of count data to measure seasonal timing of bears available to be detected along specific streams to estimate trends in annual brown bear abundance. These counts include bears that might temporarily immigrate or emigrate from the park, known as the superpopulation of bears using Katmai salmon spawning streams.

Brooks River Brown Bear Survival

Because salmon are abundant, bears in this region of Alaska tolerate each other and people in closer proximity than most other places. This tolerance creates a unique opportunity to view and study bears more closely than in other areas. At Katmai, biologists and trained technicians recognize individual bears congregating on salmon spawning streams season after season and year after year. Bears are identified by their unique physical features and individual behavioral characteristics. For example, in the photo with 5 bears at Brooks Falls, notice some bears have a lighter coat color than others. One of the bears on top of the falls has a large scar on his right hip and his ears are a lighter color than his coat. Even where the bears are fishing can help identify a bear. Usually only the most dominant bears, such as bear 856, fish in the bubbly white water below the falls, often referred to as "the jacuzzi." Similarly, only a handful of bears are successful at catching salmon from the top of the falls. Along Brooks River there have been over 200 bears described and tracked across multiple seasons and years. These are the famous bears of Fat Bear Week that are viewed by millions of people every year. Researchers are now using the sighting histories of these bears to calculate detection rates and survival.

Integrated Population Model

While advances are underway for each of these studies investigating bear density using line transect surveys in the Katmai Preserve, abundance of the superpopulation of bears using stream surveys, and survival of Brooks River bears using bear identification from fat bear week, there is still a gap in how density, abundance, and survival relate to the overall population of bears.

Katmai and MACRU researchers are now working to use these 3 datasets to estimate trends in the brown bear population using an integrated population model (IPM). An IPM is a cutting-edge statistical technique that uses the strengths of the different datasets and can allow for population estimates without invasive capture-based methods. By using the intermittent line transect survey density estimates as a base, researchers will add stream survey data to inform the model of the superpopulation of bears immigrating and emigrating annually due to varying food resources and habitat conditions. Finally, tracking the individual sighting histories of Brooks River bears will inform the model of annual brown bear survival rates.

This analysis represents a groundbreaking opportunity to deliver the first long-term perspective on how Katmai's brown bear population has changed over time. By leveraging existing datasets, researchers can uncover historical trends and patterns that inform both current management strategies and future conservation efforts. Ultimately, these efforts will equip managers with tools to fulfill the park's mission while ensuring effective monitoring of the ecosystem that sustains brown bears and their habitat.

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STUDENT RESEARCH

Incorporating Local and Indigenous Knowledge into Subsistence Management: A Katmai Caribou Case Study

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This article is an example of how the ethnographic documentation of local and Indigenous knowledge can help parks make more informed decisions. Small, resident caribou populations are important to subsistence communities. These populations are already under environmental stress, and people who depend on them have insights that can help.

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From 2020 to 2024, I conducted ethnographic research for my doctoral dissertation to document the ways in which caribou population decline, coupled with other environmental and regulatory stressors, challenges subsistence lifeways in the Bristol Bay region. This work focused primarily on a small population of resident caribou—caribou that stay in the same geographic area year-round—occupying the alpine tundra landscape in and around Katmai National Preserve (Katmai). Given their proximity to the preserve and deeply rooted ties to Katmai's resident caribou, I primarily worked with knowledge holders from Kokhanok and Igiugig, two village communities situated roughly 15 miles north of Katmai northern boundary, on the southern bank of Iliamna Lake. In this article, I summarize some of the local and Indigenous knowledge about caribou in Katmai that Bristol Bay residents shared with me and reflect on the application of that knowledge in existing regulatory systems.

My work on this topic was originally incited by concerns that the Bristol Bay Subsistence Regional Advisory Council (RAC) raised about a small population—currently around 425 animals—of caribou in Katmai. The RAC's concerns centered on the recognition thaft Katmai's resident caribou were managed as part of the Mulchatna Herd—the largest herd in southwest Alaska—when they may in fact be separate. This was a problem for subsistence hunters in Kokhanok and Igiugig because the Mulchatna Herd had crashed so dramatically that a hunting moratorium was implemented across the herd's historic range. By 2020, when I began my dissertation research, all caribou hunting in the area was closed under both state regulations and federal subsistence regulations. The RAC, highlighting the immense impact this closure had on the local subsistence economy, encouraged the National Park Service to document local and Indigenous knowledge on caribou in the national preserve.

To do this, we partnered with Kokhanok and Igiugig Village Councils to identity knowledge holders with expertise on the caribou in and near the preserve. Using ethnographic methods—semi-structured interviews, unstructured interviews, mapping exercises, and participant observation—we compiled a qualitative dataset that could be analyzed in regulatory contexts. Combined with biological data, primarily concurrent aerial surveys conducted by Katmai biologists, these data helped inform management decisions intended to protect both caribou and the subsistence lifeways of southwest Alaska.

Caribou Population Decline and Resident Herds

Caribou herds are primarily defined within Western management systems according to

A hunter from Kokhanok, sitting on his Honda, watches a small group of caribou through a rifle scope a few miles north of the Katmai boundary. The Mulchatna Caribou Herd hunting moratorium had prevented these hunters from catching caribou for over 3 years.
NPS/DILLON PATTERSON

calving ground fidelity (Skoog 1968). Caribou that calve in the same place year after year are generally considered a herd. Today, researchers, having access to better radio telemetry and genetic data, are beginning to rethink this relatively simple convention. These data show complex relationships between caribou herds in which individual caribou leave one herd to join another and whole herds split up, combine with other groups, or completely collapse (Hinkes et al. 2005, Joly et al. 2011, Colson et al. 2014). The volatility of caribou populations has caused some scientists to question the validity of the caribou herd construct altogether (Cronin et al. 2003, Mager 2012). Some researchers have suggested reframing caribou in terms of metapopulations, broadly defined populations spanning much larger regions than conventionally conceived herds (Hinkes et al. 2005). However, Colson and others (2014: 594) conclude after analyzing the genetic makeup and migration between herds in Southwest Alaska:

> Given the correspondence between herds and distinct populations, and the low rate of effective migrant exchange, we suggest that a metapopulation is not a completely accurate model of herd structure in [Southwest Alaska], as it fails to anticipate barriers to effective migration between herds. *Status quo*, herd-based management units appear to align neatly with regional structure.

Colson and others (2014) further note that the Mulchatna Herd has long been the largest herd in Southwest Alaska and one of the largest in the state. Peaking in the late 20th century, the Mulchatna Herd expanded well into the ranges of smaller herds, such as the Kilbuck Herd. Since the 1990s, however, the Mulchatna Herd's population has continued to decline. With that decline, the herd's range has also continued to shrink. As the Mulchatna Herd range narrows, there are small pockets of caribou scattered across southwest Alaska, like the resident population in Katmai. The current moratorium on caribou hunting in the region makes distinguishing between the Mulchatna Herd and these smaller populations far more relevant to subsistence communities than during times of caribou population booms. Some small populations appear to be remnants of the once-large Mulchatna Herd, while others are understood to be entirely separate herds that were adjoined to the larger herd in its expanded range. This case study highlights the importance of including local and Indigenous knowledge in responses to caribou population decline.

Since the closure of caribou hunting in the region in 2019, many locals have questioned the inclusion of Katmai's resident caribou population in Mulchatna Herd management decisions. Local caribou experts challenge the idea that the Katmai population is part of the Mulchatna Herd. Richard Wilson, a lifelong resident of the area and member of the RAC, explained the situation:

> *It's very necessary that people are able to utilize that* [Katmai] *herd. That herd is healthy and there's no reason not to. Besides what we've been trying to do is separate… that herd from the Mulchatna so it's not under the Mulchatna jurisdiction and it is now under Katmai's responsibility to look after this herd. And we're at a point now where we need this kind of information* [local and Indigenous Knowledge]. *And we need to get it down, and need to get it down quick, so these people can get back at the use of the resource here. Yeah, 'cause the state and the feds have fought long enough and we're trying to keep everybody on the right track and get it done* [reopen the hunt].

An Igiugig resident elaborated on the relationship between the two herds:

> *In the late 90s, a big piece of the Mulchatna Herd came up here. And they hung around here for about three years and then they left, but these guys* [the Katmai population] *stayed. They never went anywhere.*

Hunters in Kokhanok and Igiugig recall the Mulchatna Herd's peak as a time of abundance. During that period most hunters chose not to catch caribou in the Katmai Preserve because Mulchatna caribou were available much closer to the villages. Thinking back to the first time he saw the Katmai caribou population, one hunter from Kokhanok remembered the relative ease of catching caribou in years past:

> *When I first saw them* [Katmai's resident caribou], *must have been about 30 years ago. They were up there in wintertime. Me and my uncle, snow machining, were just driving around up there and I first saw them between Kukaklek Lake and Nonvianuk Lake* [in the preserve]. *That was about 30 years ago. I didn't shoot any there. But I didn't shoot any back then because that's farther than we normally go for caribou. I normally just… sometimes they'd be walking right by the house out here.*

Many hunters and Elders explained that since the Mulchatna Herd has become less available, there is an increased dependence on the resident caribou in Katmai. They spoke of the Katmai caribou as a distinct population that has existed at least back to the mid-20th century, when reindeer herding ended in the area (see Salmon 2014). While both Kokhanok and Igiugig hunters remember generations of hunters who observed and harvested caribou in the preserve, caribou hunting in the latter decades of the 20th century rarely occurred far from the villages. This was possible because the Mulchatna Herd, numbering well over 100,000 animals, would migrate through the Iliamna Lake region, often allowing hunters to catch caribou much closer to home. But prior to the Mulchatna Herd's peak in the 1990s, it was more common for hunters to travel further away from the villages, often to the preserve, to look for caribou. Regardless of these variable hunting patterns, both communities have maintained intimate relationships with the land now inside Katmai's boundaries as well as the caribou that live there.

Climate Stressors on the Subsistence Way of Life

Many of the knowledge holders I spoke to explained that climate change threatens the future of Alaska Native subsistence lifeways, particularly in terms of their ability to access wild foods like the caribou in Katmai. Food security is an increasing concern in many villages. And beyond immediate nutritional needs, climate change further threatens the transference of cultural knowledge and even the ability to continue living in rural Alaska. One hunter and lifelong resident of the area explained these challenges as he reflected on the relationship between climate change, caribou population decline, food security, and cultural preservation:

> *Some winters are really good here and others are really bad. And it seems like a lot of winters you might have really good snow for a while and then it's just gone. So, you can't rely on it. If I bought a new snowmachine this year, we probably wouldn't get any snow [laughs]…Winter is just more variable… When I grew up in Kokhanok, it was pretty much a given that the Iliamna Lake would freeze over. We had a dogsled team, and we'd go to the carnivals around the lake. They always had dogsled races and we'd just drive our truck across the lake to other villages. You could still do it, but it's not a guarantee.*

I asked how these changing winter conditions impacted the local subsistence economy. He responded:

> *Financially, you're buying more meat. In the past, if you couldn't get a moose during the moose season, you were generally able to get caribou. When I was younger down in Naknek, we could get, I think, five [caribou] per person [per year]. And so, it was like shopping. When the caribou were down here and you could be back in an hour with two caribou, you're only burning a small amount of gas. It's kind of like shopping, you know?*

This sentiment is shared by many in the Bristol Bay region. Caribou were once so prolific that catching them was a rather simple and quick endeavor. Caribou hunting when the Mulchatna Herd was at its peak required relatively few economic resources, like time and fuel, compared to moose hunting. Today, however, changing winter conditions make access to caribou far less predictable. Access issues, coupled with the inclusion of Katmai's resident population in the Mulchatna Herd hunting moratorium, created a situation in which the effects of climate change and regulation pose real threats to the subsistence lifeway in Kokhanok and Igiugig. One hunter described the cultural and spiritual impacts of climate change and the associated decline of caribou in Bristol Bay:

> *And it's not just for the protein part of it, but for the cultural aspects of it and the spiritual aspects of it. You're severely lacking when you go hunting at Costco for those two portions of it. And it's a real thing, it's hard to describe, but to go out and get your own caribou and your own moose, there's something fulfilling about that spiritually and culturally…. The caribou are an important part of that. There're parts of the caribou that are used for dance and things like that too, that you don't have access to anymore. When we used to get caribou, we'd bring one or two to the* [airplane] *hanger here and have some of the Elders come in and just watch us and help us skin them and butcher 'em. They would tell you what parts of the animals they used for making boots and things like that. And so, we've had a cultural revitalization program going on, including our Yup'ik dance group, Yup'ik language revitalization, and the caribou are part of that. And when the hunts are closed like this, we don't have access to that part of it.*

As climate change continues to reshape Alaska Native subsistence, the experience of caribou hunters supports the theoretical foundation of multispecies ethnography:

> a more-than-human approach to sociocultural anthropology that contends that we cannot adequately understand humanity in isolation from nonhuman species implicated in human life (Locke and Munster 2015: 1).

Alongside sustenance, Alaska Native culture, spirituality, locality, and identity are also at stake. This is why many Alaska Natives repeatedly emphasize the holistic nature of subsistence in regulatory meetings. Subsistence is not *just* about food. Subsistence is an entire lifeway, characterized by intimate relationships with the land, plants, fungi, spiritual beings, animals, and ancestors. Climate change, especially when coupled with slow-to-change or ill-informed harvest regulations, threatens the subsistence way of life holistically.

Regulatory Applications and Considerations for Future Management Decisions

Under the Alaska National Interest Lands Conservation Act (ANILCA; Public Law 96-487), the United Sates Secretaries of the Interior and Agriculture must prioritize subsistence over all other consumptive uses on federal lands in Alaska. To ensure this priority and "the continuation for the opportunity for subsistence," the secretaries have delegated authority to manage subsistence harvest to the Federal Subsistence Board (Board). The Board is thereby the decisionmaker for all proposals to change federal subsistence regulations. Operating on a bi-annual cycle, the Board accepts proposals to change fisheries regulations in odd years and wildlife regulations in even years.

Within this standard process, Igiugig Village Council submitted a proposal to the Board in 2023—for consideration during 2024 meeting—to re-open a caribou hunt for residents of Igiugig in Katmai National Preserve. The Office of Subsistence Management (OSM) analyzed the proposal, as it does for all proposals to change federal subsistence regulations, and recommended the Board adopt the proposal with the inclusion of Kokhanok residents. Because we had already systematically documented local and Indigenous knowledge on the resident population in Katmai, that information was available to the National Park Service, RAC, OSM, and Board throughout the regulatory process.

An aerial view of the Kukaklek Bench shows the area inhabited by the Kukaklek caribou population year-round.
NPS/DILLON PATTERSON

During its April 2024 meeting, the Board voted unanimously to adopt Igiugig Village Council's proposals as modified by OSM, delegating in-season management authority to the Katmai Superintendent, who now may open and close seasons, set sex restrictions and harvest limits, and broadly monitor the health of the resident population in regard to the "new" subsistence hunt. To some extent, the Board's adoption of the Katmai caribou proposal marked a shift in thinking about caribou herds in a climate-shifting Alaska. As I write this article in early 2025, it is far too early to measure the success of the Katmai hunt; however, it is worth highlighting now the importance of local and Indigenous knowledge in subsistence management broadly.

While the standard regulatory process offers many opportunities for tribal consultation and public comment, I suggest that the type of ethnographic documentation described here provides far richer and more nuanced qualitative data for the Board's consideration. Title VIII of ANILCA says that:

> the Secretary… shall undertake research on fish and wildlife and subsistence uses on the public lands [and] *seek data from, consult with and make use of the special knowledge of local residents engaged in subsistence uses* (emphasis added).

In this case, we were able to offer the Board both biological data and "specialized knowledge" shared by local subsistence experts. However, both types of information are not always available to the Board. In many cases, the availability of Western science data far outweighs that of local and Indigenous knowledge throughout the regulatory process.

This case study highlights the need for both biological and local/Indigenous knowledge in caribou management. Today, there are many other small caribou populations scattered across the historic ranges of once-large caribou herds. As many large caribou herds and their epic migrations dwindle, localized knowledge, often established through millennia of human-caribou relationships, is increasingly imperative to effective subsistence management. Here I offer an example of how ethnographically documenting local and Indigenous knowledge enabled managers to make more informed decisions about the management of a small resident caribou population.

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Flying over Kahiltna Glacier on May 25, 2024. Alaska has active glaciers with high accumulation rates. Here, the extensive crevassing extending up to the ridgeline indicates high strain rates caused by high accumulation. This is typical of the complicated topography and significant relief that is common on larger glaciers in Alaska.
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